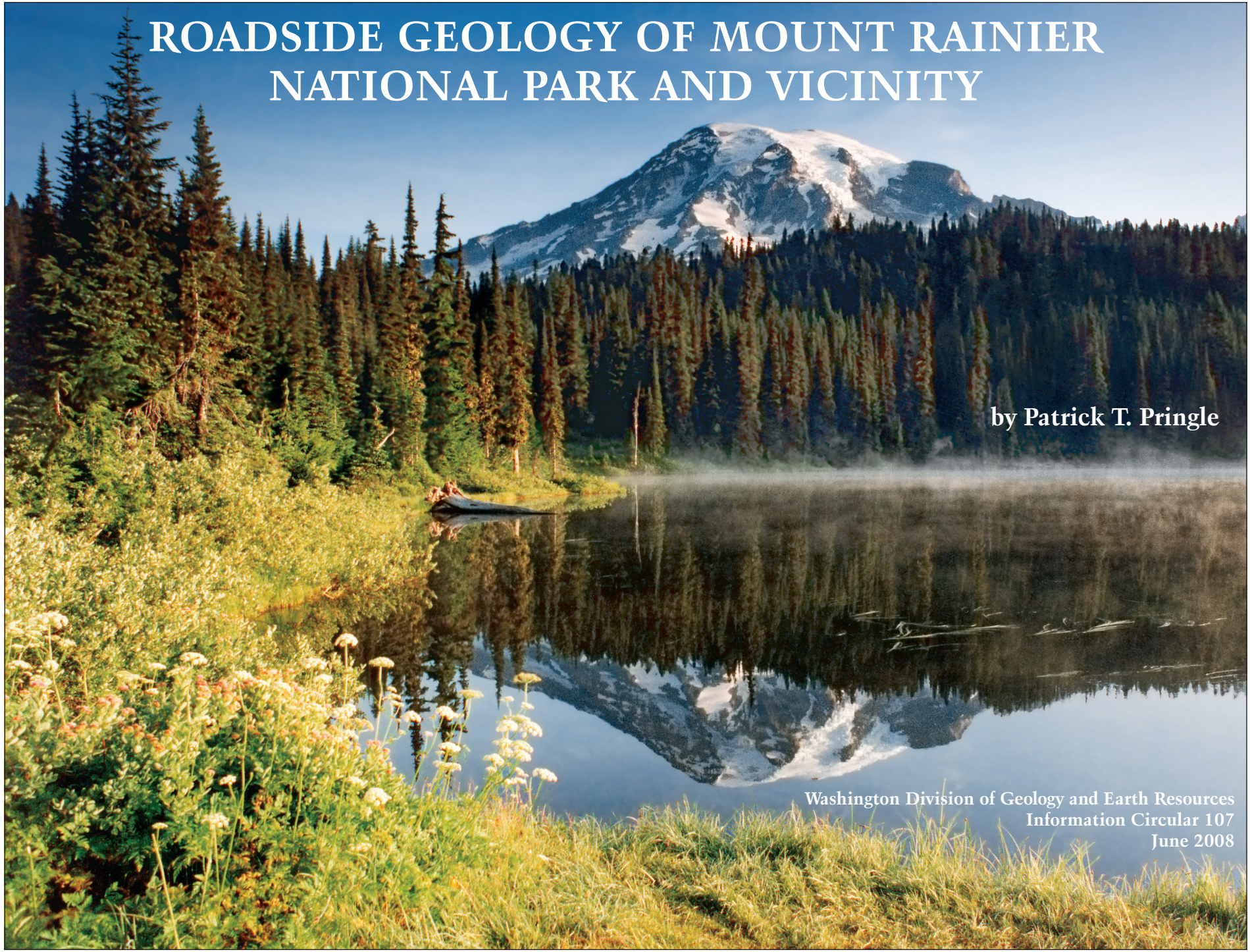
ROADSIDE GEOLOGY OF MOUNT RAINIER NATIONAL PARK AND VICINITY



by Patrick T. Pringle

Washington Division of Geology and Earth Resources
Information Circular 107
June 2008



Shaded relief map of the Mount Rainier area and adjoining Puget Lowland, southwest Washington Cascade mountains, and westernmost Columbia Basin showing Mount Rainier National Park and the location of various scenic routes (legs) of the road guide. The map was generated from 10-meter digital elevation data.

ROADSIDE GEOLOGY OF MOUNT RAINIER NATIONAL PARK AND VICINITY

by Patrick T. Pringle*
Washington Division of Geology and Earth Resources

with

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Washington Division of Geology and Earth Resources
Information Circular 107
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Front Cover: Mount Rainier and Reflection Lakes. The lakes sit on the deposits of a clay-rich lahar that began near the volcano's summit as an avalanche whose momentum carried part of it up over Mazama Ridge (behind the lake). Jim Vallance (USGS, written commun., 2002) interprets the age of the lahar underlying the lakes to be between 6,400 and 6,200 yr B.P. View is to the north. Photo taken Aug. 4, 1989, by Gayle Kuelper Putnam.

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Of all the fire mountains which, like beacons, once blazed along the Pacific Coast, Mount Rainier is the noblest.

John Muir, 1901, p. 30

PREFACE

This guidebook provides an interpretive overview of geology along many scenic highways leading to and around Mount Rainier. While the grandeur and beauty of Mount Rainier are known worldwide, its geological mysteries and complexities continue to unfold as scientists examine its cone and underpinnings and reconstruct its history from the layers left behind by past volcanic activity.

The dramatic and powerful eruption of Mount St. Helens in 1980 awakened our realization that other volcanic sentinels of the Pacific Northwest are capable of erupting and that ejected material and sediment-rich flows could travel great distances and easily reach cities and towns in valley bottoms far from the volcano. After Mount St. Helens, we could better recognize pyroclastic flow, debris avalanche, or lahar deposits and identify similar deposits on other volcanoes nearby. Suddenly these terms became part of our Pacific Northwest vocabulary. This new view of our geologic realities affected scientists too—those interested in the geologic and environmental history of this rapidly urbanizing region realized that they needed to know much more about the history and destructive potential of each volcano in the Cascade Range.

Mount Rainier is one such 'backyard' volcano that researchers have recently scrutinized—and for good reason. As demonstrated by the surprisingly large volume and mobility of its past lahars and frequency of its past eruptions, it may be one of the most dangerous volcanoes in this region. But Mount Rainier is neither the sole focus of this book nor the only geologic feature worthy of our interpretation and appreciation.

Mount Rainier sits at a geological pivot point. North-northeast of the volcano, a northwest-trending physiographic feature called the Olympic–Wallowa lineament and the White River fault zone mark a diffuse boundary, that is, an area of faults and folds that links the crustal blocks of the Cascade Range physiographic province with the distinctly different Columbia Basin to the east (see Fig. 5, p. 7, and Fig. 14, p. 18). Nearby and underneath Mount Rainier are older bodies of rock and sediment that have their own geologic history—a history of tumultuous eruptions and huge lava flows, devastating earthquakes, ice ages, giant landslides, and ancient geologic environments that sometimes differed greatly from those near Mount Rainier today.

This road guide is a compilation of the work of many researchers, several of whom continue their work at Mount Rainier or in the vicinity at the time of this writing. This guide relies heavily on the work of Dwight R. 'Rocky' Crandell, Donal Mullineaux, Richard Fiske, Cliff Hopson, Aaron Waters, Richard V. Fisher, and others whose pioneering efforts continue to provide an excellent foundation for our current and future studies. More recently, Tom Sisson, Jim Vallance, Kevin Scott, and Paul Zehfuss have added many new details to the geologic history of Mount Rainier. Mark Reid, Carol Finn, David Zimbelman, David Frank, David Lescinsky, and Tom Crowley have influenced our understanding of the hydrothermal alteration and structural aspects of the mountain; Carolyn Driedger, Andrew Fountain, Thomas Nylen, and Joe Walder have shed a new light on the recent activity of Mount Rainier's glaciers and glacial processes, and Seth Moran and Steve Malone have revealed much about the mountain's seismicity. Likewise, Paul Hammond, Don Swanson, Newell Campbell, Geoff Clayton, Russ Evarts, Rowland Tabor, Joe Vance, Tim Walsh, Bob Miller, Gary Smith, Keith Brunstad, Steve Reidel, Norm Banks, Brad Carkin, Jack Ellingson, Julie Thompson, and other geologists have added greatly to our understanding of the rocks in this part of the Cascade Range through a series of maps, reports, and theses.

I gratefully acknowledge the assistance of Jim Brazil, Tom Bush, Richard Easterly, Debra Salstrom, Bob Filson, Leslie Scott Pringle, Miriam Ballard Pringle, Tom Pringle, Adam Soule, Denise Thompson, Robin Smith, Rob Viens, Tim Walsh, Rusty Weaver, Ruth Wilmoth, Mike Bennett, Thomas Nylen, Jeff Witter, Anthony Harding, Eric Dingeldein, and others who participated in field work, and of Connie Manson, Stephen Harris, Lee Walkling, Rebecca Christie, Shirley Lewis, Diane Mitchell, Gary Reeves, Jack Powell, Ray Wells, Dee Molenaar, Ruth Kirk, and Daryl Gusey, who assisted me greatly with research contributions. Gary Ahlstrand, Roger Andruscik, Greg Burtchard, George Coulbourn, Ann Doherty, Paul Kennard, Loren Lane, Debra Osterberg, Jon Riedel, Barbara Samora, Darrin Swinney, Ted Stout, Gregg Sullivan, and Nancy Woodward of the National Park Service provided helpful assistance during various parts of this project, as did David Hirst of the U.S. Geological Survey.

Finally, I want to express my deepest appreciation to the researchers whose authorial contributions truly make this road guide a team effort: Newell Campbell, Rebecca Christie, David Frank, Wendy Gerstel, Paul Hammond, Dave Knoblach, Marv Lanphere, Beth Norman, Kitty Reed, Tom Sisson, Kevin Scott, Jim Vallance, and Tim Walsh. I am particularly indebted to Kitty Reed and Karen Meyers for their tireless, thoughtful, and valuable editorial suggestions. I am also very grateful to Anne Heinitz and Liz Thompson for their extensive GIS contributions and to Jari Roloff, who artfully worked on graphics and edited and formatted the final text. I thank Tim Walsh, Newell Campbell, Carolyn Driedger, Jim Vallance, Tom Sisson, Denise Thompson, Leigh Espy, Seth Moran, Eric Schuster, and Dave Knoblach for their reviews of portions of the text. The project was funded in part by a grant from the National Scenic Byways Program of the Federal Highway Administration. The grant was administered by the Washington State Department of Transportation. ■



Frontispiece. Mount Rainier volcano as a backdrop for artistic expression. An Asahel Curtis photograph of modern dancers from the Mary Wells School posing in the Sunrise parking area, Aug. 24, 1931. Washington State Historical Society photo 58587.

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But Mount Tahoma is single not merely because it is superbly majestic; it is an arctic island in a temperate zone.

in a letter "to the Senate and House of Representatives of the United States of America in Congress Assembled" by Hubbard, Powell, Willis, Muir, and Ritchie, June 27, 1894 (Meany, 1916, p. 291)

INTRODUCTION

Welcome to Mount Rainier National Park and the beautiful Cascade Range of south-central Washington. The legs in this road guide circumnavigate the majestic Mount Rainier volcano (Fig. 1) and cut across the southern Cascade Range from the Puget Lowland on the west, to the Columbia Basin on the east, following some of Washington State's Scenic Byways (see inside cover). Along the way, the geologically curious traveler can examine a wide variety of geologic features, including faulted and metamorphosed rocks older than the Cascade Range, as well as the faults, folds, and features of sedimentary and igneous rocks of the Cascades created before Mount Rainier was built. Roadcuts also reveal deposits of both continental and alpine glaciers, as well as the lavas and fragmental deposits of Mount Rainier (Fig. 2).

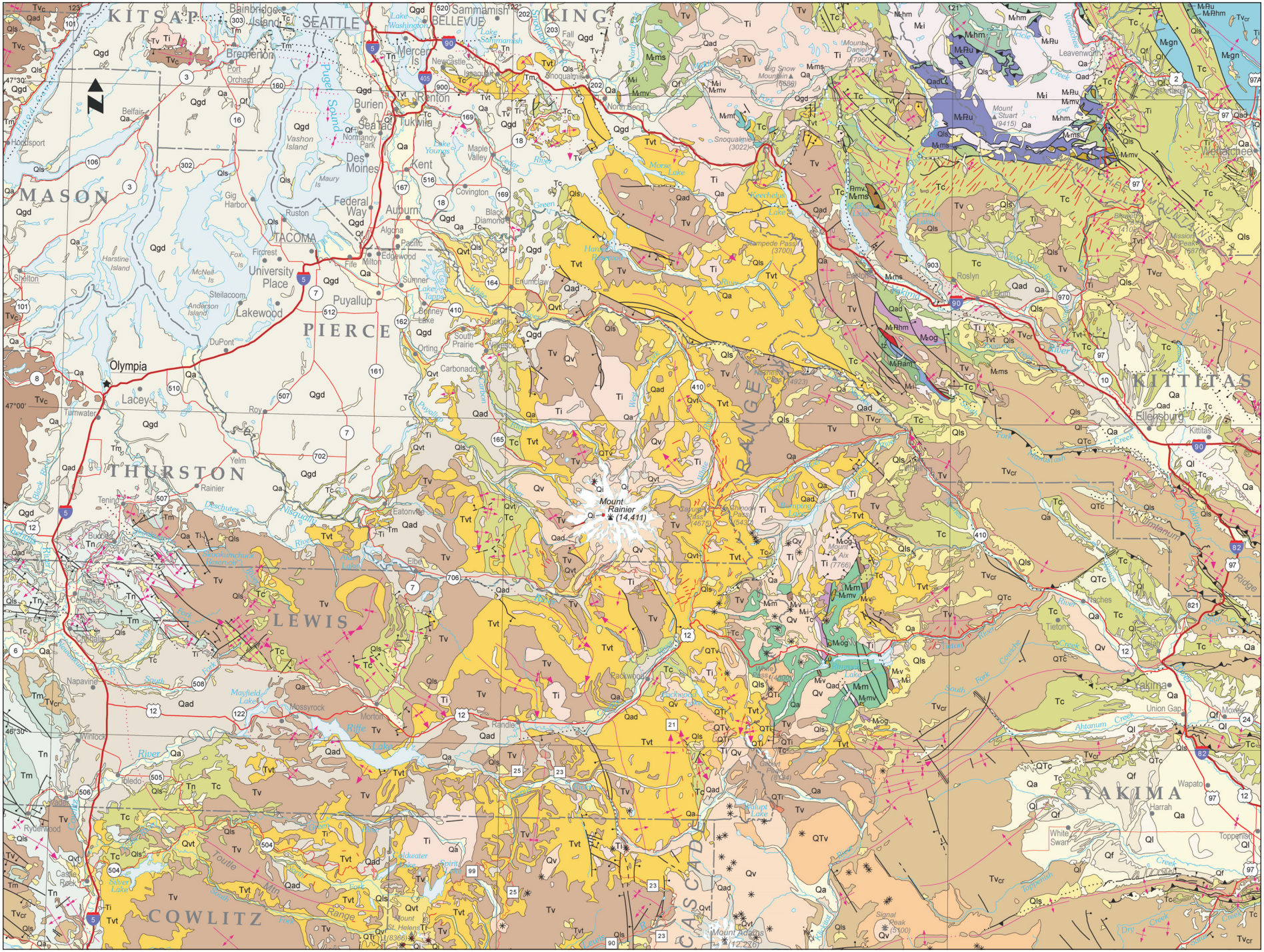
Mount Rainier is an active volcano in our backyard that poses great potential risk to the increasing population in river valleys downstream. Because of this, Mount Rainier was designated a Decade Volcano by the International Association of Volcanology and Chemistry of the Earth's Interior in 1992, one of 16 volcanoes worldwide so recognized during the International Decade of Natural Disaster Reduction. The main goal of Decade Volcano studies at Mount Rainier has been to better understand the volcano in order to reduce the deaths and societal and economic disruption that could result from inevitable future volcanic events. However, another goal has been to find out whether we can live safely near it with lessened anxiety if we better comprehend and take seriously this great peak's volcanic history.



Figure 1. Oblique aerial photo of Emmons Glacier and the east face and summit of Mount Rainier. Columbia Crest cone, the volcano's young summit cone (left), contrasts with its older, glacially gouged carapace, sectors of which have collapsed in the past, initiating lahars that flowed great distances from the volcano. Note the glacier's recent moraine and rock-covered snout. The dark feature in the center of Emmons Glacier downslope of the summit craters is a remnant of a lava flow that originated at Columbia Crest cone about 2450 years ago. The approximate age of this rock was determined using drill samples whose geomagnetic orientation was evaluated using secular variation (Jim Vallance and Tom Sisson, USGS, written commun., 2003). View is to the west. Photo taken by Austin Post, USGS, on Aug. 22, 1969.

In this book, we will review the geologic history, processes, and hazards of Mount Rainier and learn about revealing new research on the volcano and the rocks and geologic structures nearby and underneath it. We will also inspect the geologic evidence for lahars, which are probably the most important hazardous geologic phenomenon at Mount Rainier. Deposits of more than 60 postglacial lahars have been identified in the strata of the valleys that drain the volcano (Fig. 3). One of these ancient lahars, the Osceola Mudflow, is among the largest documented in the world. Along with later lahars and volcanic floods, the Osceola Mudflow radically changed the landscape downstream of the mountain.

This road guide describes and interprets the landscape and geologic features at diverse sites in Mount Rainier National Park and along highways that approach the park, including two that have been formally designated as Scenic Byways—State Route 410 and U.S. Highway 12. Primarily we will examine four aspects of Mount Rainier area geology: (1) the pre–Mount Rainier rocks and their history, (2) the glacial history and deposits of the area, (3) the history and activity of Mount Rainier volcano, and (4) the ongoing processes of erosion and landscape modification. We strongly recommend that this guide be used in conjunction with maps of Mount Rainier National Park available at visitor centers within the park and at certain stores outside the park.


KITSAP
KING
MASON
PIERCE
THURSTON
LEWIS
COWLITZ
KITTITAS
YAKIMA
CASCADE RANGE
SEATTLE
BELLEVUE
TACOMA
Olympia
Mount Rainier (14,411)
Mount Adams (12,276)
Bremerton
Bainbridge Island
Port Orchard
Renton
Kent
Auburn
Federal Way
Puyallup
Lakewood
University Place
Lacey
Tumwater
Yelm
Rainier
Eatonville
Elbe
Morton
Randle
Centralia
Chehalis
Napavine
Winlock
Toledo
Ryderwood
Castle Rock
Mossyrock
Ellensburg
Yakima
Union Gap
Wapato
Harrah
Toppenish
Tieton
Roslyn
Leavenworth
Wenatchee
Snoqualmie Pass (3022)
Stampede Pass (3700)
Naches Pass (4923)
Chinook Pass (5430)
Cayuse Pass (4675)
Mount Daniel (7960)
Big Snow Mountain (6588)
Mount Stuart (9415)
Mount Aix (7766)
Signal Peak (5100)
Mount St. Helens (8366)
Puget Sound
Lake Washington
Lake Sammamish
Lake Union
Lake Tapps
Lake Youngs
Lake Sawyer
Lake Kapowsin
Lake Wilderness
Lake Meridian
Lake Morton
Lake Sterns
Mayfield Lake
Alder Lake
Riffe Lake
Silver Lake
Spirit Lake
Walupt Lake
Clear Lake
Backwood Lake
Bumping Lake
Rimrock Lake
Tieton Reservoir
Keechelus Lake
Kachess Lake
Cle Elum Lake
Easton Lake
Morse Lake
Green River
Duwamish River
Puyallup River
Nisqually River
Deschutes River
Skookumchuck River
Black River
Chehalis River
Cowlitz River
Toutle River
Kalama River
Lewis River
Yakima River
Naches River
Ahtanum Creek
Wenas Creek
Manastash Creek
Taneum Creek
Swauk Creek
Teanaway River
Cle Elum River
Yellowjacket Creek
Peshastin Creek
Icicle Creek
Wenatchee River
Entiat River
Methow River
Okanogan River
Columbia River
Snoqualmie River
Skykomish River
Tolt River
Green River
White River
Carbon River
Mowich River
Ohanapecosh River
Cispus River
Tilton River
Klickitat River
Little Klickitat River
Rattlesnake Creek
Satus Creek
Toppenish Creek
Ahtanum Creek
Wide Hollow Creek
Dry Creek
Swauk Creek
Peshastin Creek
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Blue Buck Mtn (4100)
Mount Aix (7766)
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Signal Peak (5100)
Mount St. Helens (8366)
Mount Adams (12,276)
Hoodsport
Shelton
Belfair
Gig Harbor
Vashon Island
Maury Is
Harstine Island
McNeil Is
Anderson Island
Fox Is
Steilacoom
DuPont
Orting
Sumner
Milton
Fife
Fircrest
Algona
Pacific
Auburn
Black Diamond
Covington
Maple Valley
Des Moines
Burien
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Leavenworth
Cashmere
Peshastin
Dryden
Monitor
Tonasket
Omak
Okanogan
Brewster
Pateros
Methow
Twisp
Winthrop
Mazama
Concrete
Sedro-Woolley
Burlington
Mount Vernon
Bellingham
Ferndale
Lynden
Blaine
Sumas
Everson
Nooksack
Deming
Glacier
Maple Falls
Kendall
Acme
Lummi Island
Orcas Island
San Juan Island
Lopez Island
Friday Harbor
Anacortes
Oak Harbor
Coupeville
Port Townsend
Sequim
Port Angeles
Forks
La Push
Neah Bay
Clallam Bay
Sekiu
Joyce
Crescent Lake
Lake Ozette
Lake Pleasant
Beaver
Quillayute
Hoh River
Queets
Kalaloch
Ocean Shores
Westport
Grayland
Aberdeen
Hoquiam
Cosmopolis
Montesano
Elma
McCleary
Oakville
Rochester
Tenino
Bucoda
Grand Mound
Littlerock
Tumwater
Olympia
Lacey
Yelm
Rainier
Eatonville
Elbe
Morton
Randle
Centralia
Chehalis
Napavine
Winlock
Toledo
Ryderwood
Castle Rock
Mossyrock
Packwood
Ashford
Longmire
Paradise
Stevenson
Carson
North Bonneville
Cascade Locks
Hood River
The Dalles
Goldendale
Bingen
White Salmon
Trout Lake
Glenwood
Mount Adams
Mount St. Helens
Mount Rainier
Mount Daniel
Big Snow Mountain
Mount Stuart
Mount Aix
Signal Peak
Gilbert Peak
Mission Peak
Blue Buck Mtn
Naches Pass
Chinook Pass
Cayuse Pass
Stampede Pass
Snoqualmie Pass
Stevens Pass
Wenatchee
Leavenworth
Cashmere
Peshastin
Dryden
Monitor
Tonasket
Omak
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Brewster
Pateros
Methow
Twisp
Winthrop
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Concrete
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Mount Vernon
Bellingham
Ferndale
Lynden
Blaine
Sumas
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Glacier
Maple Falls
Kendall
Acme
Lummi Island
Orcas Island
San Juan Island
Lopez Island
Friday Harbor
Anacortes
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Neah Bay
Clallam Bay
Sekiu
Joyce
Crescent Lake
Lake Ozette
Lake Pleasant
Beaver
Quillayute
Hoh River
Queets
Kalaloch
Ocean Shores
Westport
Grayland
Aberdeen
Hoquiam
Cosmopolis
Montesano
Elma
McCleary
Oakville
Rochester
Tenino
Bucoda
Grand Mound
Littlerock
Tumwater
Olympia
Lacey
Yelm
Rainier
Eatonville
Elbe
Morton
Randle
Centralia
Chehalis
Napavine
Winlock
Toledo
Ryderwood
Castle Rock
Mossyrock
Packwood
Ashford
Longmire
Paradise
Stevenson
Carson
North Bonneville
Cascade Locks
Hood River
The Dalles
Goldendale
Bingen
White Salmon
Trout Lake
Glenwood
Mount Adams
Mount St. Helens
Mount Rainier
Mount Daniel
Big Snow Mountain
Mount Stuart
Mount Aix
Signal Peak
Gilbert Peak
Mission Peak
Blue Buck Mtn
Naches Pass
Chinook Pass
Cayuse Pass
Stampede Pass
Snoqualmie Pass
Stevens Pass

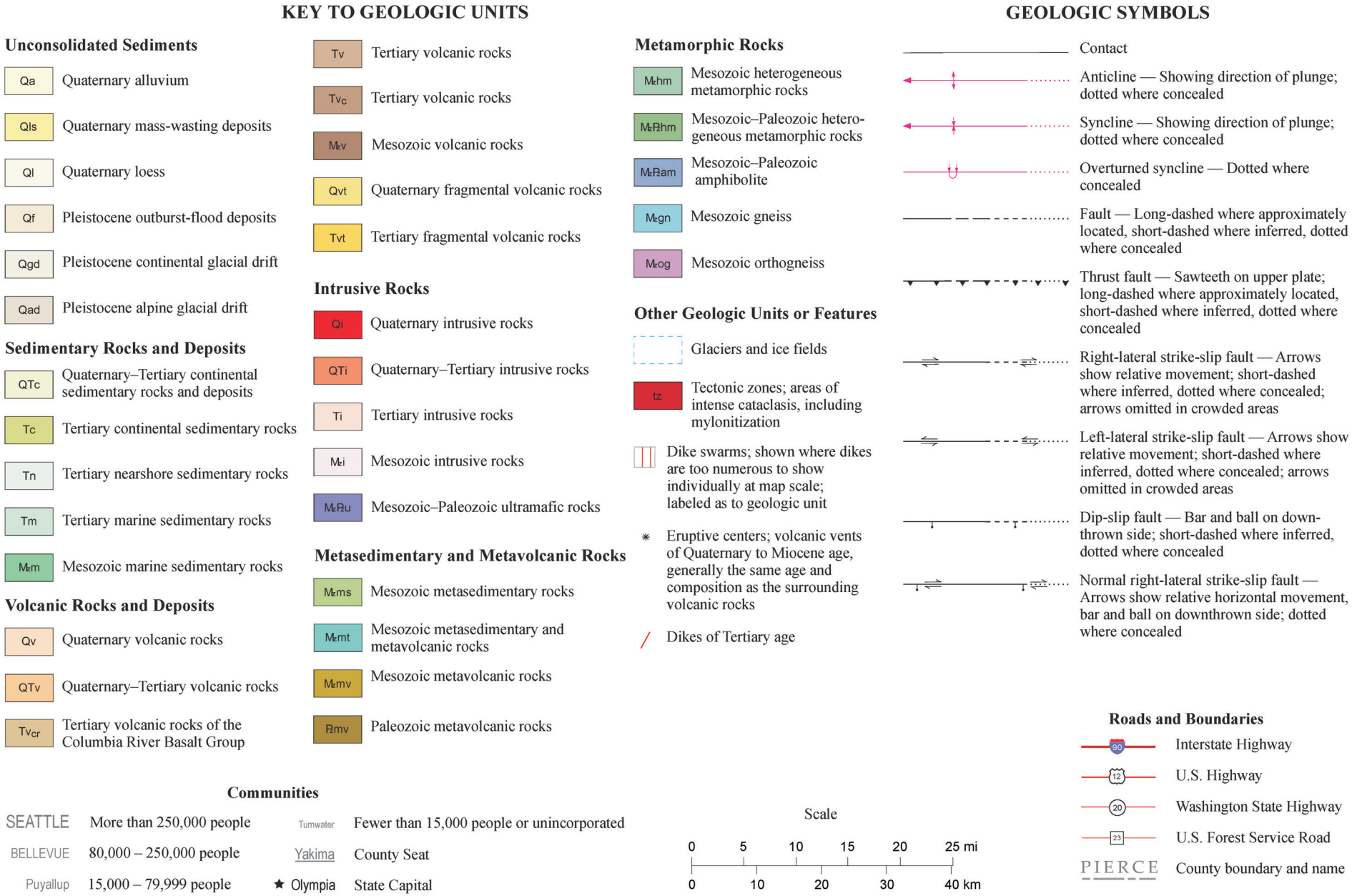


Figure 2. Simplified geologic map showing the geologic setting of Mount Rainier National Park. This map was taken from the "Geologic map of Washington State" (Schuster, 2005). Map unit contacts are approximate because the source maps were done at a smaller scale than that used in this figure. More detailed descriptions of the map units are given on page 185. Most map units contain or consist of one or more named units, and these are listed with the unit's description. The "List of Named Units" on page 188 links the formation or informal name to the map unit symbol, and thus to the unit description.

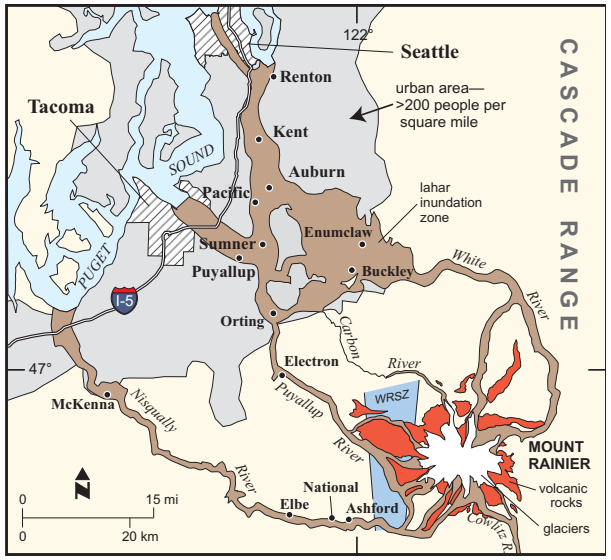


Figure 3. Areas inundated by lahars or laharic flooding (brown) from Mount Rainier in the past 6000 years. The Cowlitz River valley (lower right) was also flooded but is not shown. Hachured areas are city limits of Seattle and Tacoma; gray is the area of suburban development. Red areas are volcanic rocks of Mount Rainier; blue, the West Rainier seismic zone (WRSZ). After Sisson and others (2001).

HOW TO USE THIS GUIDE

The guidebook consists of three main parts: Part I is an introduction to the fascinating geologic history and processes of the Mount Rainier area; Part II is a road guide to the geology of Mount Rainier and vicinity along scenic and other highways; and Part III contains a list of references, followed by a glossary and other useful information.

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. In order to allow for flexibility in planning individual field trips, the guide is arranged into a series of approaches or 'legs'—mostly going toward Mount Rainier (see inside cover). Some of these follow one or several major roads designated as Scenic Byways to the volcano through neighboring mountains and valleys, and others follow minor routes. (See the listing of leg routes in Part II of the Table of Contents on page *vi*.)

Mileage. In each road leg, a mileage column enables travelers to determine the cumulative distance. To allow for differences in car odometers, many check points are included. Easily identified places, such as creek crossings, campgrounds, and road junctions, are noted. For those following the routes in reverse direction from that in the guidebook, sites will be referenced to highway mileposts whenever convenient (for example, MP 42).

If you take any side trips along the way, you'll have to keep track of and add those miles to all remaining mileages in the log. Having a pencil and paper handy, and even a calculator, will be helpful.

Directional system. Most points of interest away from the highway are indicated by an expression, such as "…on your right". If you are running the leg from the opposite direction, you need to reverse the direction and look to your left.

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). The exception is for information taken from scientific reports where the original measurements are metric; in these instances, the metric measurements are given first.

Geologic names. The geologic maps in this guide were constructed from Washington Division of Geology and Earth Resources data. The polygons depict the distribution of rocks by age and rock type—for example, unit Tv consists of Tertiary volcanic rocks. Throughout the book we refer to formations, that is, mappable geologic units of rock that may include several rock types. Formation names are considered formal in that they have been thoroughly defined and accepted by the geologic community; the part of the formation name that denotes rock type or geologic material is capitalized. The explanation for the geologic maps in the individual road legs has abbreviated descriptions of the various geologic units and symbols (see inside back cover). A map unit may cover the whole extent of a formation or may consist of part of a formation. (See p. 185 for more detailed unit descriptions and a list of formations included in the various units.) Also mentioned in this guide are informal units, for example, the Sun Top tuff, for which the rock type is not capitalized. These rock packages have not been defined and are used by geologists in a particular region as a convenient means of reference.

Table 1. Metric equivalents for English units. Unit abbreviations are in parentheses. To convert to metric units, multiply the number of English units by the metric equivalent, except for the temperature in degrees.

English unit	Metric equivalent
1 inch (in.)	2.540 centimeters (cm)
1 foot (ft)	0.305 meter (m)
1 yard (yd)	0.914 meter (m)
1 yard^3 (yd^3)	0.765 meter^3 (m^3)
1 mile (mi)	1.609 kilometers (km)
1 mile^2 (mi^2)	2.590 kilometers^2 (km^2)
1 mile^3 (mi^3)	4.168 kilometers^3 (km^3)
1 ton, short	0.907 tonne
degrees Fahrenheit (°F)	(°F–32)/1.8 = degrees Celsius (°C)

Table 2. Abbreviations used in text.

A.D.	anno Domini	Ma	mega-annum or million years (age)
cm	centimeter(s)		
ft	foot, feet	mi	mile(s)
FR	Forest Road	MP	milepost
hr	hour(s)	m.y.	million years (time span)
I-	Interstate Highway		
in.	inch(es)	s	second(s)
ka	kilo-annum or thousand years (age)	SR	State Route
		US	U.S. Highway
km	kilometer(s)	yd	yard(s)
k.y.	thousand years (time span)	yr B.P.	radiocarbon years before present (date); 'cal', calibrated with tree ring data
m	meter(s)		
mm	millimeter(s)		

Units of geologic time. Geologists use abbreviations to express geologic time. For example, Ma stands for mega-annum or million years. Points in geologic time, such as the upper and lower age limits of the Oligocene Epoch, are written as 23.9 Ma and 33.7 Ma respectively, meaning 23,900,000 years and 33,700,000 years (Fig. 4). Or a bed deposited in the Pliocene might have an age of 3.4 Ma (3,400,000 years). Spans of time, however, are indicated by the abbreviation m.y., again meaning million years. The Oligocene Epoch lasted about 9.8 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 expressed as thousands of years or as k.y. Table 2 is a quick reference for these and other abbreviations used in the text.

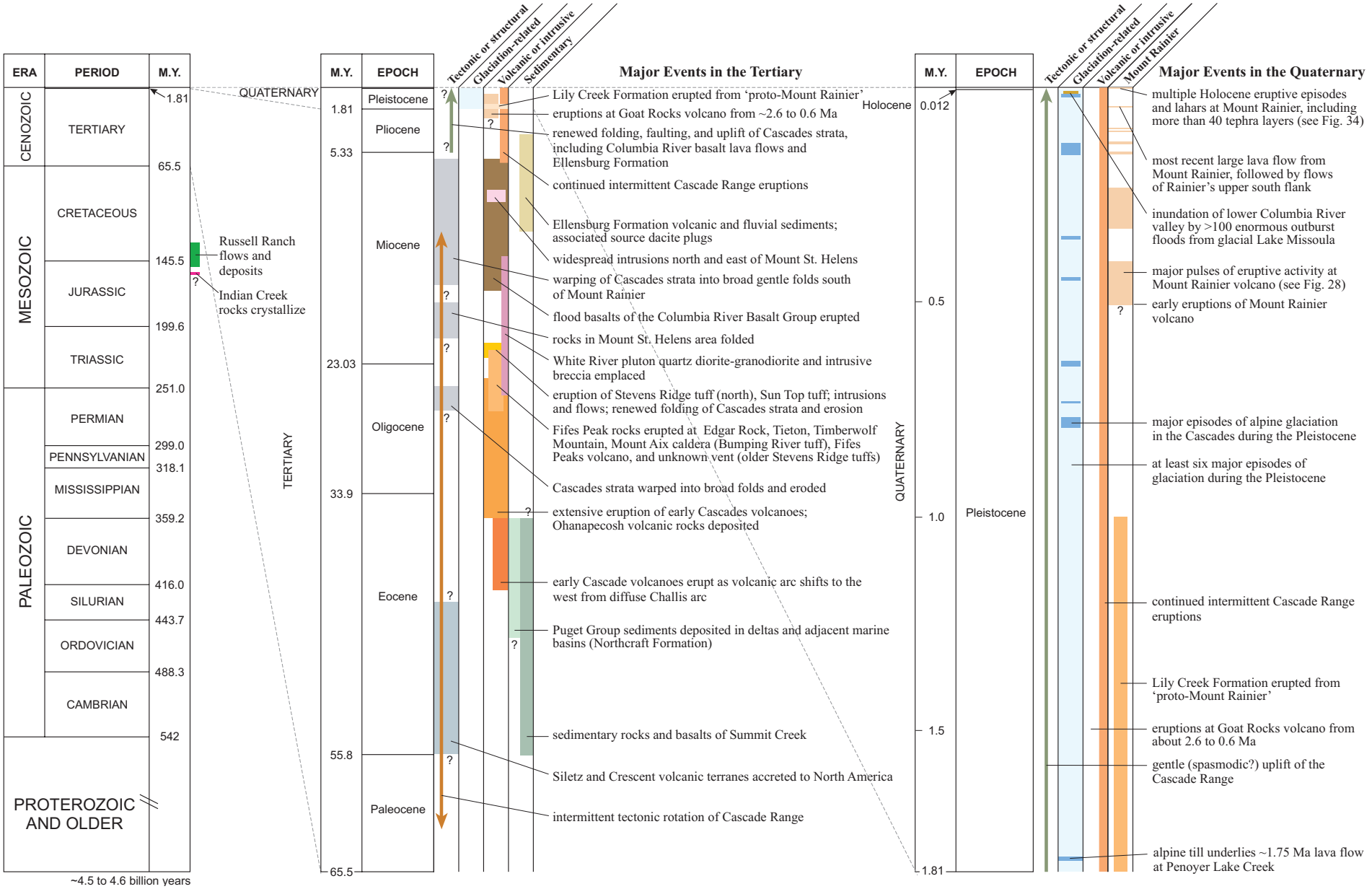


Figure 4. A simplified version of the geologic time scale showing major geologic events in the southwest Washington Cascades near Mount Rainier. The middle column is an expansion of the Tertiary, and the righthand column is an expansion of the Quaternary. The Holocene or Recent remains too small to show at this scale; the top of the righthand column is actually the present day. See Figures 28 (p. 31) and 34 (p. 37) for more information on the geologic history of Mount Rainier, including a timeline of eruptive episodes during the Holocene. M.Y., million years. The time scale used in this book is that adopted by the U.S. Geological Survey in 2007, published in USGS Fact Sheet 2007-3015 [http://pubs.usgs.gov/fs/2007/3015/].

The time scale used in this book is that adopted by the U.S. Geological Survey in 2007, published in USGS Fact Sheet 2007-3015 [http://pubs.usgs.gov/fs/2007/3015/].

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 defined as 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. For the sake of simplicity, raw (uncalibrated) radiocarbon ages are generally used in this guide; however, when a radiocarbon age has been calibrated with tree-ring data, the age will be given as 'cal yr B.P.' Ages for Mount St. Helens deposits laid down since A.D. 1479 and for selected Mount Rainier events are given in calendar years when these have been determined by use of dendrochronology (tree-ring dating).

Citation style. References to the literature are given in the text to show the source of published information. Those who may wish to delve more deeply into those sources can find the complete citation in the alphabetical list of references in Part III (p. 168). Most of the references can be found in the Washington Division of Geology and Earth Resources Library in Olympia, Wash., and in the online searchable database. (See "Websites and Phone Numbers", p. 176.) Newspaper sources can be located at Tacoma Public Library or other regional libraries. Original spellings are retained in all quotations.

Credits. Text and photos are by the author unless otherwise noted.

Glossary. A glossary of geologic terms is provided in Part III (p. 176).

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 friends, and let them do the navigating and reading while you drive. Rubbernecking to look at geologic features can be dangerous on the narrow, winding roads that lead to and traverse Mount Rainier National Park and the neighboring mountains.

Etiquette for visitors in Mount Rainier National Park. The national park is both a preserve and a natural laboratory. Professional and amateur scientists are studying geologic deposits, glaciers, ongoing geological and ecological processes, and other aspects of the park's flora and fauna. Please respect this landscape and the National Park Service regulations in your explorations. Please stay on designated trails and refrain from taking pumice, ash, rock, or plant samples from inside the boundaries of the national park. And always pack your litter out!

Entrance fees and seasonal access. Visitors who do not have a National Parks Pass must pay a modest entry fee to gain access to the national park. The road to Paradise is open much of the year. In the winter months, the road is plowed, and the Paradise Visitor Center is generally open on weekends. The Sunrise Road typically closes around the first week of October and may not open again until mid- to late June. Likewise, Cayuse and Chinook Passes generally do not open until late May and early to mid-June respectively.

Note: Gas stations are sparse in some areas, so it advisable to plan ahead for fuel.

PHYSIOGRAPHY OF THE SOUTHERN WASHINGTON CASCADES

> To one standing on the flanks of Mount Rainier, the surrounding crests and ridges appear like the waves of a turbulent sea. Although infinitely divers in sculpture, none conspicuously out-tops its fellows and, at a distance, all seem to merge into one vast platform.
>
> *Francois Emile Matthes (1916)*

> …rivers, augmented by local glaciation near their sources, have bitten well over 3,000 feet into the Cascade upland. The valleys are noteworthy because of the low, flat bottoms, the remarkably steep sides, and the extremely low gradient they possess up to within a few miles of the main divide. Adding to this decided relief, the upland surface is a maze of pinnacles, spires, knobs, and knife-like ridges which have been sharpened by small alpine glaciers. It is upon these rugged westward trending ridges and valleys that the cone of Mount Rainier is superimposed.
>
> *Howard Abbot Coombs (1935)*

The Cascade Range is a north-trending volcanic arc that runs along the western edge of the North American continent. The volcanoes of the Cascades extend some 780 mi (1300 km) from southern British Columbia in Canada as far south as northern California. While this volcanic arc includes some noteworthy young volcanoes, such as Mounts Hood, St. Helens, Rainier, Baker, and Shasta, older volcanic and intrusive rocks and some sedimentary rocks, mostly of Cenozoic age (<65 million years old), make up the bulk of the mountains in the southern Washington Cascades. Mount Rainier sits on a glaciated and eroded foundation of these older rocks, which were faulted and gently folded after deposition and, in some areas, slightly metamorphosed (to clay minerals) by hot fluids and pressure during the time they were buried. Erosion-resistant granitic rocks and some welded fragmental volcanic rocks compose many of the higher peaks in the vicinity of the volcano.

At the latitude of Mount Rainier, these mountains composed of older rock are a formidable topographic barrier. The average elevation of the surrounding peaks in the area is roughly 4920 ft (1500 m); however, many peaks are 5248 ft to 6560 ft (1600–2000 m) in height, and some, such as Cowlitz Chimneys, 6.7 mi (10.7 km) east of Mount Rainier, are as high as 7544 ft (2300 m). The width of the Cascade Range near Mount Rainier is approximately 69 mi (115 km), whereas slightly south of Rainier it is as wide as 90 mi (150 km).

The great height of Mount Rainier (14,410 ft; 4395 m) and of the adjacent Cascade Range peaks supports an extensive and richly diverse timberline parkland. While the forest line at Mount Rainier is generally at about 5200 ft (1585 m) elevation, scrubby alpine vegetation reaches as high as about 6800 ft (2073 m). The mountain's height and girth create a rain shadow on its east flank near Yakima Park, which results in less snow there and allows the timberline to extend to higher elevations in that vicinity (Arno and Hammerly, 1984). Mount Rainier and adjoining montane areas are so richly diverse floristically and bear so many ecological niches that the "arctic island" metaphor of early pioneering geologist Bailey Willis could be expanded to "arctic archipelago". Furthermore, the area's vegetation defies typical zonal or climate-related classification schemes because of the sheer variety of microclimates related to elevation and physiography, as well as the diversity of geology and the frequency of disturbances by volcanism and other geologic processes (Kruckeberg, 2002).

During the great Ice Ages of the Pleistocene Epoch, Mount Rainier and surrounding high-elevation Cascade Range peaks were the source areas of large glaciers that coalesced to form alpine ice caps and radiating valley glaciers that covered much of the montane landscape and occupied many of the modern-day river valleys of the Cascade Range. These glaciers profoundly sculpted the landscape, including some of the broad river valleys that at that time extended many miles outside the present boundaries of Mount Rainier National Park. The climate changes had their effects on the Mount Rainier area's ecosystems as well. Because the climate was colder, vegetation zones shifted, generally to lower elevations, in response, although ice-free refugia survived locally in places that remained above the glaciers (Pielou, 1991). Indeed, botanists have identified a refugium in the upper White River valley of Mount Rainier National Park as having one of the greatest numbers of tree species of any locale in the Pacific Northwest. It is amazing to ponder that certain species were able to maintain their footholds as climate fluctuated, ash from eruptions accumulated, and giant glaciers and lahars passed below.

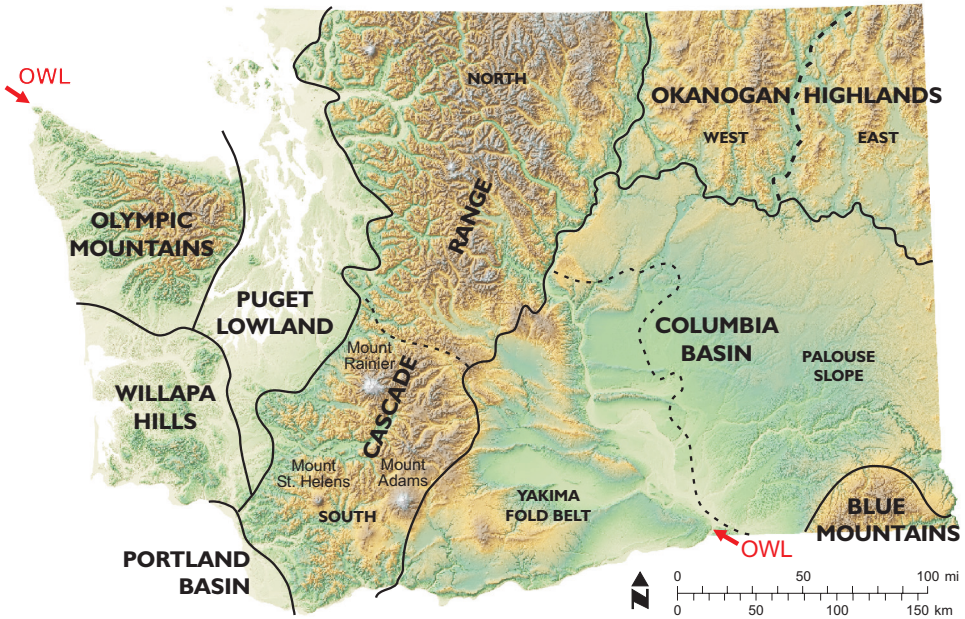


Figure 5. Relief map showing the physiographic provinces and subprovinces of Washington State. Red arrows show the general trend of the Olympic–Wallowa lineament or OWL.

The average distance from Mount Rainier to the crest of the Cascade Range to the east is about 15 mi (24 km). Because the Cascade crest or divide is to the east, all of the major river systems that drain Mount Rainier eventually flow to the west. Four of these, the Nisqually, Carbon, Puyallup, and White River systems, drain into Puget Sound, whereas the Cowlitz River system drains to the west-southwest into the Columbia River (see inside cover). During the Pleistocene, the upper reaches of all these valleys were greatly widened by huge valley glaciers originating at icecaps at and near Mount Rainier (Crandell and Miller, 1974). Additionally, all of these valleys have been partly filled by eruptions from Mount Rainier during its more than 500,000-year history, as well as by other volcanoes whose tephra has fallen over the area.

East of the Cascade crest, the Naches River system and its tributaries—the American, Bumping, and Tieton Rivers—head at various volcanic centers ranging from the early Miocene Fifes Peaks volcano (American), to the middle to late Miocene Ellensburg volcanic centers, to the Pliocene to Pleistocene Goat Rocks volcano (Tieton), to the still younger Tumac Mountain and Spiral Butte. The Naches River flows into the Yakima River at Yakima, which in turn flows some 105 mi (168 km) southeast into the Columbia River at Richland, Wash. Near the crest of the Cascades, erosion has stripped off the overlying younger rocks, revealing a mishmash of pre-Cenozoic rocks called the Rimrock Lake inlier, the oldest exposed rocks in the southwest Washington Cascades (see Fig. 14).

Rocks classified as granodiorites and, rarely, granites compose many of the most rugged Cascade peaks, such as those of the Tatoosh Range. These plutonic rocks rise in such majesty because they are harder and thus more resistant to weathering, mass wasting, and the chiseling effects of glaciers.

The Olympic–Wallowa lineament (OWL) is a major topographical feature that cuts the geologic fabric of the region in a southeasterly trend north of Mount Rainier (Fig. 5). Although the lineament seems coincident with some fault zones, it is not a continuous fault. Nevertheless, it and some of the features parallel to it, such as the White River fault zone (see Fig. 14), mark a diffuse boundary between the North Cascades and the southwest Washington Cascades, two distinctively different parts of the Cascade Range. These two main parts are different both because apparent greater tectonic uplift (and resultant erosion) has exposed older rocks to the north and possibly because the Olympic–Wallowa lineament may itself mark an ancient tectonic suture. The many tectonic terranes that characterize the North Cascades are a memory of its history of terrane accretion.

Oligocene or younger volcanic rocks can be found in the North Cascades, but in large part, they have been removed by erosion because of the greater amount of uplift in that region. In the southern Washington Cascades, the only visible evidence for terrane accretion is in the rocks of the Rimrock Lake inlier, because most of the older rocks are covered by a pile of younger volcanic rocks as much as 5 mi (7 km) thick.

The Puget Lowland physiographic province—a broad, glaciated trough—lies west of the Cascade Range and extends west to the Olympic Mountains (Fig. 5). The lowland may owe its existence to faults in the shallow crust that bound the Olympic and Cascade ranges, and that may, in turn, be influenced by much deeper faults in the subducting oceanic lithospheric slab some 30 mi (50 km) below the surface. The Puget Lowland trough channeled enormous continental glaciers that originated in the Canadian highlands to the north and is believed to have endured at least six glaciations during the Pleistocene Epoch (Easterbrook, 1994). The most recent of these glaciations was the Vashon advance of the Fraser Glaciation (Fig. 6). The main mass of the Vashon glacier reached the vicinity of Olympia, Wash., about 16,000 calendar years ago (Porter and Swanson, 1998).The ice advances and retreats produced humongous quantities of sediment that were transported into and through the lowland. The advancing glaciers shaped



Figure 6. Maximum stand of the Puget lobe, Cordilleran ice sheet, during the Vashon Stade of the Fraser Glaciation. At its maximum extent about 16,000 years ago, ice was about 5000 ft (1524 m) thick at Bellingham, 3500 ft (1067 m) thick at Seattle, and 2000 ft (610 m) thick at Tacoma. The ice had reached Olympia, and valley glaciers from Mount Rainier (not shown) extended many miles downstream of the National Park owing to expansion of glaciers in alpine areas. Glacial outwash from all the rivers draining Mount Rainier, except those of the Cowlitz River system, flowed into lakes dammed at the ice margin; overflow was shunted around the toe of the Puget lobe. The water then merged with meltwater from the Puget lobe, gathering all the drainage north and west of Mount Rainier into a stream near Eatonville that was about the size of the Columbia River at Grand Coulee Dam. Flow continued out to the Pacific Ocean via the Chehalis River valley. The Columbia has an average gradient of about 1 ft/mi (0.2 m/km); this steam had an average gradient of about 9 ft/mi (1.7 m/km). The direction of ice movement is indicated by the lines representing medial moraines on the ice surface. This figure shows the modern coastline, but when the ice was this far south, sea level was 300+ ft (~100 m) lower, and the coast then was 30 to 50 mi (48–81 km) west of its present position. Not shown are late Pleistocene ice fields or ice caps in the Cascade Range and Olympic Mountains. Redrawn from Cary (1966).

and streamlined the landscape with drumlins, and subglacial meltwaters carved deep linear troughs that we now recognize as embayments or filled embayments (Booth and Goldstein, 1994). After the ice receded, the troughs filled with water as sea level rose, but not before the glaciers and postglacial erosion had cut into the sediments, revealing many layers that recorded glacial and nonglacial geologic activity and even episodes of faulting.

GEOLOGIC HISTORY OF THE SOUTHERN WASHINGTON CASCADES

The physiography of the Mount Rainier area encompassed by this guide is itself a product of a rich history of geologic processes. Those who want to read more about the big geologic picture or find out about many of the geologic details can look to some good recent write-ups such as "Geology of the Pacific Northwest" by Elizabeth and William Orr (2001), or "The Restless Northwest" by Hill Williams (2002). Now, on to our focus on the geologic setting of the Mount Rainier area!

West of the modern Pacific coastline, the submarine volcanoes of the Juan de Fuca spreading ridge are actively creating new basaltic ocean floor (Fig. 7). On the east side of this spreading ridge, the newly created oceanic lithosphere, moving as a component of an enormous convection cell, collides with the North American plate, and then sinks—or subducts—beneath it at a rate of about 1.5 in. (3.5 cm) per year. At the same time, the entire Pacific Plate is moving north. Thus, the subduction that deforms Washington State is a complicated oblique collision that occurs in a northeasterly direction with the Juan de Fuca plate. The collision process contributes to strains that energize fault zones in the subducting slab of ocean floor, the shallow crust of the North American plate, and at the boundary between the colliding Juan de Fuca and North American plates.

Around the world, subduction complexes—continental margins where one tectonic plate meets with and sinks under another—can be characterized by an array of specific structural traits. For example, subduction gives rise to a chain of volcanoes or a volcanic arc. Likewise, a fore-arc basin is commonly situated between the subducting ocean-floor slab and the volcanic arc, whereas a back-arc basin sits behind the volcanic arc farther from the boundary between colliding plates.

Stratovolcanoes like Mounts Rainier and St. Helens, which are produced in such a volcanic arc called the Cascade Range, erupt along fault zones at the Earth's surface. These fault zones are situated directly above where the subducting oceanic crust becomes dehydrated as it reaches roughly 56 mi (90 km) depth. This is a depth at which partial melting of the subducting plate and of the overlying crust then gives birth to masses of buoyant magma that ascend through the crust along zones of weakness. Some of this magma eventually reaches the surface to erupt and form the many layers of tephra and lavas that comprise a stratovolcano.

The Cascade Range volcanic arc is bounded on the west by the Puget Lowland, a fore-arc basin. Interstate 5 runs through this basin; several of the routes in this road guide, such as Legs A, C, D, J, and K, begin in the Puget Lowland and take us across physiographic boundaries into the Cascades. The lavas of the Columbia River Basalt Group were erupted into a back-arc basin and lap onto the extreme eastern boundary of the southern Washington Cascades.

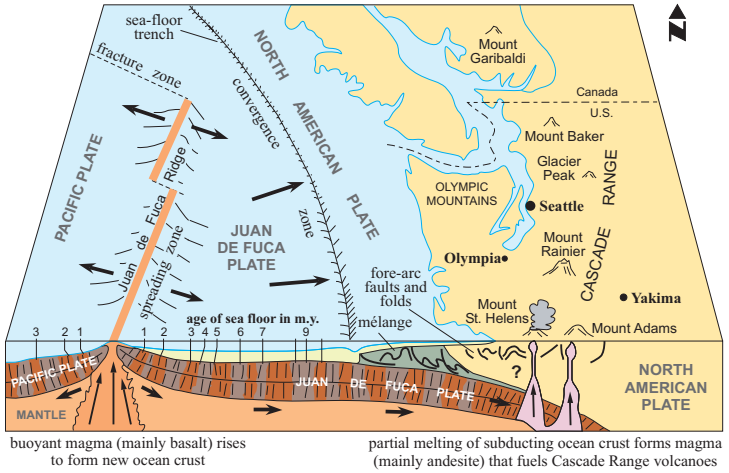


Figure 7. A diagrammatic cross section through the Juan de Fuca spreading ridge and the Cascadia subduction zone (the area from the trench east to where the Juan de Fuca plate sinks beneath the North American plate) showing the magnetic orientation of the sea floor recorded at the Juan de Fuca spreading ridge. Brown areas shown in the cross section of the sea floor indicate times when rock was created with a magnetic orientation of north; red-brown segments have reversed polarity. 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. The 'mélange' is a jumbled mixture of continental shelf blocks and oceanic sediments that is faulted and sheared at shallow depths in the subduction zone. The fore-arc folds and faults occur in a zone of crustal deformation between the subducting sea floor and the Cascade Range volcanic arc. Redrawn from Foxworthy and Hill (1982) and Uyeda (1978).

The Cascade volcanic arc has been active for about 27 m.y. The middle Tertiary volcanic rocks of the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations, upon which Mount Rainier rests, have long been documented as relicts of past volcanism. However, volcanic unrest is recorded in many other rocks as well; at times this past volcanic activity existed on a scale that dwarfed that of our modern Cascade peaks. For example, the Miocene Columbia River Basalt Group, covering the Columbia Basin east of and adjacent to the Cascade arc, includes some of the world's most extensive lava flows. The geologic history and rocks of each of these geologic groups and formations are summarized below in the section on the history of the pre– and syn–Mount Rainier rocks (p. 19)

In the immediate vicinity of Mount Rainier, the rocks of Tertiary age were gently folded along northwest-trending axes and then intruded by the Tatoosh plutonic complex granodiorite and quartz monzonite during early to middle Miocene times. Other intrusions are found in the Cascades east of Mount Rainier. Rocks of the complexly faulted, folded, and sheared Rimrock Lake inlier, which are exposed on US 12 near White Pass, are considerably older than their neighboring rocks to the west and east. Somehow, probably as a result of large-scale shearing, faulting, and folding, which assisted erosion, this block of older rock remnants has poked its head up through the cover of younger volcanic and sedimentary material. The Rimrock Lake rocks are described further on p. 19.

Geologists continue to discover new evidence about the history of the rocks in the Cascade Range. For example, geologist Paul Hammond (Portland State Univ., written commun., 2003) has mapped more than 30 volcanic vents that range in age between 12 Ma and 1 Ma in the Cascades east of Mount Rainier. Hammond and other geological detectives have found that sedimentary rock units such as the Ellensburg Formation (Smith, 1988 a,b) provide ample evidence of volcanism even where the volcanoes themselves have been largely eroded away.

At the site of the present Mount Rainier cone, an apparent hiatus in volcanic activity and plutonism of nearly 10 m.y. precedes the first evidence of a proto–Mount Rainier. Geologist Cliff Hopson first suggested that the Lily Creek Formation was a sedimentary relict of a progenitor of Mount Rainier (Fiske and others, 1963). The Lily Creek rocks are a sequence of volcaniclastic or fragmental volcanic strata whose extensive deposits are found in the Cascade foothills west of Mount Rainier. Sisson and Lanphere (1999) recently estimated the age of the Lily Creek Formation to be 1.3 to 1.2 Ma. Sisson also identified a correlative in-place lava remnant 1.03 Ma in age at Panhandle Gap (~13,000 ft; 3965 m) on Steamboat Prow at Mount Rainier.

MOUNT RAINIER'S HAZARDOUS GEOLOGICAL PROCESSES

What's past is prologue.

William Shakespeare, The Tempest (circa 1613), Act 2, Scene I

Modern Mount Rainier is the highest and third most massive volcano in the Cascade Range (Mounts Shasta and Adams are larger in volume). Until the late 1990s, we knew relatively little of the eruptive history, composition, and age of Mount Rainier volcano compared to most other Cascades Range peaks. Geologists Richard Fiske, Cliff Hopson, and Aaron Waters made the most complete description of the pre-Holocene volcanic history of Mount Rainier in their classic paper on the geology of Mount Rainier National Park (Fiske and others, 1963). Most of the Holocene history of Mount Rainier has been pieced together in greater detail through studies of its fragmental deposits—chiefly tephra, lahar, and glacial deposits (Crandell, 1963b, 1971; Mullineaux, 1974; Crandell and Miller, 1974; Scott and others, 1995). These studies continue, and every year we find out more about the mountain's past history.

Largely as a result of our rapidly growing understanding of the volcano's past eruptive history, many geologists now recognize "The Mountain" as potentially the most dangerous volcano in the Cascade Range, particularly because of the increasingly large population living along its lowland drainages (Fig. 3). These riparian areas are most at risk because of Mount Rainier's great relief and the huge area and volume of ice and snow on its cone (92 million m^2 and 4.4 billion m^3 [110 million yd^2 and 5.5 billion yd^3], respectively)(Fig. 8) that could generate lahars, or volcanic debris flows during eruptions (Driedger and Kennard, 1986). Lahars can flow rapidly along valleys for many tens of miles.

In addition, enormous (>200 million m^3; 260 million yd^3) collapses of clay-rich, hydrothermally altered rock debris from the cone that transformed into lahars have occurred at least seven times since the Mount Mazama (Crater Lake) ash was deposited (6,730 ±40 yr B.P.; Hallet and others, 1997). Among the most noteworthy of these large lahars were the Osceola, Round Pass, and Electron Mudflows (see Fig. 33). Mount Rainier's steep, glacially carved slopes, weak hydrothermally altered core, active hydrothermal system, bedding characteristics (thin lava flows and interbedded layers of fragmental debris generally slanting outward and down-

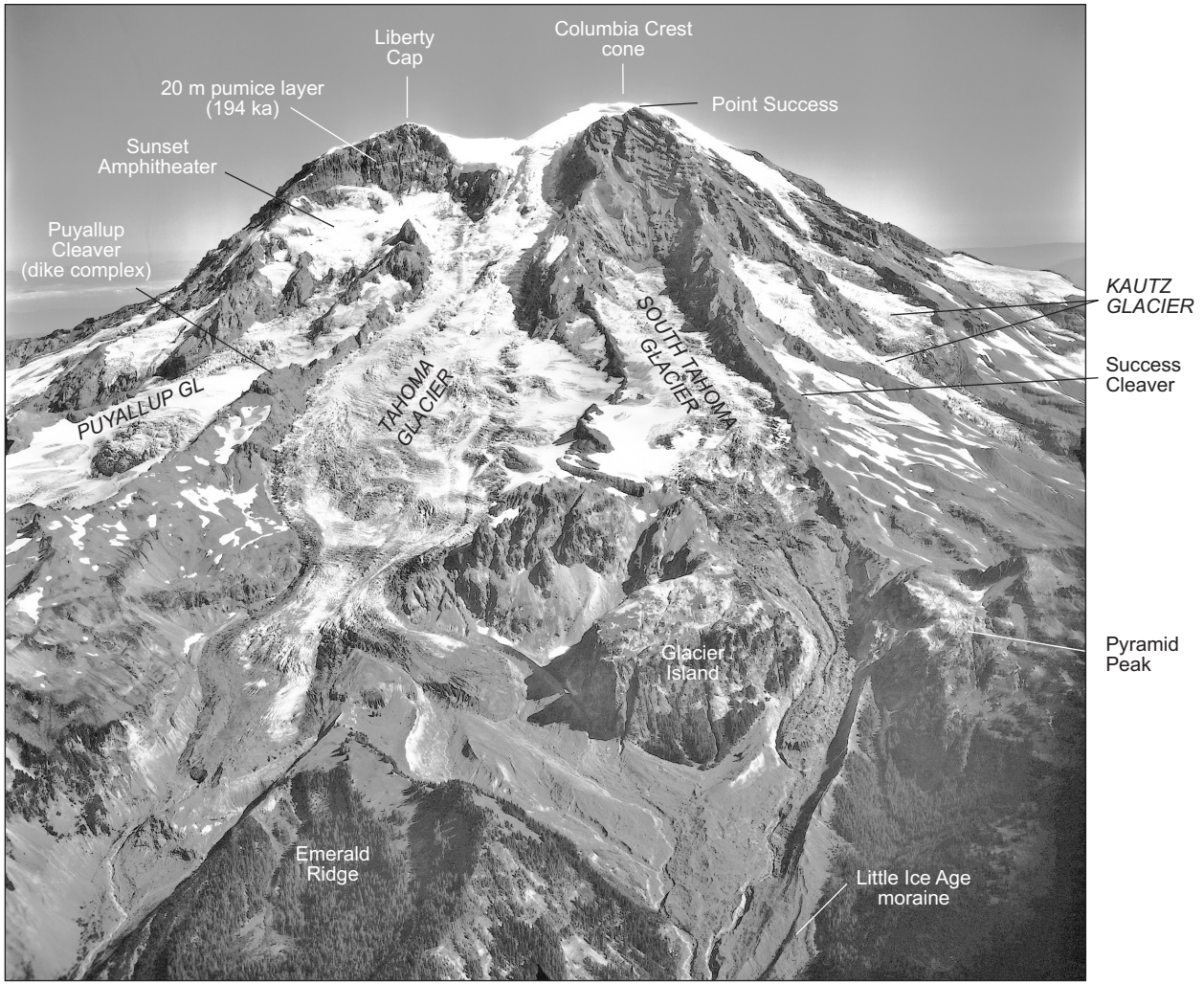


Figure 8. The impressive glacier-draped west flank of Mount Rainier. The Round Pass Mudflow (2,600 yr B.P.), a lahar about 1,000 yr B.P., and the Electron Mudflow (~A.D. 1502–1503) are major collapses that have eaten into this clay-rich upper portion of Mount Rainier. The Round Pass collapse breached the west crater wall left by the great Osceola Mudflow between Liberty Cap and Point Success, thus allowing andesitic pyroclastic flows to more easily spill down this flank of the mountain between 2,500 and 2,300 yr B.P. Geologists suspect that the Puyallup Cleaver dike complex, which was formed during a period of profuse eruptions from about 280 ka to 190 ka (Sisson and Lanphere, 1999), accelerated hydrothermal alteration and destabilization of the volcano's west flank when ground water interacted with hot magma. Both Emerald Ridge and Klapatche Ridge (out of view 1 mi [1.6 km] north-northwest of Emerald Ridge) are composed of lavas erupted from the Puyallup Cleaver dike system; however, Glacier Island and Pyramid Peak are composed largely of Miocene Stevens Ridge Formation rocks that underlie Mount Rainier. The positions of the Little Ice Age lateral moraines of the Tahoma and South Tahoma Glaciers (which once merged downslope of Glacier Island) show that these glaciers were significantly larger and extended more than a mile or kilometer farther downslope than they do today. The lowermost parts of the glaciers are covered with rock rubble. Glaciers not only help sculpt the mountain as they flow, but also are a source for ground water that plays a vital role in the eruptive and hydrothermal processes that shape the volcano. Photo by Austin Post, USGS, taken Sept. 18, 1967.

ward on dip planes), and exposure to pulses of tectonic or volcanic energy all make valleys surrounding Rainier vulnerable to future collapses. However, some valleys face a higher risk of these collapses. More details about noteworthy lahars in Mount Rainier's history can be found in the section on lahars that begins on p. 34. An aspect of these volcanic flowage processes that has surprised geologists—and that is vitally important to appreciate—is the great mobility of the past lahars and the repeated history of catastrophic downstream aggradation in valleys draining the volcano! Dramatic evidence for this lengthy history lies in forests buried by thick deposits of mud, rock, and sand, which have been found in every river valley downstream of the volcano.

MOUNT RAINIER—ACTIVE CASCADE VOLCANO

> Mount Rainier is an active volcano…
>
> *U.S. Geodynamics Committee (1994, p. 1)*

The above statement was made thematically in a National Academy of Science publication summarizing the Mount Rainier Decade Volcano workshop of 1992. As noted in this publication, the geological community had reached a clear consensus that Mount Rainier was an 'active' volcano. However, this classification has its limitations because Mount Rainier is obviously not erupting at the time of this writing. Therefore, perhaps we should more accurately describe the mountain as a 'dormant active volcano'. The American Geological Institute Glossary of Geology notes the lack of a clear distinction between active and dormant (Neuendorf and others, 2005). The Nuclear Regulatory Commission and other entities commonly have official or legal definitions of what is defined as geologically 'active'. For example, many define a fault as 'active' if it has ruptured within the past 10,000 years. Certain 'vital signs' demonstrate that Mount Rainier is active:

Seismicity: Mount Rainier averages 30 small earthquakes a year (mostly less than magnitude 2). These earthquakes are clearly focused in the plumbing system of the volcano.

Geothermal activity: Mount Rainier has fumaroles at or near the boiling point. Researcher David Frank measured temperatures as high as 180°F (82°C) at the east summit crater in 1994, and Francois Le Guern measured temperatures there as high as 187°F (86°C) in 1997 and 1998 (Le Guern and others, 2000). Because the boiling point of water at the summit of the mountain is about 187°F (86°C), the east and west crater rims are often snow-free within a day of snowstorm, and the bare summit rock is visible from as far away as Olympia, 60 mi (96 km) west-northwest of the volcano, suggesting an area of warm rock.

'Historical' activity: Mullineaux and others (1969) determined that a Mount Rainier tephra known as the 'X tephra' was probably erupted between A.D. 1820 and 1854, on the basis of the age of trees growing on the youngest neoglacial moraine on which the tephra occurs and the age of those on the oldest moraine on which it does not occur, respectively. (See mile 3.2 in Leg M, p. 156.) Ethnographic accounts suggest that the mountain was active around 1820 (Plummer, 1900), and there are some compelling accounts of eruptive activity in 1894 that were cited in the Tacoma and Seattle newspapers. Buried trees suggest inundation by debris flows or volcanic floods, certainly in Mount Rainier National Park and probably farther downstream about 200 years ago. (See details of the postglacial history of the Mount Rainier on p. 34.)

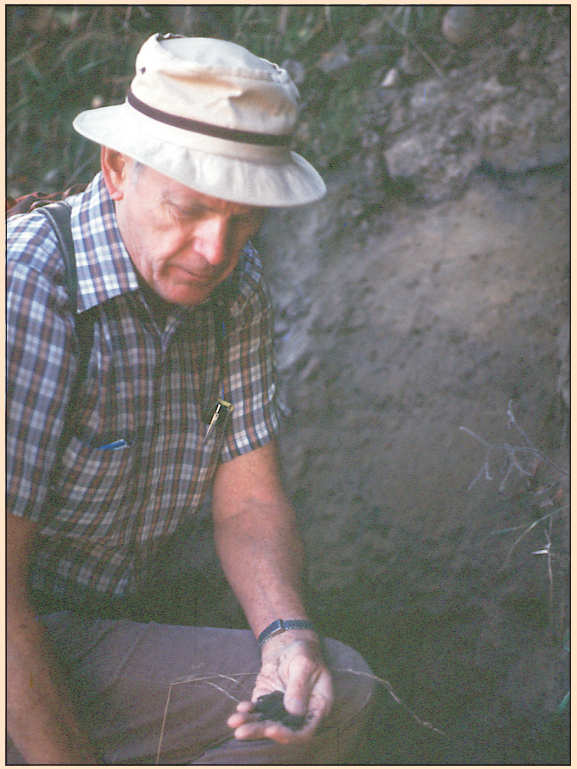
Late Holocene volcanic activity: By careful scrutiny of its deposits and discovery of numerous buried forests, several researchers have found that Mount Rainier has been much more active over the last 3000 years or so than previously thought. Much of this new information has only recently been published, such as in the selected abstracts in the 1999 Northwest Scientific Association proceedings of the Mount Rainier 100th Anniversary Symposium (Washington Division of Geology and Earth Resources, 2000) or in Sisson and others (2001).

Studies of tephra deposits by USGS geologist James Vallance and his colleagues Sue Donoghue and Jack McGeehin have revealed more than 40 eruptions took place in the past 10,000 years, including four or five between 2.7 and 2.2 ka, one about 1.5 ka, two about 1 ka, one about 500 yr B.P., and one in the early or middle part of the 19th century (the X tephra) that was also documented by Mullineaux and others (1969).

This rich evidence demonstrates that Mount Rainier has been active in recent geologic history, and thus geologists expect it to erupt again, perhaps even during the next century or two. ■

Rocky Crandell, Pioneering Geologist

One of the most important tasks for a volcanologist is accurately assessing the past history of a volcano. When U.S. Geological Survey geologists Dwight 'Rocky' Crandell and Donal Mullineaux began their pioneering studies of the fragmental deposits of Mount Rainier volcano in the late 1950s and early 1960s, they had to make interpretations about the nature of the volcanic processes responsible for the deposits, such as those left behind by lahars and pyroclastic flows, without having seen a volcano erupt! Their many discoveries about the mountain's complicated and often elusive past history created a solid foundation for researchers that followed. ■



Geologist Dwight 'Rocky' Crandell examines some sediment from a lahar deposit about 4 mi (6 km) south of Orting along the Puyallup River. In the background are deposits of the Electron Mudflow of about A.D. 1500 (above the hat's brim) and a lower sandy lahar that has been dated at 2,740 yr B.P. (Scott and others, 1995). 1991 photo.

PART I. GEOLOGIC HISTORY AND SETTING

EARLY INHABITANTS, ACCOUNTS, AND EXPLORATION OF THE AREA

…looking for stl' a'litu'd (magic power)…[a man] went to the mountain, T'qo'bdd…and began to climb…At the top of the mountain the man found a lake…Takobed said, 'you have come to stay one night so I can talk….you shall grow to be an old man…at the time of your death…my head will burst open and…the water…will flow down the hillsides'…The man died, and it was so…The head of T'qo'bdd burst open and the water rushed down…and swept the trees from the valley. The prairie about the town of Orting was called by us, swe'kW, which means 'open', because the flood cleaned it and left it covered with porous stones…

"The Young Man's Ascent of Mount Rainier" (first version), related by Tom Milroy of the Upper Puyallup tribe (Ballard, 1929, p. 143); [appears as "The Lake on Mount Rainier", p. 32 in Clark, 1953]

Archaeological studies, such as that by Mehringer and Foit (1990), have used radiocarbon dating to show that early American natives were established in Washington State by at least 11,000 yr B.P., during the time of the Clovis culture, and probably as early as 13,500 yr B.P. (Fiedel, 1999). In the Puget Lowland, artifacts found in 1972 beneath the Osceola Mudflow deposit (5000 yr B.P.; 5600 cal yr B.P.)(Fig. 9) provide evidence that people had an encampment or village in the area of Enumclaw before, and possibly at the time of, the humongous lahar (Williams, 1973; Hedlund, 1976, 1983). Most of the artifacts found by archaeologist Gerald Hedlund's group are composed of andesite and basalt, whereas later tools are more commonly made of chert, jasper, chalcedony, or even obsidian (Kirk and Daugherty, 2007). According to Hedlund (Green River Community College, written commun., 2004), who discovered the artifacts under the Osceola deposit, most are composed of Cascade rock material, although one piece of obsidian likely originated in Oregon.

Archaeologist Greg Burtchard of the National Park Service and his colleagues (1998) summarized archaeological findings at Mount Rainier National Park. They reported at least 30 sites within the park that collectively demonstrate that local tribes used the area, particularly alpine meadows, for at least 3400 years and possibly as many as 8500 years. One site, the Fryingpan rock shelter, was used between about 2000 and 900 years ago.

There is no doubt that heavy fallout of tephra had major effects on Mount Rainier–area Indian tribes and on the river systems on which these peoples depended for their livelihood. Mullineaux (1974, 1996) and Crandell (1971) have mapped the thickness and widespread distribution of Mount St. Helens pumice and ash in such localities as the Cowlitz River valley, particularly layer Yn, which was erupted about 3500 yr B.P. As an example of the severity of environmental disturbance caused by the thick tephra fallout of this paroxysmal eruption and later eruptions, archaeological surveys detected an apparent hiatus in American Indian settlements from about 3600 to 1600 yr B.P. where fallout was heavy and a probable corresponding increase in settlements in nearby plateau areas away from the fallout (north and east of Mount St. Helens) (McClure, 1992). The smaller eruptions of pumice and scoria from Mount Rainier would have had more localized effects.

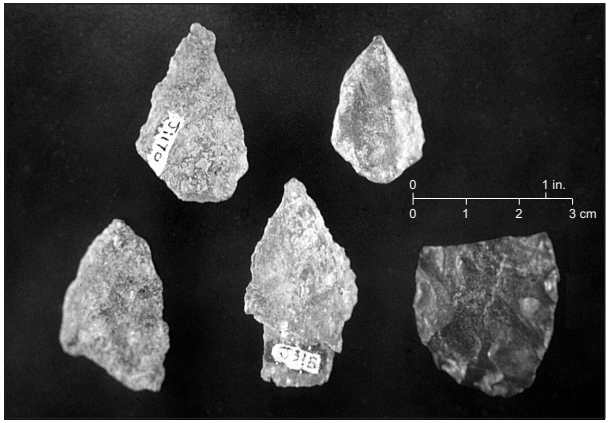


Figure 9. Several of the more than 200 artifacts found at the Jokumsen archaeological site near Enumclaw. These lithic artifacts include a broken scraping tool and several pieces that were possibly being made into arrowheads, but remained unfinished. According to Gerald Hedland, whose class excavated this site in 1972, many of the artifacts were fabricated from rocks found locally or in the Cascade Range. A geologist identified one of the artifacts as obsidian from Newberry Volcano. This site was buried by the Osceola Mudflow about 5600 years ago. Photo courtesy of Gerald Hedlund.

As noted in the section on lahars and volcanic disturbances (p. 34), the history of river systems that drain volcanoes is commonly dominated by landscape and ecological disturbances. These disturbances can drastically affect both the flora and fauna of a valley. After the 1980 eruption at Mount St. Helens, for example, a large herd of Roosevelt elk grazed on fireweed and other vegetation that were among the earliest successional species to become established in the upper reaches of the hummocky debris-avalanche deposit in the North Fork Toutle River. Elk footprints were even seen in the 1980 Crater during the mid-1980s! It is not too hard to imagine that at Mount Rainier, the so-called charismatic megafauna such as the elk would have taken advantage of the pioneering vegetation in lahar-disturbed stream valleys for decades following some of Mount Rainier's eruptions. Tribal peoples likely adjusted their hunting

and gathering techniques to take advantage of these temporary changes in habitat and flora distribution.

Legends and ethnographic accounts include those that relate Indian experiences with volcanism at Mount Rainier. The legend excerpt printed at the beginning of this section allegorically describes the Electron Mudflow, which inundated the Puyallup River valley from Mount Rainier's upper west flanks to at least as far as the town of Puyallup in about A.D. 1503 (on the basis of the author's provisional analysis of annual growth rings of trees buried by the lahar). Several legends tell of whales burrowing through the ground to cause the White River to flow south into the Puyallup River valley and then to Puget Sound (Ballard, 1929). The whales represent forces of great power and could describe the great Mount Rainier lahar or lahars that flowed along the White River and then into Puget Sound about 1100 to 1200 years ago both south via the Puyallup River valley as well as north via the Duwamish River valley. Alternatively, this tale could also represent the rupture of the Seattle fault, which no doubt shook this area heavily within a few years or decades after the lahar, as it raised the lowermost Duwamish River valley by as much as 20 ft (6 m) almost instantaneously.

In his paper "Recent Volcanic Activity" (1893), early Pacific Northwest scientist Frederick Plummer reported:

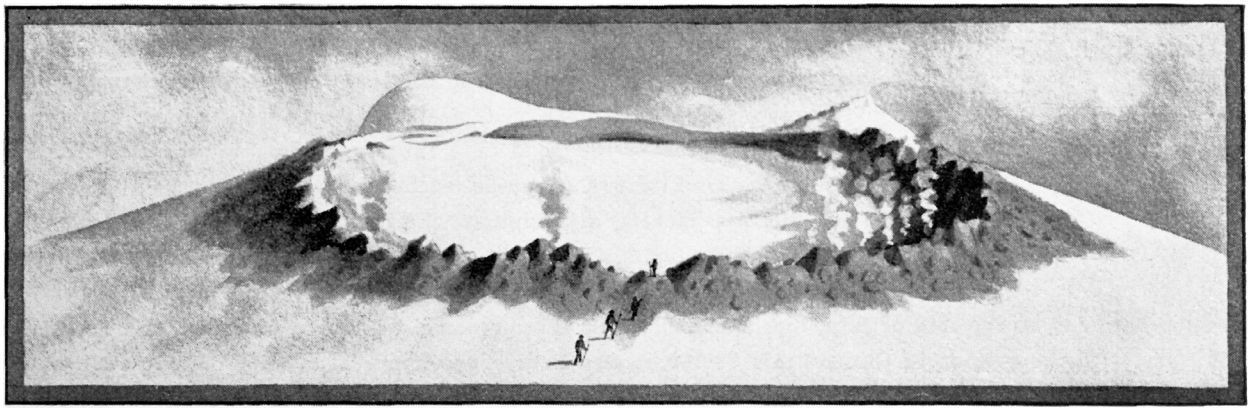


Figure 10. This illustration by C. C. Maring in Ingraham's "Pacific Forest Reserve and Mount Rainier" (1895) shows the active fumaroles of Mount Rainier's east crater in the late 1880s. View is to the northwest with Liberty Cap visible in the background above the crater rim on the right. Graphic reproduced by permission of Special Collections, University Archives, University of Washington Libraries.

> According to John Hiaton (now living) it was about the year 1820 that he witnessed an eruption of Mount Tacoma* [Mount Rainier], accompanied by fire, noise and earthquake. He had heard from older members of his tribe that this had happened many times…

Hiaton was a member of the Puyallup Tribe. An earthquake such as that described by Hiaton could have dislodged a landslide. Coincidently, a landslide–debris fan deposit along Tahoma Creek has been dated to about the early 1820s (on the basis of the author's tree-ring analysis of a Douglas-fir tree buried by the debris) and may be associated with this narrative. (See Leg M, p. 155.) Likewise, Hiaton's story may be describing the eruption of Mount Rainier's layer X tephra, whose age has been bracketed to between 1820 and 1854 by the use of dendrochonologic studies (Mullineaux and others, 1969).

HISTORIC ACCOUNTS OF ACTIVITY AT MOUNT RAINIER

One of the first European-Americans to visit Mount Rainier was William Fraser Tolmie, who became chief factor of Fort Nisqually in 1833. Tolmie visited the west side of what is now Mount Rainier National Park in August and early September of 1833 in search of medicinal herbs. He was the first non-Indian to record a visit to the mountain, traveling on horseback along the "Poyallipa" River and crudely describing the west flanks of Mount Rainier. Unfortunately, his account is poor in details, probably because it rained during much of his visit.

Author Stephen Harris summarizes many of the historic accounts of Mount Rainier eruptions in his classic books "Fire and Ice" (1980) and "Fire Mountains of the West" (2005). Harris tabulated more than 16 alleged eruptions between 1820 and 1994. According to Harris, a Yakama Indian named Saluskin reported that in 1855 he had guided two men to the east flank of Mount Rainier and that on their return from the summit they reported "ice all over...lake in center…and smoke…coming out all around like sweat house". Those who have visited the summit craters will appreciate this description as being accurate (Fig. 10).

Long-time Mount Rainier Naturalist Floyd Schmoe wrote "…actual record exists of feeble eruptions in 1843, 1854, 1858, and 1870" (Schmoe, 1925). Frederick Plummer, mentioned in the previous section, described activity at Mount Rainier beginning on Oct. 18, 1873. The fact that "clouds of smoke were seen pouring from the highest peak of Mount Rainier" hints that the "smoke" may indeed have been an ash and gas emission from the volcano, not unlike those that were commonly visible at Mount St. Helens throughout the early 1980s and that once again emanated from the volcano during the more recent eruptive activity that began in late 2004. Harris (2005) also reports that pioneer settler Len Longmire recalled "a series of brown, billowy clouds issuing from the crater in 1879 and again in 1882…" Plummer (1893) reported another eruptive disturbance on June 16, 1884.

John Muir, the famous naturalist who founded the Sierra Club, visited Mount Rainier in 1888 and climbed to the summit (Muir, 1902). While he did not witness eruptive activity, he was impressed by the youthful form of the two summit craters and became a strong advocate for the creation of Mount Rainier National Park.

> We remained on the summit…looking about us at the vast map-like views, comprehending hundreds of miles

* Mount Rainier was also called 'Mount Tahoma' or 'Mount Tacoma', anglicized versions of its American Indian name, 'Tacobet' or 'Tahoma'. Kirk (1999) has an informative discussion of the history of the name.

> of the Cascade Range, with their black, interminable forests and white volcanic cones in glorious array reaching far into Oregon; the Sound region, also, and the great plains of Eastern Washington, hazy and vague in the distance. Of all the land only the snowy summits of the great volcanic mountains, such as St. Helens, Adams, and Hood, were left in sight, forming islands in the sky. We found two well-formed and well-preserved craters on the summit, lying close together like two plates on the table with their rims touching…Sulfurous fumes and steam issue from several rents, giving a out a sickening smell that can be detected at a considerable distance.
>
> *John Muir (1902)*

One of the more controversial reports of historic eruptive activity at Mount Rainier concerns the eruption of 1894. Many eyewitness accounts of the activity were reported in newspapers such as the *Tacoma Ledger* and *Seattle Post-Intelligencer*. It is convincing that several of the eyewitnesses who were watching the mountain from different locations saw "smoke" issuing in a similar form and within the same time frame. All noted good visibility before the event.

> …every few seconds…a huge volume of smoke, quite dark in the center, shot up from the west rim of the crater, and then would die down again' [a few minutes past 6:00 am on Nov. 21st] …for over a half an hour she watched it…
>
> *Account by Mrs. S. B. Selmes of Seattle*
> *(*Seattle Post-Intelligencer, *Nov. 21, 1894, p. 8)*

> Great puffs of this smoke would come up at regular intervals of about fifteen seconds… They would rise in conical form…
>
> *Henry Surry, day jailer at Seattle Police headquarters [ca. 6:20 am on Nov. 21]*
> *(*Seattle Press-Times, *Nov. 21, 1894, p. 1)*

The above depictions suggest a phenomenon similar in appearance to a typical ash and gas emission such as those of Mount St. Helens in the 1980s (Fig. 11).



Figure 11. An ash and gas emission from the Lava Dome at Mount St. Helens, April 16, 1983. The emissions occur when superheated ground water flashes to steam in the volcanic vent and incorporates ash and rock debris as it escapes. Similar emissions were likely witnessed at Mount Rainier during the late 1800s. The Mount St. Helens 1980 Crater rim is about 1 mile (1.6 km) across. View is to the south.

GEOLOGICAL STUDIES OF THE MOUNT RAINIER AREA

EARLY GEOLOGIC RECONNAISSANCE OF THE REGION

> Mount Rainier is a typical example of a lofty volcanic cone built largely of projectiles, but containing also many lava streams…at one time the mountain was more lofty than it now is, its reduction in height being due to an explosive eruption which blew away the upper 2,000 feet of the original cone, leaving a great crater in the truncated remnant…at a more recent date, two small craters were formed by mild explosive eruptions within the great crater and nearly filled it. The rebuilding of these secondary craters partially restored the symmetrical outline of the top of the mountain, but gave to it a dome shape instead of a conical summit.
>
> *George Otis Smith (1897)*

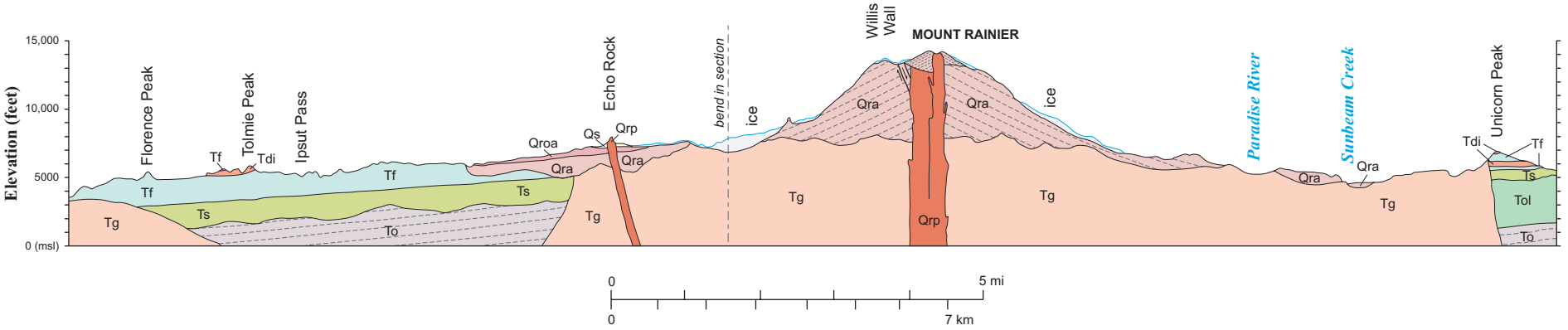
Geologists conducted early descriptive reconnaissance studies of the rocks and physiography of south-central Washington beginning in the mid-1800s. George Gibbs (1855) made an early reconnaissance of the area and described the rocks. Samuel Emmons (1871), representing Clarence King's 49th Parallel Corps, climbed Mount Rainier in 1870 to collect rock specimens and describe the glaciers. Hague and Iddings (1883) used Emmons's specimens to prepare a paper on Mounts Hood, Shasta, Lassen, and Rainier. Using chemical analysis and petrography, they described Mount Rainier as consisting mostly of hypersthene andesite and noted that the lavas of the other volcanoes studied were similar.

Late in the 19th century, Israel Russell and George Otis Smith studied Mount Rainier in more detail. Russell (1897) described most of the glaciers at Mount Rainier and wrote an exciting narrative of his trip to the volcano's summit area. Smith wrote about Mount Rainier's geology (1897, 1900) and about rocks of the Cascade Range east of Mount Rainier, including some of the earliest descriptions of the Goat Rocks area.

Francois Matthes wrote a detailed account of Mount Rainier's glaciers (1914) and published regular observations about their activity until 1946.

PIONEERING STUDIES OF THE MODERN ERA

Modern studies of Mount Rainier area geology began in the 1950s with the work of Richard Fiske, Cliff Hopson, Aaron Waters, Dwight 'Rocky' Crandell, Donal Mullineaux, and H. H. 'Hank' Waldron. Fiske, Hopson, and Waters (1963) produced the first detailed geologic map of Mount Rainier National Park. They described the pre–Mount Rainier rocks in great detail and discovered that a little more than 37 million years ago a chain of volcanoes had erupted in a coastal plain at the present site of Mount Rainier and sent mudflows and volcanic debris into the sea. These profuse eruptions produced a great thickness of debris, more than 10,000 ft (3000 m) in some areas. Visitors to the Mount Rainier area can see the greenish Ohanapecosh Formation, the remains of these eruptions, near the Nisqually Entrance (Leg A), along West Side Road (Leg M), SR 123 (Leg G), US 12 (Legs C and H), along Backbone Ridge (Leg B), and between Cayuse and Chinook Passes (Leg F). Fiske and his coauthors also described pauses in the eruptive activity; these were followed eventually by later outpourings of lava and volcanic debris, including the great explosive volcanic eruptions recorded in the Stevens Ridge Formation and the lavas and intrusive rocks of the Fifes Peak Formation. (See new information on these rocks in "27 Ma to about 22 Ma" on p. 23.) The Stevens Ridge eruptions discharged such large quantities of hot ash and lapilli that the sheets of volcanic debris melted together to form welded lapilli tuff. Some of these deposits are ex-



Qs **Surficial deposits (Quaternary)**—Alluvium, mudflows, and glacial deposits

Andesite of Mount Rainier (Holocene–Pleistocene)

Qroa Olivine andesite flows from Echo Rock and Observation Rock vents

Qra Hypersthene-augite andesite and minor olivine andesite in thick intracanyon lava flows and associated mudflows near base of volcano; thinner flows and interlayered breccia on upper slopes

Qrp **Mount Rainier plugs and dikes (Pleistocene)**—Central plug of opalized andesite in Sunset Amphitheater; satellite plugs of olivine andesite at Echo Rock and Observation Rock; radial dikes

Tg **Tatoosh pluton (Miocene–Pliocene)**—Central pluton and associated stocks of granodiorite and quartz monzonite; subordinate amount of quartz diorite; contact breccia and fine-grained border rocks

Tdi **Intrusive rocks associated with Tatoosh pluton (Miocene–Pliocene)**—Diorite, quartz diorite, granodiorite, and quartz monzonite porphyry; swarms of sills, dikes and irregular small intrusive bodies clustered mainly near borders of the Tatoosh pluton and associated stocks

Tf **Fifes Peak Formation (Oligocene–Miocene)**—Basalt, basaltic andesite, and andesite flows; minor rhyolite flows, ash flows, and tuff breccia; volcanic sandstone and siltstone of epiclastic and pyroclastic origin

Ts **Stevens Ridge Formation (Oligocene–Miocene)**—Rhyodacitic ash flows; subordinate amounts of volcanic breccia, sandstone, and siltstone of epiclastic and pyroclastic origin

Ohanapecosh Formation (Eocene)

Tol Local thick accumulations of basaltic andesite flows and lithified coarse mudflow deposits

To Volcanic breccia, sandstone, and siltstone of epiclastic and pyroclastic origin

Figure 12. A generalized cross section of Mount Rainier and selected basement rocks. The section trends roughly east–west through the cone and is slightly more than 20 mi (32 km) long. Modified from cross section D of Plate 1 in Fiske and others (1963).

posed along the Stevens Canyon Road about 1 mi (1.6 km) southwest of Box Canyon along Leg B and also along Legs D, F, and O.

Fiske, Hopson, and Waters further described how the Tatoosh granodiorite intruded the older rocks (Fig. 12). They estimated that the Tatoosh rocks were early Miocene to early Pliocene in age on the basis of relations with rock units of the Fifes Peak and Ellensburg Formations (Fiske and other, 1963). They also mapped Mount Rainier's lavas, which they named Mount Rainier Andesite, in greater detail than any previous studies and speculated on the age of the volcano and its most recent eruptions; however, they lacked defining radiometric ages.

Dwight R. 'Rocky' Crandell of the U.S. Geological Survey (USGS) started describing and mapping the deposits of lahars in detail in the 1950s. In a series of classic studies, Crandell carried our understanding of the volcano and its history to new heights. He was the first geologist to interpret the widespread deposits of rock and mud on the Enumclaw Plateau as those of the humongous Osceola Mudflow, which was generated when the summit of Mount Rainier collapsed and flowed as far as Puget Sound (Crandell and Waldron, 1956). His detailed descriptions and interpretations of more than 55 lahars provided the first indication that these slurries were a significant and potentially destructive volcanic process at Mount Rainier (Crandell, 1963a,b, 1971). In 1974, he produced the first map depicting the hazards from Mount Rainier volcano. Crandell also compiled a detailed map of the surficial deposits at Mount Rainier and, with geologist Robert Miller, produced a thorough description of the glacial deposits with a history of the Mount Rainier region (Crandell and Miller, 1974). In addition, he penned several fine descriptive articles, such as the "The Geologic Story of Mount Rainier" (1969a, revised 1983).

At about the same time Crandell was working in the Puget Lowland west of Mount Rainier, USGS geologist Donal Mullineaux was working slightly farther to the north, near Auburn. He too noted deposits of the Osceola Mudflow, including those that had spilled over from the White River drainage into that of the Green River. At Crandell's instigation, Mullineaux later began looking at the tephra deposits at Mount Rainier and compiled a report describing the pumice and pyroclastic deposits in Mount Rainier National Park (1974). Mullineaux noted ten pumice layers that he could associate with eruptions from Mount Rainier and eleven "exotic" tephra layers: ten from Mount St. Helens, and one from Mount Mazama (Crater Lake). From his studies of

the tephra layers, he not only learned of Mount Rainier's explosive eruptions, but also concluded that Mount St. Helens was a particularly explosive volcano. These observations about Mount St. Helens led both Mullineaux and Crandell to further study this young upstart volcano south of Mount Rainier. The observations and reconstructions of Crandell and Mullineaux are particularly impressive when we realize that they had not witnessed an actual eruption. They were able to reconstruct much of the history and flow dynamics of volcanic processes fairly accurately simply by studying the deposits these processes left behind on the flanks of the volcano, downwind, and in valleys downstream.

POST-1980 STUDIES OF MOUNT RAINIER VOLCANO

More modern studies of Mount Rainier began in the mid-1980s and continue today. Because of their observations at Mount St. Helens, geologists now not only realized the seriousness of the hazards at Mount Rainier, but they also have more experience interpreting flow history from the deposits on a volcano's flanks and in distal valley bottoms. The author is grateful to have participated in one such study with USGS geologists Kevin Scott and Jim Vallance (Scott and others, 1995). The team applied their knowledge of flow processes of lahars at Mount St. Helens to a reinterpretation of lahar deposits at Mount Rainier. While doing so, they found many new outcrops of laharic debris and used radiocarbon techniques to establish ages of forests and other organic debris that had been buried by the flows. The result has been an improved understanding of the behavior and triggering mechanisms of past lahars at Mount Rainier and a better idea of the probability and scale of future lahars. These studies have yielded a more accurate hazard assessment for Mount Rainier that is based on the probability of future events of a certain size and type, instead of on a relative hazards map that simply shows greater danger closer to the volcano.

While Scott and his team were examining lahar deposits during the early 1990s, USGS geologist Tom Sisson was conducting a serious study of Mount Rainier's lavas and fragmental debris. Sisson, like the aforementioned authors, used newer dating techniques to construct a detailed chronology of the mountain's activity. Sisson and collaborator David Lescinsky (Lescinsky and Sisson, 1998) also came up with a novel hypothesis regarding how some of Mount Rainier's thick lava flows were emplaced: the lavas were erupted adjacent to large valley glaciers and cooled against ice, which later melted away! Their model has broad application to other volcanoes that have been glaciated and to the understanding of the geomorphology of glaciated volcanoes.

Jim Vallance has re-examined tephra deposits described by Mullineaux and has identified more than 30 so-called "lithic-rich tephras", nearly all of which he infers are juvenile. He has associated those layers with lahars and pyroclastic flow deposits in drainage basins that radiate away from the mountain. (See "Lahars, Tephra, and Buried Forests" on p. 34.) His detailed analysis of the past eruptions in conjunction with ongoing studies of lahar stratigraphy has allowed him to construct a more accurate portrayal of past eruptions and has shown that the mountain was active for extended "eruptive periods" (see Fig. 34). Other geologists who have contributed details to the lahar stratigraphy since 1980 include Paul Zehfuss and Brian Atwater of the University of Washington, Joe Dragovich of the Washington Division of Geology and Earth Resources, Steve Palmer of Geodesign Inc., Marco Cisternas of Universidad Austral de Chile, and the author. The work of these researchers and others will be examined below.

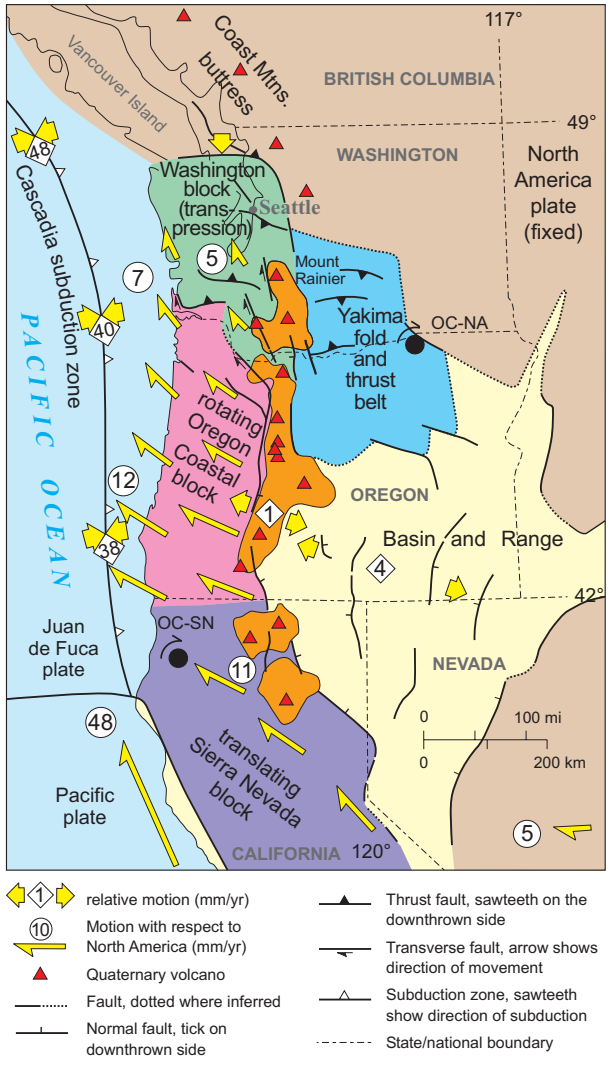
Other post-1980 studies, such as those by Carol Finn, Jim Crowley, and Mark Reid of the USGS and David Zimbelman of G. O. Logic, have examined the degree and extent of hydrothermal alteration at the peak and the stability of its steep slopes. Improved assessments of the location and extent of such alteration can enable geologists and planners to better forecast which valleys or areas would be most susceptible to clay-rich or cohesive lahars, the type that commonly begins as a collapse or failure of part of the mountain and can transform into a far-traveling lahar, such as the Electron Mudflow.

GEOLOGIC STRUCTURES OF THE MOUNT RAINIER AREA

In the early 1980s, geologists used the magnetic properties of the Cascade Range and coastal Pacific Northwest rocks and the history of their deformation from about 62 to 12 Ma to show that these rocks had not only been folded and faulted, but had also been rotated clockwise—in one place as much as 52 degrees (Wells, 1990). Geologists have now linked the rotation and shortening in these rocks to a northward migration of a fore arc along the coast having creeping rates averaging about 8 mm (0.3 in.) per year (Wells and others, 1998)(Fig. 13). The Eocene Puget Group sedimentary rocks and overlying Ohanapecosh Formation and other Oligocene rocks were warped into a series of northwest-trending folds during the Miocene. Evarts and Swanson (1994) constrained folding of the Cascade Range near Mount St. Helens to between 21 and 12 Ma on the basis of the tilting of intrusive rock bodies of known ages. Deformation and faulting continued, as shown by deformation of rocks younger than 12 Ma (Hammond, and others, 1994), and is evidently ongoing today as demonstrated by geodetic measurements. Reiners and others (2003) suggest most uplift of the Cascade Range postdates 15 Ma and that uplift near Mount Rainier may have occurred about 5 Ma (Reiners and others, 2002). Swanson (1997) noted that the gradient of the 80-km (50 mi)-long valley that was filled by the Tieton Andesite flow from Goat Rocks volcano is steeper than the gradient of the present Tieton River valley and that this could demonstrate uplift since emplacement of that flow. He also noted that near Oak Creek Wildlife Recreation Area on US 12 west of Naches, the base of the flow is very near present river level. While Swanson dated the Tieton Andesite at 1 Ma, Paul Hammond's recent Ar-Ar age for the flow is 1.64 Ma (oral commun., 2008), hence base level for this stretch of the Tieton River has not changed significantly in the last 1.0 to 1.6 million years.

Geologists continue to document young or active faults in the shallow or upper crust of the Pacific Northwest (Fig. 14). The faults are likely the result of the northward translation mentioned above and (or) other crustal deformation associated with plate movements. Some of these faults, for instance, the Seattle Fault, have ruptured, probably catastrophically, as recently as 1100 years ago. Others, like the St. Helens zone and the West Rainier seismic zone, are characterized by many small earthquakes (see Figs. 3 and 14). Submerged forests in some intertidal areas of the southern Puget Lowland probably record abrupt movement on faults in the Olym-

pia and (or) Tacoma areas (Sherrod, 2001). Some of these faults may have ruptured about the same time as, or more recently than the Seattle Fault. Researchers have questioned whether an earthquake on one of Washington's shallow crustal faults could trigger slope failures at Mount Rainier. (See "Seismicity" on p. 44.) In general, we have only a limited knowledge of the history of these shallow fault zones in the Earth's crust and thus are not yet able to definitively link seismic activity in these areas to specific lahar or mudflow events.



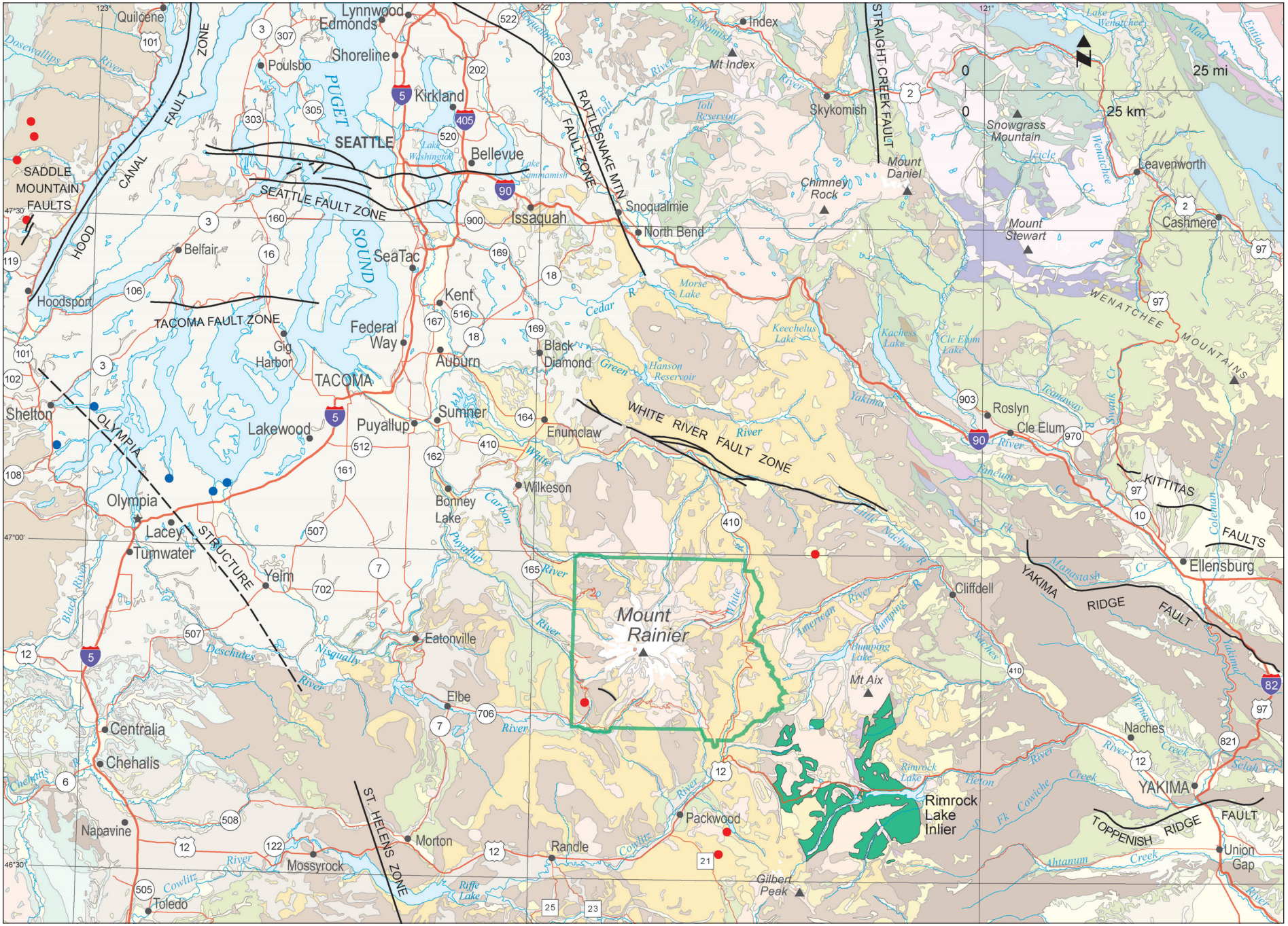
THE YAKIMA FOLD AND THRUST BELT

The Yakima fold and thrust belt is a group of roughly equally spaced anticlinal ridges in the westernmost part of the Columbia Basin of central Washington. In satellite view, these ridges look like rumples that form in a throw rug. They range from a couple to many tens of miles in length and in two places exceed 600 m (1969 ft) in height—Cleman Mountain (950 m; 3117 ft) and Rattlesnake Mountain (800 m; 2625 ft) (Reidel and Campbell, 1989; Reidel and others, 1989, 1994). Three of the Yakima folds lie within the area covered by this road guide: Bethel Ridge, Cleman Mountain, and the western part of Yakima Ridge (inside front cover). These three folds are in the extreme western part of the Yakima Fold Belt, where it merges into the Cascade Range. Geologists have tried to learn more about the ridges and to determine just how their formation is associated with the regional tectonic and (or) volcanic history—and they conclude that ridge formation is related to both (Reidel and others, 1989). In a broad view, the folds are a result of buckling of the Columbia River Basalt Group lavas in response to regional deformation. The Columbia River basalt's last 15.5 million years are of a transpressive nature—a glancing-blow collision in the slow motion of geologic time. The folding was in response to (1) the oblique subduction of the Juan de Fuca plate under the North American plate and (2) the shallow-crustal tectonic forces brought on by the dynamics of the coupling of the North American plate with the Pacific plate (Fig. 13). Many of the folds, particularly those in the interior of the fold belt, are thought to have formed as a reverse or thrust fault forced the rocks upward, but it has yet to be clearly demonstrated that faults core Bethel Ridge.

Figure 13. The tectonic setting of Cascadia. The Juan de Fuca plate is subducting along the barbed Cascadia subduction zone. The migrating Cascadia fore-arc terrane is divided into Washington, Oregon Coastal (OC), and Sierra Nevada (SN) blocks. The velocity of the tectonic blocks (yellow arrows) is calculated from a pole of rotation at point OC–NA (North America). The Oregon block is also rotating around pole OC–SN. The velocity of the Oregon Coastal block is calculated for post-Eocene time. The north end of the Oregon block squeezes the fore-arc area of Washington (green) against the buttress-like mass of crystalline rocks in the Canadian Coast Mountains. This causes north–south compression, uplift, thrust faulting, and consequent earthquakes. The orange areas are volcanic rocks of Quaternary age. Modified from Wells and others (1998, 2002).

From looking more closely at the fold structures, can we see if they are connected with the Olympic–Wallowa lineament (OWL) and (or) the northwest-trending fault zones along the White River and the upper reach of the Naches Rivers? Can we learn something about the structural history of the lineament and the north-trending Straight Creek fault to the northeast by looking carefully at these folds and nearby faults? Do the lineament and associated faults include remnants of a tectonic suture that is many tens or even hundreds of millions of years old? Geologists have mapped and interpreted differences in the pattern and structure of the folds north and south of the OWL (Hooper and Conrey, 1989; Campbell, 1989). Some folds south of the lineament, such as Bethel Ridge, tend to trend somewhat southwest, while those to the north, such as Cleman Mountain, tend to be oriented to the northwest. The Bethel Ridge and Cleman Mountain folds might partially demonstrate what those differences represent. For example, Hooper and Conrey (1989) explained that the southwest-trending folds south of the OWL are oriented in response to right-lateral displacements spread over several northwest-trending fault structures, or "megashearing" (Fig. 15). They cite similar tectonics in the Brothers fault zone of Oregon. Hammond and others (1994) found that a northwest-striking fault that forms the southern boundary of the OWL has as much as 50 m (164 ft) of vertical displacement (east-side up)—representing a sort of northward-compressional displacement west of the lineament—and terminates the eastern extent of the Fifes Peak Formation at the Little Naches River. They further noted that this fault has displaced both the Columbia River Basalt Group and the overlying Ellensburg Formation; hence the OWL has likely "been active during the mid-Tertiary through at least deposition of the Ellensburg Formation, 12–5 m.y. ago" (Hammond and others, 1994). Walsh (1986a) used disparities in the maturation of coal north and south of the lineament to infer that much of the subsidence to its north had taken place during the Oligocene and that the thicker sequences of Quaternary deposits to the north of the lineament indicate some movement continued until at least that time.

Major questions about the Yakima folds remain. Their answers could shed more light on the mechanisms responsible for their formation. For example, are some of the folds cored by pre-basalt sediments, or do the folds die out before reaching the base of the basalt?


Quilcene
Lynnwood
Edmonds
Shoreline
Poulsbo
Kirkland
Bellevue
SEATTLE
PUGET SOUND
SEATTLE FAULT ZONE
SADDLE MOUNTAIN FAULTS
HOOD CANAL
HOOD CANAL FAULT ZONE
Belfair
SeaTac
Issaquah
Snoqualmie
North Bend
Index
Mt Index
Skykomish
STRAIGHT CREEK FAULT
RATTLESNAKE MTN FAULT ZONE
Snowgrass Mountain
Mount Daniel
Chimney Rock
Mount Stewart
Leavenworth
Cashmere
WENATCHEE MOUNTAINS
Hoodsport
TACOMA FAULT ZONE
Gig Harbor
Federal Way
Kent
Auburn
Black Diamond
TACOMA
Shelton
OLYMPIA STRUCTURE
Lakewood
Puyallup
Sumner
Enumclaw
WHITE RIVER FAULT ZONE
Roslyn
Cle Elum
KITTITAS FAULTS
Olympia
Lacey
Tumwater
Yelm
Wilkeson
Bonney Lake
Ellensburg
YAKIMA RIDGE FAULT
Cliffdell
Mount Rainier
Eatonville
Mt Aix
Elbe
Centralia
Chehalis
Naches
YAKIMA
Rimrock Lake Inlier
Packwood
TOPPENISH RIDGE FAULT
Union Gap
Napavine
Morton
Randle
Mossyrock
ST. HELENS ZONE
Toledo
Gilbert Peak
Riffe Lake
Morse Lake
Keechelus Lake
Kachess Lake
Cle Elum Lake
Hanson Reservoir
Rimrock Lake
Bumping Lake
Tieton
Tolt Reservoir
Lake Washington
Lake Sammamish
Lake Wenatchee
25 mi
25 km

PRE– AND SYN–MOUNT RAINIER ROCKS

The Cascade Range volcanic arc, which extends from southern British Columbia as far south as northern California, has been produced by subduction of Pacific Ocean crust beneath the North American continent over about the past 40 m.y. The arc and its underlying rocks are not homogeneous. Along the arc's length, basement or older rocks, as well as structural features and their history, vary widely. In the North Cascades of Washington, the isolated volcanoes of Quaternary age typically erupted in the midst of a patchwork of accreted terranes, whereas in Oregon, they erupted onto a broad platform of lavas and volcaniclastic rocks. Thus, the southern Washington Cascades are unique because of their location slightly south of the OWL where younger volcanic cones sit unconformably on folded and altered volcanic rocks of late Eocene to early Miocene age (Evarts and Swanson, 1994). Although the OWL separates the physiographic provinces of the North and South Cascades (Fig. 5), chunks of the accreted pre-Cenozoic terranes poke through the Cascades volcanic pile and sedimentary rocks in this area, and rocks of one such body, known as the Rimrock Lake inlier, are discussed below.

Pre–Cascade Range sedimentary rocks of the middle Eocene, the Puget Group, indicate that the area of the central Washington Cascades was then fairly flat and consisted of flood plains, coastal deltas, and swamps—a coastal environment (Buckovic, 1979; Vance and others, 1987). Geologists have estimated that the combined thickness of Puget Group and pre–Mount Rainier lavas, fragmental volcanic rocks, and intrusions exposed both east and west of Mount Rainier National Park is more than 4 mi (6 km)! Violent eruptions of the early Miocene volcanoes in this area are particularly noteworthy because of the sheer number of closely spaced calderas that erupted over several million years of history (Fig. 16). The uplift and erosion of the Cascade Range has exposed parts of these volcanic centers and their deposits.

Figure 14. Location of prominent known or suspected faults that show evidence of displacement during the Quaternary (Rogers and others, 1996). This is a simplified version of Figure 2. See p. 11 for an explanation of map colors, which have been lightened to highlight the faults. Nearly all of the faults shown have been documented since 1987. The faults formed as blocks of crustal rock responded to strain caused by subduction of the Juan de Fuca plate and by the shearing and compression of the upper crust in response to the northward movement of the Pacific plate. Geologists have been eager to find out if rupture of one of these faults could trigger a collapse or landslide at Mount Rainier. The Rimrock Lake inlier is composed of chunks of accreted pre-Cenozoic terranes poking up through Cascades volcanic and sedimentary rocks. The dots show locations where subfossil trees have been discovered. The trees were killed by submergence or burial, in some places by volcanism (blue) or by drowning in lakes dammed by landslides (red). The subsidence or landslides may have been triggered by seismic activity.

ROCKS OF THE MESOZOIC RIMROCK LAKE INLIER

The Rimrock Lake inlier is a complex body of Mesozoic sedimentary, igneous, and metamorphic rocks exposed in the southwest Washington Cascades. These rocks are best seen along US 12 near White Pass (see Fig. 14, p. 18.) Just how and when these older rocks were exposed (and where they originally formed) are matters of debate. In other areas of Washington, bodies of relatively older rocks are exposed in the cores of anticlines or anticlinoriums. Perhaps the rocks of the Rimrock Lake inlier have been uplifted along steeply dipping faults that both cut the complex and separate some of its major rock units, such as the Russell Ranch Formation and the Indian Creek Gneiss. Hammond and others (1994) described the Rimrock Lake inlier as "a structural uplift, about 25 km [16 mi] wide and 40 km [25 mi] north–south." In their early history, at least some of the Rimrock Lake inlier rock units may have been transported as exotic terranes and then accreted onto the continental margin, as were many rock bodies in the North Cascades. Perhaps offshore volcanic arc islands were scraped off a subducting oceanic plate and metamorphosed as they were sutured to the western margin of the continent. Later, the whole complex may have been lifted up relative to the surrounding rocks along faults.

The Rimrock Lake inlier consists of two main rock units: the Indian Creek complex and the Russell Ranch Formation. The Late Jurassic Indian Creek complex is a group of intermediate to mafic plutonic igneous rocks that have been differentially metamorphosed; it includes the Indian Creek Gneiss. The Russell Ranch Formation is a tectonic mélange of marine sedimentary and volcanic rocks that are at least in part of Late Jurassic and Early Cretaceous age (~145–130 Ma). It consists mainly of arkosic sandstones and mudstones with minor cherty conglomerates as well as pillow lavas (altered to greenstones), likely formed at an oceanic ridge, and reworked water-lain tuffs derived from pre–Cascade arc volcanoes (Miller, 1989). The presence of ribbon cherts suggests that some of the sediments formed in deep-water marine environments.

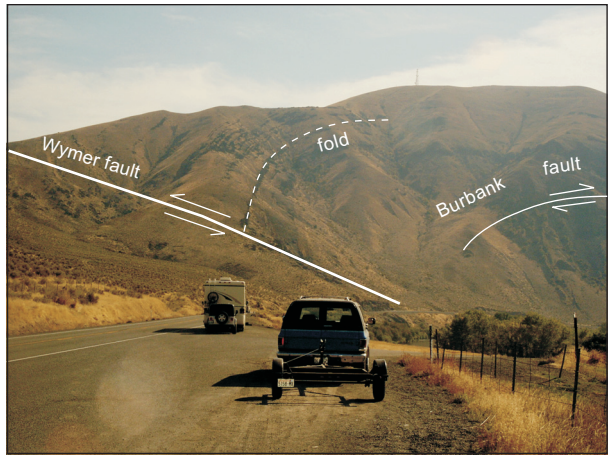


Figure 15. Folded (dashed line) Columbia River basalt flow units exposed in Umtanum Ridge where it is cut by the Yakima River canyon along SR 821 about 17 mi (27 km) north of Yakima. Thrust faults (solid lines) core the ridge here. Arrows show direction of movement. The younger Wymer fault may cut the Burbank fault at depth (Jack Powell, Wash. Dept. of Natural Resources, written commun., 2006). View is to the southeast. Modified from Mabry (2000).

Geologist Bob Miller (1989) has suggested that the Indian Creek complex likely represents the roots of an ancient volcanic arc of Late Jurassic age that could be correlative with similar plutonic rocks in the Northwest Cascades. U-Pb zircon ages from the Indian Creek rocks indicate that they crystallized at about 154 Ma (Miller and others, 1993). Miller also suggested a possible correlation of the Russell Ranch complex sedimentary rocks with those of the Western mélange belt and with sedimentary rocks of the Constitution Formation exposed on Orcas Island. The Constitution Formation rocks are marine metasedimentary rocks of Cretaceous or Jurassic age—they predate the mid-Cretaceous thrust faulting that occurred between 100 and 85 Ma in the North Cascades. The Western mélange belt includes Late Jurassic to Early Cretaceous graywacke, argillite, chert, metagabbro, and Permian marbles, all of which were likely accreted to North America, probably after the Early Cretaceous and before the middle Eocene (Tabor, 1987).

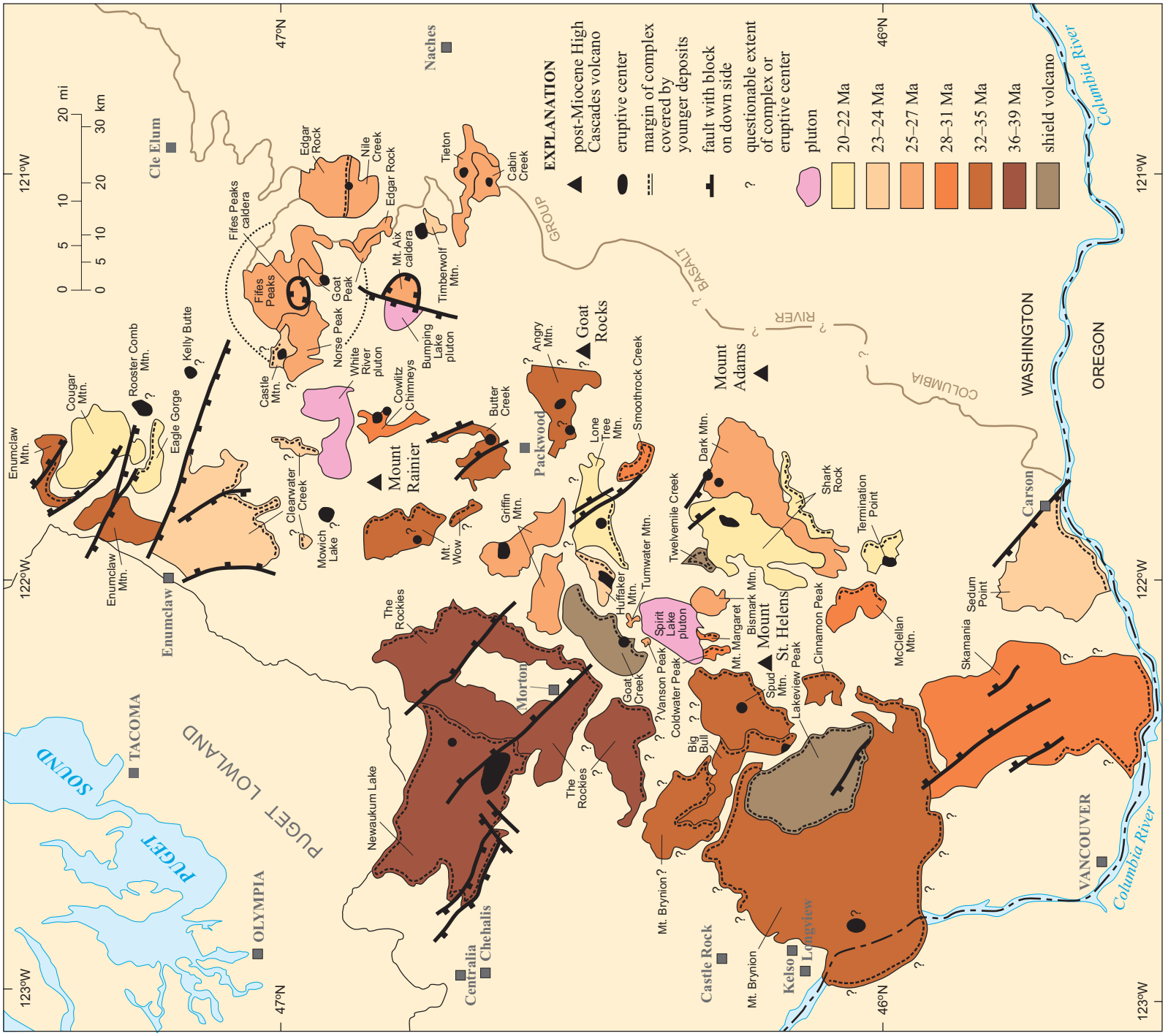


Figure 16. Lava-flow complexes in the southern Washington Cascade Range, modified from Hammond (1998). In his paper, Hammond grouped the complexes based on age and longitude in order to evaluate the structural deformation that has affected the Cascade Range. A lava-flow complex is the eroded remnant of a stratovolcano. Because the cone is least resistant to erosion, it is the first part of the volcano to be degraded, generally exposing an array of dikes and plugs that were the feeders to the volcano. Eventually erosion exposes the apron of lava flows. Here the outline of a complex is its area of outcrop. Many complexes have poorly defined margins and lack a recognizable eruptive center. The dotted 12-km- (7.5 mi) radius ring around Fifes Peaks volcano indicates its possible former areal extent. For comparison, the bases of Mount Rainier and Mount Adams have radii of 12 and 13 km (7.5 and 8.1 mi), respectively. Most complexes are named informally after geographic landmarks rather than the stratigraphic unit composing the complex to avoid confusing the nomenclature. On the eastern slope of the Cascades, lava flows of the Columbia River Basalt Group and the post-middle Miocene High Cascades volcanoes overlap some complexes and may conceal others. The southern two complexes dip below the Columbia River into Oregon.

THE TERTIARY CASCADE RANGE—A TECTONIC TRANSITION AND EPISODIC VOLCANISM

by Patrick T. Pringle and Paul E. Hammond*

55.8 Ma to 43 Ma (early to middle Eocene time)

Before formation of the Cascade Range, rivers draining a granitic highland to the east and northeast of where the range is now 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. Some of these rocks are visible along SR 165 on the way to Mowich Lake (Leg K), SR 508 (Leg I), and SR 7 between Elbe and Morton (Leg I). Near Ashford along SR 706 in Leg A, Puget Group rocks compose the high cliff north of town. The locations of the deltas and flood plains in which the Puget Group sediments were deposited suggest that before accretion of the basaltic Crescent Formation rocks during the middle Eocene, the paleo-shoreline was roughly near the route of Interstate 5 (I-5) or slightly to the west. The orientation of this coastline placed much of western Washington in a coastal lowland, thus explaining the abundant coal deposits formed during this period (Fig. 17). Large bodies of Eocene basalt (known as the Siletzia and Crescent terranes) that were originally part of the oceanic plate were wedged against and accreted to the North American plate during this interval. These rocks probably extend to the east beneath Mount Rainier, but likely not farther than the Rimrock Lake inlier. Sediments that continued to erode off highlands slowly covered these basalts during the latter half of this interval.

Vance and others (1987) described sedimentary rocks that are coeval with the Puget Group in the valley of Summit Creek, about 18 mi (27 km) southeast of Mount Rainier. The Summit Creek rocks are tilted nearly vertical and are locally overturned near their contact with the pre-Tertiary Rimrock Lake inlier. Importantly, the top section of Summit Creek rocks is in conformable contact with volcanic rocks of the overlying Ohanapecosh Formation, indicating a relatively quick transition between the units.

43 Ma to about 37 Ma (late Eocene time)

Some of the earliest Cascade Range volcanoes probably erupted in a wide coastal plain, an environment like that of present-day Fuego Volcano in western Guatemala (Buckovic, 1979). Throughout most of western Washington, these volcanoes produced predominantly mafic lavas, although more felsic rocks and tuffs have been recognized. Southwest of the present location of Mount Rainier, shield volcanoes (Fig. 16) erupted basaltic lavas that became interbedded with the alluvium of the river systems. 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, is an erosional remnant of this volcanic system; the deposits are called the Northcraft Formation. These rocks generally display a greenish color typical of the clay and zeolite minerals that formed as a result of burial in a volcanic-arc environment of high heat flow.

37 Ma to about 27 Ma (late Eocene to late Oligocene time)

The start of late Eocene time was marked by a significant relative rise in sea level (or transgression) and retreat of the shoreline to the east. At about the same time, a pulse of volcanism apparently interrupted the established drainage systems, blocking the transport of the sediment from eastern sources that had been deposited as the Puget Group. A new volcanic arc was born slightly farther east than the Northcraft volcanoes and extended about 1300 km from southern British Columbia, Canada, southward into California. These early Cascade Range volcanoes produced lava and fragmental deposits at a rapid rate, including some rhyolites. In southwest Washington, volcanic rocks of the Hatchet Mountain Formation, Goble Volcanics, and voluminous Ohanapecosh Formation were erupted during this time. 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. Fiske and others (1963) inferred that the Ohanapecosh rocks were deposited in a submarine setting; however, later workers have found accretionary lapilli, which are not likely to survive deposition in aquatic environments, and no evidence of the pillow lavas that are commonly associated with submarine emplacement of lava (Vance and others, 1987). As a result, they feel that much of the volume of Ohanapecosh rocks was deposited in subaerial settings. The lower Ohanapecosh Formation rocks are interbedded with the Puget Group in a number of places. Known late Eocene to early Oligocene volcanic centers in the Mount Rainier area were at or near Mount Wow and Cowlitz Chimneys in Mount Rainier National Park (Fig. 16).

There were volcanic centers south of US 12 at Spud Mountain and Bismark Mountain, in The Rockies (northwest of Morton), and in other localities. During this time, the silica content of the lavas near the location of present-day Mount Rainier gradually increased; basalt and basaltic andesite gave way to andesite and dacite. The corresponding increase in the viscosity of the lava caused more explosive eruptions; therefore, production of fragmental volcanic deposits increased and lava flow volumes decreased. The deposits and erosional remnants of these volcanoes or their "plumbing systems" are exposed throughout the area and are noted in the road guide.

Subsidence took place during deposition of the Ohanapecosh Formation rocks, thus allowing great amounts of accumulation, and evidently ceased by the end of Ohanapecosh time. The bulk of the Ohanapecosh sediments in Mount Rainier National Park probably originated from areas outside the park boundaries. After Ohanapecosh time, relief was positive, that is, the landscape became irregular, with broad valleys and volcanic hills. Relief was probably less than 1 km (3281 ft) over a wide area east of what is now Mount Rainier.



Figure 17. A bed of coal in rocks of the Eocene Puget Group on Forest Road (FR) 59 about 1.5 mi (2.4 km) north of SR 706. The coal bed is about 3 ft (0.9 m) thick. The pole-like feature is a small tree that has fallen on the outcrop. 1997 photo.

* See "Contributors", p. ii, for affiliation.

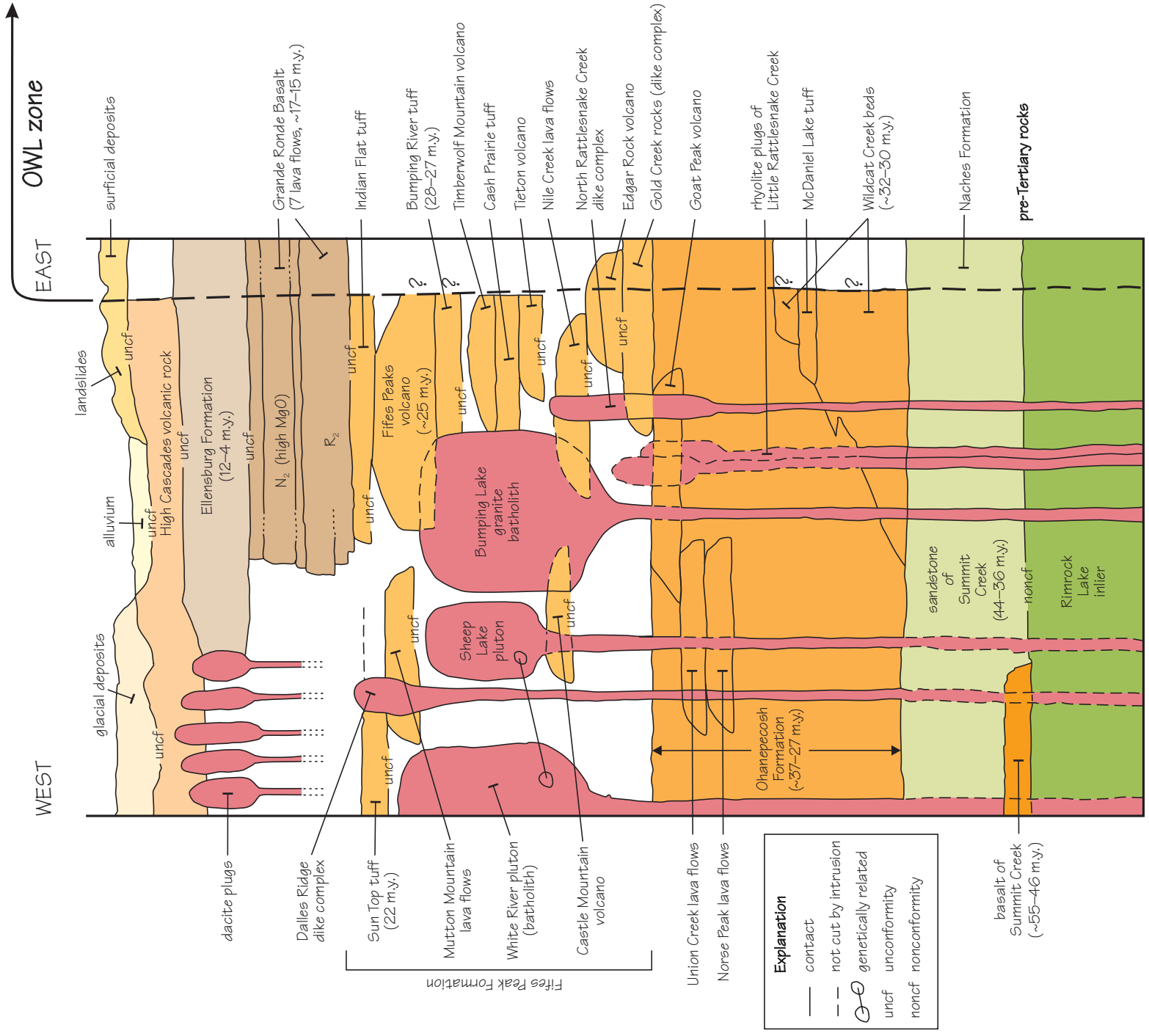


Figure 18. A schematic columnar section of principal rock units east of Mount Rainier National park. Units are shown in stratigraphic order—no scale in time, thickness, or size implied. OWL zone, rock units of the Olympic–Wallowa lineament. Modified from an unpublished section by Paul E. Hammond, 2008.

27 Ma to about 22 Ma (late Oligocene to early Miocene time)

The southern Washington Cascade Range consisted of multiple churning cauldrons of volcanic activity during latest Oligocene through earliest Miocene time. Great caldera-forming eruptions produced welded tuffs and ash flows (Hammond and others, 1994) (Fig. 16). The Mount Aix caldera, south of present-day Bumping Lake, is 6.2 by 8.7 mi (10 by 14 km), making it the largest caldera of its age in the Cascade Range. Another caldera in this vicinity was at Fifes Peaks, north of Bumping Lake. Geologist Paul Hammond found no evidence of a caldera at Dalles Ridge, 18 mi (29 km) northeast of Mount Rainier, from which the Sun Top tuff was believed to have erupted; however, at the east contact of this tuff is breccia where the tuff evidently plowed into a high ridge of lava flows and intrusive rocks. Hammond notes that intrusive rocks near Mount Fremont on the northeast flank of Mount Rainier might be the source of the tuff.

Rocks and deposits of the Fifes Peaks volcanoes are widespread. In ongoing studies, Hammond and his coworkers are using many new radiometric ages in combination with hundreds of detailed geochemical analyses of the rocks east of and at Mount Rainier to paint a very detailed picture of the age, location, and structure of the Fifes Peaks volcanoes and their stratigraphic relations with the other middle Tertiary rocks (Hammond and Brunstad, 1993; Hammond and others, 1991, 1993). Among the new information collected by Hammond and his team: the Fifes Peak Formation is neither the same age nor composition as the rocks at the volcano at Fifes Peaks, and the older Stevens Ridge Formation named by Fiske and others (1963) consists of compositionally distinct tuffs of different ages. Hammond's new radiometric ages and chemistry for the Edgar Rock volcano (~26 Ma), Tieton volcano (~25 Ma), and for many other volcanoes and volcanic deposits are helping to tie these deposits to eruptive centers, as well as establishing a better timeline for eruptive events in the Cascades (Fig. 18).

22 Ma to about 5 Ma (early Miocene to late Miocene time)

During this time, volcanism seems to have slowed down in the Cascades, although perhaps not as much as previously estimated. Because the area was being tectonically lifted, much evidence of the volcanoes of this age and their deposits has been eroded away. Certainly in the Mount St. Helens area, volcanism was being fueled by the Spirit Lake pluton (~22–20 Ma; Evarts and others, 1987). Miocene intrusive features such as dikes and sills, many of which may have fed volcanic eruptions, are fairly common. Intrusions in the region have been dated at 22 Ma to 18 Ma.

Hammond's 2004 unpublished mapping shows that at 22 Ma, the basalt–andesite volcanic activity that characterized the Ohanapecosh and Fifes Peak Formations ceased. Then a lull lasted until 16.5 Ma, when Grande Ronde Basalt lava flows encroached onto the area of the upper Naches River basin. Hammond depicts another lull from about 15.5 Ma until 11 Ma, when explosive dacite volcanism commenced and dominated activity through about 0.5 Ma.

The rocks of the Tatoosh pluton, under and near Mount Rainier on the south and southeast, are predominantly the eroded roots of a volcanic complex from which the welded tuff exposed at The Palisades in Yakima Park on the northeast side of Mount Rainier at Sunrise is inferred to have erupted (Fiske and others, 1963). Radiometric ages of the Tatoosh rocks range from 25.8 to 14.1 Ma and show that the magma injections spanned some 12 m.y. (Mattinson, 1977).

Hammond maintains a distinction between the Tatoosh pluton and White River batholith, pending careful comparisons of the composition and isotope content of the two. He suggests that if the Stevens Ridge tuff at its type locality was erupted from the Tatoosh pluton at 25 Ma and the Sun Top tuff erupted from the White River batholith at 22 Ma, this indicates a difference in time of evolution of the two plutons and that they probably are separate bodies. Regardless of this distinction, the 12-m.y. span of time for these intrusive rocks near Mount Rainier is consistent with the idea that plutons can be incrementally emplaced (Glazner and others, 2004).

Folding in the upper Naches River basin east of Mount Rainier occurred by 27 Ma, affecting the Naches and Ohanapecosh Formations and the Summit Creek sandstone, this last unit informally named by Ellingson (1959, 1972). Thereafter, Fifes Peaks lavas were tilted, but not folded until lavas of Edgar Rock volcano (12–5 Ma) in the OWL were folded, and the Tieton volcano in the Oak Creek syncline was slightly downwarped. Grande Ronde Basalt and the overlying Ellensburg Formation were also deformed at this time. Gentle folding of the Cascade rocks near Mount St. Helens probably began after 21 Ma and before 18 Ma (Evarts and others, 1987).

Between 17.5 and 6 Ma, huge volumes of lava erupted from linear vents in eastern Washington, eastern Oregon, and Idaho, forming the Columbia River Basalt Group, a series of flood basalts (Reidel and Hooper, 1989)(Figs. 19 and 20). Over several weeks or months, a few of the flows evidently traveled hundreds of miles west along part of the course of the ancestral Columbia River to reach the southern Washington–northern Oregon coast. Because the Columbia River Basalt Group flows were so extensive, they can be used as an indicator of the amount of subsequent uplift and folding of rocks. For example, after their eruption about 16.5 Ma, rocks of the Grande Ronde Basalt, one of several formations that make up the group, were uplifted at least 0.6 mi (1 km) in the Cascades north of Mount Adams in comparison with rocks of the same formation in eastern Washington.

Numerous dikes and sills were intruded north and east of Mount Rainier during this time. Before several recent studies, few volcanic products had been correlated with these intrusions, although Smith (1988a) and Smith and others (1988, 1989) had provided some constraints on the ages and general locations of volcanic centers that could have produced volcanic sediments. However, Paul Hammond has made chemical correlations of intrusive bodies with volcanic sediments of the Ellensburg Formation (12–4 Ma) and has identified at least six large dacite plugs in the Cascade Range east of Mount Rainier that are remnants of domes or dome-producing volcanoes that were the likely sources of some of the Ellensburg Formation. Other deposits produced by explosive volcanism and that likely correlate with the Ellensburg deposits can be found at Voight Creek, northwest of Mount Rainier, at Hammer bluff (near Cumberland, 8 mi [12 km] northeast of Enumclaw), and at Vasa Park near Lake Sammamish, more than 50 mi (80 km) north-northeast of Mount Rainier.

5 Ma to Holocene (Pliocene through Pleistocene and into Holocene time)

Volcanism in the Cascades picked up again at approximately 5 Ma. However, not much evidence for it is found near Mount Rainier. The first eruptions in the Indian Heaven volcanic field, about 50 mi (80 km) to the south of Mount Rainier, occurred slightly before 0.73 Ma (Hammond, 1989, 1990), although some basalts in that

area have been dated at 3.7, 3.0, and 1.7 Ma. Hammond has also identified and characterized dozens of vents during his study of volcanism in the area between White Pass and Naches Pass. Furthermore, while working with Robert Duncan of Oregon State University, he obtained ages on many—mostly dacitic—volcanic vents in that area that are less than 5 m.y. old. A 3.8-Ma vent at Nelson Butte may have been the source of one of the ash beds in the uppermost Ellensburg Formation.

Clayton (1983) documented 25 volcanoes in the White Pass area that were active within the last 4 m.y. He estimated a minimum age for Spiral Butte on the basis of his provisional identification of Mount St. Helens layer C tephra in its summit crater—C tephra has been reinterpreted at about 45 ka by Berger and Busacca (1995, 1996). However Tom Sisson and Marvin Lanphere (USGS, written commun., 2004) report an $^{40}Ar/^{39}Ar$ age of about 102 ka for Spiral Butte lava.

Goat Rocks volcano, 30 mi (48 km) to the southeast of Mount Rainier, was active between about 3.2 Ma and 1.0 Ma (Swanson, 1990). Sisson and Lanphere (1999) obtained an age of about 1.8 Ma from lavas at 'St. Paul Peak', an informally named summit about 16 mi (26 km) northwest of Mount Rainier. They suggest that peak may be a vent area because a 1.5- to 2-m (5–6.6 ft)-thick pumice fall deposit there includes clasts as large as 20 cm (7.9 in.), hinting that the clast origin was not very far away. Tom Sisson (USGS, written commun., 1998) identified another vent area at Three Sisters Ridge, only 10 mi (16 km) southeast of Enumclaw, that is 359 ka. The basaltic andesite at this vent area is similar to that of Echo Rock and Observation Rock on the northwest flank of Mount Rainier.

Thick deposits of volcaniclastic rocks of the Lily Creek Formation have been mapped along the flanks of the Cascade Range west of Mount Rainier. These deposits are nearly 1.3 m.y. old and likely were deposited as lahars. These flows originated from a volcano that stood at or near the present location of Mount Rainier; however, Sisson found the only known in-place lava remnant (1.03 Ma) of this approximate age at Panhandle Gap on the east flank of Mount Rainier slightly east of the Fryingpan Glacier. Crandell (1963a) interpreted the Lily Creek rocks as probable upstream equivalents of the pumiceous Alderton and Puyallup Formations in the Puget Lowland. The latter two formations are separated by the Stuck Drift of Crandell and others (1958). Researchers have identified lahar runout deposits from about 1 Ma exposed in the north valley wall of the Puyallup River near Tacoma and in other locations (Borden and Troost, 2001; Troost and others, 1999). All of these findings attest to the persistence of volcanic activity since the Eocene. ■

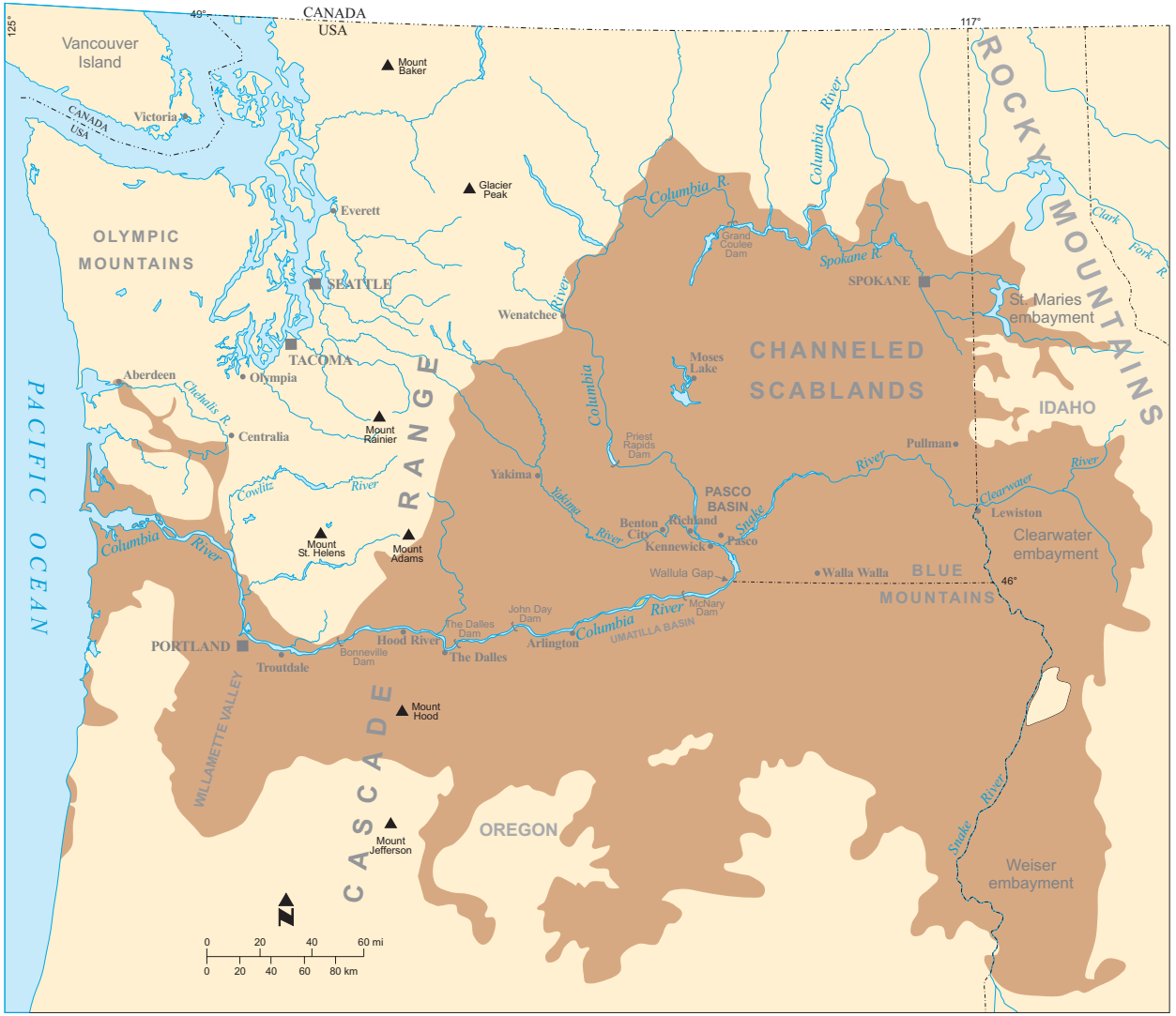


Figure 19. Diagrammatic sketch showing the combined extent of all Columbia River Basalt Group units (brown). Offshore extent is not shown. Modified from Reidel and others (1994).

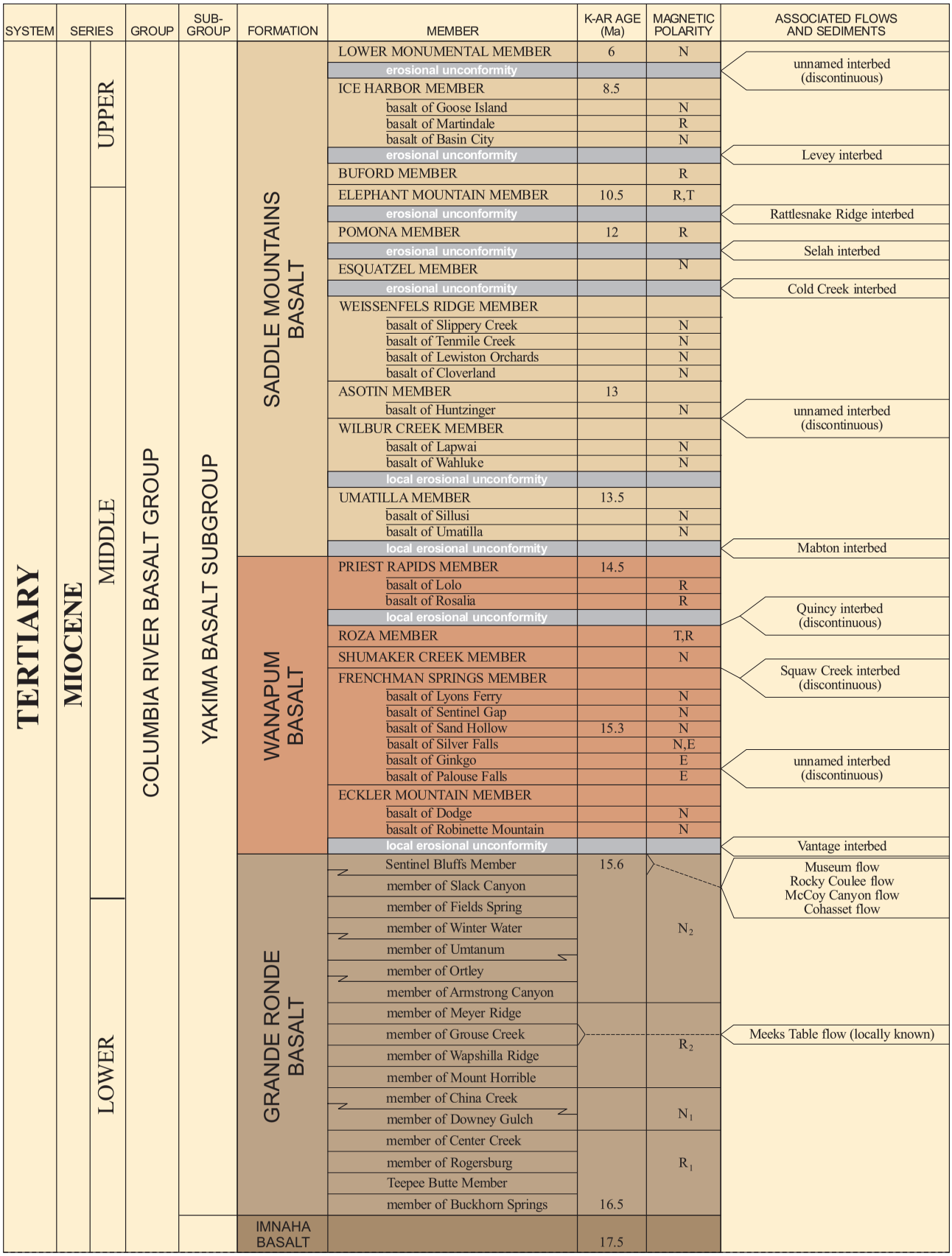


Figure 20. The Columbia River Basalt Group is a stack of lava flows that is more than 10,000 ft (~3050 m) thick in the central Columbia Basin. The typical flow averages about 120 ft (~37 m) in thickness, and many flows cover only small areas. The order of units shown here was determined by field relations, and the units are further distinguished by their geochemistry and geomagnetism. (For an explanation of the letters in the magnetic polarity column here, see the "Paleomagnetism" sidebar, p. 104.) Aquifers commonly found between flows can be stratigraphically located by the characteristics of their bounding flows. The expressions 'basalt of' and 'member of' indicate that the names are considered informal. Modified from Swanson and others, 1979; Reidel and others, 1989, 2003; Reidel, 1998; and discussions with R. C. Evarts.

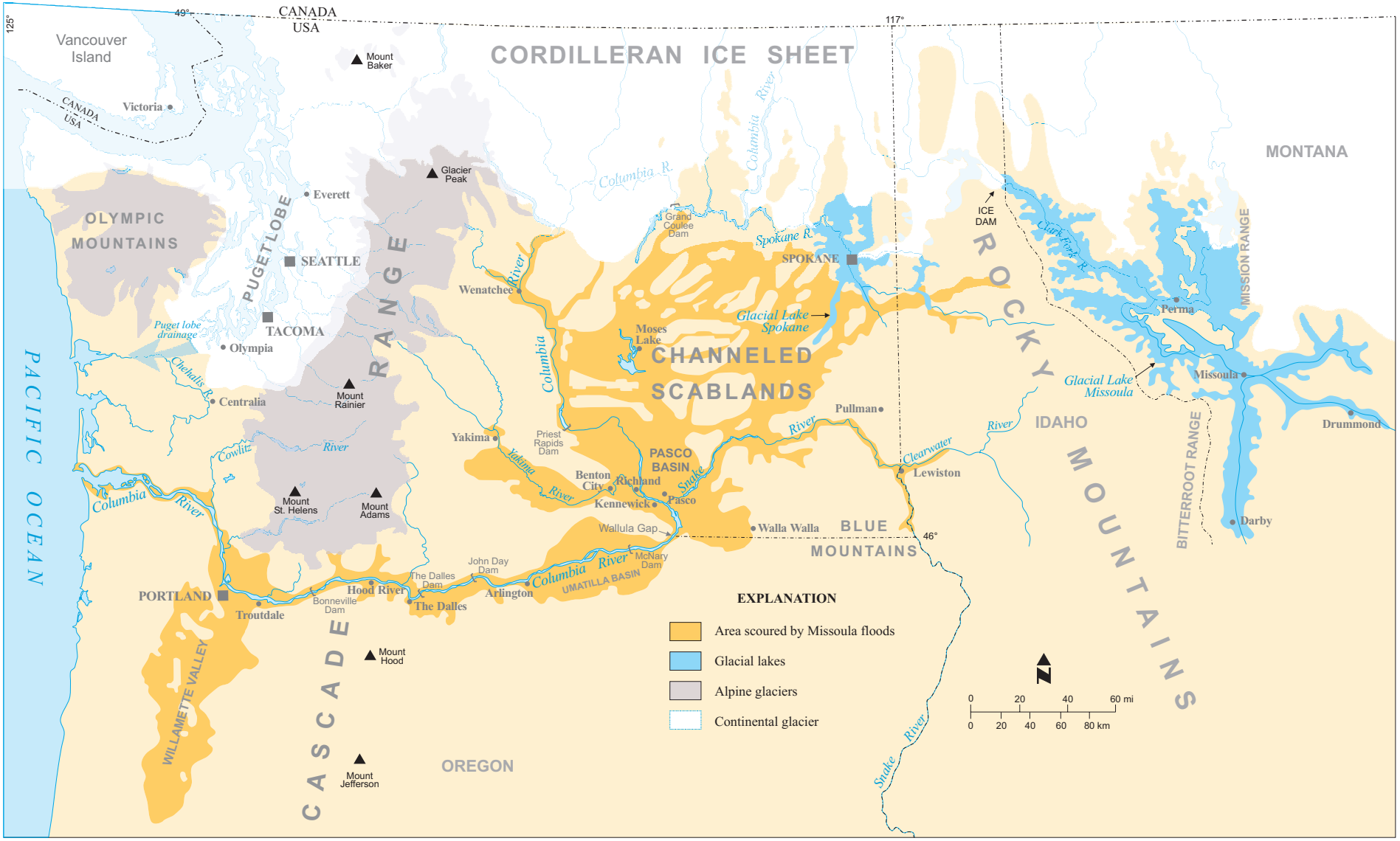


Figure 21. Diagrammatic sketch showing the approximate maximum extent of the Pleistocene continental and alpine glaciers in the Pacific Northwest. See Figure 6 for a more accurate depiction of the Chehalis River drainage during the Pleistocene. As in Figure 6, the modern Pacific coastline and drainage is shown. At the time of maximum ice advance, sea level was low enough that the coastline was actually beyond the west margin of this map. Also shown in this sketch are areas inundated by outburst floods from glacial Lake Missoula, which filled the Clark Fork valley in western Montana. The Channeled Scablands were created where these enormous floods stripped off soil and quarried and carved intertwining channels, known as coulees, in the underlying basalt. The repeated failure of the ice dam released a 2000-ft (600 m) wall of water that rushed across eastern Washington again and again. The flood pathways converged in the Pasco Basin, where there was a narrow exit for the waters—Wallula Gap. The narrowness of the gap caused the floodwaters to back up and form a 1200-ft (365 m)-deep lake covering more than 3500 mi^2 (9000 km^2). Other temporary lakes were created by similar events near The Dalles and Portland, Oregon. (Modified from Waitt, 1985; Hammond, 1989; Weis and Newman, 1989; and Bjornstad, 2006.)

GLACIATION IN THE MOUNT RAINIER AREA—THE GREAT PUGET LOBE, ALPINE ICE CAPS, AND ENORMOUS VALLEY GLACIERS

During the Pleistocene, the polar ice caps expanded greatly. In North America, enormous continental ice sheets moved from northern latitudes toward the south, sending great lobes of ice into Washington State as many as ten times (Fig. 21). The most recent of these, the Puget lobe of the Vashon glacier, moved south through the Puget Lowland between the Olympic Mountains and Cascade Range to about 15 mi (24 km) south of Olympia (Fig. 6), nearly reaching as far south as at least one earlier ice sheet. In addition to the visits of the Puget lobe, at least two and probably as many as four

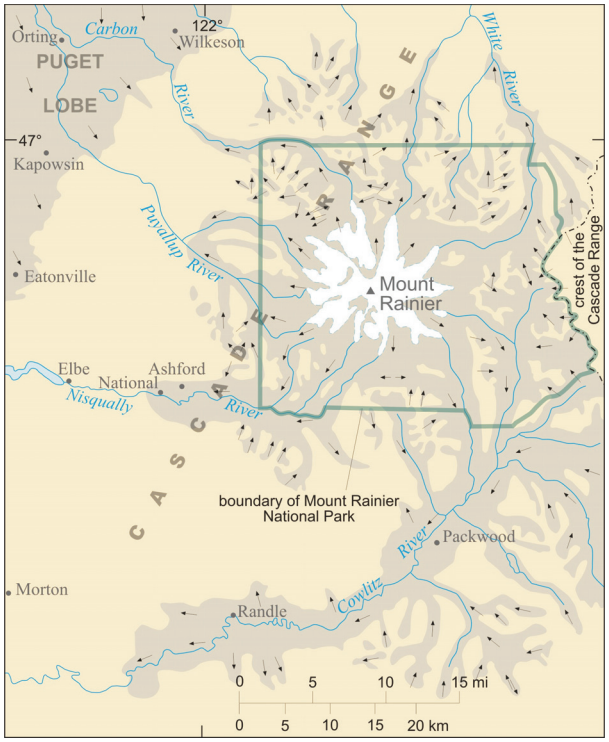


Figure 22. The extent of glaciers at Mount Rainier and in the adjacent mountains during the most recent major glaciation is shown by the gray shading. Also shown is the Puget lobe, the edge of which marks the boundary between the Puget Lowland and the Cascade Range. Arrows show the direction of glacier movement. White areas are those covered by glaciers today. Modified from Crandell (1969b).

major episodes of alpine glaciation are recorded in the southern Washington Cascades during the Pleistocene. Fewer advances of alpine ice are recognized, probably because their deposits are not as well studied as those of the continental ice sheet. Waitt and Thorson (1983) contend that alpine glaciers were most extensive in the Cascade Range from 20 to 16 ka, while the Puget lobe of the Vashon glacier (Cordilleran ice sheet) did not reach its greatest extent until 15 to 14 ka.

The great lobe of continental ice that moved south into the Purcell Trench lowland of northern Idaho at the end of the Pleistocene Epoch created an enormous glacial lake near the present day location of Missoula, Mont., by damming the Clark Fork River (Pardee, 1910) (Fig. 21). Huge outburst floods from glacial Lake Missoula repeatedly coursed down the Columbia River between 16,000 and 12,000 yr B.P. (Bretz, 1923; Bretz and others, 1956; Baker, 1973; Waitt, 1980, 1985; Atwater, 1986). These spectacular floods, numbering perhaps as many as 100, inundated the area near Yakima east of the Cascade Range, carved out the eastern Washington coulees, and, among many other valleys, also deposited slackwater sediments along the lower reaches of the Cowlitz River to an elevation of at least 130 ft (40 m) (Waitt, 1984; Walsh and others, 1987). Tephra deposits from Mount St. Helens (~13,000 yr B.P.) are interbedded with these flood deposits and have helped date some of the flood events.

During the Pleistocene, alpine glaciers repeatedly spread over much of the Cascade Range and down onto parts of the adjoining lowlands. In the southern Washington Cascades, these glaciers originated in the highlands near Mounts Rainier, Adams, and St. Helens (Figs. 22 and 23). When these glaciers were at their maximum extent, they coalesced and created an ice cap over much of the crest of the Cascades. During each glacial episode, the movements of these glaciers radically modified the terrain by stripping off large volumes of rock, carving cirques and large U-shaped valleys, depositing glacial debris, and, as they melted, scouring the landscape with huge quantities of sediment-laden meltwater (Fig. 24).

Rocks in till of middle Pleistocene age (~0.8–0.13 Ma) show that the alpine glaciers that predate Mount Rainier (~0.5 Ma) had their source in the granodiorite highlands of the Tatoosh Range, the Carbon River area, to the east and southeast of Mount Rainier, including Goat Rocks volcano, and on a volcanic cone that sat at the present site of Mount Rainier. Abundant and widespread glacial deposits, including till, outwash, and moraines, record these extensive older glacial advances.

Hayden Creek glaciation (~170 to 130 ka)

Much erosion near Mount Rainier can be attributed to the extensive Hayden Creek alpine glaciation of about 170 to 130 ka that coincides with marine isotope stage 6 (Petit and others, 1999; Fig. 25), although Evarts and others (2003) have found have found evidence that some mapped Hayden Creek Drift is as old as marine isotope stage 8 (~275–250 ka). Crandell (1969b) named deposits of this glaciation the Hayden Creek Drift for a stony till exposed along the Mowich Lake Road near Hayden Creek, about 5 mi (8 km) northwest of Mount Rainier. 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 White, Mowich, Puyallup, Nisqually, and Tilton River drainages (Figs. 22 and 23). The moraines and deposits left behind show that a large valley glacier of Hayden Creek age extended down the Cowlitz River for 63 mi (105 km) from Mount Rainier and along the Nisqually River valley about 30 mi (48 km) from Mount Rainier to the west end of Alder Lake (Crandell and Miller, 1974). Glaciers no doubt dammed many tributary valleys to form meltwater lakes.

Evans Creek glaciation (22 to 15 cal yr ka)

The Evans Creek, the most recent major alpine glaciation in the Mount Rainier area, was a substage, or stade, of the latest major regional glaciation, called the Fraser Glaciation. Neglecting latitudinal differences, it likely lasted from about 22,000 to 15,000 cal yr B.P., the period of time for which evidence suggests glacial conditions in the southern Oregon Cascade Range (Colman and others, 2004; Rosenbaum and Reynolds, 2004). During this time, icecaps were less extensive than they were during Hayden Creek time. Valley glaciers from an icecap at Mount Rainier extended down the Cowlitz River 38 mi (64 km), down the Nisqually 19 mi (30 km),

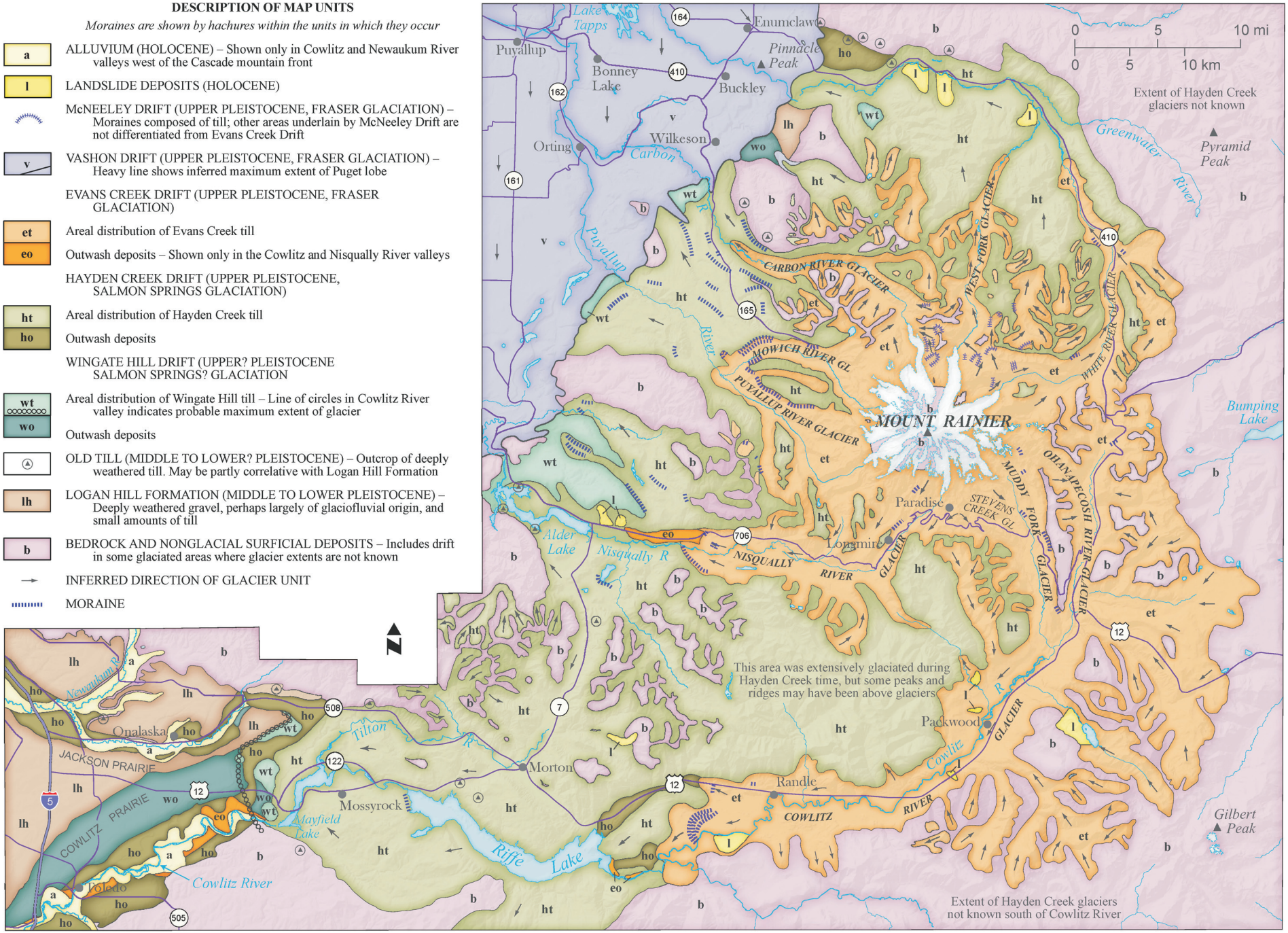


Figure 23. Distribution of surficial deposits and extents of Pleistocene glaciers in the vicinity of Mount Rainier. Modified from Crandell and Miller (1974) and Walsh and others (1987).

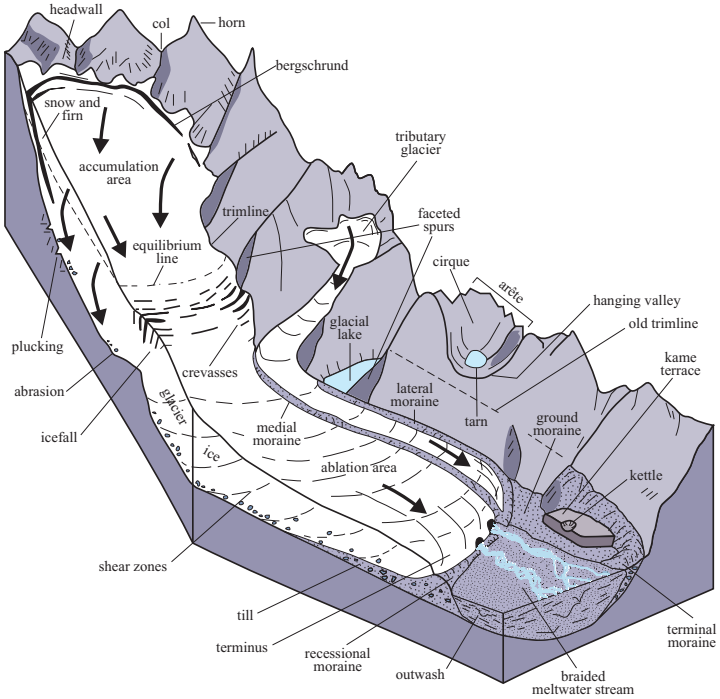


Figure 24. Oblique cross-sectional sketch showing structural and depositional features of an alpine (valley) glacier, including zones of snow and ice accumulation and ablation and alpine erosional features. Redrawn from Skinner and Porter (1992).

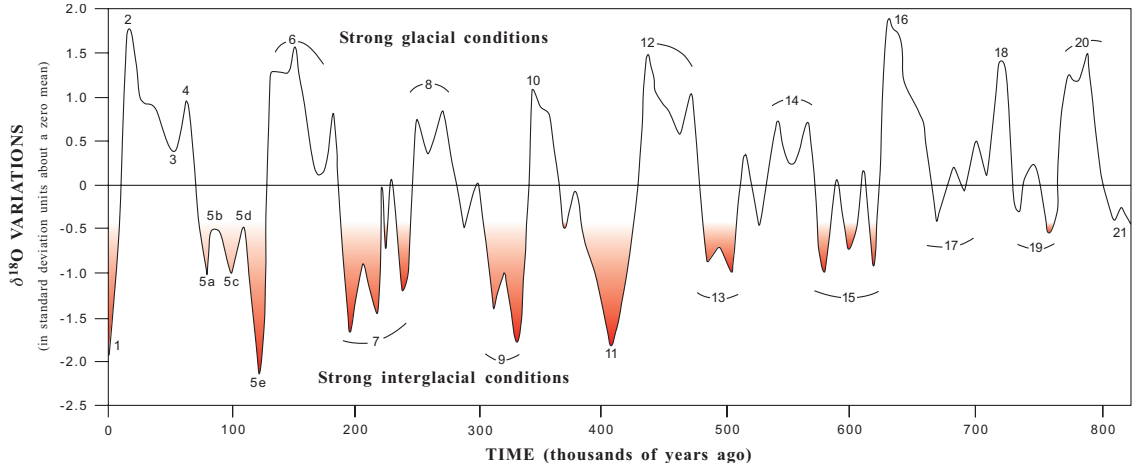


Figure 25. Marine oxygen-isotope stages for the past 800,000 years (from Morrison, 1991). The graph shows variations between $^{18}O/^{16}O$ over time. The numbers within the graph are stage numbers; the even-numbered peaks (at top) are glacial maxima, and the odd-numbered troughs (at bottom) are interglacial minima. The red areas indicate interglacial episodes, based on a cutoff at –0.5 $\delta^{18}O$ oxygen-isotope values (equivalent to Holocene interglacial values—the relatively milder climate of the past 10 ka). Note that this latter 800 ka of the Quaternary Period is dominated by times of glaciation.

down the Puyallup and Mowich about 16 mi (26 km), and down the White River 24 mi (38 km).

The floors of cirques, small bowl-shaped glacial valleys, carved during Evans Creek time are found as low as 2700 ft (824 m) elevation near Mount Rainier. Lakes known as tarns now occupy some of the cirques; Mowich, Crescent, Hidden, Shriner, Deadwood, Placer, Miners, and Blue Lakes as well as Lakes Eleanor, George, Allen, and Ethel are good examples.

Late Pleistocene McNeeley advance (12 to 10 ka)

At Mount Rainier, Crandell and Miller (1974) found moraines that were mantled with pumice layer R from Mount Rainier, which they estimated was erupted about 8,900 to 8,800 yr B.P. They named this glacial debris the McNeeley Drift for cirque moraines lying at an altitude of 5900 ft (1800 m) about 0.4 mi (0.7 km) south of McNeeley Peak. The drift is underlain by ground moraine of Evans Creek age and in places by bedrock scoured by an Evans Creek glacier.

Geologists and climatologists are trying to understand how ice ages begin and end and to what extent regional and local ice advances are synchronous with a specific ice age. They are interested in the McNeeley Drift because it was thought to have been deposited by glaciers during the Younger Dryas period, a time of very cold climate that began about 11,500 yr B.P. and lasted for about 1000 years during

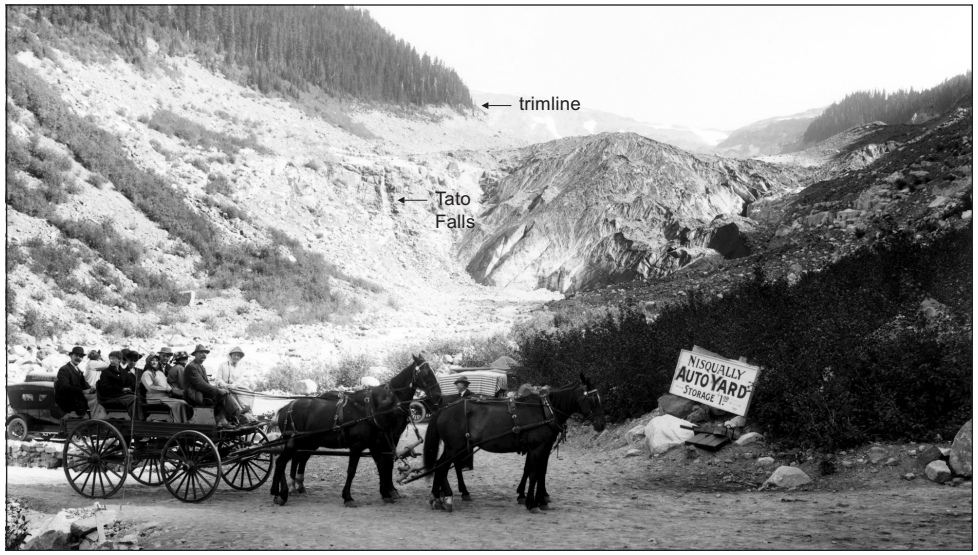


Figure 26. These tourists in 1914 got a closer look at the Nisqually Glacier's terminus than we do today. The terminus was just 300 ft (100 m) or so upstream of the Nisqually Bridge. The bridge was rebuilt about 245 ft (75 m) farther downstream after a 1955 washout. The old road no longer exists. In 1914, the glacier was much nearer its maximum downstream extent during the Little Ice Age than it is today. Tato Falls is visible slightly downstream of the glacier's terminus near the left center of the picture. Notice the location of the trimline of young vegetation (arrow) that denotes the maximum extent of the glacier during the Little Ice Age. Photo (no. 30965) courtesy of the Washington State Historical Society.

a regional deglaciation. Heine (1997) studied the period of transition from the Pleistocene to the Holocene (which includes the Younger Dryas) near Mount Rainier by coring meadows, bogs, and lakes to study tephra layers and estimate the age of the McNeeley Drift. He identified two sets of McNeeley moraines and was able to determine that those deposited first were older than 11,320 to 11,120 yr B.P. (11,370 to 11,050 cal yr B.P.), which would probably place them before the Younger Dryas period, whereas the younger McNeeley moraines, which he dated by means of two radiocarbon ages on wood in outwash deposits, were created between 9,550 and 8,990 yr B.P. (10,900–9,950 cal yr B.P.) (Heine, 1997, 2000). Thus the second McNeeley advance seems to have happened near the end of the Younger Dryas, near the onset of warmer conditions, and was apparently not precisely synchronous with the coldest conditions.

Neoglacial advances

Several minor advances of the glaciers within the last 10,000 years have been recorded; we call these the neoglacial advances. The earlier of the two most studied neoglacial advances reached their maximum between 2,800 and 2,600 yr B.P. The most recent episode, often called the "Little Ice Age", has been documented at Mount Rainier both by historic accounts and by tree-ring analysis of trees growing on, or adjacent to, moraines (Sigafoos and Hendricks, 1961, 1972), by using lichens (Burbank, 1981), and by use of historic photos (Veatch, 1969). Worldwide, the Little Ice Age lasted from about A.D. 1250 until the mid-1800s and was particularly cold between 1560 and 1850. Judging by moraines left by these ice advances, the glaciers at Mount Rainier were once much thicker and extended about a mile (2 km) farther down river valleys than at present (Fig. 26). (See "The Glaciers of Mount Rainier", p. 43.) Sigafoos and Hendricks (1972) found that eight of Mount Rainier's glaciers started to recede between 1830 and 1850, and they discovered moraines that had formed before A.D. 1363. Crandell and Miller (1964) also identified older moraines, including a lateral moraine along the Carbon Glacier that formed before A.D. 1217, determined by the the age of the oldest tree growing on the moraine. Even the more robust glaciers of these neoglacial advances were but puny versions of the huge and extensive glaciers of the Pleistocene Epoch. A booklet that provides an excellent overview of Mount Rainier's glaciers and their historic fluctuations is Driedger's "A Visitor's Guide to Mount Rainier Glaciers" (1986).

LAVA AND ICE—GROWTH AND ERUPTIVE STYLE OF MOUNT RAINIER

by Thomas W. Sisson and Marvin A. Lanphere*

The early lavas of Mount Rainier flowed onto an erosion-dissected mountainous landscape composed mainly of rocks of Tertiary age and minor remnants of an ancestral Mount Rainier volcano, at a time when thick, extensive glaciers blanketed the terrain. Prior to the late 1990s, the ages of Mount Rainier's lava flows were poorly known. Many flows were shown to be covered by, and thus older than, glacial sediments known as the Hayden Creek Drift that were deposited about 140 ka, but only two direct age determinations of 320 and 600 ka, made by the K-Ar method, had been produced for Mount Rainier and these were from the same lava flow (Crandell and Miller, 1974). We have since determined many new and more precise radiometric ages for Mount Rainier lava flows and fragmental deposits, and thus we have gained a much improved understanding of how and when the Mount Rainier cone was constructed over the past half-million years (Sisson and Lanphere, 1999).

Mount Rainier is dominated by lava flows, about 90 percent of which are similar appearing, plagioclase-rich two pyroxene andesites that range in chemical composition to plagioclase-rich two-pyroxene dacites. In detail, many rocks also contain trace amounts of the minerals hornblende and (or) olivine, and a few are sufficiently rich in hornblende or olivine to be classified as hornblende andesite or as basaltic andesite. There are no known flows of basalt erupted from Mount Rainier, despite several localities with "basalt" in their place names.

Lava flows high on Mount Rainier typically have massive interiors and rubbly tops, with combined thicknesses of 10 to 50 m (~30–150 ft) per flow. Stacks of successive flows have been eroded into alternating cliff bands (flow interiors) and rubble slopes (flow tops), imparting the characteristic layered or stair-stepped appearance of Mount Rainier's higher ridges and headwalls. The lava flows are fewer but much thicker (≤300 m or about 1000 ft) on the volcano's lower flanks, both because larger eruptions were necessary to advance lava flows to these distances and because the lower elevation

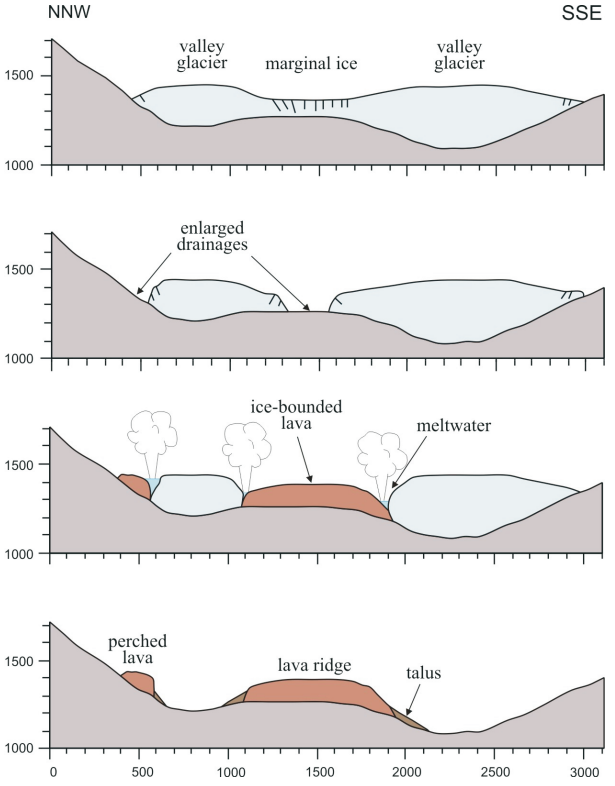


Figure 27. Sequential cross-sectional views (top to bottom) of proposed ice-marginal formation of ridge-forming and perched lava flows. The lava flows are confined by thick glacial ice. This allows the lava to pond. Later melting of the glaciers exposes the thick lava margins. Glassy lava fragments and subhorizontal or misshapen columns on flow margins attest to the presence of ice. Elevations and horizontal distances in meters. Modified from Lescinsky and Sisson (1998).

* See "Contributors", p. ii, for affiliation.

lavas were confined against valley-filling glaciers and so accumulated to greater thicknesses (Lescinsky and Sisson, 1998). These lower elevation flows form the network of ridges that radiate from the volcano, much like the spokes of a wheel. Lescinsky and Sisson (1998) proposed that the glaciers that filled the flanking valleys at the times of eruptions prevented the lavas from reaching valley floors and caused them to advance along the margins of the ice streams (Fig. 27). When the ice emptied from the valleys at the end of the Pleistocene, the lava flows were left perched high above the adjacent valley floors. Nearly all of the thick ridge-forming lava flows have lost their rubbly tops due to erosion, and some have glacial polish and striations on their upper surfaces showing that they were overtopped by ice. Besides lava flows, recent fieldwork has revealed local welded and non-welded block-and-ash flow deposits—evidence for explosive volcanism—that (with one exception) were not previously recognized at Mount Rainier.

A total of approximately 140 km³ (34 mi³) of magma is estimated to have erupted from Mount Rainier in the past half-million years (Sherrod and Smith, 1989). Mount Rainier's lava flows extend as far as 22 km (~14 mi) radially from the present summit location, and individual far-traveled flows have volumes of as much as 9 km³ (about 2 mi³). However, far-reaching lava effusions of such large volume were limited to periods from 500 to 420 ka and from 280 to 190 ka when the volcano was especially active (Figs. 28 and 29); such voluminous and extensive lava flows would be unlikely today. More probably, lava flows would travel no farther than 10 km (~6 mi) from the summit and would have volumes less than 0.5 km³ (0.1 mi³), as has been typical for the volcano for the last 40,000 years. When lava next erupts from Mount Rainier, the flows will probably emanate from the summit and will likely remain within the region of, or extend just beyond, present-day glaciers (≤6–10 km). In doing so, the lavas would entrench into and melt snow and ice, spawning floods and lahars.

But first, an ancestral Mount Rainier

The mountain we call Mount Rainier is not the first volcano to have grown at that location. Construction of an ancestral Mount Rainier was taking place from about 2 to 1 million years ago, as is shown by a remnant of a lava flow dated at 1.03 Ma, preserved at Panhandle Gap on Mount Rainier's east slope, and by an extensive apron of fragmental volcanic debris to the northwest of Mount Rainier that makes up the Lily Creek, Puyallup, and Alderton Formations. Volcanic clasts from the Lily Creek Formation are dated directly by the ^{40}Ar-^{39}Ar method at 1.2 and 1.3 Ma. Ages of the nearby Alderton and Puyallup Formations have not been measured directly, but the deposits predate (are covered by) the Lake Tapps tephra (Blunt and others, 1987) produced from the 1.15 Ma eruption of Kulshan Caldera near Mount Baker (Hildreth, 1996) and are younger than 2.4 Ma as is indicated by their reversed magnetic polarity (Blunt and others, 1987). Ancestral Mount Rainier was a large volcano, similar to that of today, as is shown by the radial system of ridges and deep canyons that had developed prior to the inception of the modern volcano (Hopson, 1966), as well as by the voluminous volcanic sediments shed from it that form the Lily Creek, Alderton, and Puyallup Formations. It was similar to today's Mount Rainier in additional respects, having produced andesite and dacite lava flows, lahars, and pumiceous lahars. Lahars were likely generated by the interaction of lavas and pyroclastic flows with glaciers. Although ancestral Mount Rainier's volcanic activity waned after 1 Ma, eruptions did not cease entirely. Small remnants of lava flows with ages between those of the ancestral and modern edifices are exposed locally in the headwaters of the Carbon and Cowlitz drainages. Nevertheless, eruptive output declined to the extent that erosion stripped away nearly all of the ancestral edifice.

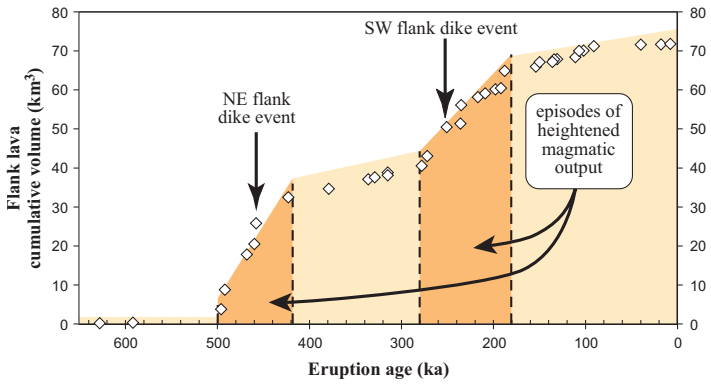


Figure 28. A cumulative growth curve for flank lavas of Mount Rainier based on geologic mapping and K-Ar and Ar-Ar dating by Sisson and Lanphere (1999). Each diamond symbol represents a mapped and dated lava flow or lava flow group. The large arrows show emplacement of large dike systems. Redrawn from Sisson and others (2001).

Off to an effusive start—Mount Rainier's lavas of 500 to 400 ka

The birth of modern Mount Rainier began about 500 ka with pyroclastic flows burying the deeply eroded remnants of the ancestral volcanic center (Sisson and others, 2001). Deposits of these early pyroclastic flows are exposed as breccias in the Glacier Basin area on Mount Rainier's northeast flank and extend up to Steamboat Prow. The birth of the modern volcano is placed at 500 ka because lava flows, pyroclastic flows, and other volcanic products were emplaced nearly continuously and voluminously from that time onward, unlike the earlier sparse volcanic record. The large (3–4 km³ or 0.7–1 mi³) Burroughs Mountain andesite lava flow erupted shortly after and partly buried the initial pyroclastic flow deposits (Stockstill and others, 2002). Other large lava flows also erupted during this period. These include those that form Grand Park, Old Desolate–Marjorie Lake, the unnamed ridge between the North and South Mowich River valleys, the large unnamed ridge between the Mowich River and Rushingwater Creek (8–9 km³ or ~2 mi³), and the Colonnade. All of these ridge-forming lava flows have ice-contact features preserved high above deep valleys; therefore, the adjacent valleys must have been ice-filled canyons at the time of the eruptions, rather than having been largely excavated by later erosion (Fig. 27). Some radial dike systems, which contributed to hydrothermal alteration of the volcano, formed at this time and likely fed vents on the mountain's flanks.

From about 400 ka to 280 ka, Mount Rainier's volcanic output diminished substantially (Fig. 28). Exceptions are the 370 ka lava flow that makes up Rampart Ridge and Cushman Crest and that underlies the toe of the Wilson Glacier—again with ice contacts locally on the margins. Another noteworthy deposit from that time period is the thick pumice layer exposed on the north side of the crest of Sourdough Ridge, immediately north of Sunrise. This more than 2-m (6.6 ft)-thick fallout pumice is the only known deposit from Mount Rainier that contains abundant biotite. Crandell (1971), who first identified this pumice, thought its volume must have been similar to some of the larger Mount St. Helens pumice layers (1–4 km³ or 0.24–1 mi³ as bubble-free dense rock). Our new age for this pumice of about 380 ka, and its excellent preservation suggest that the crest of Sourdough Ridge has not been

under ice for the last 300,000 years (Sisson and Lanphere, 1999).

Another period of accelerated volcanism—Mount Rainier from 280 to 190 ka

From 280 to about 190 ka, Mount Rainier volcano again erupted copiously. The lava flows of Sunset Park, Klapatche Ridge and St. Andrews Park, Mount Ruth, Meany Crest, Cowlitz Park, and Whitman Crest were erupted during this time. Outpourings of lava also constructed the upper northwest sector of the volcano, including the Mowich Face and Liberty Cap. All of the large flank flows have ice-contact features that indicate the volcano erupted when the valley systems were filled with glacial ice. The happenstance of their eruption next to glaciers demonstrates what many paleoclimatologists have noted in their documentation of the Earth's climate during the Pleistocene Epoch: warm interglacial periods like the one we now enjoy have been relatively short intervals separated by lengthy periods of glaciation (Fig. 25). The volcanic record at Mount Rainier indicates that large glaciers filled the immediate valleys around Mount Rainier except perhaps during the strongest interglacial periods. Though impressive, Mount Rainier's present-day glaciers are shrunken remnants of the great ice streams that dominated the landscape during most of the growth of the volcano.

The largest radial dikes on the west flank of Mount Rainier intruded during the 280 to 190 ka period of voluminous eruptions, and along with dike emplacement came intense hydrothermal alteration in the adjacent rocks as well as in the conduit system. This alteration would later help destabilize the volcano. A prominent white pumice band exposed in Sunset Amphitheater (see Fig. M-6, p. 158) was erupted toward the end of this high-output interval, at about 190 ka. This pumice is also preserved locally on the upper margins of Burroughs Mountain, showing that the upper surface of that plateau has not been glaciated since about 200 ka. The pumice is also exposed along the road to Sunrise where talus covered and preserved it (Leg E). This pumice layer, too, was as voluminous as some of the larger Mount St. Helens pumice eruptions. Walsh and others (2003) have identified "richly pumiceous sand" on the southern tip of Ketron Island in south Puget Sound, 75 km (45 mi) to the northwest of Mount Rainier. The chemical compositions of the Ketron Island bulk pumice and of its constituent glass and mineral grains match those of the pumice

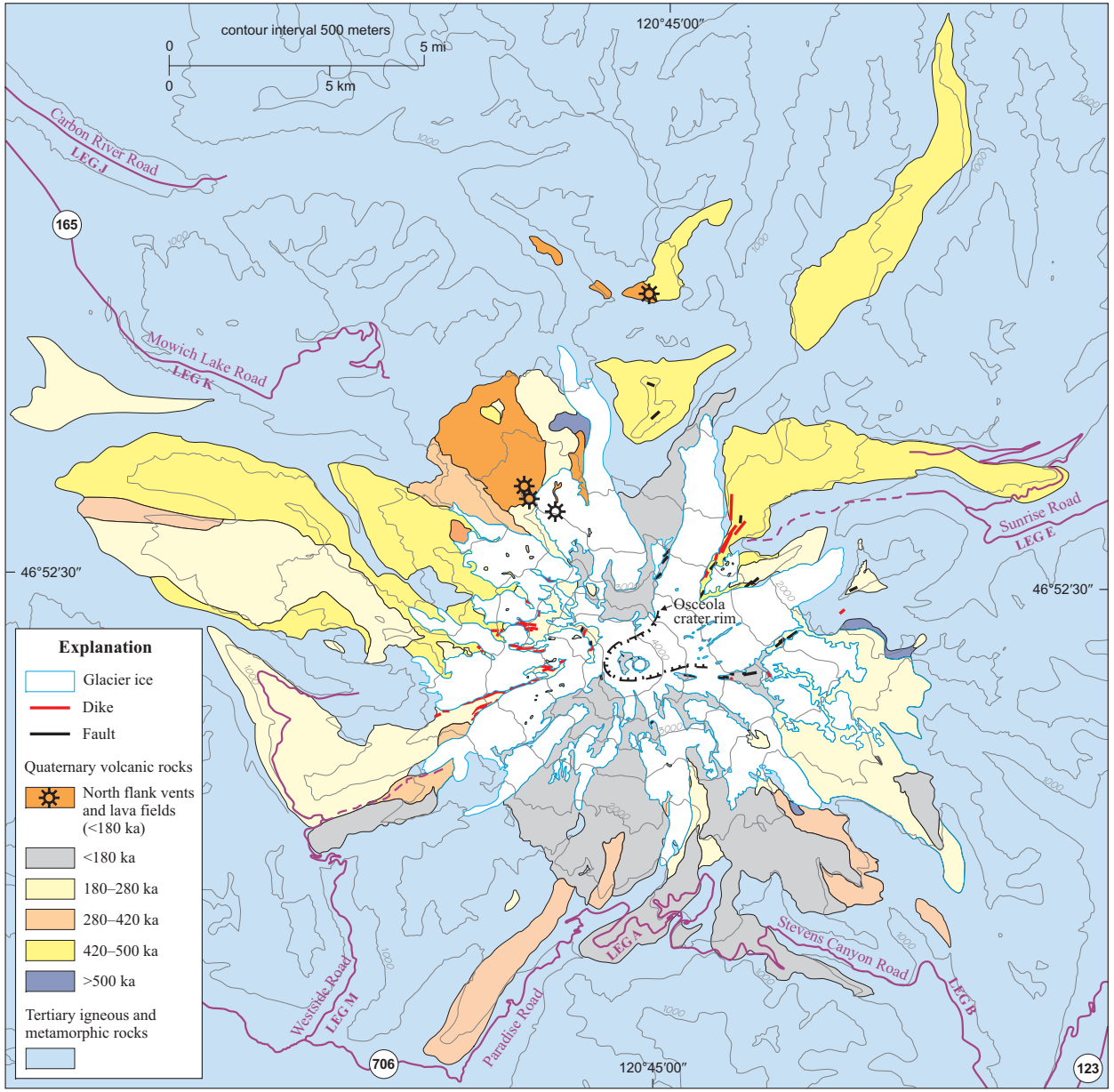


Figure 29. Simplified geologic map of major lava flows and eruptive products from Mount Rainier. Ages of flow units from Sisson and Lanphere (1999).

exposed in Sunset Amphitheater, indicating that they probably result from the same eruption. Walsh and his co-authors note that the Ketron Island deposit has features that imply transport from the east and southeast (roughly the direction of Mount Rainier) along river channels, and they surmise that Cormorant Passage, the

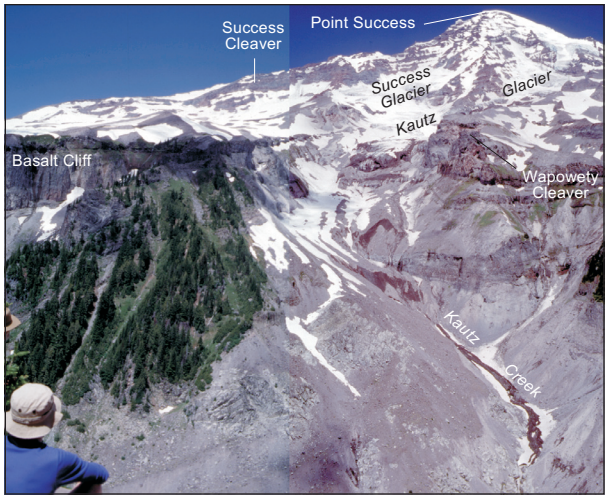


Figure 30. Kautz Glacier and canyon from Mildred Point (elev. 5935 ft; 1809 m). Basalt Cliff is a welded block-and-ash flow erupted about 100 ka (Sisson and Lanphere, 1999). The same welded deposit crops out in the cliff face at the upper right above Kautz Creek. View to the north-northwest; taken in 1994.

water body that separates the island from the mainland, did not exist at the time the tephra-bearing sand was deposited. Evidently the depression now occupied by Cormorant Passage was carved out by the Puget lobe of the Vashon glacier, which advanced into the southern Puget Sound region about 13,500 years ago (Borden and Troost, 2001).

To the present

The volcanic interval from 280 ka to 190 ka waned gradually: the stack of lava flows that composes Little Tahoma Peak commences with a large basal flow about 195 ka in age, large flows at mid-heights having an age of 150 ka, and one at the summit with an age of 130 ka. Thin dikes with contiguous areas of hydrothermal alteration and locally altered fractures cut these lava flows. Some of these dikes possibly fed high flank vents, which would have produced an oblong shape in the upper edifice, accounting for the displaced position of Little Tahoma Peak east of Mount Rainier's central vent. The volcanism during this time also produced lava flows of upper Ptarmigan and Emerald Ridges. Also at 130 ka, the dacite of Bee Flat erupted from a vent near Windy Gap, 7 km (4 mi) north of Mount Rainier. The magma that formed the Bee Flat lava flow was atypical for Mount Rainier in having abundant hornblende. This eruption was probably too far from the central conduit to have been fed by a dike from Mount Rainier itself.

After about 120 ka, Mount Rainier's lavas became relatively small in extent and volume, and erosion, possibly accompanied by collapses of the volcano's flanks, again incised the upper edifice. The ice-bounded lava flow atop Mazama Ridge that extends into Stevens Canyon erupted at about 90 ka (Lescinsky and Sisson, 1998), immediately after eruption of a thick (≤200 m or ~600 ft) pyroclastic flow that filled in what is now the headwater of Kautz Creek and that welded to form Basalt Cliff, Pearl Falls, and the area below Mildred Point (Fig. 30). The anomalous thickness of the pyroclastic flow deposit is possibly due to its having melted through and embanked behind thick ice that filled the lower Kautz drainage. Basaltic andesite lavas erupted from flank vents at Echo and Observation Rocks at about 100 ka and built up the lava flow field of Spray Park. The basaltic andesites of Spray Park are unlike typical Mount Rainier magmas in their chemical compositions and in their abundance of olivine. Like the Bee Flat lava flow, the vents at Echo and Observation Rocks were probably fed from magmas that arose adjacent to, rather than emanated laterally from, the nearby Mount Rainier magmatic system.

Eruption frequency and volume increased again from 40 to about 20 ka, though not to the same degree as the earlier stages that produced multiple, far traveled lava flows. The dacite lava flow that makes up Rickssecker Point and Narada Falls (again with evidence of ice contacts) is the sole lava flow from this young episode to extend much beyond the edifice flanks. This 40-ka dacite is overlain unconformably by another 40-ka lava flow (more ice contacts) that shallowly floors the Muir

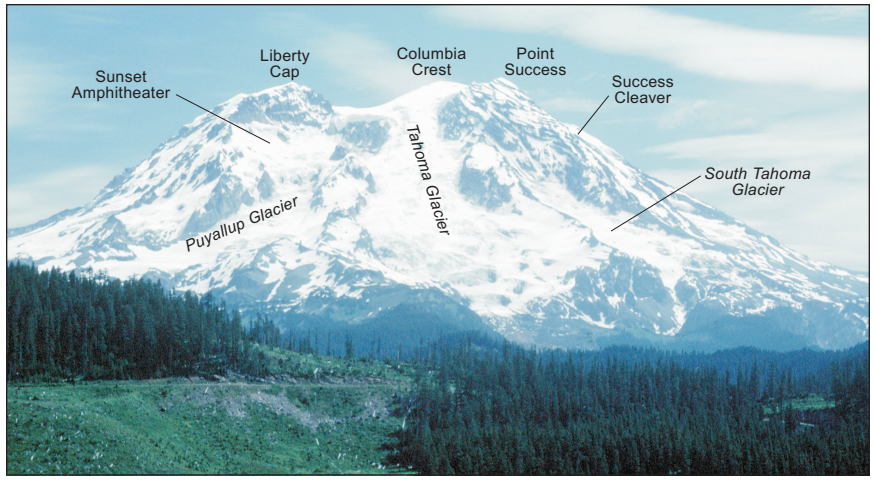


Figure 31. Mount Rainier's chiseled west face reveals interbedded layers of lava and fragmental debris, dikes, glaciers, and landforms that tell many stories of its past. The youthful Columbia Crest summit cone fills the gaping crater left after the 5,000 yr B.P. (5,600 cal yr B.P.) Osceola Mudflow carried away the former summit. The alcove in the upper left is the Sunset Amphitheater, one possible source area for the Electron Mudflow, which inundated the lower Puyallup Valley about A.D. 1500. The large radial dike complex that protrudes up between Puyallup and Tahoma Glaciers fed eruptions between 280 and about 190 ka. The stack of lava flows that forms Point Success (the south peak) and Success Cleaver is less than about 40,000 years old. View to the east from Glacier View Wilderness; taken June 1993. (See also Fig. 22, p. 27.)

Snowfield, that is in turn overlain by the slightly younger high-elevation lava flows that make up the upper south flank of Mount Rainier's edifice: at Camp Muir, Point Success and Success Cleaver, Gibraltar Rock, and Tahoma Cleaver (Fig. 31). Similar-aged lava flows on the north flank form upper Curtis and Liberty Ridges, and much or all of the Willis Wall. These numerous upper-edifice lava flows bury the post-120 ka erosion surface. Rarely, some of these young lava flows drape the steep side of a high ridge, such as on Success and Tahoma Cleavers, with glassy ice-contact features on the flow top facing the adjacent valley. Relations like this show that the cleavers were flanked with thick ice when they were constructed, and that recession of the glaciers at the end of the Pleistocene, rather than deep erosional incision, accounts for much of the ridge-and-headwall form of the upper mountain. An easily accessible ice-confined lava flow from that time forms a broad bench west of Cushman Crest, and its ice-contact margins, consisting of cliffs of glassy columns, overlook the trail leading to Comet Falls.

Details of Mount Rainier's volcanic history in the period from about 40,000 years ago to the time of the great Osceola Mudflow collapse of about 5,600 years ago are very poorly known. Stacks of successive thin lava flows form high headwalls and ridges. These lava sequences are cut by few deep erosional breaks, possibly indicating that eruptions followed one another in rapid succession with little time for erosional incision. Unfortunately, nearly all of the rocks in those high-elevation localities are too young and glassy to date accurately by current K-Ar or ^{40}Ar-^{39}Ar methods. Plant material is effectively absent in those alpine regions, precluding radiocarbon age measurements. What details are known come mainly from studies of postglacial (<10 ka) tephras and lahars, as opposed to the edifice itself. Deciphering Mount Rainier's latest Pleistocene and early Holocene volcanic history remains a challenging research problem.

Thumbnail sketch of Mount Rainier's eruptive personality

Effusions of andesite and low-silica dacite lavas dominated Mount Rainier's eruptive history, which also included subordinate block-and-ash pyroclastic flows; lava domes and large tephra falls were rare. This eruptive style contrasts with that of Mount St. Helens, whose history is characterized by growth of lava domes with associated collapse-generated aprons of talus and small pyroclastic flows, large pumiceous tephra eruptions, and some lava flows. The striking difference in eruptive behavior between the volcanoes probably results from subtle differences in their magma types. On average, Mount Rainier's magmas are slightly hotter and more fluid, promoting lava flows and allowing the quiescent escape of otherwise explosive volcanic gases. Excepting the Osceola Mudflow and a few other events, Mount Rainier's eruptions would not have been particularly impressive from the standpoint of their explosive violence, but the extensive lahar deposits, including some containing abundant alteration products and others composed of fresh rocks, show that its eruptions can be devastating. Lava and pyroclastic-flow eruptions can generate lahars though interaction with snow and glacial ice. Pyroclastic flows can generate lahars by sweeping across, scouring, incorporating, and melting snow and ice and thereby transforming directly into lahars. Lava eruptions onto glaciers can also generate lahars by meltwater sluicing off flow-top rubble and shattered flow margins and by mobilizing periglacial debris. Minor tephras deposited on snow high on a volcano can also generate destructive lahars, such as took place at Nevado del Ruiz in 1985, destroying the town of Armero, Colombia, and killing ~23,000 people. The thick stacks of lava flows on upper Mount Rainier, with few interrupting erosional breaks, as well as multiple thin tephras deposited during the Holocene are evidence that Mount Rainier has periods when small-volume eruptions recur frequently over extended time intervals (perhaps >100 years). Although individually small, the cumulative effect of years of ongoing eruptions and lahars would be costly and disruptive to anyone living nearby.

Of equal concern is the possibility that portions of the upper edifice could collapse. The far-traveled and voluminous (~4 km^3 or 1 mi^3) Osceola Mudflow that floors much of the Puget Lowland between Tacoma and the southernmost outskirts of Seattle began during a modest eruption when clay-rich, hydrothermally weakened rock collapsed from the volcano's summit and eastern flank, accompanied by a Mount St. Helens-style directed blast. The collapse removed altered rock from the volcano's east flank and probably from most of the upper mountain, leaving an amphitheater-shaped crater open to the east that subsequent eruptions have largely filled, but a region of intensely altered and weakened rock remains on the upper west flank above the Puyallup River system. Strong shaking by earthquakes during renewed volcanic activity, or deformation of the upper edifice by magmatic intrusions, might cause that altered region to collapse, creating lahars capable of reaching densely populated areas. Such failure could take place very early during build-up to an eruption, would be largely independent of the nature of the eruption, and possibly could happen during noneruptive times due to simple gravitational collapse of weakened rocks or dislodgement by a large regional earthquake. Since the end of the Pleistocene, all but one of Mount Rainier's far-traveled lahars took place during eruptive periods. Mainly for this reason, spontaneous collapse, or collapse triggered by a regional earthquake, are not considered as highly likely events, though these possibilities cannot be ruled out entirely. Because of the multiple processes that could trigger collapse and their uncertain timing, edifice flank failure is the most difficult hazard to predict and monitor at Mount Rainier, although considerable progress has been made in identifying collapse-prone areas. ■

LAHARS, TEPHRA, AND BURIED FORESTS—THE POSTGLACIAL HISTORY OF MOUNT RAINIER

by James W. Vallance and Patrick T. Pringle*

Most of the Holocene history of Mount Rainier—its last 10,000 years—has been documented by studies of its layers of fragmental debris, chiefly tephra, lahar, and glacial deposits (Fig. 32). These layers record ash and pumice plumes, pyroclastic flows, lahars, and advances of glaciers in response to climate changes. Geologists Dwight "Rocky" Crandell (1963b, 1971) and Donal Mullineaux (1970, 1974) conducted the pioneering research on the deposits and history of Mount Rainier. However, following the eruptions of Mount St. Helens, geologists sought more details about Mount Rainier's eruptive processes and wanted to apply what they had learned from Mount St. Helens to their interpretations of deposits at other volcanoes. New studies focused on several key aspects of mass wasting and volcanism at Mount Rainier. Investigations of lahars that moved as far as 100 km (60 mi) downstream and the hazards associated with them began with the work of USGS geologists (Scott and others, 1992, 1995; Vallance and Scott, 1997). These efforts continued with studies of buried forests (Pringle, 2000, 2003), the subsurface deposits (Dragovich and others, 1994; Palmer, 1997), and laharic aggradation in the lowlands (Zehfuss and others, 2003a,b; Zehfuss, 2005). With Sue Donoghue and Jack McGeehin, we have reevaluated Holocene volcanism at Mount Rainier and attempted to link volcanism to inception of devastating lahars. Results of these studies are summarized below.

* See "Contributors", p. ii, for affiliation.

From the volcano assessments conducted thus far, it is clear that the postglacial history of Mount Rainier is dominated by lahars. More than 50 large lahars have been identified; many flowed tremendous distances—more than 100 km (60 mi) from the volcano into Puget Sound (Fig. 33). Relations between some Holocene tephra and lahar deposits remain speculative, but the great majority of lahars were probably initiated by eruptions.

Explosive eruptions at Mount Rainier during the Holocene Epoch have produced only ten recognized pumiceous tephras (Mullineaux, 1974) and as many as 30 lithic-rich, vesicle-poor tephra layers (Vallance and Donoghue, 2000). The cumulative amount of tephra erupted in the past 10,000 years totals more than 0.5 km^3 (0.1 mi^3). Roughly 30 to 40 percent of this volume erupted between 7,500 and 6,800 cal yr B.P. Layer C erupted about 2,200 cal yr B.P. during the Summerland eruptive period of Vallance (2000) and Sisson and others (2001) accounts for about 60 percent of the volume of postglacial tephras at Mount Rainier and is the most widespread, covering much of the eastern half of Mount Rainier National Park with 2 to 30 cm (1–12 in.) of lapilli, blocks, and bombs. It is also one of the most-coarse grained of the Rainier tephras: volcanic bombs 25 to 30 cm (10–12 in.) across were hurled more than 8 km (4.6 mi) to the east of the summit—some onto Goat Island Mountain. Bombs from layer D were even bigger, as much as 50 cm (20 in.), and were propelled to the south 8 km onto Mazama Ridge (Mullineaux, 1974). Columbia Crest, the 250-m (820 ft)-high summit cone, appears to be younger than layer C because that tephra unit does not drape it (Mullineaux, 1974).

Mount Rainier has been much more active in Holocene time than previously suspected. Past workers (such as Crandell and Mullineaux) recognized ten pumiceous tephra layers and inferred from that a similar number of eruptions (Fig. 34). However, a careful accounting of nondescript fine-grained tephras adds at least an additional 30 ash layers to the total (Vallance and Donoghue, 2000; Vallance, 2000). These tephras contain lithic fragments, but they also contain glass shards and sparse pumice particles. The glass shards, pumice particles, and, in some places, associations with other magmatic products at the volcano, like lava flows and pyroclastic-flow deposits, indicate that the tephras are magmatic in origin (not phreatic as previously supposed).



Figure 32. Tephra layers 0.4 mi (0.7 km) north-northwest of the ranger station at Sunrise, Mount Rainier National Park. Labeled tephra layers show that tephra units at Mount Rainier include 'exotic' layers from other volcanoes, such as layer O from Mount Mazama (Crater Lake, 7,600 cal yr B.P.) and layer Yn (3,800–3,600 cal yr B.P.), set P (3,000–2,500 cal yr B.P.), and layer Wn (A.D. 1479) from Mount St. Helens. Rainier tephras are commonly brown, like layer R (~10,000 years old), or dark brown (thin layers between O and F and above P). Rainier tephra set F (5,600 cal yr B.P.) has an unusual light-yellow color because of the hydrothermal clay it contains. The 2,200-year-old tephra layer C is visible as friable gray lapilli at the top of the section among the bushes. There are more than 30 Rainier tephra layers, most of them thin and nondescript, in this section above layer R, and hence deposited in the past 10,000 years. Most of these layers are rich in vesicle-poor grains that are commonly coated with fluidal magmatic glass. Photo is figure 7 in Mullineaux (1974).

The pumiceous and vesicle-poor tephras cluster in time into eruptive periods and episodes (Fig. 34) (Vallance, 2000). The pumiceous tephras originated when continuous explosive eruptions injected particles high into the atmosphere (Fig. 35). In contrast, vesicle-poor layers originated as ash that billowed off pyroclastic flows, small explosions during periods of lava extrusions, and isolated explosions at the vent. As small as these eruptions might have been, they are significant because many of them caused lahars that swept tens of kilometers down valleys that radiate away from Mount Rainier (Fig. 34).

The R tephra and Cowlitz Park eruptive episodes—Pre–Osceola Mudflow activity of Mount Rainier

Mount Rainier's earliest Holocene eruptions occurred as the last of its Pleistocene valley glaciers melted away, and, as a result, the tephras are not well preserved. During this period, the volcano produced at least one pumiceous tephra (layer R, about 10,200 to 9,600 cal yr B.P.) to the east and northeast and at least two subsequent vesicle-poor tephras. A lahar from this period is about the same age as layer R and originated as a collapse of hydrothermally altered, weakened rock on the volcano's upper south flank.

About 2,000 years later, major eruptive episodes of Cowlitz Park time (Sisson and others, 2001) produced the A, L, and D tephras of Mullineaux (1974) and many lahars. Between about 7,500 and 6,900 cal yr B.P., several large clay-poor lahars flowed along the White River valley. The largest of these traveled as far as Puget Sound via the White River's ancient channel along South Prairie Creek. Those who study well driller's records or 'logs' will recognize this sandy lahar deposit directly underneath the Osceola Mudflow in many locations. At about this same time, a clay-rich lahar slid off Mount Rainier's south flank, overtopped Mazama Ridge, and also flowed along the Paradise and Nisqually River valleys far beyond present-day boundaries of Mount Rainier National Park. Reflection Lakes now sit on its hummocky debris, although the hum-

mocks are now largely hidden by vegetation (see cover photo; Fig. 34).

The Osceola eruptive episodes—Mount Rainier's summit slides away and flows to Puget Sound

The Osceola Mudflow of 5,600 cal yr B.P. had an initial volume of about 2 to 2.5 km³ (0.5–0.6 mi³), transformed from an enormous debris avalanche into a lahar within a few kilometers of its source, and grew in volume to nearly 4 km³ (1 mi³) through erosion and incorporation of sediment by the time it reached the Puget Lowland (Vallance and Scott, 1997). It finally poured into Puget Sound more than 100 km (60 mi) downstream from Mount Rainier (Crandell, 1971). The initial collapse was to the northeast, but the lahar then flowed north and finally west as it sloshed and surged along the White River valley (Fig. 33). East of the Cascade mountain front, the mudflow filled valleys to depths equal to a football field on end (80–150 m or 263–492 ft) and moved at speeds of 65 to 80 km/hr (40–50 mi/hr), as calculated using the height of the runup of the lahar onto several obstacles as it flowed (Vallance and Scott, 1997). It covered 150 km² (58 mi²) of upland valleys and 210 km² (81 mi²) of Puget Lowland. Dragovich and others (1994) used well logs to delineate an additional 190 km² (73 mi²) of Osceola Mudflow deposits in the subsurface, 160 km² (62 mi²) of which were apparently emplaced under the water of Puget Sound.

The Osceola Mudflow dramatically rearranged the White River system in the Puget Lowland and precipitated rapid progradation of delta fronts in Puget Sound. In pre-Osceola time, the White River had flowed along what had been the margin of the Puget lobe of the Vashon glacier during the last ice age—what is now the approximate course of South Prairie Creek (Crandell, 1963b, 1971). The Osceola Mudflow effectively plugged the connection between the White River and South Prairie Creek so that when the White River drainage was reestablished, it flowed northwestward across the Vashon drift plain rather than southeast along the drift plain margin as it had before.

At the time of the Osceola Mudflow, more than 38 km (24 mi) and 14 km (9 mi) of the lower Duwamish and Puyallup River valleys, respectively, were open water of Puget Sound (Fig. 36)(Dragovich and others, 1994). The influx of sediment of the Osceola Mudflow, the removal or burial of all vegetation on 210 km² (81 mi²) of

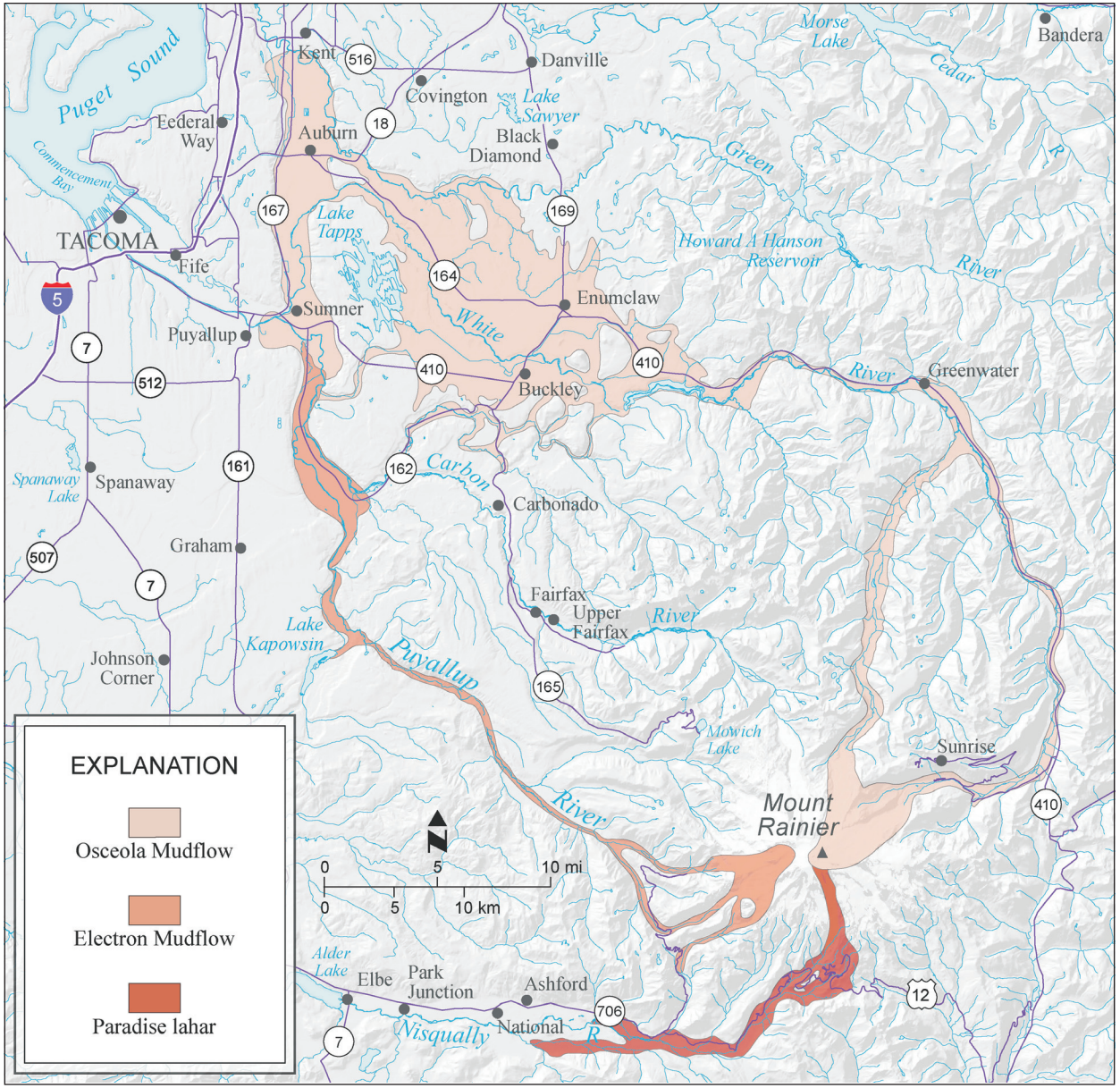


Figure 33. Inferred original extent of areas inundated by voluminous clay-rich lahars spawned by Mount Rainier during the past 6000 years, specifically the Osceola and Electron Mudflows and the Paradise lahar. More recent studies show that the Electron Mudflow likely reached the Nisqually River. Adapted from Crandell (1971).

Puget Lowland, and the alteration of the course of the White River (including shortening of its channel) resulted in a catastrophic landscape disturbance. Effects included erosion and incision of channels, and transportation of Osceola Mudflow, Pleistocene glacial drift, and other unlithified deposits into Puget Sound. Palmer (1997) and Zehfuss (2005) document rapid progradation of the Puyallup delta following deposition of the Osceola Mudflow.

The Osceola Mudflow and coeval tephra (layer F) contain alteration minerals, indicating that they shared the same origin. Both contain pyrite, quartz, and clay minerals such as smectite, illite, and kaolinite (Mullineaux, 1974; John and others, 2003). The clay and alteration minerals formed in Mount Rainier's edifice before transportation and deposition. From proportions of these minerals in deposits, Vallance and others (2003) infer that the pre-eruption volume of altered rock within the edifice could have been 0.5 km³ (0.1 mi³). Clay-rich lobes of the tephra have distribution patterns that suggest laterally directed, phreatic explosions. The lobes have distribution axes to the northeast that coincide with the axis of the crater left by the Osceola sector collapse. In contrast, wind direction, as indicated by distribution of the pumiceous tephra that accompanied the Osceola Mudflow collapse, was to the east. Explosive decompression of superheated water within the volcano at the time of its edifice collapse may have blasted the unusual, pyrite-bearing clay-rich tephra to the northeast (Vallance and Scott, 1997; Vallance and others, 2003).

Tephra documents numerous eruptions in the period after the Osceola Mudflow. The tephras, however, have small volumes, and Vallance and Scott (1997) infer that activity during this period was predominantly effusive. Lava flows apparently rebuilt Mount Rainier's edifice sufficiently that early-stage flowage deposits of the next eruptive period spilled west as well as northeast. The Osceola eruptive period probably ended about 4,400 cal yr B.P.

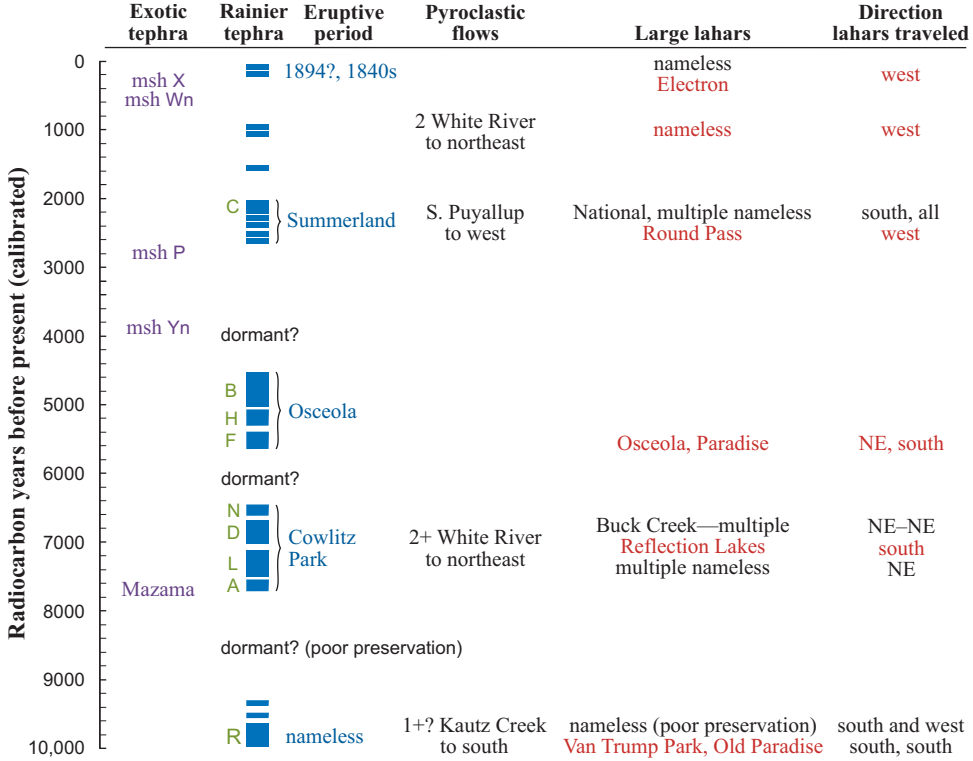


Figure 34. Eruptive periods and major lahars (>20 km or 12 mi long) at Mount Rainier during the Holocene. Blue bars show generalized eruptive periods, and green letters give tephra layer designations. Purple text indicates exotic tephra layers from Mount St. Helens (msh) and Mount Mazama (Crater Lake) that are found at Mount Rainier. Red text indicates clay-rich lahars; others are clay-poor. Ages of lahars from Scott and others (1995) and ongoing field work by Jim Vallance (USGS), the author, and Paul Zehfuss (Shannon and Wilson, Inc.).

The Summerland eruptive period—Extensive eruptions, pumice, and lahars

The Summerland eruptive period (~2,700–2,200 cal yr B.P.) includes numerous, small vesicle-poor ashes and one voluminous pumiceous tephra. On the basis of abundant pumice and scoria, Mullineaux (1974) recognized only one tephra (layer C at 2,200 cal yr B.P.) in this period. Fluidal glass and sparse pumice show that there are more than a dozen additional tephras distributed throughout the Summerland period (Vallance, 2000). These tephra layers are small-volume, thin, vesicle-poor ashes that occur in high meadows east of the volcano. In sharp contrast, the penultimate tephra (layer C) was the most voluminous pumiceous tephra of Holocene time from Mount Rainier. Lahars generated by eruptions during the Summerland eruptive period traveled great distances along nearly all drainages and now underlie parts of the towns of Greenwater, Enumclaw, Buckley, Auburn, Kent, Orting, Sumner, Puyallup, Fife, Ashford, Elbe, McKenna, Nisqually, and Packwood.

Tephras of the Summerland period coincide with an edifice collapse, pyroclastic flows, effusions of lava, and lahars. A lahar and ash with a calendar age of about 2,700 yr B.P. were initial manifestations of Summerland eruptions. Several tephras and an edifice collapse that caused the Round Pass mudflow occurred next, followed by pyroclastic flows to the west and northeast and lava flows to the northeast. The pyroclastic-flow deposits are located in the upper South Puyallup River valley. Lahars spawned by these pyroclastic flows moved far down valleys on all sides of the volcano. The paleomagnetic properties of lavas at Columbia Crest cone suggest Rainier's youngest lava flows erupted near the end of Summerland time about 2,000 years ago.

The clay-rich Round Pass mudflow originally described by Crandell (1971) occurred early in the Summerland eruptive period. The Round Pass mudflow removed a bite-shaped section from the outside, or west side, of the Osceola Mudflow crater, so that subsequent eruptive products could spill west as well as northeast. Trees buried by the Round Pass mudflow are dated at about 2,600 cal yr B.P. It is the only Summerland lahar with flank collapse of hydrothermally altered rock as its origin. Along the trail to Lake George from Round Pass, Crandell found deposits of this lahar more than 300 m (1000 ft) above the valley bottom! In valley bottoms, deposits of the Round Pass mudflow are as thick as 30 m (100 ft), have hummocky surfaces, and contain megaclasts of Mount Rainier Andesite and a few large blocks of Ohanapecosh Formation. Although most of the Round Pass mudflow was deposited in the upper

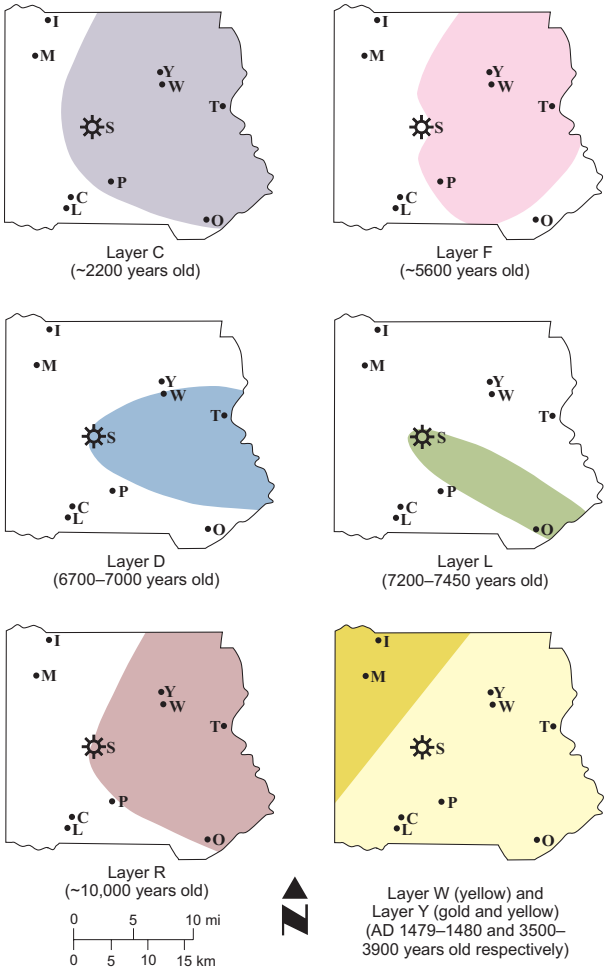


Figure 35. Generalized distribution of select pumiceous tephra layers within Mount Rainier National Park. Layers W and Y came from Mount St. Helens; the others originated at Mount Rainier. Letters represent the following localities: C, Cougar Rock campground; I, Ipsut Creek campground; L, Longmire; M, Mowich Lake; O, Ohanapecosh campground; P, Paradise Park; S, summit crater; T, Tipsoo Lake; W, White River campground, and Y, Yakima Park. Based on Mullineaux (1974).

20 km (12 mi) of the Puyallup River valley, a distributary of this lahar flowed down Tacoma Creek and then along the Nisqually River at least as far as Ashford.

A number of post–Round Pass lahars flowed down the White, Nisqually, Cowlitz, and Puyallup River drainages. These were clay-poor lahars, probably caused by interactions of hot rock and ice during eruptions or, less likely, expulsions of crater-lake water.

Ongoing geologic studies reveal episodic sedimentation in response to Summerland lahars at places far from Mount Rainier. Palmer (1997) dated some wood debris at about 2,700 cal yr B.P. from more than 18 m (60 ft) below the surface at Black River near Tukwila (about 8 km [5 mi] north of Kent in the Duwamish River valley). The wood was likely transported along the White River during or shortly after an early Summerland lahar. Summerland deposits and buried trees crop out in the lower reaches of the Duwamish River, only about 10 km (6 mi) upstream of where it discharges into Elliott Bay at the Port of Seattle; these trees have calendar ages between 2,700 and 2,100 yr B.P. (Zehfuss and others, 2003a). Kevin Scott documented extensive inundation of the Nisqually valley by lahars (Scott and others, 1995). Deposits of Summerland lahars are exposed in the Nisqually River basin as far as McKenna, about 80 km (50 mi) downstream of Mount Rainier. Further, andesitic sand deposits that underlie the Nisqually delta are apparently Summerland lahar runouts. Evidence of these deposits and buried trees comes from excavations, geotechnical borings, ground-penetrating radar, and pumiceous sediments ejected in sand volcanoes during the magnitude 6.8 Nisqually earthquake of 2001. Investigations of earthquake-triggered liquefaction in the city of Puyallup suggested that liquefiable sand units were lahar runout deposits from Mount Rainier that occurred 2,300 cal yr B.P. (Palmer and others, 1991; Pringle and Palmer, 1992).

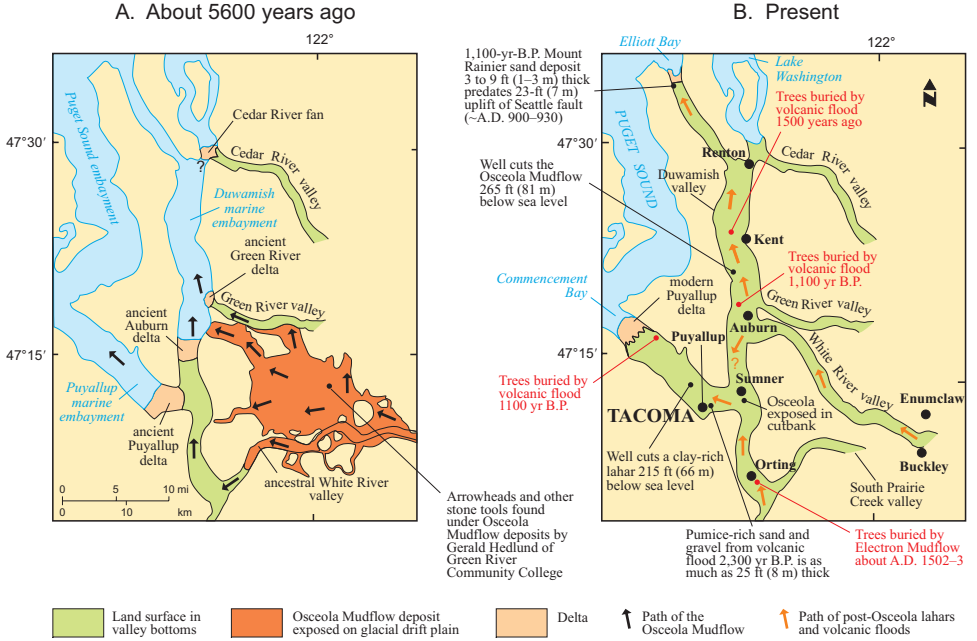


Figure 36. Approximate extent of the Osceola Mudflow, area of post-Osceola alluviation of the Puget Lowland near Seattle and Tacoma, and selected locations of forests buried by post-Osceola events (shown in red). Modified from Dragovich and others (1994) and Luzier (1969).

Mount Rainier during the last two millennia—Eruptions, lahars, and buried forests

About 1,500 and 1,100 yr B.P., lahars, at least one of which was triggered by a small explosive eruption of Mount Rainier, traveled as far as Auburn and Kent. About 1,500 years ago, small explosive eruptions of Mount Rainier produced tephras that blanket alpine meadows high on the flanks of the volcano east and south of the summit and at least one lahar that descended tributaries of the White River and flowed as far as the Puget Lowland. Subsequent erosion and downstream aggradation produced andesitic sand deposits several meters thick along the Duwamish valley between Auburn and Seattle (Zehfuss, 2005). About 1,100 years ago, an eruption of the volcano produced a lahar similar to that of 1500 years ago in the White River drainage. Reworked andesitic sand deposits derived from the 1100-year-old eruption crop out as far downstream as the Port of Seattle (Pringle and others, 1997; Cisternas, 2001; Zehfuss and others, 2003b; Zehfuss, 2005). Correlative andesitic sand deposits and the forests bur-

ied by them have been identified at Pacific, Kent, Renton, and Fife in the lower Duwamish and Puyallup River valleys. Two layers of trees buried between about 1,200 and 1,100 yr B.P. have been exhumed near Fife; snags were buried in growth position at about 5 m (15 ft) depth, and logs were transported, then buried horizontally at slightly shallower depths. It appears that trees from both layers were alive at the same time and may have died in the same lahar-related depositional event. These widespread sandy, clay-poor lahars and thick post-lahar deposits demonstrate that a small eruption at Mount Rainier can have catastrophic effects on valleys far downstream. Furthermore, multiple buried forests show that such volcanic disturbances have occurred four times in the past 3000 years (Zehfuss, 2005).

More than 60 trees have been exhumed from Electron Mudflow deposits near the town of Orting since the summer of 1993. 'Wiggle-matching' of radiocarbon samples from one of the large exhumed stumps shows that this clay-rich lahar was deposited between A.D. 1490 and 1510 (Bronk Ramsey and others, 2001). Given a 20-year interval for matching, subsequent tree-ring study, or dendrochronology, shows that the Electron Mudflow occurred about A.D. 1502 to 1503.

The Electron Mudflow began as a sector collapse of Mount Rainier's upper west flank near Sunset Amphitheater, but its onset cannot be correlated with volcanism. Possible triggers include an eruption so small its tephra is not preserved, hydrothermal explosions, or a tectonic earthquake. Regardless of triggering mechanism, key factors contributing to the Electron edifice collapse include continual hydrothermal weakening of the rocks and voluminous, water-saturated, clay-rich rock west of the summit. Deposits are thin despite flow depths as great as 30 m (100 ft) downstream as far as 30 km (19 mi), suggesting that the Electron Mudflow was very fluid and underwent minimal downstream attenuation of discharge.

Lahars and lahar-runout sands that are 300 to 500 years old crop out along the White and Nisqually Rivers as far as 50 km (30 mi) downstream of Mount Rainier. Lahars 300 to 500 years old crop out near the confluence of the main and west forks of the White River. Lahar runout sands of similar age are exposed near Mud Mountain Dam. The town of Longmire within Mount Rainier National Park is built on young lahar deposits adjacent to the Nisqually River channel. Near National, lahar deposits about 500 years old underlie low terraces along the Nisqually River. Farther downstream, subfossil wood in deposits of andesitic sand has a similar age. A buried stump slightly upstream of McKenna (Scott and others, 1995), and wood fragments in channel fill deposits at the Nisqually delta (Barnhardt and others, 2000) yielded ages of about 500 cal yr B.P. ■

STEWING IN ITS OWN JUICES—MOUNT RAINIER'S HYDROTHERMAL SYSTEM

by David Frank and Patrick T. Pringle*

On a clear day, particularly from areas west of Mount Rainier, one can see evidence that Mount Rainier's summit has warm spots! Within a day or so after a snowstorm, bare rock often becomes visible on the outer slopes of the summit cone (Fig. 37). Fumaroles or steam vents, some near the boiling point of water, heat the ground in areas of the summit craters and melt the snow and ice that accumulate there.

Mount Rainier's hydrothermal system consists of hot upward-flowing volcanic gases that melt snow and ice and maintain ground water at the volcano's summit, allowing warmed water to percolate back down into the edifice. This narrow central zone of heat emission not only maintains snow-free areas at the summit craters, but also forms the caves in the summit icecap (Moxham and others, 1965; Frank, 1985). Other Cascade Range volcanoes such as Mount Baker and Mount Hood also have hydrothermal areas with fumaroles and ice caves.

Thermal activity from Mount Rainier can be seen today in three types of settings (Frank, 1995):

(1) near-boiling point fumaroles and extensive heated ground at the East and West Craters on the volcano's summit, where the boiling point is about 187°F (86°C);

(2) lower temperature fumaroles, as warm as 140°F (60°C), and heated ground in a small area on Disappointment Cleaver on the upper east flank of the volcano; and

(3) two clusters of low-temperature sulfate- and carbon dioxide–enriched thermal springs, as warm as 63°F (17°C) and 77°F (25°C) respectively, in valley walls adjacent to the west margins of the Winthrop and Paradise Glaciers.

Climbers' reports and remote sensing surveys indicate that small areas of activity similar to that at Disappointment Cleaver occur elsewhere in the upper flank headwall areas. Additional thermal springs are present within the park but beyond the outcrop area of Mount Rainier Andesite. The former spa areas of chloride- and carbon dioxide–enriched thermal springs issue from thin sediments that overlie Tertiary rocks in the valley bottoms of the Nisqually and Ohanapecosh Rivers. Longmire Springs in the Nisqually River valley have maximum temperatures of 77°F (25°C) and have produced an extensive area of travertine and tufa mounds. (See "Longmire Springs" sidebar, p. 57.) The relative proportions of dissolved constituents at Longmire Springs

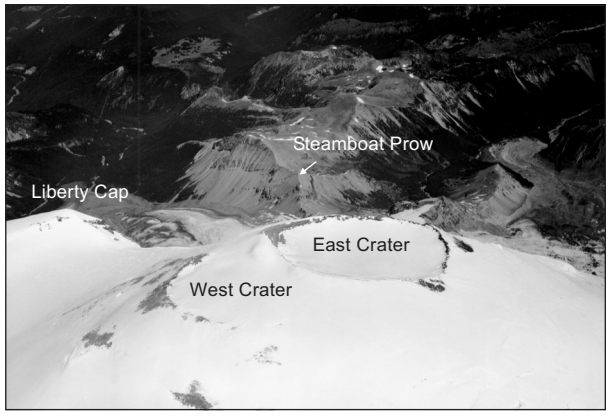


Figure 37. Aerial-oblique photo of Columbia Crest summit cone at Mount Rainier. Steamboat Prow is visible in the background. The bare ground along the rims of West and East Craters is kept snow free by geothermal heat. Some fumaroles in the East Crater are at the local boiling point (186°F; 86°C). View is to the east-northeast. Photo courtesy of Austin Post, taken Sept. 11, 1964.

* See "Contributors", p. ii, for affiliation.

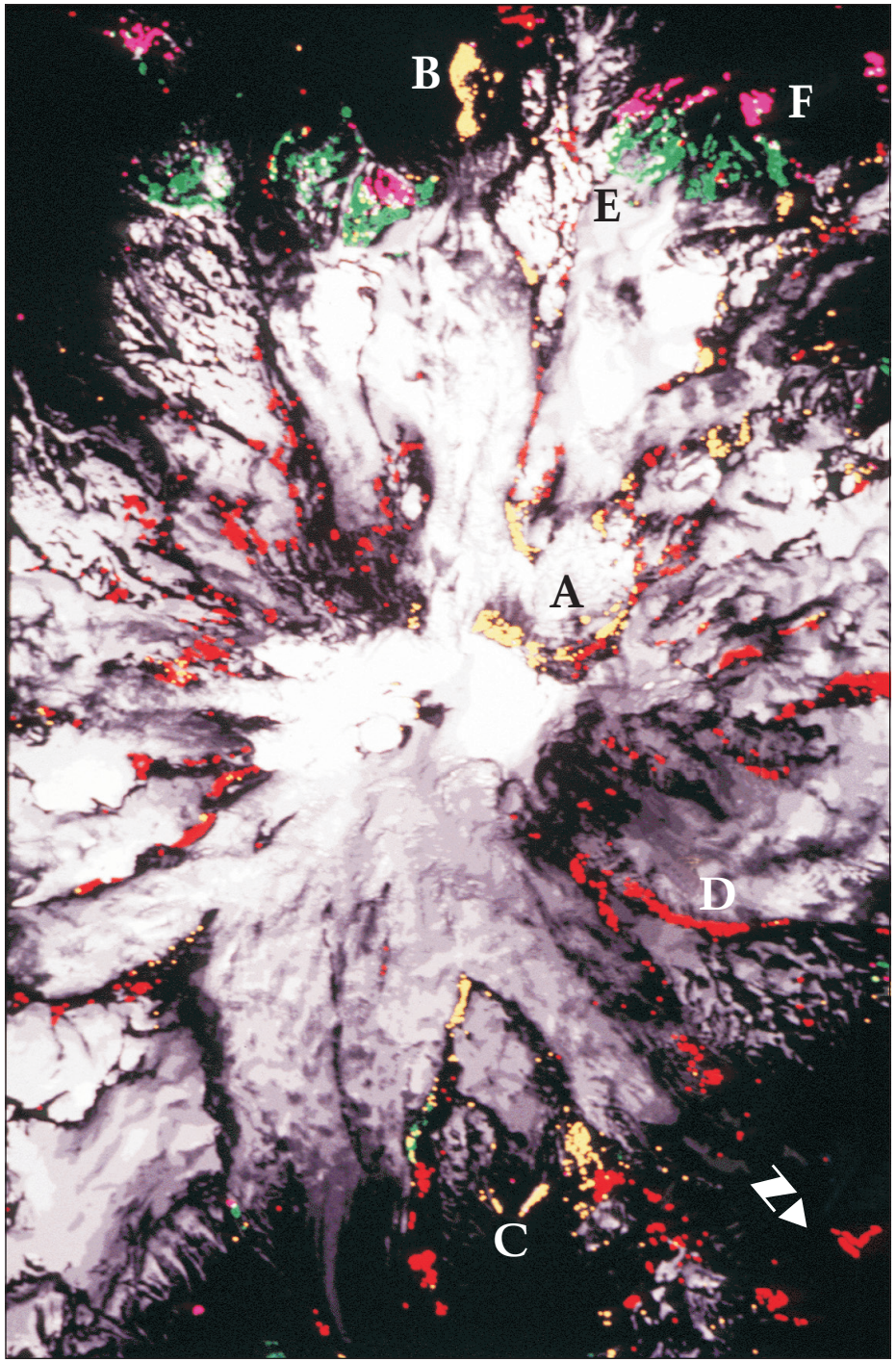


Figure 38. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) image of Mount Rainier. Note that north is toward the lower right. This image shows different types of altered rocks in various colors (Crowley and Zimbelman, 1997) and demonstrates where weak rocks are localized on Mount Rainier. Yellow areas (A and B) represent the weakest rocks—victims of argillic alteration, in which feldspar minerals have altered to slippery clay minerals such as kaolin and smectite, as well as to sulfates and various silica forms. Columbia Crest summit cone and East Crater are visible slightly left of center. 'A' indicates pervasively altered rocks of Sunset Amphitheater (arcuate feature above and to right of the summit) and upper Puyallup and upper Tahoma Cleavers to the right and left, respectively. 'B' is avalanche debris interpreted by Crandell (1973) to have been shed from Sunset Amphitheater in the early part of the 20th century. 'C' represents altered material originally deposited by the Osceola Mudflow. Red areas at 'D' show iron-oxide alteration along Curtis Ridge. Magenta areas at 'F' show alteration to minerals such as sericite in pre–Mount Rainier rocks, and the green area in the upper part of the photo indicates chlorite-rich areas in Tertiary rocks. 'E' is a large, radial andesitic dike that fed lavas between about 280 and 190 ka (Tom Sisson, USGS, written commun., 2003). The dike also caused hydrothermal alteration that contributes to destabilization of the mountain. Image courtesy of Jim Crowley, USGS, taken in 1997.

are similar to those of higher altitude springs though more concentrated. Winthrop and Paradise thermal springs, and conceivably Longmire Springs, can be accommodated by a geochemical model that describes their derivation from similar acidic sulfate-chloride waters that originate in a central, steam-heated hydrothermal system in the upper part of the volcano. Cooling of thermal waters during transit away from the hydrothermal system to lower elevations could take place by dilution with shallow cold ground water. The water composition of these three sets of thermal springs ranges from sodium sulfate water at Winthrop springs, sodium sulfate bicarbonate water at Paradise springs, to sodium calcium bicarbonate chloride water at Longmire Springs, showing respectively enrichment of calcium and chloride and depletion of sulfate.

Hydrothermal activity has played an important role in the construction and destruction of Mount Rainier, as well as in localizing its zones of weakness. Hydrovolcanic activity (phreatic eruptions) produces fragmental deposits. Hydrothermal alteration forms secondary hydrothermal minerals from primary volcanic minerals, which results in changes in the permeability of the primary rocks and also a loss in the strength of the deposits. Among alteration minerals are soft clay minerals that produce mechanically weak deposits and thus contribute to localized instabilities that produce lahars such as the Osceola and Electron Mudflows.

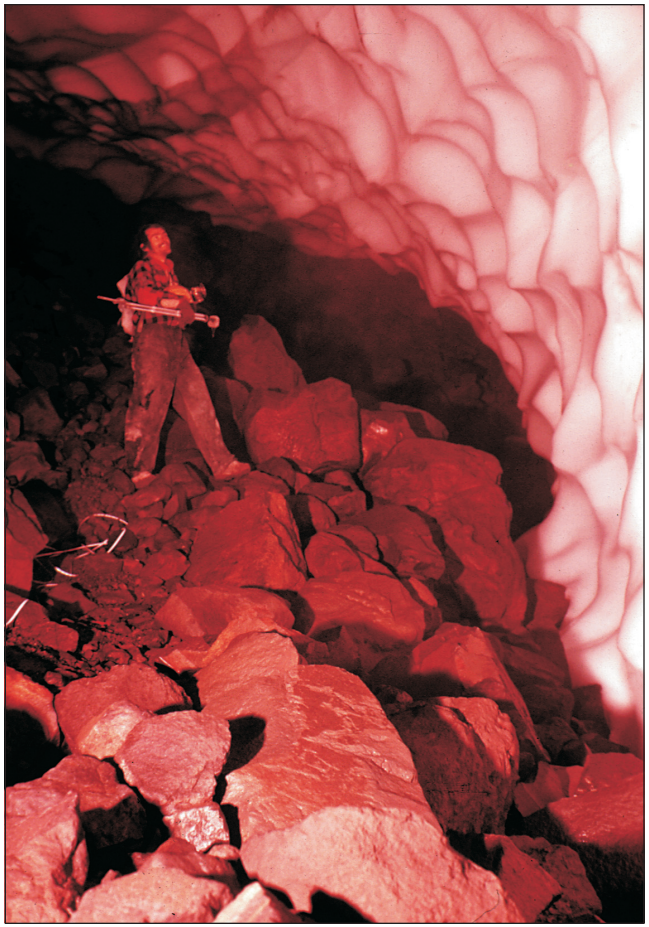
Several types of geologic studies have confirmed that there are concentrations of these weak materials in certain areas of Mount Rainier, both in active thermal areas and in 'fossil' deposits that show no evidence of lingering hydrothermal activity (Zimbelman and others, 2000). Frank (1995), Zimbelman and others (2000), and Rye and others (2003) described areas that display argillization and silicification (forms of alteration), both as pervasive masses and as selective pockets, lenses, and veins. These studies also examined alteration in landslide deposits to evaluate the distribution through time of alteration on the volcano. Crowley and Zimbelman (1997) used satellite imagery to map alteration minerals exposed at the surface of the volcano (Fig. 38). Finn and others (2001) were able to confirm and refine estimates of the extent of these areas of alteration and provide added information on the depth by using the mag-

netic and electromagnetic properties of rocks via helicopter-borne surveys; areas of intensely altered rock are both weakly magnetic and have low resistivity. Combined results of all such studies suggest that hazards from generation of lahars by collapse of incompetent hydrothermally altered rock today are most likely on the west side of Mount Rainier.

Hydrothermal alteration of Tertiary rocks also occurs in the Mount Rainier area. For example, Glacier Basin contains altered Tertiary rocks associated with ore deposits. (See "Mining in Glacier Basin" sidebar on p. 98.) A copper-silver mining camp there (now abandoned) was situated on such an area, and colluvium derived from those rocks may have contributed some clay-size minerals to the Osceola Mudflow, according to Zimbelman (1996; Zimbelman and others, 1994). Other areas of hydrothermally altered Tertiary rock are scattered throughout the park near the east and west sides of Winthrop Glacier, near the confluence of June Creek and the Carbon River, near Mowich Lake and the Mowich River, near Glacier Island and Pyramid Peak, and near the confluence of the Paradise and Nisqually Rivers. ■

MOUNT RAINIER'S SUMMIT CAVES AND LAKES

Mount Rainier's summit craters provided shelter for some of the earliest climbers and have been the focus of scientific curiosity because of their geothermal activity. Hazard Stevens and Philoman Van Trump were probably the first to spend the night in a cave in the West Crater in 1870, and geologists Bailey Willis, Israel Russell, and George Otis Smith and party spent the night in the steam caves of East Crater in 1896. In "The Challenge of Rainier" (1984), geologist and mountaineer Dee Molenaar relates the history of some of the earliest attempts to explore the summit cave system, including the story of Jim and Louis Whittaker's 1954 descent more than 300 ft (91 m) down the inner slope of East Crater. Glaciologist Maynard Miller conducted further explorations of the crater area in 1960 (Miller, 1960). Geologists Eugene Kiver and Martin Mumma of Eastern Washington State College, now Eastern Washington University, completed a map of the steam caves in East Crater on Aug. 17, 1970—100 years to the day after the Stevens–Van Trump visit (Fig. 39)(Kiver and Mumma, 1971). They estimated that the crater was as much as 500 ft (152 m) deep and described hissing fumaroles and areas of ground as hot as 187°F (86°C) (near local boiling point at 14,410 ft or 4392 m). In 1971 the personnel of Project Crater located a small lake in West Crater (Millller, 1960). In 1972, Bill Lokey of Tacoma, now a professional emergency manager and accomplished mountaineer, wore a wet suit into the 32°F (0°C) lake to estimate its depth to be about 17 ft (5.2 m) (Kirk, 1999; Lokey, 1973). Kiver (1975) has suggested that this lake is probably the highest crater lake in North America (Fig. 40). Such a lake had been mentioned earlier—Yakama Indian guide Saluskin guided two climbers to the summit around 1854 and reported that they had seen a lake in the summit crater (Haines, 1962).

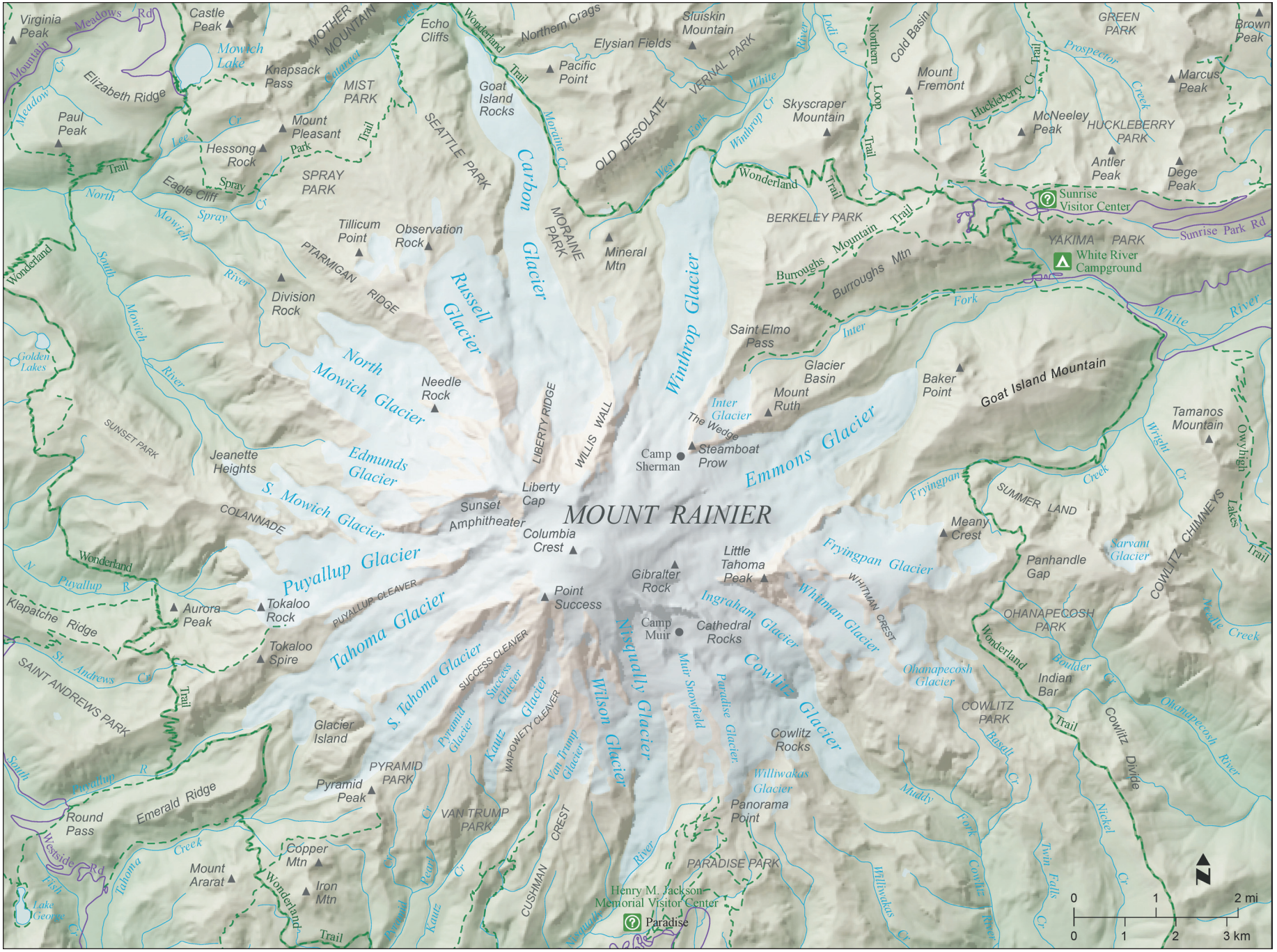


In ongoing investigations of the summit caves, researcher Francois Le Guern has found little hydrogen sulfide in the summit gases and low carbon-dioxide concentrations in the pure fumarolic gases (1% maximum), not enough to be potentially lethal. During investigations in 2003, he found that parts of the roofs of the caves in both East and West Craters had collapsed because of the warm summer conditions (Francois Le Guern, Centre National de la Recherche Scientifique, Yvette, France, written commun., 2003).



Figure 40. A summit cave in West Crater in 1972 during exploration and mapping of the cave system. The small crater lake, visible between the person and the ice wall, is likely the highest lake in North America. National Park Service photo.

Figure 39. *(left)* Dennis Collins investigates the summit cave network at Mount Rainier during the first effort to map it. The large blocks of andesite are an 'ice-barred ridge', an accumulation of rubble at the base of a slope at the wall of the ice cave. Photo courtesy of Eugene Kiver, Eastern Wash. Univ., taken in 1971.


MOUNT RAINIER
Carbon Glacier
Russell Glacier
Winthrop Glacier
Emmons Glacier
North Mowich Glacier
Edmunds Glacier
S. Mowich Glacier
Puyallup Glacier
Tahoma Glacier
S. Tahoma Glacier
Nisqually Glacier
Wilson Glacier
Ingraham Glacier
Whitman Glacier
Cowlitz Glacier
Fryingpan Glacier
Ohanapecosh Glacier
Williwakas Glacier
Success Glacier
Pyramid Glacier
Kautz Glacier
Van Trump Glacier
Paradise Glacier
Muir Snowfield
Inter Glacier
Sarvant Glacier
Virginia Peak
Castle Peak
Mowich Lake
Elizabeth Ridge
Paul Peak
Hessong Rock
Mount Pleasant
Knapsack Pass
MOTHER MOUNTAIN
MIST PARK
SEATTLE PARK
SPRAY PARK
Eagle Cliff
Echo Cliffs
Goat Island Rocks
Northern Crags
Pacific Point
Elysian Fields
Sluiskin Mountain
VERNAL PARK
OLD DESOLATE
Skyscraper Mountain
Mount Fremont
Cold Basin
GREEN PARK
Brown Peak
Marcus Peak
McNeeley Peak
HUCKLEBERRY PARK
Antler Peak
Dege Peak
Sunrise Visitor Center
Sunrise Park Rd
BERKELEY PARK
YAKIMA PARK
White River Campground
Burroughs Mtn
Mineral Mtn
MORAINE PARK
Tillicum Point
Observation Rock
PTARMIGAN RIDGE
Division Rock
Saint Elmo Pass
Glacier Basin
Mount Ruth
Baker Point
Goat Island Mountain
Tamanos Mountain
Owyhigh Lakes
Needle Rock
LIBERTY RIDGE
WILLIS WALL
The Wedge
Camp Sherman
Steamboat Prow
Jeanette Heights
SUNSET PARK
COLANNADE
Liberty Cap
Sunset Amphitheater
Columbia Crest
Gibralter Rock
Point Success
Little Tahoma Peak
Camp Muir
Cathedral Rocks
Meany Crest
SUMMER LAND
Panhandle Gap
COWLITZ CHIMNEYS
OHANAPECOSH PARK
Indian Bar
COWLITZ PARK
Cowlitz Rocks
Panorama Point
PARADISE PARK
Henry M. Jackson Memorial Visitor Center
Paradise
Aurora Peak
Tokaloo Rock
Tokaloo Spire
PUYALLUP CLEAVER
SUCCESS CLEAVER
WAPOWETY CLEAVER
WHITMAN CREST
Klapatche Ridge
SAINT ANDREWS PARK
Glacier Island
PYRAMID PARK
Pyramid Peak
Emerald Ridge
Round Pass
VAN TRUMP PARK
CREST
CUSHMAN
Copper Mtn
Iron Mtn
Mount Ararat
Lake George
Westside Rd
Wonderland Trail
Owyhigh Lakes Trail
Cowlitz Divide
Nickel Creek
Twin Falls
Needle Creek
Boulder Cr
Basalt Cr
Muddy Fork
Ohanapecosh River
Fryingpan Creek
Wright Cr
Prospector Creek
Huckleberry Cr Trail
Northern Loop Trail
Lodi Cr
White River
Inter Fork
Meadows Rd
Mowich Lake Trail
Spray Cr
Lee Cr
Meadow Cr
Mountain Cr
Saturate Cr
Moraine Cr
West Fork
Winthrop Cr
North Mowich River
South Mowich River
Golden Lakes
Wonderland Trail
Burroughs Mountain Trail
Sunrise Park Rd
Owyhigh Lakes Trail
Cowlitz Divide
Ohanapecosh River
Nickel Creek
Twin Falls
Boulder Cr
Basalt Cr
Muddy Fork
Williwakas Cr
Cowlitz River
Pyramid Cr
Kautz Cr
Van Trump Cr
Success Cr
Tahoma Cr
Fish Cr
St Andrews Cr
South Puyallup R
North Puyallup R
Wonderland Trail
Tahoma Creek
Westside Rd
Lake George
Mowich River
Golden Lakes
Sunset Park
Jeanette Heights
Colannade
Klapatche Ridge
Saint Andrews Park
Emerald Ridge
Round Pass
Glacier Island
Pyramid Peak
Pyramid Park
Van Trump Park
Copper Mtn
Iron Mtn
Mount Ararat
Cushman Crest
Paradise Park
Henry M. Jackson Memorial Visitor Center
Paradise
Sunrise Visitor Center
White River Campground
Yakima Park
Berkeley Park
Huckleberry Park
Ohanapecosh Park
Cowlitz Park
Summer Land
Meany Crest
Panhandle Gap
Cowlitz Chimneys
Indian Bar
Cathedral Rocks
Camp Muir
Camp Sherman
Steamboat Prow
Mount Ruth
Baker Point
Goat Island Mountain
Tamanos Mountain
Owyhigh Lakes
Sarvant Glacier
Ohanapecosh Glacier
Williwakas Glacier
Panorama Point
Cowlitz Rocks
Paradise Glacier
Muir Snowfield
Inter Glacier
Van Trump Glacier
Kautz Glacier
Pyramid Glacier
Success Glacier
Wapowety Cleaver
Success Cleaver
Puyallup Cleaver
Whitman Crest
Liberty Ridge
Willis Wall
Colannade
Sunset Amphitheater
Liberty Cap
Columbia Crest
Point Success
Gibralter Rock
Little Tahoma Peak
Aurora Peak
Tokaloo Rock
Tokaloo Spire

THE GLACIERS OF MOUNT RAINIER

Glaciers, as it turns out, are the architects of Mount Rainier; they are the ultimate sculptors. Their fluctuations visible within a human lifespan, no matter how dramatic at first glance, are well within the range of normal glacier behavior. With virtual certainty, minor changes to climate will continue, as will the fluctuations of glaciers.

Carolyn Driedger, USGS geologist, quoted by Craig Welch in the Seattle Times, July 15, 2002

Creeping kinematic waves move through glaciers like a Slinky™ spring in slow motion.

Leslie Scott Pringle, amateur geologist, oral commun., 2002

…the névé extending from the shoulders of the southwestern peak to those of the north, a width of several miles, descends a vertical distance of 2000 feet below the crater rim, an immense sheet of white granular ice, having the general form of a mountain surface, and broken only by long transverse crevasses, one of those observed being from one to two miles in length: it is then divided up by the several jutting rock masses or shoulder of the mountain into the Nisqually, Cowlitz, and White River [now Emmons] glaciers, falling in distinct ice cascades for about 3000 feet at very steep angles, which sometimes approach the vertical. From the foot of these cascades flow the glaciers proper, at a more gentle angle, growing narrower and sinking deeper into the mountain as they descend. From the intervening spurs, which slope even more gradually, they receive many tributary glaciers, while some of these secondary glaciers form independent streams, which only join the main river many miles below the end of the glaciers…the bed of the Cowlitz Glacier is generally parallel to that of the Nisqually…the ice cascades in which each originates, fall on either side of a black cliff of bedded lava and breccia scarcely a thousand feet in horizontal thickness, while the mouths [termini] of the glaciers…are about three miles apart…The lower extremity stretches out as it were into the forest, the slopes on either side, where not too steep, being covered by mountain fir…

E. F. Emmons, in King (1871)

Mount Rainier's glaciers are among the most fascinating and changing geologic features on the volcano. They have played an important role in eroding the cone, and, by giving birth to a ground-water system within the volcano, they also contribute to the alteration of the volcano, its susceptibility to collapse, and its style of eruption. In addition, the glaciers generate vital stream flow for major northwest rivers, some of which are tapped for hydroelectric power and irrigation.

Mount Rainier has a volume of snow and glacier ice equivalent to that on all the other Cascade Range volcanoes combined. Including the perennial snow bodies, glaciers cover about 35 mi^2 (91 km^2) of the mountain's surface—about 9 percent of the total park area—and have a volume of about 1 mi^3 (4.2 km^3) (Driedger and Kennard, 1986). For comparison, this volume would fill Seattle's Safeco Stadium 2600 times (Driedger and others, 2006). Several of Mount Rainier's 26 named glaciers (Fig. 41) have been the focus of classic studies of neoglacial moraine development and glacial dynamics (Sigafoos and Hendricks, 1961, 1972; Crandell and Miller, 1974; Burbank, 1981; Porter, 1981; Heliker and others, 1984). As shown by Emmons' statements in 1871, above, early geologists observed Mount Rainier's glaciers as they were just beginning to recede from their advanced positions during the Little Ice Age. (See "Neoglacial Advances", p. 30.) At that time, the toes of these expanded glaciers extended "into the forest". The Nisqually Glacier, for example, had moved to a position 650 to 800 ft (198–244 m) downvalley from the present site of the uppermost Nisqually River bridge (Driedger, 1986). Driedger goes on to note that during this time, Tahoma and South Tahoma Glaciers merged at the base of Glacier Island and the terminus of Emmons Glacier reached within 1.2 mi (1.9 km) of the White River Campground (Driedger, 1986) (Fig. 8). The glaciers kept retreating into the 1920s, then faster until about 1950, when many began to advance again because of lower temperatures into the 1980s.

Nylen and others (2000) found that Mount Rainier's glacial cover shrank 18.5 percent between 1913 and 1962. This rate slowed significantly from 1971 to 1994. Nylen documented that glaciers smaller than 5 km^2 (~2 mi^2) decreased by about 35 percent between 1913 and 1994 (Nylen, 2004). Nylen and his colleagues also observed that the glaciers on the southeastern and southwestern flanks suffered the greatest losses.

Glacial-outburst floods from South Tahoma Glacier repeatedly scoured Tahoma Creek during the late 1960s and the middle 1980s to early 1990s and continue sporadically from year to year. The floods are usually associated with seasonally extreme weather—either unusually warm or unusually wet conditions (Walder and Driedger, 1994). The Tahoma Creek events are discussed in detail in the road guide for Leg M. Similar events have occurred in many other drainages, most notably Kautz Creek and Nisqually River, during historical time (Driedger and Fountain, 1989).

Seismic monitoring at Mount Rainier began in 1963 when a seismometer was set up at Longmire; another was installed in 1972 at Mount Fremont (Moran, 1997). On average, about 30 small earthquakes per year occur under Mount Rainier, making it one of the most seismically active volcanoes in the Cascade Range after Mount St. Helens (Malone and Swanson, 1986)(Fig. 42). Malone and others (1991) noted that more than 800 seismic events have been located within a 1600-km^2 (618 mi^2) area centered on Mount Rainier during the past 20 years. Geologists are monitoring the earthquake activity at Mount Rainier because they want to become familiar with its 'background seismicity' during this dormant interval and because they expect that eruptive activity at Mount Rainier will be preceded by a systematic increase in seismic activity.

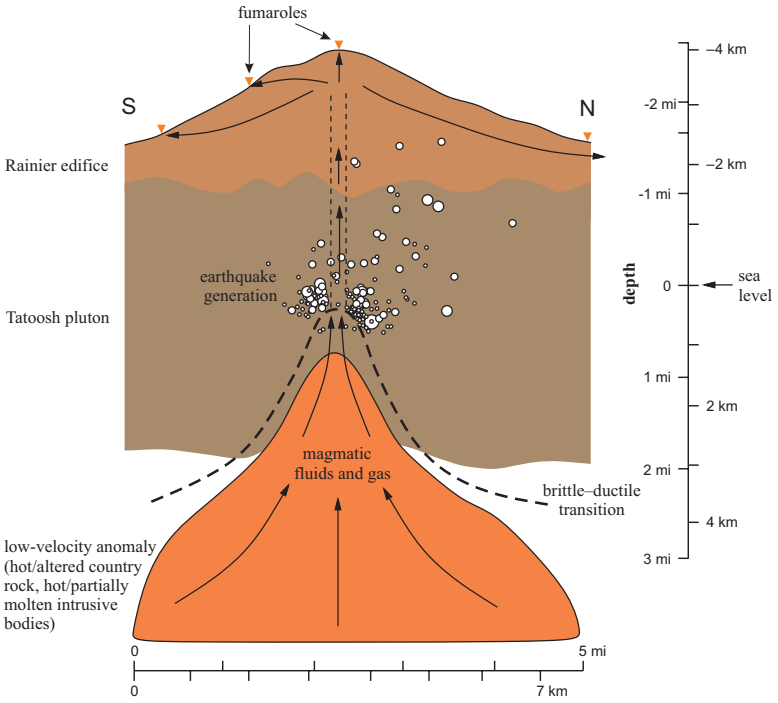


Figure 42. A conceptual model of the magmatic-hydrothermal system beneath Mount Rainier showing rising fluids. The model is derived from geochemical and seismic constraints. White dots show hypocenters (locations) of high-frequency volcanic earthquakes. Modified from Moran and others (2000).

Researchers from the Pacific Northwest Seismograph Network at the University of Washington installed two additional seismometers on the flanks of Mount Rainier in 1989 and another at Camp Muir in 1993. They studied data recorded by these and other nearby seismometers over the 1990s in order to investigate the nature of earthquakes that occur directly beneath Mount Rainier and also to better characterize the 'plumbing system' beneath the volcano.

The researchers found that on average about two earthquakes having a high-frequency signal occur directly beneath the summit in a given month (Fig. 43). They noted that these high-frequency 'volcano-tectonic' earthquakes occur in several clusters located from 1.2 mi (2 km) above to 0.6 mi (1 km) below sea level, well below the inferred base of the volcanic edifice (Moran and Malone, 2000). Researchers' calculations suggest that Mount Rainier's volcano-tectonic quakes are occurring on normal faults because of hydrothermal circulation within and below the base of the edifice that weakens rock and (or) reduces effective stress to the point that gravity-induced slip (and thus volcano-tectonic earthquakes) can occur.

Moran and others (2000) found that the velocities of seismic waves were slightly reduced at depths of 2.5 to 8.7 mi (4–14 km) beneath Mount Rainier, which indicates the presence of hot rock with small amounts of magma and (or) magmatic fluids. This could be the source for heat and magmatic fluids that feed existing surface fumarole fields.

Analysis of tectonic earthquake activity has led to the identification of a north-trending fault zone west of Mount Rainier (Crosson and Frank, 1975; Weaver and Smith, 1983). The proximity of shallow crustal fault zones to Mount Rainier is significant because earthquake activity in that zone could cause slope failures at the volcano. For example, a regional tectonic earthquake triggered a deadly debris avalanche at Ontake volcano in Japan in 1984 (Nagaoka, 1987).

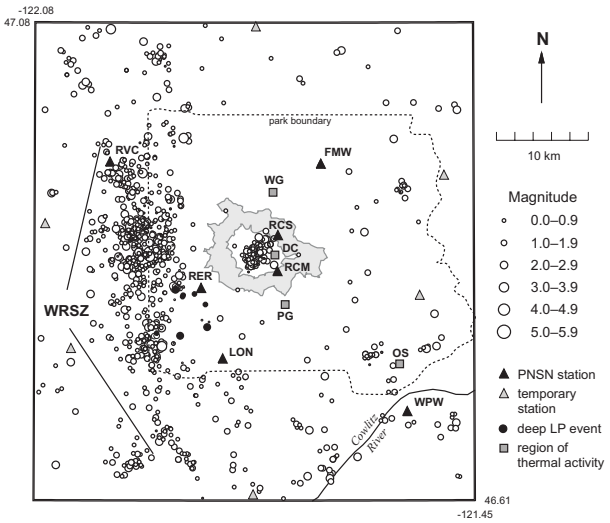


Figure 43. Seismicity in the area surrounding Mount Rainier for the period 1989 through 1997. Black triangles are permanent Pacific Northwest Seismic Network (PNSN) stations; gray triangles are temporary stations run 1995 to 1996. Hollow circles are earthquakes; solid black circles show locations of deep, long-period (LP) events; gray squares correspond to off-summit geothermal fields. DC, Disappointment Cleaver; OS, Ohanapecosh Hot Springs; PG, Paradise Glacier; WG, Winthrop Glacier; WRSZ, Western Rainier seismic zone. PNSN seismometer stations: FMW, Mount Fremont; LON, Longmire; RCM, Camp Muir; RCS, Camp Schurman; RER, Emerald Ridge; RVC, Voights Creek; WPW, White Pass. The gray ring shows the area between 7,500 and 10,000 ft elevation. In late 2006, a swarm of low-magnitude crustal earthquakes rumbled through the area 7 mi (~12 km) west of the mountain. Modified from Moran and others (2000).

Surficial events are another type of seismicity at Mount Rainier that include the seismic signals generated by rock falls, avalanches, debris flows, and 'glacier quakes' (Weaver and others, 1990).

AN OVERVIEW OF VOLCANIC PROCESSES AND HAZARDS

by Patrick T. Pringle and Kevin M. Scott*

How recent volcanic eruptions have changed our views about volcanic processes and hazards

The eruption of Mount St. Helens that began in 1980 was one of the most closely watched major volcanic eruptions of its kind in history. It was televised worldwide, and it marks a major turning point in the way we perceive the processes and hazards at volcanoes. The intensive studies of Mount St. Helens and of other erupting volcanoes such as Mount Pinatubo in the Philippines and, more recently, Augustine Volcano in Alaska, have not only dramatically increased our understanding of how volcanoes work, but also have helped us to better interpret the deposits on a volcano's flanks or in valleys around it. These deposits are the keys to understanding a volcano's past eruptions and behavior. This heightened awareness, as well as the graphic images of Mount St. Helens eruptions, have noticeably increased public and media interest in volcanoes and volcanology.

At Mount St. Helens, for the first time geologists could obtain a fairly complete, 'real-time' record of volcanic activity (earthquakes, ground deformation, and gas emissions) before, during, and after eruptive episodes by using computers to process data about the status of the volcano. The availability of instantaneous or 'real-time' data has allowed scientists to better resolve the patterns of eruptive behavior at other volcanoes, such as at Mount Pinatubo in 1991, and it has helped improve communications and warning systems. At Pinatubo, for example, tens of thousands of lives and millions of dollars in property damage were saved by monitoring of the volcano that produced an accurate prediction of a major eruption.

Generally speaking, composite volcanoes (stratovolcanoes), such as Mount Rainier, that are associated with subduction zones may be characterized by the following: lava flows and domes, pyroclastic density currents, lahars (and smaller debris flows), and debris avalanches. Studies at Mount St. Helens and other volcanoes have improved our ability to recognize the causes and potential scale of these volcanic processes. We have also developed an increased awareness and understanding of the secondary effects of volcanic eruptions or activity, such as sediment-clogged stream valleys and lakes dammed by volcanic landslides or deposits. The effects of these hazards may continue for years or decades after an eruption. (See "Secondary Effects of Eruptions and Lahars", p. 48.)



Figure 44. The August 7, 1980, pyroclastic density current at Mount St. Helens. Photo courtesy of Pete Lipman, USGS, taken from Johnston Ridge, about 5 mi (8.5 km) north-northwest of the volcano.

The 0.6-mi^3 (2.5 km^3) debris avalanche from Mount St. Helens on May 18, 1980, was the largest landslide witnessed in historic times. Studies of its hummocky deposits have since led to recognition of more than 200 similar deposits at volcanoes around the world (Siebert, 1996). These observations have spawned an increased recognition of slope-stability hazards (that volcanoes are subject to collapse), as well as the role of snow and ice in hydrothermal alteration or weakening of a volcanic cone. One of the major concerns of volcanologists is that future collapses at some volcanoes will generate far-traveling lahars (volcanic mudflows). Mount Rainier has an extensive history of such collapses.

A working knowledge of volcanic processes is important for several reasons. First, because we are a growing human population moving ever closer to active volcanoes, it is in our best interests to take steps to reduce our risks from hazardous volcanic processes that we can forecast. We know from catastrophes around the world that we have to take these risks seriously—the costs and losses can be great. At the same time, we shouldn't needlessly fear volcanoes. We will address the important issues related to mitigation of volcanic risks in the next section, "Coping with future volcanic hazards" (p. 49). These processes have left a rich sedimentary record, and they will someday affect this area again. Readers who want a more complete discussion of volcanic processes and their deposits should seek out the following sources: Tilling (1989, chapter 2), Fisher and Schmincke (1984), Cas and Wright (1987), and Decker and Decker (1998).

Lava domes and flows

Sticky high-silica lavas have a fairly high viscosity and therefore tend to pile up and form domes. These lavas cannot flow as readily as those having a lower viscosity, such as the Hawaiian basaltic lavas. Recently, lava domes have been constructed at Mount St. Helens during many episodes of activity from 1980 to 1986 and from 2004 through 2007. These 'dome-building' eruptions included both intrusion of new magma into the dome and extrusion of lobes of lava onto the dome's surface. Lava domes can be hazardous to humans when they explode or collapse. Dome collapse can produce pyroclastic flows and surges, lahars, and floods. However, recent observations of lava erupting at other steep, glaciated volcanoes suggest that resulting floods and lahars are relatively small (Major and Newhall, 1989). Mount Rainier has produced many lava flows, but has only one possible lava dome.

The main hazard from lava flows is damage or total destruction by burying, crushing, or burning of everything in their path. Generally, highly viscous lava flows do not flow far from the volcano. Lava flows can melt snow and ice, but they commonly do not produce major floods and lahars because they do not mix turbulently with snow and ice unless they break apart. They can, however, melt large quantities of glacial ice, and that water can be released as jökulhlaups.

Pyroclastic density currents

'Pyroclastic density current' is a general name for various types of flows of hot gas and rock down the slopes of a volcano (Fig. 44). These flows of particulates are formed by the gravitational collapse of lava domes, lava flows, and eruption columns (Scott, 1989). Pyroclastic flows, pyroclastic surges, and directed blasts (sometimes called 'lateral blasts') are all types of pyroclastic density

* See "Contributors", p. ii, for affiliation.

currents. From flow characteristics that geologists have inferred from deposits, typical pyroclastic density flows have two main components: (1) a ground-hugging, dense basal portion (the 'flow'), and (2) a turbulent ash-cloud surge (the 'surge') that extends out from the flow and can move across the landscape over topographic barriers. It's important to understand how each part of a pyroclastic density current can behave.

Pyroclastic flows are masses of hot (572°–1472+°F or 300°–800+°C), dry rock debris and gases that move along the ground surface at velocities ranging from ten to several hundred yards (meters) per second (Scott, 1989). Direct hazards of pyroclastic flows are asphyxiation, burial, incineration, and impact. Pyroclastic flows can also generate lahars and floods by quickly melting snow and ice, dam tributary valleys, and start fires. Pyroclastic flows are strongly controlled by topography and are likely to be restricted to valley floors. Most pyroclastic flows from composite volcanoes are limited to within 9 to 15 mi (15–25 km) of a volcano.

Hot pyroclastic surges, because they are less concentrated and less dense than pyroclastic flows, are not necessarily confined to valleys and can affect more extensive areas—they can travel many tens of miles (kilometers) from the volcano. Pyroclastic surges can also generate secondary pyroclastic flows. Surges are responsible for many catastrophes, including 30,000 deaths in 1902 at Mount Pelée in Martinique and 2000 in 1982 at El Chichon volcano in Mexico. They can trigger devastating lahars, such as that in 1995 at volcano Nevado del Ruiz, Colombia, that killed more than 23,000 people (Wright and Pierson, 1992). Cold or base surges typically result from explosive interactions of magma and water, such as that witnessed at Kilauea, Hawaii, in May 1924 and, on a smaller scale, at Mount St. Helens with the post-1980 phreatic (steam) explosions on the Pumice Plain and in the crater.

Directed blasts are very powerful, laterally focused explosions such as that at Mount St. Helens in 1980 and at Bezymianny Volcano, Kamchatka, in 1956. Blasts can affect large areas (230 mi^2 or 600 km^2 at Mount St. Helens). However, most Holocene examples of blasts in the Cascades were evidently considerably less energetic and extensive than Mount St. Helens' great 1980 blast; examples are the F tephra layer at Mount Rainier and the "Sugar Bowl" (1,200 yr B.P.) explosion and March 1982, February 1983, and May 1984 small explosive events at Mount St. Helens (Crandell, 1987; Pierson, 1999).

Lahars and laharic floods

Lahars are rapidly moving volcanic debris flows (mudflows) or mixtures of rock debris that are mobilized by water and originate on the slopes of a volcano (Vallance, 2000). Typically, they are restricted to stream valleys.

Although geologists have long realized that lahars can originate in several ways, Scott (1988) identified two major flow types from sedimentary characteristics that he related to their origin and flow behavior: 'clay-rich' (cohesive) and 'clay-poor' (noncohesive). Scott's classification scheme has been useful, not only for interpreting the genesis and flow processes of ancient lahars from the sedimentary characteristics of their deposits, but also for recognizing their downstream transformations, so that correlative deposits now can be identified in widely separated locations. Sand and gravel deposits that are derived from lahars have even been recognized in Miocene lahars (Luker, 1985). For example, we found that the thick channel-fill deposit of andesitic sand and gravel underlying the City of Puyallup is the downstream equivalent of a block-and-ash flow and lahar upstream in the Puyallup River valley (Palmer and others, 1991; Pringle and Palmer, 1992). The two deposit types and, by inference, the flows that yielded those deposits have also been referred to as 'muddy' (clay rich) and 'granular' (clay poor).

Clay-poor lahars generally contain less than 5 percent clay-size particles in their matrix. These flows typically begin as a watery flood surge that incorporates sediment and becomes a debris flow as it travels (Fig. 45). This debris flow then rapidly transforms downstream to more diluted flow types, such as lahar-runout flows and floods, because of sediment deposition (particularly the coarser fraction) and (or) incorporation of water as the flow moves downstream (Fig. 46). The many causes of these clay-poor lahars include:

- Interaction of a pyroclastic density current with snow and ice,
- Meteorologically induced erosion of tephra (or other fragmental debris) from the slopes of a volcano (rainstorm or rain-on-snow events),
- Failure of a landslide-dammed lake, and
- A glacial outburst flood or jökulhlaup.

Clay-rich lahars typically have greater than 5 percent matrix clay and commonly begin as volcanic landslides. The largest landslides from volcanoes are called sector collapses. These commonly remove the summit of the volcano, leaving a characteristic horseshoe-shaped crater, and have a volume of 0.2 mi^3 (1 km^3) or more. Reid (1995) has suggested that pressurization from hot fluids within a volcano may initiate such collapses.



Figure 45. A geologist examines the clay-rich Round Pass mudflow deposit from Mount Rainier near the town of National, about 12.4 mi (20 km) flow distance from Mount Rainier. The Round Pass mudflow has been dated at 2600 yr B.P. (Crandell, 1971; Scott and others, 1995). Overlying it is a clay-poor lahar deposit, whose age has been estimated at 2,500 yr B.P. Both of these flows may have traveled along the Nisqually River as far as Puget Sound. The contact between these two flows is about at shoulder level on the lowest person. The large log on the left is embedded in the Round Pass mudflow. View to the south; taken October 2000.

Smaller landslides that do not involve the volcano's summit are called 'flank collapses' (Scott and others, 2001). These may also become clay-rich lahars that inundate areas well beyond 30 mi (50 km) from the source volcano; the Electron Mudflow at Mount Rainier is a classic example of such a flow. Flank collapses have a variety of triggers, including eruptions, intrusions, magmatic activity that destabilizes the edifice (such as hydrothermal alteration, phreatic [steam] activity, and earthquakes), or simple gravity (Swanson and others, 1995).

Clay-rich lahars can have enormous volumes and flow great distances. The Electron, Round Pass, Paradise, and Osceola mudflows at Mount Rainier and the Middle Fork Nooksack flow at Mount Baker are noteworthy local examples (see Fig. 33, p. 36). The volume of the Electron Mudflow has been estimated at more than 300 million yd^3 (0.25 km^3) (Crandell, 1971; Scott and others, 1995) and the volume of the Osceola Mudflow deposit at about 0.8 mi^3 (3.8 km^3) (Dragovich and others, 1994; Vallance and Scott, 1997), making it one of the world's largest lahars.

Inundation height, runout length, velocity, and duration of flood wave for lahars can vary widely. Spacing between events, amount of available sediment for bulking, and other factors can change the scale of hazards and of the sedimentation and landscape effects from lahars.

Debris avalanches

A volcanic debris avalanche is a type of volcanic landslide—specifically, a flowing mixture of rock, soil, and miscellaneous debris, with or without water, that moves away from a volcano at high speed under the influence of gravity. Debris avalanches are an end member of a continuum of mass-wasting processes at composite volcanoes. As noted above, large lahars at some highly hydrothermally altered volcanoes, such as Mount Rainier, have undoubtedly transformed directly from such volcanic landslides. Scott and others (2001) discuss a number of examples of this and related phenomena. Had the 1980 debris avalanche at Mount St. Helens transformed in this way, it could have traveled much farther and potentially have caused significantly more damage in downstream areas. Since the Mount St. Helens events, hummocky debris-avalanche deposits have been recognized at several hundred volcanoes around the world (Siebert, 1996). The deposits of a debris avalanche can reach a great thickness, for example, in excess of 650 ft (200 m) at Mount St. Helens (Glicken, 1986, 1998). Therefore, even if a debris avalanche does not transform into a lahar or flow more than 9 mi (15 km) from a volcano, it can cause drastic, long-term environmental changes throughout the affected drainage basins by altering the equilibrium of stream systems and providing a source of sediment and small-scale landslides, as well as temporary lakes.

The nature of the hazard from debris avalanches and its relation to hydrothermal alteration and destabilization of a volcanic cone also indicate that sector-collapse events (very large debris avalanches noted above) can affect any drainage heading on a volcano. These major collapses are more likely in sectors of the volcano where alteration is at a more advanced stage.

Debris flows and jökulhlaups

Debris flows can result from collapse and stream incision of stagnant, debris-covered ice downstream of the receding termini of active glaciers. These debris flows, which are triggered by glacial outburst floods or 'jökulhlaups', have been especially pronounced at Mount Rainier where, as at all Cascade Range volcanoes, glacier recession has occurred with the climate warming that has followed the end of the Little Ice Age at about A.D. 1850 (Walder and Driedger, 1993, 1994). The largest historic debris flow at Mount Rainier occurred in Kautz Creek on Oct. 2, 1947. Approximately the lower mile (1.6 km) of the Kautz Glacier progressively collapsed in response to heavy rain, producing surges of debris that probably extended into the Nisqually River and farther downstream to the southwest boundary of Mount Rainier National Park (Richardson, 1968; Crandell, 1971).

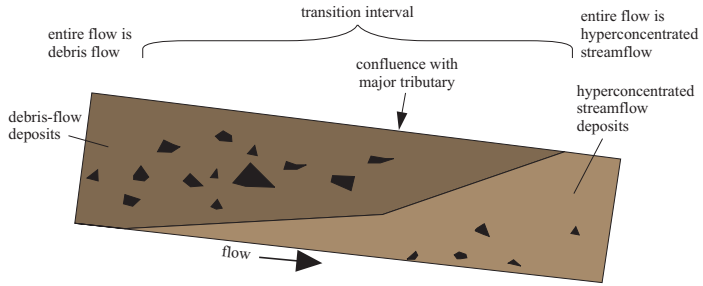


Figure 46. The transformation of a clay-poor lahar to a more dilute hyperconcentrated flow as it moves downstream away from the volcano. Observations of how lahars undergo changes in their concentration and flow properties along their courses as they move away from a volcano now help geologists to recognize lahar-related deposits that are far downstream of a volcano. Modified from Scott (1985).

Since 1986, clusters of glacial outburst floods have occurred from the active terminus of South Tahoma Glacier, the most recent lasting from 1986 to approximately 1993. These floods were triggered both by rainfall and by periods of unseasonably hot weather. They transformed and bulked to debris flows as they crossed and incised a large area of stagnant, debris-rich ice.

The debris flows have obliterated a picnic area and the lowest 0.6 mi (1 km) of the Tahoma Creek hiking trail and have repeatedly damaged Westside Road, the principal access route to national park trails and facilities on the southwest side of Mount Rainier. (See Leg M, p. 156, mile 3.2.) Their suddenness and rapid movement downvalley make them dangerous to any objects in their path. Several individuals have witnessed the debris flows, but no one has yet been injured. However, about 60 persons were stranded on July 14, 1988, when a debris flow destroyed sections of Westside Road south of Round Pass, between Tahoma Vista and Fish Creek.

As of July 1994, 15 debris flows had been recorded in the flood sequence that began in 1986, and a total of 23 since 1967. Crandell (1971) described several earlier debris flows that swept through this same area, and Scott and others (1992) and Vallance and others (2002) discussed the sedimentary characteristics of two recent flows in Van Trump Creek. Not all the damage has directly resulted from debris flows. Meteorologic floods in the disturbed Tahoma Creek drainage caused dramatic shifts in the channel in 1990, 1995/96, and 2006. These relatively small events, while posing a hazard mainly to areas in the national park, have frustrated efforts to keep Westside Road open and have served as a reminder of the much larger, less frequent debris flows.

Small debris flows in Van Trump Creek in 2001 triggered evacuations and an emergency response (Bailey and Woodcock, 2003). (See Leg A, p. 63, mile 43.5.) However, those events resulted when meltwater from the glacier overflowed a lateral moraine and spilled into the drainage basin of Van Trump Creek at about 9000 ft (2742 m) elevation on Mount Rainier's south flank (Vallance and others, 2002). The sudden influx of meltwater into that basin's saturated fragmental debris, which moved down Van

Trump Creek as a series of debris flows, spilled over Christine Falls and into to the Nisqually River. Some hikers or campers were startled by the loud rumbling of the debris flows, but luckily none of them was injured by the event.

Another glacier-related and potentially hazardous process is floods or debris flows produced by breakouts of moraine-dammed lakes. Terminal neoglacial moraine dams have failed in numerous places in the Oregon Cascades, but no significant historic examples have yet occurred at the five volcanoes in Washington. A lake impounded by the neoglacial terminal moraine of the Emmons Glacier has enlarged significantly in recent years, and its level is being monitored by USGS and National Park Service scientists. Failure of the moraine dam could produce a debris flow large enough to put a downstream campground at risk.

As we might expect, glacial outburst floods and debris flows have occurred in many other Mount Rainier drainages during historical time (Driedger and Fountain, 1989) and at Glacier Peak and Mount Baker. Many small debris flows, such as the aforementioned, probably will not be preserved or recognized in the geologic record (Cameron and Pringle, 1990). They do, however, cause localized ecological disturbances (Frenzen and others, 1988) and hazards, and they occur more frequently (on annual or decadal scales) than larger flow types.

Secondary effects of eruptions and lahars

The secondary effects of the 1980 Mount St. Helens eruption serve as a reminder that landscape disturbances caused by volcanoes, such as severe sedimentation in downstream areas, can persist long after initial eruptive activity has ceased (Major and others, 2000). At Mount St. Helens, dramatic post-eruption erosion and sedimentation and the ongoing potential of floods from lakes that were impounded by the 1980 debris avalanche presented costly engineering problems.

From 1980 to 1984, an estimated 8 million tons (~7.3 metric 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. 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. Large floods in the area included rain-on-snow events in the mid-1990s that triggered the most significant sedimentation in the Toutle River downstream of the Mount St. Helens since the 1980 eruption (Major and others, 2000). For comparison, at Mount Pinatubo volcano in the Philippines during 1991 (the year of the cataclysmic eruption), Janda and others (1996) measured post-eruption rates of sediment yield as high as 3.8 million m^3 (5 million yd^3) of sediment per square kilometer of watershed, and as high as 1600 m^3 (~5000 yd^3) of sediment per square kilometer per millimeter of rainfall, an order of magnitude higher than at Mount St. Helens!

The 1980 Mount St. Helens debris-avalanche deposit dammed numerous tributary valleys of the North Fork Toutle River. The deposit dam raised Spirit Lake more than 165 ft (50 m) higher than its pre-eruption level. It also blocked the courses of Coldwater, Castle, and Jackson Creeks to form lakes. On at least five occasions from 1980 to 1982, the collapse of a sediment dam released a small lake or pond adjacent to the debris avalanche and caused minor floods. However, public concern has focused on Spirit, Coldwater, and Castle Lakes, the three largest lakes impounded by the debris avalanche.

In the 1980s, geologists recognized that some lahar deposits represented enormous floods that had resulted from breakouts of lakes that were in similar settings at the volcano in ancient times (Scott, 1988). Scott noted that some of these ancient 'lake-breakout' lahars had discharges greater than 9 million ft^3/s (250,000 m^3/s) at about 19 mi (30 km) flow distance from the volcano—equivalent to the modern Amazon River in flood! Similar blockages no doubt occurred at Mounts Rainier, Mount Baker, and Glacier Peak in the past, and dam-break floods will likely recur.

Long-term volcanic disturbances

The rivers that drain stratovolcanoes are typically disturbance-dominated streams. This is because lahars or other volcanic flowage deposits commonly cause large-scale changes in the stream beds that later result in years or even decades of channel adjustments. Post-eruption flood events at Mount St. Helens and Mount Pinatubo in the Philippines have graphically demonstrated that what would be a 'normal' flood event can grow drastically when there is a large amount of sediment available for floodwaters to pick up and transport—even more than a decade after the initial volcanic disturbance.

Consider the Puyallup River: its past lahars may be among the best known in the world—both the Osceola and Electron Mudflows left thick deposits in their downstream reaches. Stratigraphic evidence clearly shows that the river is dominated by lahar deposits from Mount Rainier at the source to Commencement Bay at Puget Sound. In the Puyallup River's upper reaches, upstream of the Mowich River, there are thick accumulations of the Round Pass mudflow (2,600 yr B.P.), including hummocky topography similar to that displayed by the 1980 debris avalanche at Mount St. Helens. The river is still mostly perched; it has not yet cut through the lahar deposit and still sits atop the deposits of the Round Pass mudflow in that area. Interpretations of well logs where the river debouches from the Cascade Range front onto the Puget Lowland at Electron indicate the deposits of the most recent large lahar, the Electron Mudflow, are probably about 50 ft (~15 m) thick. Those same deposits are as much as 20 ft (6.1 m) thick at Orting, 7 mi (11 km) downstream. Examination of well logs and rock cuttings retrieved from drilling at Orting shows a stack of lahars and laharic sediments interbedded with fluvial sediments. Lahars have aggraded the stream bottom there an estimated 60 to 65 ft (19.5–21 m) over at least the past 6400 years or so. The Osceola Mudflow, another prominent stratigraphic marker, occupies the interval between roughly 50 and 30 ft (15 and 9 m) depth there, depending on location in the valley. It's clear that aggradation, not erosion, is the long-term geomorphic trend in this river valley and at nearly all valleys whose rivers drain composite volcanoes. While those rivers in affected valleys typically stabilize within a few decades of a volcanic disturbance, they stand a good chance of being inundated by future lahars during subsequent eruptions. ■

COPING WITH FUTURE VOLCANIC HAZARDS

More than 150,000 people reside on the deposits of previous lahars [from Mount Rainier]…During the past few millennia lahars that have reached the Puget Sound lowland have occurred, on average, at least every 500 to 1,000 years. Smaller flows not extending as far as the lowland occur more frequently. If lahars of the future happen at rates similar to those of the past, there is at least a one in seven chance of a lahar reaching the Puget Sound lowland during an average human life-span.

Driedger and Scott (2002)

Volcano monitoring—Listening for signs of restlessness

Just as a change in our own 'vital signs' can provide clues to our own health, so changes in a volcano's physical condition can presage a change in its eruptive status. Geologists mainly use seismicity, deformation, and volcanic gas monitoring to detect changes in a volcano's behavior (Tilling, 1989; Ewert and Swanson, 1992).

Seismometers remain the most effective tool for monitoring volcanic activity. Scientists expect that any eruptive activity at Mount Rainier will be heralded by a sustained increase in the number and size (magnitude) of earthquakes in the volcano. As noted above in the section on seismicity, seismologists have made substantial progress in interpreting the wide variety of earthquakes that occur at volcanoes. They have classified these earthquake characteristics in order to determine the type of volcanic activity and its location.

Deformation monitoring focuses on measuring the changing shape of a volcano, typically swelling. Continued increases in the rate of swelling of a volcano can help to indicate if and when an eruption is imminent. Field techniques can be as simple as measuring movement along thrust faults and expansion of radial cracks in the crater floor with a carpenter's steel tape or more sophisticated types of measurements using surveying equipment such as electronic distance-measuring devices and theodolites. At Mount St. Helens and other volcanoes, geologists are now relying on use of precise GPS (global positioning system) instruments whose data are radioed back to a volcano observatory in 'real time'. The GPS devices can be lowered onto an active area of the volcano using helicopter sling loads, thus reducing risk of having geologists on the ground at the volcanic vent. Strainmeters and electronic tiltmeters placed on the Lava Dome at Mount St. Helens also can 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.

Measurements of gas discharge are commonly made with aircraft-mounted sensors, as well as with handheld devices. While water vapor is the most abundant volcanic gas, those that have proven most useful for monitoring volcanic changes are CO_2 and SO_2 (McGee and Gerlach, 1995).

Two fairly new methods of monitoring volcanoes are forward-looking infrared thermography (FLIR) and interferometric synthetic aperture radar (InSAR). The infrared sensors, handheld or mounted on aircraft, measure radiant heat energy. InSAR compares phase information from satellite images taken at different times and can detect displacements in the Earth's crust as small as 1 cm (0.4 in.)(Pritchard, 2006). While the effective use of InSAR is limited because of its dependence on clear atmospheric conditions, it has proven to be an excellent tool for reconnaissance surveys in remote areas. For example, InSAR has recently revealed details about uplift at South Sister volcano in central Oregon (Dzurisin and others, 2006) and at Yellowstone caldera (Wicks and others, 2006).

Another important monitoring tool developed by the scientists at the USGS Cascades Volcano Observatory is the acoustic flow monitor (AFM). AFMs are geophones that can be tuned to listen for ground vibrations within a specific frequency range (Lahusen, 1996). They are particularly useful for detecting the characteristic high frequency vibrations of debris flows such as lahars, which are in the range of 30 to 80 Hz (cycles per second). The USGS has installed AFMs in the Puyallup and Carbon River valleys so that potential lahars can be detected.

The combined use of the above techniques has proven to be effective way to monitor changes in a volcano's behavior. However, while work continues on refining instrument sensitivity and developing other techniques to help geologists understand volcano behaviors, around the world these technologies and methods mostly have been applied on an ad hoc basis to volcanoes showing signs of activity. When multiple volcanoes become active, as they did in late 2004 when several Alaskan volcanoes and Mount St. Helens were simultaneously active, instrumentation capabilities can become challenged. Volcanologists hope to establish a proactive, fully integrated, national-scale volcano monitoring effort so that they can improve instrumentation as well as alerting and forecasting capabilities, and thus provide more authoritative information on volcanic activity (Ewert and others, 2005).

Assessing volcanic hazards—Learning from the past record of volcanic activity

Volcanic hazards are destructive natural processes, such as those mentioned in preceding sections, that have a moderately high probability of occurring. 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 hazardous 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 location and extent of the resulting deposits. Once field mapping investigations are completed, the geologist compiles a report and maps to show the areas that are likely to be affected by future hazardous volcanic processes (Hoblitt and others, 1998). The studies of Mount Rainier lahars mentioned above ("Lahars, tephra, and buried forests", p. 34, and "An overview of volcanic processes and hazards", p. 45) have shown that there are two main styles of lahars that form in different ways (Driedger and Scott, 2002). For planning purposes, therefore, these lahars can be characterized as distinc-

tive flow types that have a range of sizes (volumes) and a given probability of occurrence (Fig. 47). The respective hazard designations for these flow types are discussed in greater detail below in the section on land-use planning concerns related to lahar hazards at Mount Rainier. Additionally, the sedimentary characteristics of these different types of lahar deposits influence the behavior and strength properties of soils, and thus have important implications for the design of structures and civil works in river valleys surrounding volcanoes. For example, foundations should be adequately designed to cope with the liquefaction hazards that are caused when strong earthquakes shake saturated volcanic sand deposits.

Mitigation of risks from volcanic hazards

The three most important components of reducing the losses from volcanic hazards 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 reduction of volcanic risk 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.

Citizens who witnessed the 1980 Mount St. Helens eruption via global media saw volcanic processes, such as the destructive lahars, that they could visualize at other volcanoes, such as Mount Rainier. Terms like lahar, pyroclastic flow, tephra, and ash cloud entered the lexicon, yet a basic understanding by the public of hazardous geologic processes seemed lacking. Scientists and emergency managers who worked at Mount St. Helens in response to its 1980–1986 eruptions formed "working groups" to address volcanic hazards issues at other active volcanoes. The working groups provided a framework that encouraged communication about volcanic hazards at many levels. Members of the working groups represented government, schools, corporations, and the public. Beginning in 1990, the Mount Rainier volcano hazards working group met regularly, took field trips to see lahar deposits and buried trees, and wrote a volcano response plan—now accessible via the Internet. (See "Websites and Phone Numbers", p. 176.) Together, they learned about the need to talk with government representatives early, to avoid a 'doom and gloom' approach, and to focus on clarifying the scale and probability relationships of volcanic processes at Mount Rainier. Armed with revised USGS volcano hazard maps (Hoblitt and others, 1998), the working groups built a knowledge base and trust among themselves and the public via pre-existing communication networks. Members of the working group have compiled an educational guide to the volcano (Driedger and others, 2006).

Some schools and communities downstream of Mount Rainier have been responding to the increased awareness of volcanic hazards by holding evacuation drills to prepare for a lahar emergency. The Orting schools in particular have held drills in which students walk to the safe higher ground at the margins of the valley. If a lahar is detected by a series of acoustic flow monitors (mentioned above), a radio message will be sent to Pierce County Emergency Management and to the U.S. Geological Survey's Cascades Volcano Observatory. Sirens are now in place; however, their role will likely be replaced or enhanced in the future by programmable weather radios to be installed in public facilities and homes.

In Orting, the Bridge for Kids project has made progress in obtaining funding for a pedestrian bridge across the Carbon River. This bridge would shorten the evacuation time to safe locations on higher ground on the east side of the Carbon River.

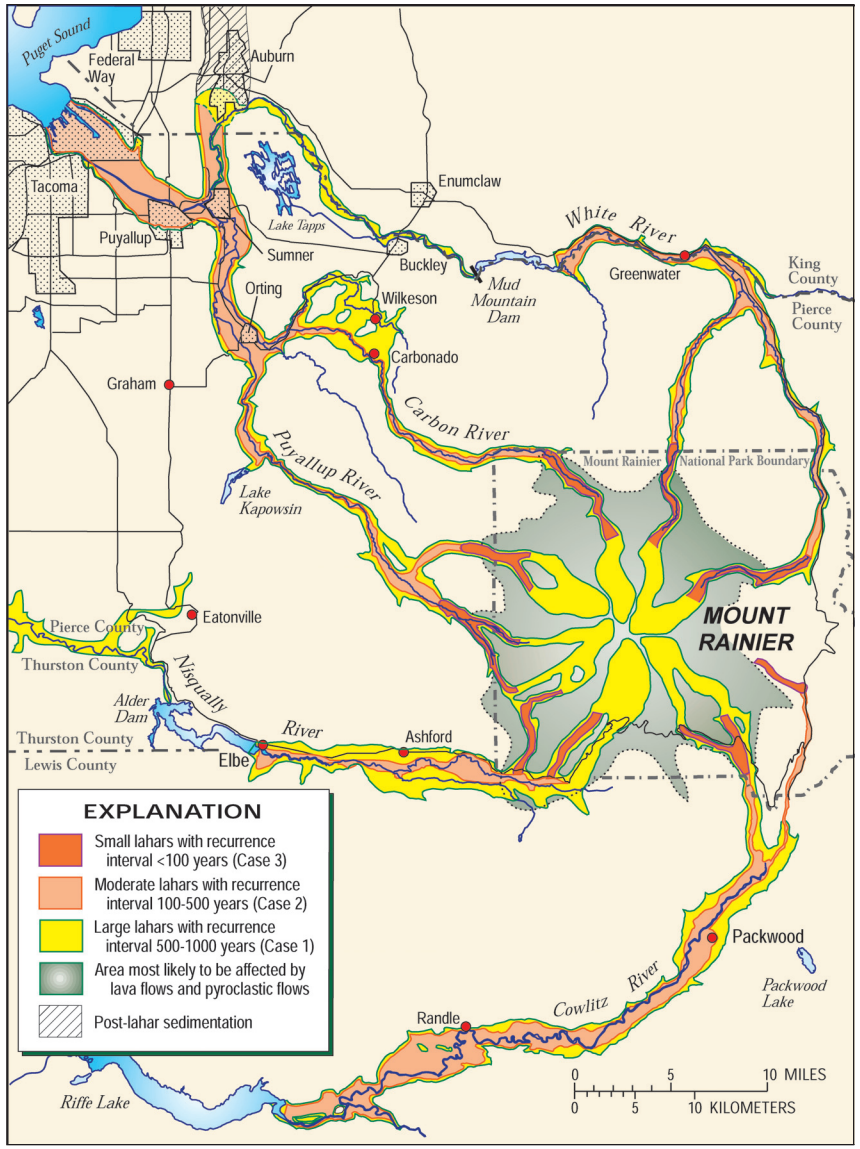


Figure 47. Hazard zones for lahars, lava flows, and pyroclastic flows from Mount Rainier (Hoblitt and others, 1998). The colored areas could be inundated if events similar in size to those of the past occurred today. Major lahars have occurred on average every 500 to 1000 years and smaller flows more frequently. The hazard from lahars is not equal in all valleys. The Puyallup Valley is the valley most susceptible to lahars caused by flank collapse, owing to the weak rocks composing the upper west flank of the volcano. The zone of lahar-related flooding extends as far as Elliott Bay and the shipping docks in the Port of Seattle north of this map area. Risk to individual drainages will continue to be refined as scientists learn more about the volcano.

Land-use planning concerns related to lahar hazards at Mount Rainier

A major consideration of land-use planners and emergency managers with regard to lahar hazards at Mount Rainier volcano is the susceptibility to a clay-rich lahar, such as the Electron Mudflow. This type of lahar, which commonly begins as a collapse of a weak part of the volcano, has a likelihood of occurring about every 500 to 1000 years, and the risks are greater on the west side of Mount Rainier because of the large amount and nature of 'rotten' or weak fragmental rock high on the volcanic cone on that side. Recent mapping of rock magnetism at Mount Rainier by geologist Carol Finn and her colleagues (2001) shows an area containing a large amount of hydrothermally altered rock on the mountain's upper west flank; this mushy, slippery rock can be detected because it is demagnetized. It should be no surprise that this area of the Mount Rainier cone has given rise to some notable and sizeable lahars, the most recent being the Electron Mudflow (ca. A.D. 1502). In rare instances, these clay-rich lahars may occur with little or no warning. Just such an event occurred at Mount Ontake, Japan, in 1984 (Yanase and others, 1985; Nagaoka, 1987).

The stratigraphic record of enormous megathrust earthquakes in the Cascadia subduction zone (see Fig. 7, p. 9), as well as our increasing recognition of shallow-crustal fault zones in Washington (see Fig. 14, p. 18) and their possible triggering of landslides by seismic shaking (Pringle and others, 2000b), amplifies the need for further study of this mass-wasting process at composite volcanoes and of possible evidence for past large earthquakes close to a volcanic cone. Nevertheless, most volcanologists agree it is far more likely that a clay-rich lahar would be triggered by an eruption than an earthquake.

For land-use planners, emergency managers, and anyone trying to better understand the risks at a volcano, the U.S. Geological Survey has classified lahars mainly on the basis of their mode of genesis. In their report "Volcano Hazards from Mount Rainier, Washington", Hoblitt and others (1998) designated a clay-rich, or cohesive lahar like the Electron Mudflow as the "Case 1" category. (See "Lahars and laharic floods" on p. 46.) The more localized hazards on the west side of the volcano are related to mode of genesis of a lahar (possible collapse), not solely to its probability. Sector collapses are nearly always associated with an eruption or hydrovolcanic activity (magma–water interactions) such as steam explosions. Consequently, precursory volcanic activity, such as volcanic earthquakes, swelling, and (or) gas emissions, should provide us with a degree of warning before such an event. This is why there has been a great interest in the lahar warning system in the Puyallup River basin, which is downstream of Rainier's fragile west slope. Although there is no guarantee of an effective pre-event warning that will lead to evacuation of large populations potentially at risk long distances from a volcano, lahars can be detected close to their sources because of their characteristic vibrations (Lahusen, 1996). Therefore, the USGS has installed an array of ten acoustic flow monitors in two drainages of Mount Rainier to provide warning that a lahar is occurring.

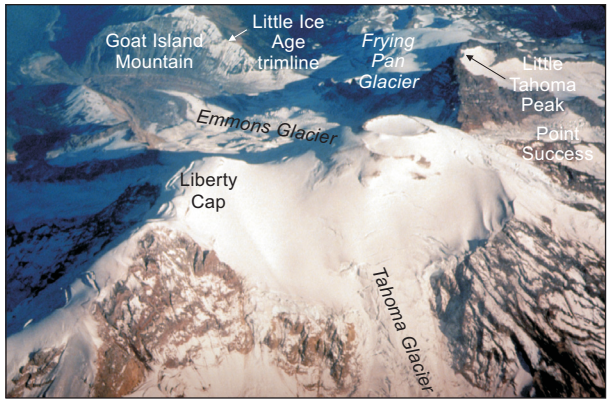


Figure 48. The twin summit craters of Mount Rainier. Columbia Crest cone (right) sits in and nearly fills the large crater created by the collapse that led to the 5,600-cal-yr-B.P. Osceola Mudflow. Little Tahoma Peak is visible in the upper right corner. Clockwise from left center to upper left: Winthrop Glacier, Steamboat Prow, debris-covered terminus of Emmons Glacier, and base of Goat Island Mountain. Sisson and Lanphere (1999) estimate the age of the thin, south-dipping lava flows in lower right at less than 40 ka because they were erupted after the large flow of that age forming Ricksecker Point. View to the east. Photo taken by Tom Bush, Pierce College, in November 2001.

However, it is the "Case 2" clay-poor lahars, mostly originating with the production of meltwater during volcanic eruptions, that are best represented in the geologic record. The hazards of these lahars are more evenly spread out around the mountain because the Columbia Crest cone (Fig. 48), which would be the most likely source area for an eruption, has essentially filled up the crater it grew in and so drains into multiple rivers, such as the Puyallup, White, and Nisqually. Clay-poor lahars also have been far more common in Mount Rainier's past than clay-rich lahars. Still, some drainages, such as the Cowlitz River, although susceptible to inundation by lahars and volcanic floods, probably remain somewhat less vulnerable to these Case 2 processes because of topographic factors.

In summary, although not uniform, the risk of lahars can be portrayed as volcano-wide, with a particular concern being the huge lahars that pose a risk to lowland communities far downstream by burying them with many feet of sediment. However, for the citizen who is concerned about hazards of lahars, it is important to know that, despite their huge size and long flow distances, lahars typically behave according to the laws of physics and have a scale and flow behavior that constrains their extent within topographically definable areas downstream of a volcano. This realistic understanding reduces the sensationalism of threats from lahars and allows us to take lahar hazard maps, such as that by Hoblitt and others (1998), seriously as positive information for planning and preparedness options, while at the same time acknowledging the lahars' potential for catastrophic destruction.

Effective communication about volcano hazards

The tragedy at Armero, Colombia, in 1985, in which more than 23,000 people were killed by a lahar, demonstrated dramatically just how urgently scientists and emergency preparedness managers needed to improve communications during volcanic emergencies. Geologists who responded to the Armero disaster saw that it was essential to guarantee timely transmission of volcanic hazards information to the public, including the timing and nature of the hazards, possible areas that could be at risk, and the explicit instructions on how to prepare for emergencies and seek safety. To refine the communications process, geologists have sought to improve and clarify the terminology used in assessing possible volcanic activity. In some instances, these efforts resulted in remarkable and fortuitous monitoring feats (for example, at Mount Pinatubo in the Philippines) through which local populations received adequate warning of an impending volcanic emergency and many lives were saved via timely evacuation.

In any geologic emergency, geologists find it is an ongoing effort to help local residents and the general public understand what to expect from what may happen. If

citizens could better understand what a lahar is, how it flows, how thick the flow could be, and how far and how fast it could go, they would be better prepared to live more comfortably near the volcano because they would know how to react. In order to prevent confusion and misunderstandings, geologists now maintain distinctions among three types of public statements when describing volcanic activity:

(1) Factual statements, which provide information but do not anticipate future events.

(2) Forecasts, which are comparatively imprecise statements about the nature of expected activity. These are typically based on the past history and potential of a volcano and on geologic mapping.

(3) Predictions, which are relatively precise statements about the time, place, nature, and size of impending activity. These are generally 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 among scientists, government officials, and the public and can foster serious efforts toward improving regional and local emergency response and land-use plans (Swanson and others, 1985). ■

Recent Geomorphic Evolution of the Landscape

Residents of the Pacific Northwest won't have to wait for a Mount Rainier eruption to witness profound landscape changes at the volcano. Ongoing erosion and mass wasting can cause big changes in the land surface. The storm of Nov. 6 and 7, 2006, for example, dumped 18 in. (45 cm) of rain on Mount Rainier National Park in 24 hours. The floods and landslides caused so much damage to facilities, campgrounds, trails, and roadways that the Park Service closed the park down for the first time in about 60 years. Park officials estimated that the total damage to the park could be as high as $30 million dollars, more than half of which would be needed to repair the many roads that were destroyed (Mayor, 2006). ■



Aerial-oblique view to the south of Kautz Creek on Nov. 8, 2006, showing the channel after the catastrophic flooding of the two previous days, when 18 in. (46 cm) of rain fell within 24 hours. The pre-flood channel (to the right) was filled with sediment and debris, possibly by a debris flow, which caused the stream to cut a new channel farther to the east (left) across the surface of the 1947 debris flow deposit. The width of the old channel here is about 150 ft (46 m). The larger trees on the left are part of an older forest growing on the east valley wall of Kautz Creek. Photo by Mike Gauthier of the National Park Service.

PART II: ROAD GUIDE TO THE GEOLOGY OF THE MOUNT RAINIER AREA

LEG A: WESTERN APPROACH

Tacoma to Paradise via State Routes 7 and 706 and the Nisqually River valley

by Patrick T. Pringle and Elizabeth S. Norman*

This historic route follows much the same path as the original 'Road to Paradise', the first highway to the alpine meadows of Mount Rainier, constructed in 1916. The 49-mi (78 km) route rises from near sea level to about 5400 ft (1646 m) at Paradise (49 mi or 78 km) (Fig. A-1). The highways from Interstate 5 (I-5) to the beginning of this road log at the junction of State Routes (SRs) 7 and 702 traverse the gently rolling Puget Lowland, mostly on glacial till or outwash with isolated large boulders called erractics. Within a mile (1.6 km) after its junction with SR 702, SR 7 cuts through the valley of Tanwax Creek, a 'cross valley' cut into Vashon glacial drift. The road then descends through older deposits, including Pleistocene-age lahars from Mount Rainier and the underlying grayish Mashel Formation sediments of Miocene age, before crossing the Ohop Valley, a broad former glacial spillway. It then enters the Cascade Range near La Grande.

From about Tanwax Creek to as far east as Eatonville, the highway passes over a landscape that was modified by at least one large, late-glacial flood whose spillway was more than 6 mi (~9.5 km) wide. From the Ohop Valley east, this leg generally follows the Nisqually River valley, whose broad upper reaches formerly held large valley glaciers that extended from an ice cap in the Mount Rainier area during the Ice Ages. Coal-bearing sedimentary rocks of the Puget Group (of Eocene age) and volcanic and intrusive rocks of the ancestral Cascade Range (Eocene to Miocene in age) are visible en route between the Ohop Valley and Mount Rainier National Park.

* See "Contributors", p. ii, for affiliation.

During the past 12,000 years, many lahars have flowed down the Nisqually River valley from Mount Rainier. Some of the enormous lahars and their associated floods buried forests as far downstream as Puget Sound (although in areas outside Mount Rainier National Park, they remained within the confines of the Nisqually River valley).

About 13 mi (21 km) east of Elbe, the road reaches the Nisqually Entrance to Mount Rainier National Park. The landscape changes dramatically as you drive onto the south flanks of Mount Rainier volcano through ancient forests of enormous trees, across rushing glacier-fed rivers, through a ghost forest killed by debris flows at Kautz Creek, and along enormous ridges of lava and fragmental debris from volcanic eruptions.

The glacially carved canyons within Mount Rainier National Park offer spectacular views at every turn of the road, and the vegetation changes dramatically, both as the road climbs into the timberline environment and during the progression of the seasons.

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0
0.0 This leg of the field guide starts on SR 7 at its intersection with SR 702. This location is about 21 mi (34 km) south of the SR 7 junction with SR 512. To get there from I-5, take SR 512 east at I-5 Exit 133, then go south on SR 7. Or, drive east on SR 510 from I-5 Exit 111 (near Olympia), and go about 26 mi (42 km) east via Yelm and SRs 510, 507, and 702. The junction of SR 7 and 702 is about 10 mi (16 km) east of the SR 702 turnoff at McKenna. From this point continue south on SR 7. Or, take an alternate trip via Eatonville (Leg N, p. 159) that rejoins SR 7 about 15 mi (24 km) from here along this leg.

0.1
0.2 Milepost (MP) 36.

1.8
2.9 Cross Tanwax Creek.

2.6
4.2 On the east (left) side of SR 7 about 2.6 mi (4.2 km) north of Stringtown Road, a resident has arranged Stonehenge-like monoliths of large dark rocks (Fig. A-2). Boulders like these are commonly scattered on some parts of the Vashon Drift plain in this area; they are mostly andesite, but there is some granodiorite and other rock types. They were deposited by one or more great floods of water and debris that originated in the Cascade Range—the source area of the andesitic and granodioritic rocks—at a time when the Vashon ice sheet had receded somewhat from its maximum position, but before the Ohop valley was cut to its present depth by glacial meltwater. The catastrophic flood(s) was initiated when glacial Lake Carbon (Fig. A-3), an interconnected network of lakes dammed by the Puget lobe near the present canyon of the Carbon River south of Carbonado, suddenly drained (Pringle and others, 2000a; Goldstein and others, 2002). A landslide blocked the spillway, located along Fox Creek in the Cascades about 4.5 mi (7.2 km) southwest of Carbonado, and when it was breached, its debris probably augmented the flood. The southwest-trending valleys downstream in this area, such as that of Tanwax Creek, were in-

Figure A-1. *(right)* Geologic map for Leg A (four consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987a,b) and Schuster, 2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.

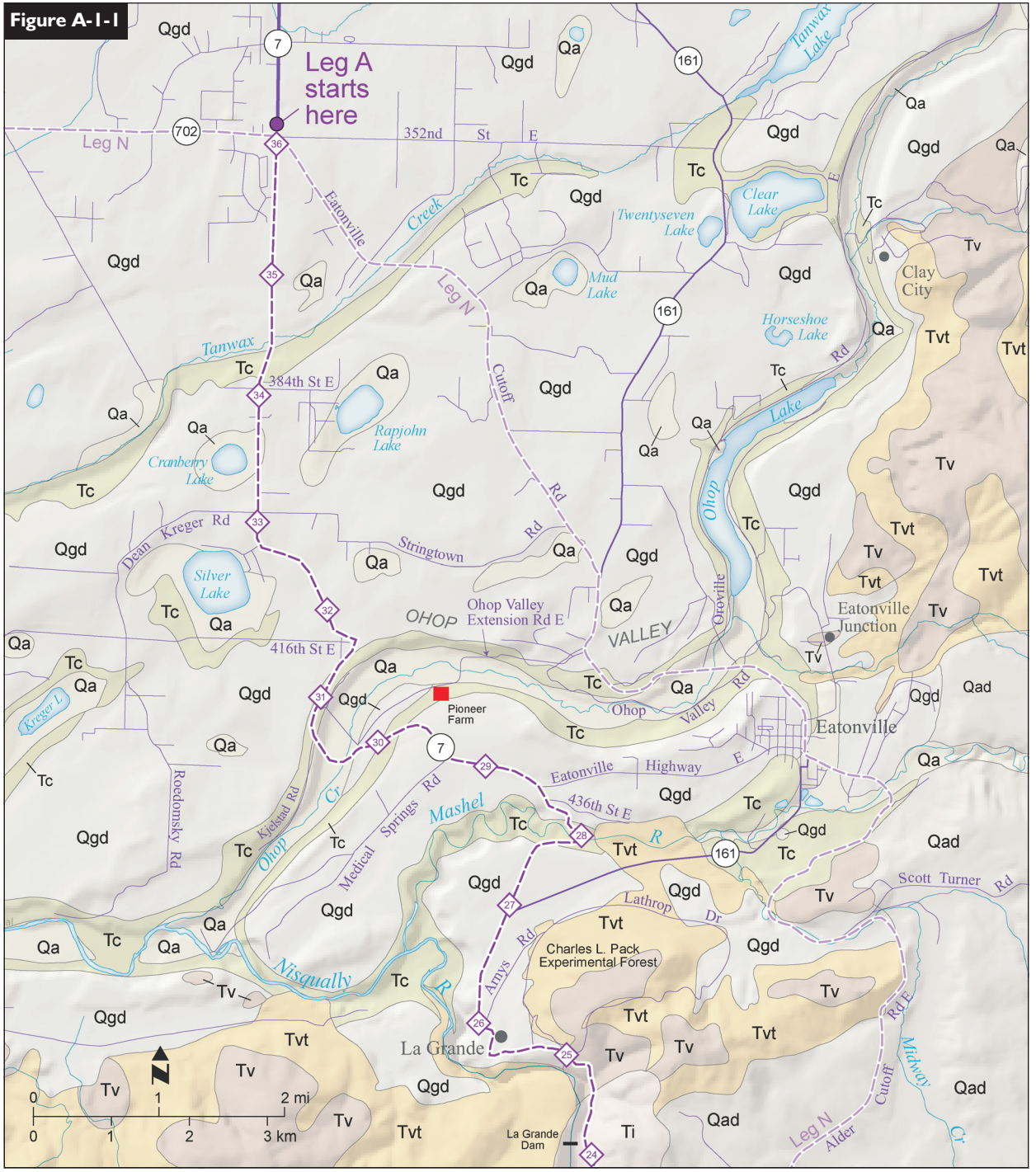
cised by this flood. You will be crossing the floodway channel between MP 36 and MP 27.

3.1 Stringtown Road.
5.0

4.0 The road descends to the floor of the Ohop Valley,
6.4 a major outwash channel that was carved by torrents of meltwater during the retreat of the Puget lobe of the Vashon ice sheet. Along this stretch of road, bouldery Vashon Drift sits on discontinuous older Pleistocene alluvium, including ash from Mount St. Helens and lahar(?) deposits from Mount Rainier (Fig. A-4). These deposits, in turn, rest on unconsolidated sediments of the Miocene



Figure A-2. Abundant andesite boulders at 'stonehenge' visible from SR 7. Boulders of andesite and granodiorite are strewn like glacial erratics across the glacial drift plain from Tanwax Creek to the Mashel River. These boulders were apparently deposited when drainage from a glacial lake in the vicinity of the Carbon River canyon was temporarily dammed by an earthflow of Lily Creek Formation volcanic debris. The dam breached, and the flood incorporated boulders and cobbles of andesite from the landslide, depositing them tens of miles farther downstream.



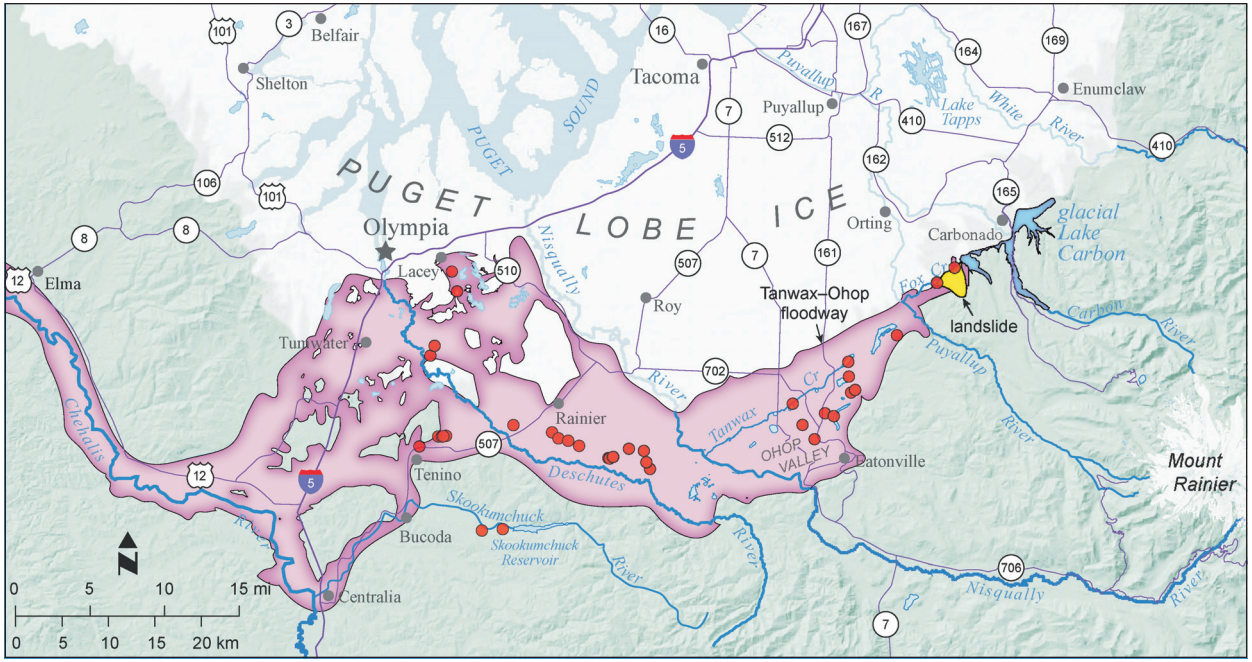


Figure A-3. Shaded relief map of the area that may have been inundated by the Tanwax Creek–Ohop Valley late-glacial flood (area shaded pink), showing the glacial flood channels cutting southwest and west across the generally north–south fabric of the glacial fluting and drumlins (not visible at this scale). Also shown are the Puget lobe of the continental ice sheet (area shaded light blue), the earthflow (yellow) that blocked the Fox Creek glacial spillway, and glacial Lake Carbon (dark blue), which was likely one of an network of interconnected ice-marginal lakes that drained catastrophically. Red dots are some of the locations of larger andesite and granodiorite boulders or boulder fields deposited by the flood. Further study may show that other drainages to the south of the pink area and not shown on this simplified map were also affected by the floods.

Mashel Formation, visible on the west (right) side of the road as you descend. The Mashel Formation consists mostly of fluvial and some lacustrine deposits that contain abundant pumice and other volcanic rocks. The pumice has not been studied, so its source and age are not yet known. The massive bouldery deposit capping the west valley wall surface is probably Vashon till.

5.7 *9.1* Cross Ohop Creek.

5.9 *9.5* Pioneer Farm tourist area, about 0.7 mi or 1.1 km northeast of SR 7 on Ohop Valley Road East.

6.1 *9.8* MP 30.

7.5 *12.0* Junction of SR 7 with the Eatonville Highway. Stay on SR 7.

8.1 *13.0* Cross the Mashel River.

8.5 *13.6* If weather conditions allow, west-bound visitors returning from Mount Rainier may have a glimpse of the mountain as they descend into the Mashel River valley (Fig. A-5).

9.0 *14.4* MP 27. Junction of SR 7 with SR 161 to Eatonville. Stay on SR 7.

9.4 *15.1* Charles L. Pack Experimental Forest. This experimental forest and research center is affiliated with the University of Washington. It is a 'working forest' that hosts a variety of research projects and meetings. The public can hike, bike, ride horses, or travel alone along a barrier-free self-guided trail.

10.0 *16.0* MP 26. Entrance to La Grande Dam, the lower of two dams on the Nisqually River. Alder Dam is



Figure A-4. Professor Barry Goldstein (left) and two students examine rocks from a Mount Rainier lahar deposit (lower layer) underlying Vashon(?) till along the west side of the Ohop Valley (SR 7). The buff-colored blobs above their heads are megaclasts, boulders of fragmental debris suspended in the matrix of the lahar deposit.



Figure A-5. Snow-laden Mount Rainier, 25 mi (40 km) to the east, from an informal pullout along SR 7 slightly east of the Mashel River. Even within a day of a snowstorm, bare rock exposed near the tip of the young summit cone at Columbia Crest provides evidence of the volcano's active geothermal system.

visible on the right 2 mi (3.2 km) farther east along the road. The bedrock in roadcuts near this locality marks the entrance to the Cascade Range. From mile 10.8 to 11.1 (km 17.2–17.8), the rock



photo by Dave Norman

Figure A-6. Andesite of Miocene to Oligocene age near Alder Dam overlook. View is to the north.

in the outcrops on the left (north) is andesite of Miocene to Oligocene age (Fig. A-6).

11.0 17.7 MP 25. Viewpoint for La Grande Dam. The rocks north of the road near this viewpoint are andesites that were stained because of hydrothermal alteration along fractures. During this kind of low-temperature change, minerals such as hornblende and biotite are replaced by chlorite, calcite, and (or) other minerals. Here, the yellow color may be caused by iron minerals or pyrite transforming to the iron-oxide limonite.

12.6 20.3 Viewpoint for Alder Dam. The dam marks the approximate maximum westward extent of a glacier that occupied the Nisqually River valley during the extensive Hayden Creek glaciation (~170–130 ka; Petit and others, 1999). No end moraine is visible in the Nisqually valley; however, Crandell and Miller (1974) identified Hayden Creek till north of the valley near here and a Hayden Creek end moraine southwest of Mineral Lake, about 9 mi (14.4 km) to the southeast.

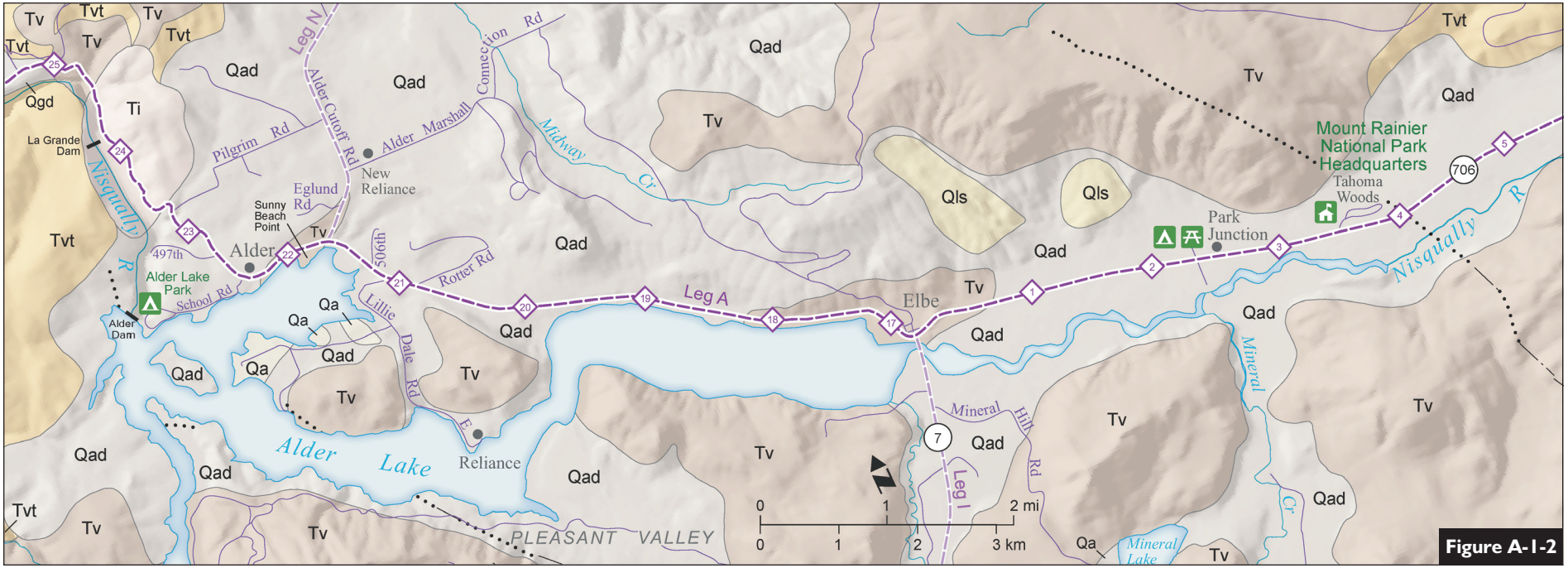
Alder Dam was completed in 1944. The dam is 330 ft (100.5 m) tall, 1500 ft (457.2 m) long, and 120 ft (36.6 m) thick at the base while only 15 ft (4.5 m) thick at the top (Coombs, 1989). It can generate 50,000 kilowatts of electricity.

The 7.5-mi (12 km)-long Alder Lake is a fairly small impoundment, and its storage capacity becomes smaller annually as sediment from Mount Rainier forms a delta at its east end. Based on a 1985 resurvey, the lake held about 286 million m³ (374 million yd³) of water at its 'normal' pool level, and its maximum capacity was about 301 million m³ (394 million yd³). Therefore, less than 14.6 million m³ (19.1 million yd³) of storage would be available, should a lahar enter the reservoir. One



photo by Dave Norman

Figure A-7. Columnar jointing developed in Miocene basaltic andesite that contains visible plagioclase crystals. View is to the north near Elbe.



Longmire Springs

by Rebecca A. Christie and Katherine M. Reed

Some History

In 1883, the story goes, guide James Longmire's hobbled horses wandered off from his base camp and 'found' mineral springs, for which Longmire soon filed a mineral claim under the provisions of the Federal Placer Act. In 1885, Longmire constructed a rough trail to the springs and opened a small hotel.

By 1896, Longmire and local native workers completed a dirt road from Ashford to the springs that was good enough for stages carrying visitors to traverse. Daily stages were operating on this route by 1909. To get to the springs, one could also take the Northern Pacific Railroad from Tacoma to Yelm and travel from Yelm to Longmire on saddle horses. Another rail day-trip route was from Tacoma to Ashford, thence to the springs. In 1890, round-trip passage, including board, cost $12.00; board and treatment at the springs was $8.00 per week (Martinson, 1966). Car travel to the park began in 1907; before long, automobiles brought far more visitors than the trains.

A competing comfortable hotel, the National Park Inn, was built by the Tacoma and Eastern Railway Company (also called the Tacoma Eastern Railroad) in 1905–06. In 1908, the Longmires built another rustic hotel and a tenting facility. The Longmire Springs Company leased land from the family for yet another hotel, the National Park Annex, which had replaced the original inn that burned in 1926; it was rebuilt in 1990. (See Allaback and Jacobson, undated, for more information.) Concerns about lodging prices and the condition of facilities led to a gradual eviction of the Longmires. The family sold the property to the federal government in 1919. Also in 1919 (*Seattle Post-Intelligencer*, July 19, 1919), the Rainier National Park Company arranged a lease until 1936 for Longmire Springs. By that time the park had moved its headquarters to Longmire. The first administration building (1916) has become the museum and visitors center. The structures in Longmire Historic Developed Area are historic landmarks; their "Rustic Style" was chosen to blend into the surroundings.

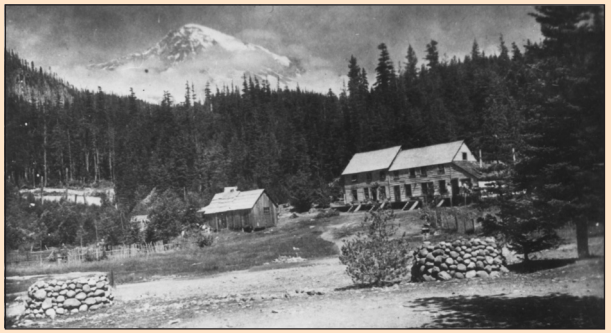
The Springs

An advertisement for Longmire's Medical Springs in the 1890 Tacoma newspaper, *Every Sunday*, claimed that the waters could cure "rheumatic pains, catarrah, piles, and other incurable afflictions". According to an early Park Service report, "Several kinds of mineralized waters spring from the ground on this tract and little care is exercised to prevent pollution. A large amount of this water has a temperature of 70ºF on reaching the surface. It is heavily charged with sulphur....Other waters are charged with iron, and still others are sweet, cool, and sparkling" (Reaburn, 1915). Another early report indicates the spring waters "range in temperature and mineral content from cold carbon dioxide (CO_2)–charged springs to hot sulphur-iron springs" (Glover, 1936, p. 72). David Frank (written commun., 2007) notes: "Although the springs have some sulfate content and precipitate some pyrite in aragonitic mud, they are primarily bicarbonate-chloride waters precipitating carbonates (calcite, aragonite, and some rhodochrosite). The springs also have relatively high concentrations of iron that contribute to the pyrite in the reduced environments (aragonitic mud), and iron oxyhydroxides in the oxidized environments (surface pools and streams)." There was actually no proven health benefit.

Of about 50 mineral springs identified in an early Park Service report in the area, two were developed: Iron Mike and Soda Springs, both enclosed in the 1920s. Iron Mike earned its name because of the iron content of the water and the iron-rust color of its deposits (U.S. National Park Service, 1934?). A National Park Service report dated 1934 reported that the temperature of the water in the springs was as high as 85°F (29°C). More recent studies (H. M. Majors, unpub. report, 1964; Korosec, 1979; Frank, 1985) found variation in the configuration of springs relative to earlier reports, probably as a result of water diversion and flooding by beaver dams and travertine deposits. Frank (1995) reported temperatures ranging up to 28°C, and flow to 0.1 liter/second (82°F and about 1.5 gallons/minute). Sustained maximum temperatures in springs he sampled were as high as 25°C. Travertine and tufa deposits line the warmer springs, with the most extensive travertine mound in the west central part of the meadow. The southeastern springs have 'moderate gas discharge' (possibly CO_2) but very little water flow, whereas the western springs have more flow and higher temperature (Frank, 1995). Symonds and others (2003) measured the gas content of Soda Spring in 1997–98 and found it to be 99.6 to 99.8 percent CO_2. Frank (written commun., 2007) adds, "The small springs in shallow depressions across the trail from Soda Spring are ones that have accumulated dead birds now and then, presumably from suffocation". (See also the "Ohanapecosh Hot Springs" sidebar on p. 125.) ■



Longmire Springs Hotel (later called the National Park Inn Annex) at Longmire circa 1916. View is to the northeast with Eagle Peak in the background. Courtesy of University of Washington Libraries, Special Collections, A. H. Barnes photo 433A.



Longmire Springs Hotel, probably built 1906, with the southeast flank of Mount Rainier in the background and enclosed springs. Courtesy of University of Washington Libraries, Special Collections, photo 'nps longmire cabins'.

concern is that this storage volume is probably not large enough to contain the most dangerous type of lahar, the clay-rich type that could occur if a sector of Mount Rainier collapsed without warning—an event that, although rare, has occurred at other volcanic mountains. Such a lahar, if large enough, could generate waves that would overtop the dam. However, geologists think it is most likely that precursory volcanic activity, such as increases in the number and size of volcanic earthquakes, would provide advance warning of eruptive activity and, with it, the greater potential for a lahar. If that happens, the reservoir could be drawn down at a maximum rate of about 0.3 percent capacity per hour, or more slowly if the area is already experiencing a seasonal flood event.

13.0 *20.9* MP 23.

13.5 *21.7* Alder Lake Park and Alder Dam. This side road leads about 1 mi (1.6 km) to the dam viewpoint and Boathouse Campground.

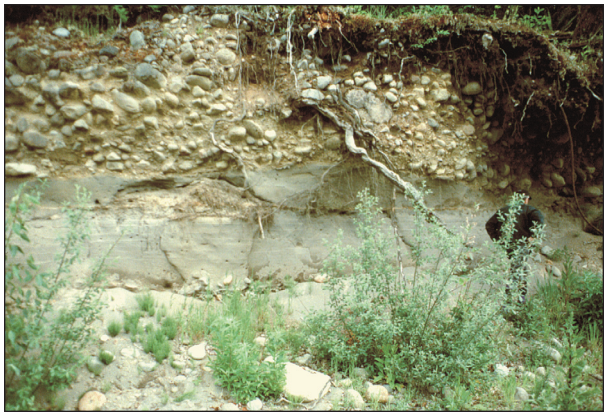


Figure A-8. USGS geologist Kevin Scott (right side of photo) examines an assemblage of bouldery lahars and finer grained lahar-runout deposits near National along the north bank of the Nisqually River. Radiocarbon ages on carbon found in these deposits show these lahars were likely produced during the Summerland eruptive episode at Mount Rainier, some time after the Round Pass mudflow (~2,600 yr B.P.) but before Mount Rainier C tephra (~2,200 yr B.P.). Each of several gray layers below the upper bouldery unit is a runout from a lahar.

14.1 *22.7* MP 21. On a fine day, Mount Rainier can be seen looming ahead.

14.2 *22.8* Sunny Beach Point. Andesite of Tertiary age crops out north of the highway.

14.4 *23.1* Junction of SR 7 with the Eatonville/Alder Cutoff Road (Leg N). Stay on SR 7. Alder Lake is on the south side of SR 7.

16.0 *25.7* MP 20. The sharp peaks of Sawtooth Ridge are visible ahead in the distance, showing layers dipping off to the south (right). The layers are rocks of the Ohanapecosh Formation, whose ages range from about 36.5 to 28 m.y. (Walsh and others, 1987). These rocks include volcaniclastic layers, as well as some lavas, and are cut by many intrusions of dacite and andesite.

19.2 *30.8* At Elbe, continue straight ahead on SR 706. SR 7 turns to the south here as Leg I (p. 137). The outcrop on the left near the junction exhibits columns developed in Miocene basaltic andesite that contains visible plagioclase crystals (Fig. A-7).

Nadeau (1983) reported that this area may be one of the oldest settlements along the river, first settled by the native tribes. James Longmire expanded on the trails the local peoples had used to create a trail to his resort near Mount Rainier. (See the "Longmire Springs" sidebar on p. 57.)

20.2 *32.5* MP 1.

22.1 *35.6* Just past MP 2, the road ascends a small terrace. Most of the valley bottom here is underlain by post-glacial lahars from Mount Rainier, many deposited in the past several thousand years.

22.2 *35.7* MP 3.

22.5 *36.2* The Tahoma Woods area. Slightly before the access road to the Mount Rainier National Park administrative offices, the road ascends a small terrace. A stack of lahar and lahar-runout deposits, many of which were triggered during eruptive activity at Mount Rainier between about 2,600 and 500 yr B.P., is exposed along the Nisqually River near here. The lahars were not quite deep enough to have inundated this terrace, which is veneered by Evans Creek–age (22–15 cal yr ka) glacial outwash capped locally by loess (Fig. A-8).

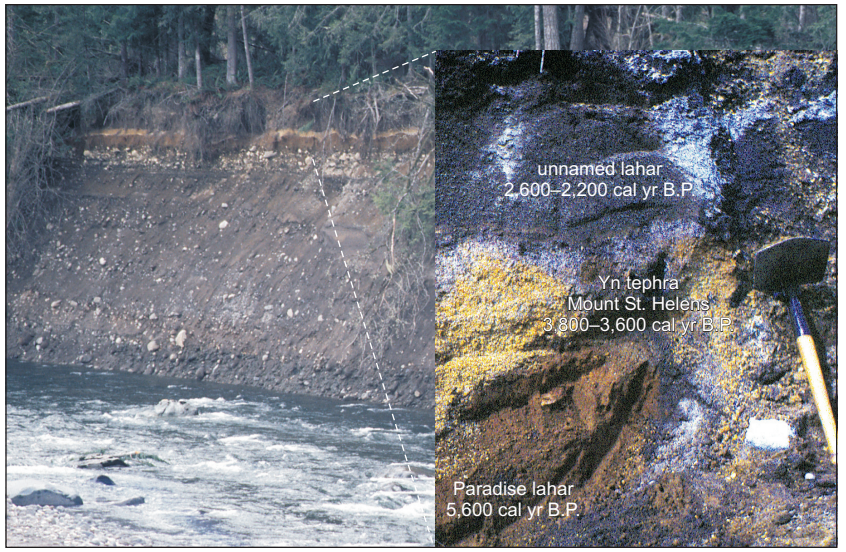


Figure A-9. A lahar of Summerland age is exposed at the Nisqually River bridge at National. The bank is about 25 ft (8 m) in height. The colored layers below the terrace surface (inset) are also exposed in a drainage ditch along the road about 200 ft (60 m) south of the bridge. They are, from bottom to top, the brownish Paradise lahar, about 5,600 cal yr B.P.; the yellowish Yn tephra layer erupted from Mount St. Helens about 3,800 to 3,600 cal yr B.P.; and the grayish unnamed lahar triggered by an eruption at Mount Rainier between 2,600 and 2,200 yr B.P. The trenching tool in the inset is about 18 in. (45 cm) long. View to the southeast.

25.3 *40.7* Forest Road (FR) 92 on the left gives access to the Mount Tahoma Trail System.

25.8 *41.5* **OPTIONAL SIDE TRIP:** Volcanic deposits at the bridge at National. The bridge was washed out in the flood of November 2006. This is a 2.6-mi (4.2 km) round trip on a bumpy gravel road to see evidence of an eruption at Mount Rainier that sent a wave of pumiceous sand far down the Nisqually River. Take 553rd Street (labeled "South District Access") at about 0.5 mi (0.8 km) to the Nisqually River. The deposit of at least one clay-poor lahar is exposed upstream of the bridge on the left (south) bank, where it is the thin gray top layer (Fig. A-9). That lahar deposit sits on a yellow Mount St. Helens pumice called the Yn layer (3.6 ka), which in turn rests on the reddish-brown Paradise lahar from Mount Rainier (5 ka). This sandy, Summerland-age lahar is just below the Mount Rainier C tephra (2,200 yr B.P.). Deposits of a 500-yr-B.P. lahar veneer the flood plain north of the bridge (Jim Vallance, USGS, oral commun., 2004). Near here, a 6- to 12-ft (1.8–3.7 m)-thick sandy gravel deposited by the Summerland-age lahar caps a terrace that is 60 ft (18 m) higher than this location, thus showing that the peak wave of the lahar was substantially higher than indicated by the deposit at this site. This minimum thickness is five times the recorded stage height (12.18 ft or 3.7 m) of the largest historic flood measured here on Feb. 8, 1996! A few hundred yards downstream of this bridge, the 2.6-ka Round Pass mudflow underlies the sandy lahar layer and contains many large

trees that it uprooted in its passage from the flanks of the volcano.

The flood wave of the Summerland-age lahar was high enough to have buried trees at least as far downstream of Mount Rainier as McKenna, near Yelm, more than 35 mi (56 km) away, and no doubt it reached the Nisqually River delta. This lahar is an example of a clay-poor lahar. It probably began when a pyroclastic density current was erupted at the summit of Mount Rainier and collapsed on the mountain's flanks. Volcanic bombs having radial jointing have been identified in the lahar deposit (Figs. A-10 and A-11). As it flowed downslope, the current eroded glaciers, melted snow and ice, and incorporated enough sediment to generate a lahar. As the lahar traveled downstream along the Nisqually River, it gradually deposited sediment and added water to become a lahar runout. In this state of transformation, it likely still had the characteristics of a thick slurry, at least until it reached the Ashford–National area, where yard (meter)-size masses of unconsolidated, bedded Mount St. Helens pumice and soil were transported as intact blobs within the flow. A more turbulent, lower-concentration flow could not have transported so large a mass of loose sediment as a single block in this way.

Remember to compensate for the mileage (2.6-mi [4.2 km] round trip) along the side trip.

26.3 *42.3* Town of Ashford.

27.2 *43.7* MP 8.

29.3 *47.1* Kernahan Road becomes Forest Road 52 leading south to Packwood and US 12 in the Cowlitz River valley. It provides access to hiking trails such as the High Rock Trail, which provides an excellent view of Mount Rainier and Kautz Creek from the tip of a hogback ridge south of Mount Rainier National Park. From here to Goat Creek, you pass along tightly folded sedimentary rocks of the Puget Group, on the skyline north of the road). Buried trees were exposed along the Nisqually River in this reach by the record flood of November 2006 that temporarily closed Mount Rainier National Park. Near one location, the 500-year-old lahar, Summerland-age lahar, and log-bearing Round Pass mudflow deposits were lying atop a 2-ft (~0.5 m)-thick layer of Mount St. Helens Yn tephra, which in turn was sitting on a clay-rich, log-bearing lahar, possibly the Paradise lahar.

29.5 *47.4* FR 59, which leads north into the Glacier View Wilderness Area.

30.1 *48.4* MP 11. Cross Copper Creek 0.2 mi (0.3 km) east of the milepost.

31.4 *50.5* Goat Creek cascades seasonally over a debris fan of large boulders and cobbles. Debris flow deposits from this fan sit atop a deposit that is correlative with the clay-poor lahar exposed at National. From Goat Creek to the Nisqually Entrance of Mount Rainier National Park, you are driving in the Ohanapecosh Formation. Northeast-dipping beds of volcanic breccias and tuffs are visible just west of the park entrance.

32.8 *52.7* Mount Rainier National Park, Nisqually Entrance (elev. 2023 ft or 617 m).

33.2 *53.4* Braided channels of the Nisqually River here occupy the former site of the Sunshine Point Campground (Fig. A-12). The November 2006 flood re-

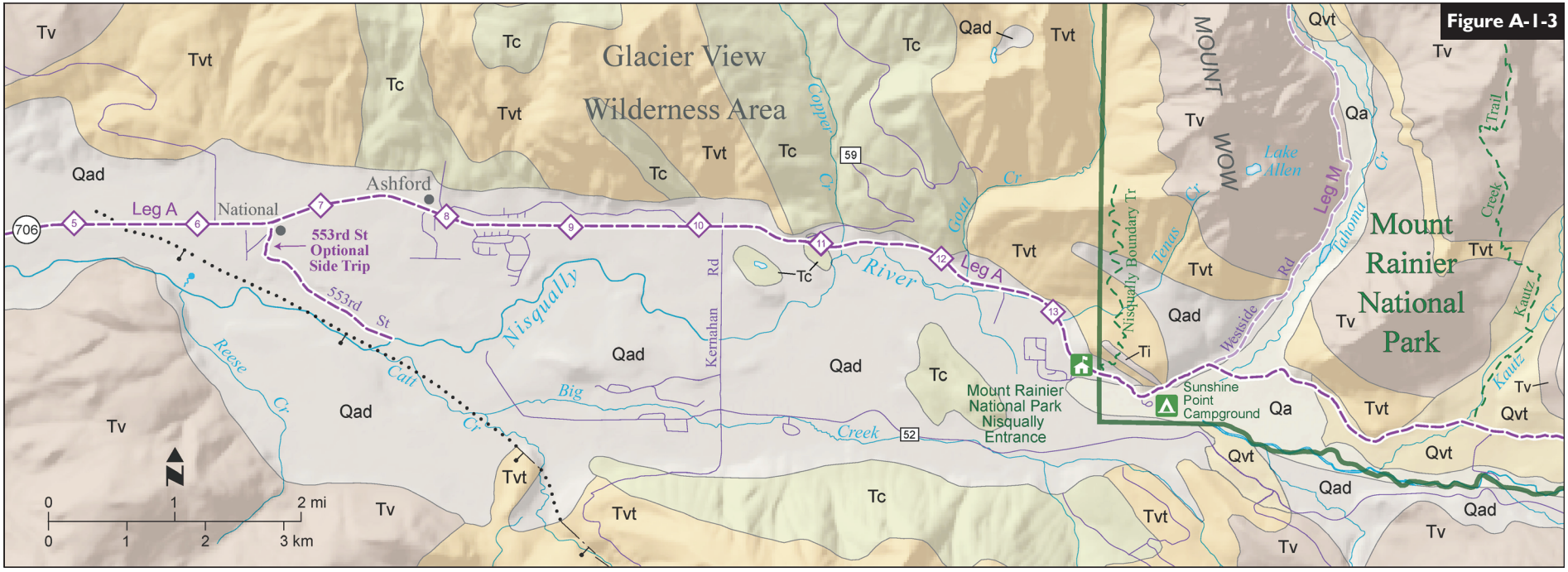




Figure A-10. A breadcrust bomb, or prismatically jointed boulder, in a Summerland-age lahar. Such volcanic bombs are molten when erupted and cool rapidly, developing these radial fractures. (See Fig. A-11.) Trenching tool is about 18 in. (45 cm) long.

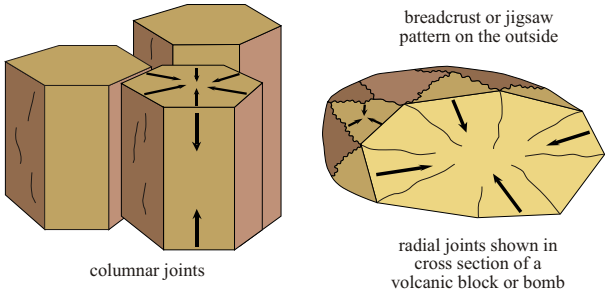


Figure A-11. Sketch of columnar jointing in a lava flow and prismatic or radial jointing in a volcanic bomb. Small arrows show the direction of contractions during cooling; thicker arrows show the direction of cooling. Joints are caused by contraction.



photo by Beth Norman

Figure A-12. Braided channels of the Nisqually River here occupy the former site of the Sunshine Point Campground. A small remnant of the campground is on the left. Taken September 2007.



photo by Dave Norman

Figure A-13. An outcrop of tuffaceous volcaniclastic rocks of the Ohanapecosh Formation near the Nisqually Entrance.

moved most of the terrace on which the campground sat. The outcrop on the left is Ohanapecosh Formation tuffs with blocks of andesite, as well as a pumiceous unit (Fig. A-13).

33.8 *54.4* MP 1. Westside Road. Although this is one of Mount Rainier National Park's less traveled areas, it offers access to some excellent hiking destinations and places to view the effects of the glacial outburst floods of the 1980s and 1990s. For a description of the geology along Westside Road, see Leg M (p. 155).

34.0 *54.7* The cobble bars near the bridge over Tahoma Creek are predominantly flood deposits from 1990 and later. Much of the material from the series of glacial outburst debris flows that began in 1986 was deposited farther upstream.

Continue east toward Kautz Creek.

35.3 *56.8* An outcrop of basaltic andesite from Mount Rainier is exposed across from a pullout on the right (Fig. A-14).

36.2 *58.2* Kautz Creek. Many tall snags near the Kautz Creek parking lot and observation point (north of the road and slightly east of the bridge) are remnants of trees that were killed by the damaging debris flow of Oct. 2 and 3, 1947 (Fig. A-15). North of the bridge, deposits of that debris flow and of previous lahars are exposed. The debris flow buried the old road with 20 ft (6 m) of rock and mud and temporarily dammed the Nisqually River (Fig. A-16). In the November 2006 storm, the creek radically changed its course 0.2 mi (0.3 km) eastward of its previous channel and has cut into the 1947 debris fan. (See the "Recent Geomorphic Evolution of the Landscape" sidebar, p. 52.)

USGS hydrologist Donald Richardson (1968) suggested that the 1947 debris flow was the result of intense downpours combined with the release of additional water from Kautz Glacier. Other outburst debris flows, considerably smaller than that of the 1947 event, occurred at Kautz Creek during the summers of 1985 and 1986. Some of the shorter snags visible in the river are possibly part of older buried forests that predate the trees killed in 1947. Notice that some of the tree species (Douglas-fir and western hemlock) are decomposing much faster than others (western redcedar).

On clear days, the high cirque of Sunset Amphitheater is visible to the north from this viewpoint. This chiseled west face of Mount Rainier has been the source of many lahars.

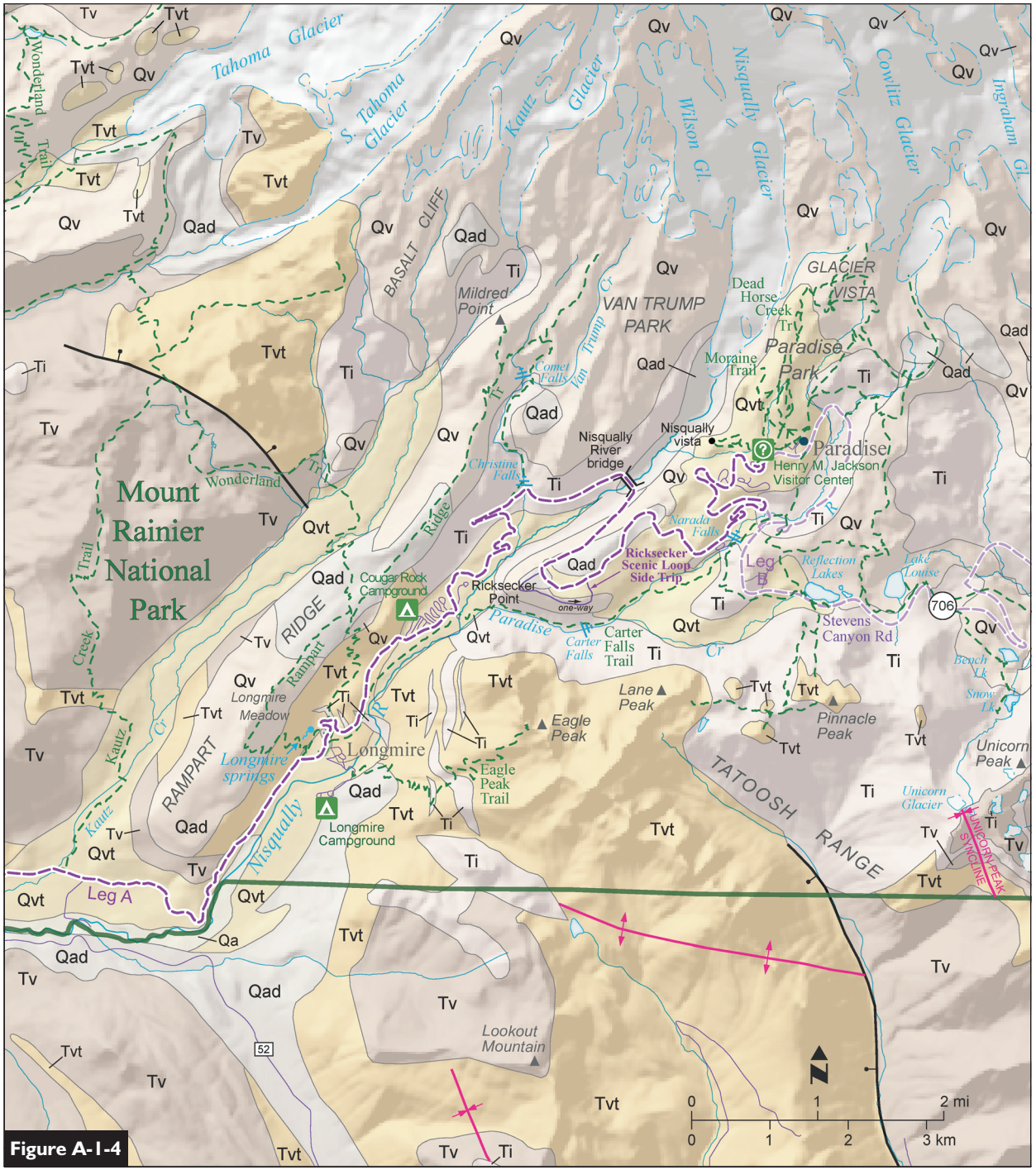


Figure A-1-4



photo by Dave Norman

Figure A-14. An outcrop of basaltic andesite from Mount Rainier, about 1 mi (1.6 km) west of Kautz Creek.

37.8
60.8

MP 5. View of the Nisqually River.

39.1
62.9

Longmire. (This is a good place to purchase detailed maps of the park.) The museum at Longmire was the original park headquarters. Geologist Rocky Crandell (1971) found that both the right and left banks of the Nisqually River here had been inundated by lahars that post-dated Mount St. Helens Wn ash layer because the ash veneers older surfaces nearby but not the young terraces adjacent to the river here. That ash, which is 2 to 3 cm (0.8–1.2 in.) thick in this area of the park, was erupted from Mount St. Helens late in A.D. 1479 (or possibly early in 1480), so it is a useful marker bed for relative dating of recent deposits (Yamaguchi, 1983; Fiacco and others, 1993).

Crandell also noticed a relatively youthful forest and boulder levees on the south side of Longmire Meadow and, on the basis of the age of the oldest tree growing on the surface there, inferred that a lahar buried this portion of the right bank sometime before 1860. Boulder levees, which delineate the margin of a small debris flow deposit south of Longmire Meadow, separate trees of different ages and show that these lahars did not inundate the entire terrace. An excavation at the old Longmire gas station to remove its aging fuel tanks revealed a stump rooted more than 15 ft (5 m) below the surface that had been buried by a

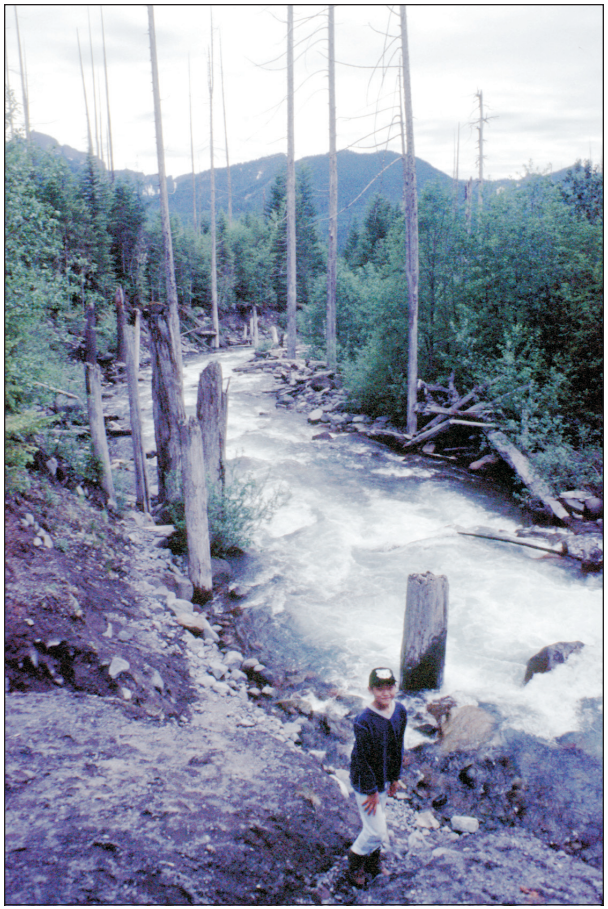


Figure A-15. Snags at Kautz Creek killed by the debris flow of Oct. 2 and 3, 1947. View is to the south from a bridge over Kautz Creek in 2001. The creek abandoned this channel during the great flood of November 2006 and cut a new channel into the 1947 debris fan about 0.5 mi (0.8 km) farther east.

thick cobble-boulder gravel. Tree-ring studies show that this tree died sometime after A.D. 1686—the tree lacked bark, so a precise year for its death could not be determined. The cobble-boulder deposit likely is older than the pre-1860 debris flow mentioned earlier. The ages of the oldest trees growing on a lahar deposit that caps the left bank of the river near here reveal that the deposit was laid down after A.D. 1479 but before about 1570.

The late-2006 flood damaged the Longmire sewage line and knocked down the power lines



Figure A-16. Aerial oblique photo of Kautz Creek (center) showing the extent of the 1947 debris flow. This glacial outburst event temporarily dammed the Nisqually River (right) and buried the old park road under 20 ft (6 m) of rock and mud. In the flood of November 2006, Kautz Creek shifted its course about 0.5 (0.8 km) to the east. Photo by Austin Post, USGS, taken Sept. 22, 1966

that crossed the Nisqually River. It also severely eroded the park facilities parking lot.

At Longmire Meadow, water at temperatures as high as 28°C (82°F) is discharged through and around low travertine mounds (Fig. A-17). These features are spectacular in the winter and early spring when their orange-red colors contrast with the snow in the surrounding meadow. The largest mound and highest temperatures are found in the west part of the meadow. National Park Service records refer to about 50 springs in existence in 1919 and 1920. Fewer than half that number have been documented in recent years, probably because of flooding by beaver dams. Temperature measurements show no significant change through most of the 20th century. Geologist David Frank, who has studied the hydrothermal system at Mount Rainier in detail, used 1983 measurements (temperature, chemistry, and discharge) of inflow and outflow streams at the meadow to estimate



Figure A-17. View from the Trail of the Shadows at Longmire showing an area of travertine deposition. The travertine is deposited by mineral-rich spring waters that emerge in this meadow. Oxidation of the iron-rich water produces the orange coatings of iron oxyhydroxide precipitates and bacteria. The base of Eagle Peak is visible in the distant background. For more information on Mount Rainier's mineral springs, see p. 57 and 123.

that Longmire springs provides 8 percent or less of the hydrothermal discharge from the park (Frank, 1985, 1995). Frank also analyzed the travertine mounds and found that they are composed mostly of calcite and aragonite and a small amount of rhodochrosite, a reddish carbonate mineral that contains manganese. Other carbonate minerals probably occur in small amounts. Some of the ponds around the mounds contain an oxygen-

photo by Beth Norman

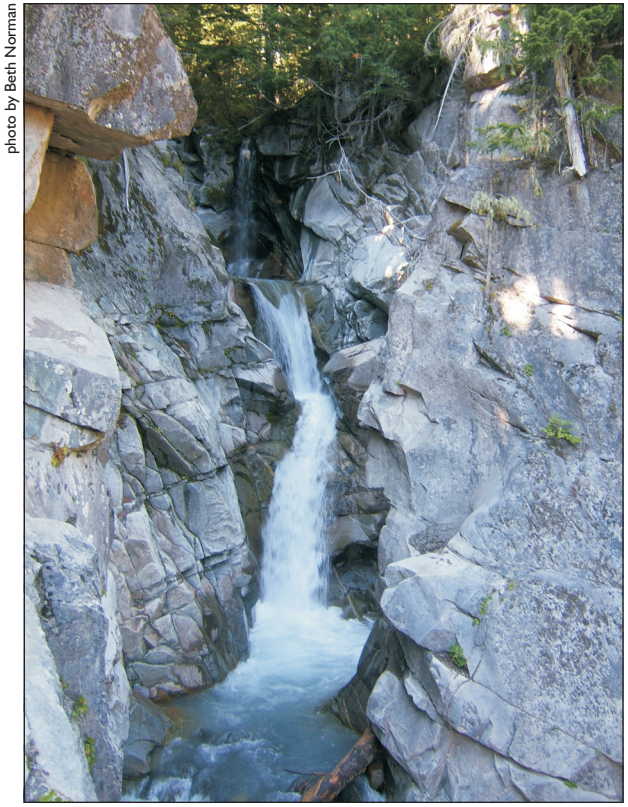


Figure A-18. Carter Falls from below the bridge. The falls, which cuts Tatoosh granodiorite, is about 1.3 mi (2 km) east of the Cougar Rock area on the Wonderland Trail.

poor, aragonitic mud with pyrite and a high dissolved iron content. Oxidation of the iron-rich water produces orange coatings of iron oxyhydroxide precipitates downstream of the meadow. (Learn more about Mount Rainier's hydrothermal system on p. 39.)

39.7
63.8 Wonderland Trail and parking area. The large outcrop on the left is a slightly altered andesite of the Ohanapecosh Formation.

41.3
66.4 Carter Falls Trailhead pullout on the right (Fig. A-18) and a view of Ricksecker Point.

41.4
66.6 Lahar deposits near Cougar Rock Campground and the former Nisqually River footbridge. Yellow layer Yn tephra that was erupted about 3500 years ago from Mount St. Helens underlies two lahar deposits here. Layer Wn ash, erupted from Mount St. Helens late in A.D. 1479, mantles the surface in this area. Crandell (1971, p. 42) found a tree growing on the surface in which the oldest ring was aged at about A.D. 1180. Hemstrom and Franklin (1982) extended the minimum age of the terrace even further, to about 1000 years old, using ring counts of stumps on the same surface.

The footbridge (destroyed in 2003) was a good place to observe the thick, valley-filling lava flow that composes Ricksecker Point across the valley to the northeast. At one time it was thought that this flow and others like it were deposited in valleys, which were then rapidly incised adjacent to the resistant lava flow. However, Lescinsky and Sisson (1998) found glassy lithic fragments at the edge of the flow that indicated it had flowed into the valley along side of, and cooled next to, a large valley glacier. The edges of many other valley-filling flows look similar to this one, so geologists have concluded that it was not uncommon for lava to come to rest next to glaciers. (See Fig. 27 on p. 30 and related discussion in Leg B, p. 70, mile 8.8.)

For about the next mile, the road ascends in hairpin turns, passing by Evans Creek till plastered high on the valley wall and ending on a terrace of assemblage C lahars of Crandell (1971).

photo by Beth Norman



Figure A-19. Well-developed columnar jointing exposed on the valley wall of Rampart Ridge as seen from a bridge that crosses the Nisqually River. The andesite flow is dated at 370 ka (Sisson and Lanphere, this volume).

photo by Beth Norman



Figure A-20. This thick porphyritic andesite lava flow at Ricksecker Point is one of the youngest major lava flows at Mount Rainier. The flow has local platy jointing. View to the north.

Assemblage C is bounded by Mount St. Helens tephra layers Yn and Wn. The Nisqually River has both aggraded its bed and laterally eroded its banks upstream of Cougar Rock Campground since the mid-1990s, and bouldery deposits are now visible above the roadbed locally.

43.3
69.7 Trailhead to Comet Falls and Van Trump Park. A steep trail leads to these destinations. Those who take the time to hike up to Mildred Point will be rewarded with spectacular views of Kautz Glacier and its canyon and of Basalt Cliff, a welded block-and-ash flow (see Fig. 30, p. 33).

43.3
70.0 Tatoosh granodiorite (Miocene) at Christine Falls. In August of 2001, a series of debris flows roared down Van Trump Creek and over the falls, frightening hikers and campers and triggering a media scare about a possible eruption and lahar from Mount Rainier. Geologists from the USGS Cascades Volcano Observatory flew over the creek to its source and found that the debris flows began when glacial meltwater, impounded at 9000 ft (2743 m) adjacent to the Kautz Glacier, overtopped a Little Ice Age lateral moraine and flowed into the Van Trump drainage basin (Vallance and others, 2003). Downcutting and lateral erosion by the meltwater caused failures of the saturated fragmental deposits along Van Trump Creek, which

then cascaded as boulder-rich debris flows more than 6000 ft (1830 m) to the Nisqually River. These slurries then continued for some distance along the Nisqually River, causing minor flooding. It was probably the record snowfalls of the mid-1990s that caused the water to pond by creating a thick kinematic wave of glacial ice that moved through Kautz Glacier. This thickening evidently formed a physical boundary at about 9000 ft (2743 m) that diverted the impounded meltwater along the glacier's left lateral moraine into the adjoining drainage of Van Trump Creek. Similar kinematic waves in response to very large snowfall years have been observed during Park Service surveys at other glaciers, including the Nisqually Glacier.

44.4 *71.0* Nisqually River bridge. Well-developed columns exposed on the valley wall of Rampart Ridge (see map on p. 61) to the west are part of a Quaternary Mount Rainier Andesite flow dated at 370 ka (Fig. A-19). (See "Lava and Ice", p. 30.) The Nisqually Glacier has been the subject of many observations, measurements, and investigations (Heliker and others, 1984) and is probably the most-studied glacier in the 48 conterminous states. The extent of the latest, or Little Ice Age advance of the Nisqually Glacier is clearly marked by a trimline of scoured bedrock and young trees and by lateral moraines that slope downvalley toward the terminal position reached by the glacier in about 1840 (see Fig. 26, p. 29). From its maximum recession position in about 1950, about 1.7 mi (2.7 km) upstream of the 1840 position, the glacier has re-advanced but shows no clear trend in motion. Excellent summaries of the research and of the activity and history of the glacier are found in Heliker and others (1984) and in Driedger (1986).

Historic debris flows—many probably related to glacial outbursts—and floods in this drainage have been discussed in papers by researchers such as Richardson (1968), Crandell (1971), and Hodge (1972). The present bridge was constructed after a 1955 outburst flood; the flow wave of that flood was augmented by landslides from the lateral moraine of the Nisqually Glacier. Remains of the pre-1955 bridge, a much lower structure, are slightly upstream.

44.6 *71.7* Tatoosh granodiorite is exposed on the right, slightly past (south of) the Nisqually River bridge.

45.2 *72.7* The road ascends along the west margin of a thick porphyritic andesite lava flow with local platy jointing (Fig. A-20).

45.6 *73.4* **OPTIONAL SIDE TRIP:** Ricksecker Point Scenic Loop. (This loop is about 1 mi [1.6 km] long and will add about that distance to the remaining mileages.) Turn right onto the scenic loop road at Ricksecker Point. This loop, which skirts the edge of deep glacial valleys, is well worth the trip for the visitor with a bit of extra time. This promontory is composed mostly of a thick Mount Rainier lava flow, mentioned at mile 45.2, whose steep and rubbly edges border the road between the Nis-

photo by Beth Norman



Figure A-22. Pinnacle Peak in the Tatoosh Range as seen from the north. Most of the peak is composed of Tatoosh granodiorite; however, its top and lower western flanks are composed of the older Stevens Ridge rocks that the granodiorite intruded.

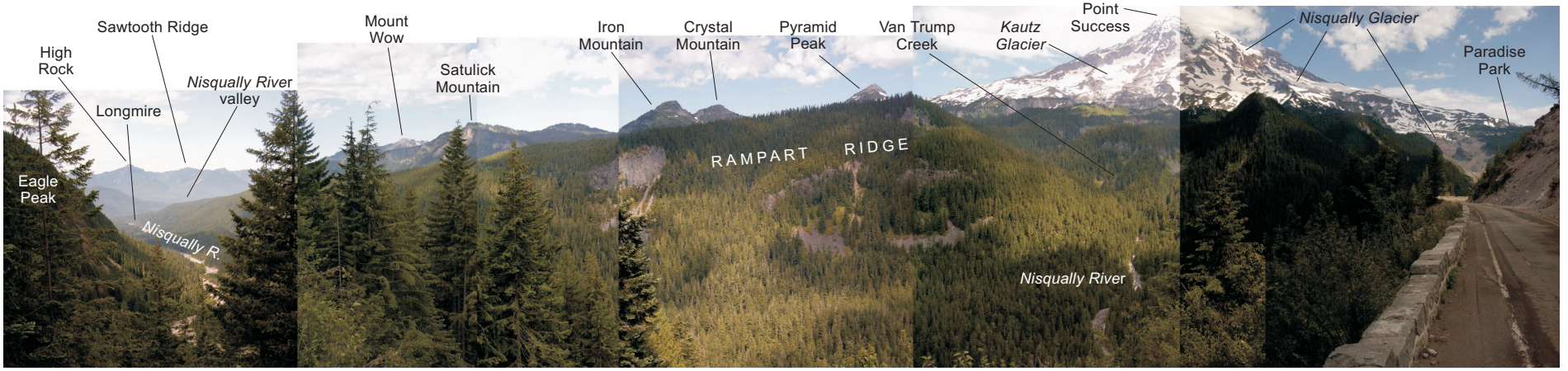


Figure A-21. A panoramic montage view with Paradise Park to the northeast, Mount Rainier to the north, and Eagle Peak in the Tatoosh Range to the southeast (extreme left). Photo taken from a viewpoint at the tip of Ricksecker Point, which sits on a ridge-forming stack of lavas that may be as young as 40 ka. The Nisqually River valley is in the foreground, and Rampart Ridge, which has been estimated to be about 300 ka by USGS geologist Tom Sisson, forms the opposite valley wall of the Nisqually River. Tertiary rocks that compose Mount Wow have been folded and make up the west limb of the north-northwest-trending Unicorn Peak syncline, whose axis trends almost directly away from the viewer in the left center of the photo. The rocks of Sawtooth Ridge and Mount Wow consist of the Ohanapecosh Formation (~36–28 Ma; Vance and others, 1987), whereas rocks of Iron and Crystal Mountains and Pyramid Peak are the younger Stevens Ridge Formation (~25 Ma; Paul Hammond, oral commun., 2006).

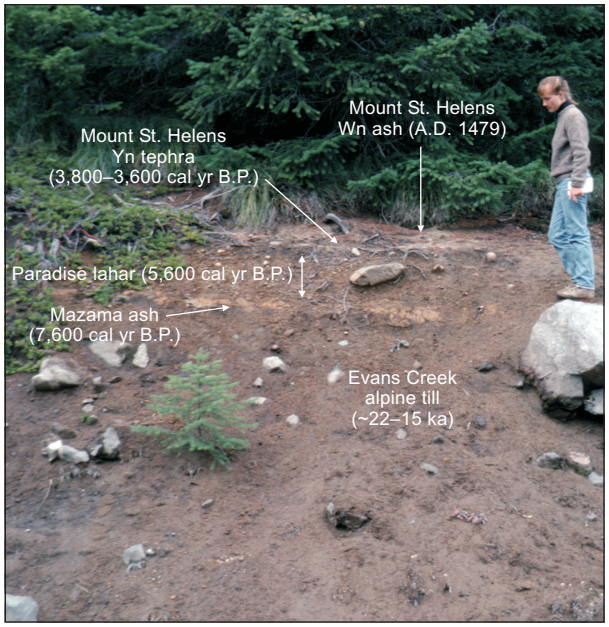


Figure A-23. Geologist Ruth Wilmoth examines the Paradise lahar deposit at Ricksecker Point. This layer is more than 800 ft (244 m) above the valley bottom! The 'exotic' ash layers that have been dated, such as those from Mount Mazama (Crater Lake) and Mount St. Helens, provide useful marker beds for assessing the relative ages of young geologic deposits. The boulders on the slope have weathered out of the Evans Creek till. Photo taken in 1992.

photo by Dave Norman



Figure A-24. The outcrop in Figure A-23 as it appears today. You can still see the large boulder and several other identifying features, but the ash layers are no longer visible. Lahar and ash deposits may be difficult to spot as they are easily eroded and covered.

photo by Beth Norman

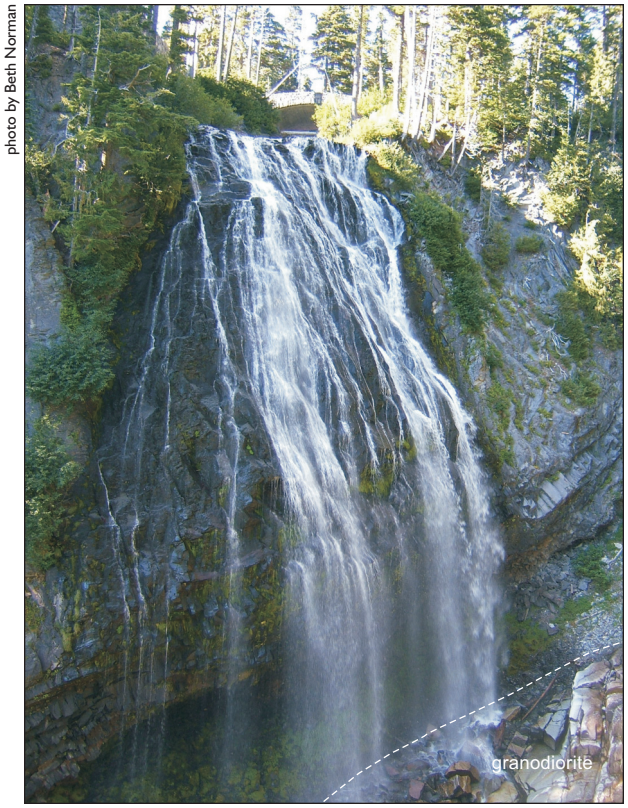


Figure A-25. Narada Falls. The contact between the lava flow and the underlying Tatoosh granodiorite is exposed at the falls.

qually River bridge and the turnoff to Stevens Canyon Road. Geologist Tom Sisson has found that this is the youngest large lava flow at the volcano, with a radiometric age of about 40 ka.

The first turnout offers a clear view of Mount Rainier, the upper Nisqually River valley, and Nisqually Glacier. On a fine day, the second turnout will reveal a grand panorama from Mount Rainier to the folded Eocene volcanic rocks of Sawtooth Ridge to the southwest (Fig. A-21). The Unicorn Peak syncline in the pre–Mount Rainier rocks is visible to the northwest. At the second pullout (0.1 mi; 0.16 km) is an outcrop of blocky, flow-banded, light-gray andesite. This is the glassy edge of the Mount Rainier lava flow referred to above.

Continue about 0.9 mi (1.5 km) from the beginning of the loop and pull to the extreme right-hand side of the road into a pullout so that following traffic can pass safely. The central part of the Tatoosh Range looms to the south. The contact between the bedded rocks of the Stevens Ridge Formation to the west and the Tatoosh pluton to the east is located between Lane Peak and Pinnacle Peak (Fig. A-22). This is one of the unusual situations in which we see older rocks (Stevens Ridge) overlying the younger Tatoosh granodiorite, which was intruded into the Stevens Ridge rocks.

The lava flow and flow breccia exposed near this last turnout along the Ricksecker loop road are overlain by Evans Creek Drift (22–15 cal yr ka), by rubbly deposits of large glaciers that occupied the Nisqually and Paradise River valleys during the most recent ice age until about 15 ka, and by deposits of Holocene age—including the Paradise lahar and several ash layers (Figs. A-23 and A-24). The Paradise lahar deposit can be identified from the road as the approximately 1-m (3.3 ft)-thick layer that sits on a thin (2–10 cm; 0.8–4 in.) orange band of volcanic ash from Mount Mazama, also known as layer O (~6.7 ka; Hallet and others, 1997). Mount St. Helens tephra layers Yn and Wn are the most visible deposits that overlie the Paradise lahar near the top of this exposure.

Identified and described in detail by Crandell (1963a, 1971), the Paradise lahar is unusual because of its great flow thickness here and apparent rapid downstream attenuation. The deposit is about 270 m (800 ft) above the valley floor of the Paradise River at this location, indicating the lahar was at least that deep. Downstream the lahar was still more than 70 m (230 ft) thick, and its deposit is 1.2 m (4 ft) thick where it overlies layer O at Longmire. The low ratio of deposit thickness to flow depth, combined with the wide variation in clay content, suggest the Paradise lahar may have been catastrophically ejected. It must have come sloshing along the Paradise River valley much the same way a luge banks back and forth along its chute of ice.



Figure A-26. A trail in the alpine meadows at Paradise Park. Boulders and clayey yellowish-orange sediments exposed in trail cuts are deposits of the Paradise lahar (~5,600 cal yr B.P.). Nisqually Glacier is above the hiker and Cowlitz Glacier is to the upper right. Wilson Glacier behind the trees to the left is tributary to the Nisqually River. Kautz Glacier is in the upper left corner of the photo. View is to the north-northwest.

Crandell (1971) observed that the Paradise lahar generally is a very thin deposit and lacks constructional topography except at Reflection Lakes (Leg B) where hummocks are visible and the lakes occupy shallow depressions in the deposit. He bracketed the age of the Paradise lahar at about 6,600 to 6,000 yr B.P. because it overlies Mazama ash and appeared to underlie tephra layer D from Mount Rainier. However, Scott and others (1995) found wood at three locations near this site that ranged from 4,625 to 4,955 yr B.P., the youngest being at this Ricksecker Point outcrop. These radiocarbon ages indicate that the Paradise lahar is significantly younger than originally thought and might be related to the same episode of volcanism that produced the Osceola Mudflow (see Fig. 34, p. 37). Work by Vallance (USGS, written commun., 2003) suggests that the lahar underlying Reflection Lakes is older than the Paradise lahar.

Return to the main road and turn right to continue toward Paradise. Remember to compensate for the mileage along this side trip.

46.7
75.1 Crude columnar jointing is common in outcrops of Mount Rainier Andesite in north-side roadcuts along this stretch. Scattered exposures of brown-to-orange, poorly sorted, unstratified debris and orange and yellow boulders are remnants of the Paradise lahar.

47.4
76.3 Pullout with a good view of the Tatoosh Range to the southeast. Reddish beds of the Tertiary Stevens Ridge Formation volcaniclastic rocks are visible on Pinnacle Peak to the south.

47.7
76.7 Narada Falls Viewpoint (restrooms). A trail leads down to viewpoints of the waterfall as it flows over lava columns (Fig. A-25). The contact between the lava flow and the underlying Tatoosh granodiorite is exposed at the falls.



Figure A-28. Glacial grooves, striations, and fractures in Mount Rainier Andesite near Panorama Point are telltale evidence of the work of past glaciers. The sculpting is accomplished by 'tools' (rocks) incorporated by the ice that move with it. The glacier moved from lower right to upper left. Marker pen for scale (5.25 in. or 13 cm).

48.4
77.9 Turnoff to Stevens Canyon and Ohanapecosh (Leg B); continue straight ahead toward Paradise. Tatoosh granodiorite with inclusions is exposed on the right.

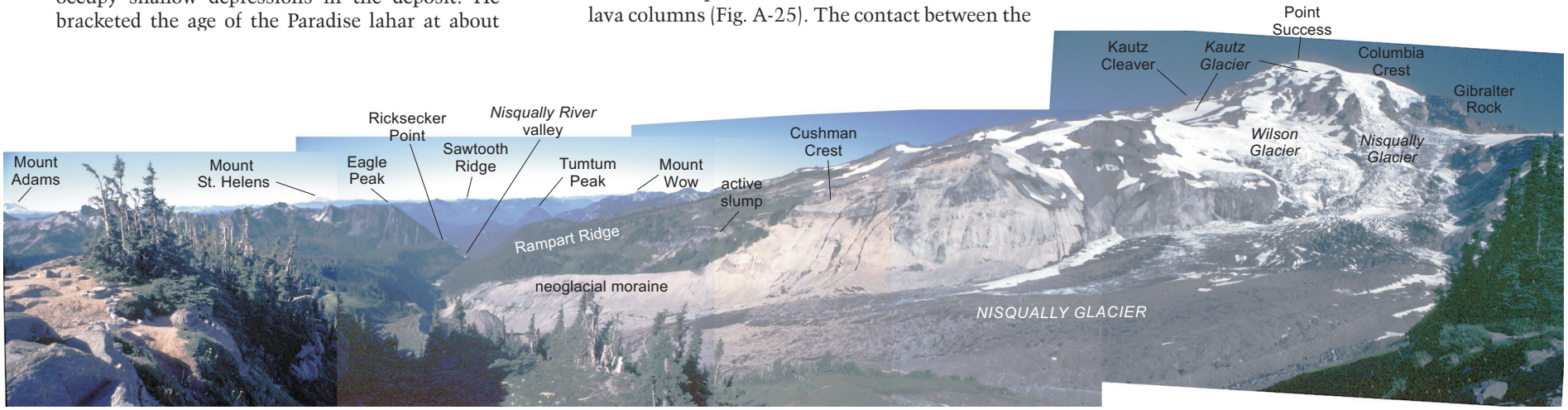


Figure A-27. A panorama from Glacier Vista in the meadows at Paradise Park. Mount Rainier is on the right (north) and Mount Adams is on the extreme left (south-southeast). This vista shows the rewards of making the hike (1100 ft or 300 m elevation gain) from the Paradise area.

49.4
79.0 Pullout on the left, offering a good view of Mount Rainier to the north and the glacially serrated peaks of the Tatoosh Range to the south. An outcrop of the Paradise lahar deposit contains a large block of andesite.

50.3
80196 Paradise area. Pull into the parking lot of the Henry M. Jackson Memorial Visitor Center. Numerous large boulders in the Paradise lahar deposit lie on the ground surface in this area. The lahar deposit and various tephra layers are visible in exposures at the parking area and along the trails that weave through the alpine meadows (Fig. A-26). A map of trails is available at the information desk. A hike to Glacier Vista (3.7 mi [6 km] round trip; elev. gain about 1000 ft [300 m]) will allow the visitor to observe the Nisqually Glacier, neoglacial moraines, and Mount Rainier lava flows, breccias, and block-and-ash deposits (Fig. A-27). A shorter hike along an asphalt trail to Nisqually Vista provides an excellent view of the glacier's terminus. The more energetic hiker can venture farther up to Panorama Point for additional views of the Nisqually and Wilson Glaciers, the layers exposed in uppermost Rampart Ridge, and glacial striations (Fig. A-28). The Moraine Trail, accessible via the Dead Horse Creek Trail, is a 3-mi (4.8 km) round trip that accesses spectacular views of the glacier. The trail ends at the left lateral moraine that was created during the Little Ice Age and offers a close-up view of the terminal area of the Nisqually Glacier.



Figure A-29. An historic photo of Paradise ice caves. These caves no longer exist because Paradise Glacier has receded past this location. National Park Service photo taken by Ranger Potts in 1953.

The ice caves in this area, once a favorite destination of glacier aficionados, are no longer safe and have been closed (Fig. A-29).

You can start Leg B at the north end of the Paradise parking area and continue that leg by turning left onto Stevens Canyon Road after about 2.3 mi (3.7 km), or you can return to the Nisqually Entrance to Mount Rainier National Park by turning right.

Remember to reset your odometer when you start another leg. ■

LEG B: PARADISE TO OHANAPECOSH VIA STEVENS CANYON

This 21-mi (34 km)-long leg begins in the timberline environment of Paradise in the Nisqually River watershed and descends the Paradise River valley before crossing over into Stevens Canyon and the Cowlitz River watershed (**Fig. B-1**). This route is one of the youngest in Mount Rainier National Park, having been dedicated on Sept. 4, 1957.

Starting at Paradise, the route crosses the Paradise River and passes lava columns, ash deposits, and the scenic Reflection Lakes nested on the deposits of a lahar that plowed over Mazama Ridge more than 6000 years ago. The road then descends into Stevens Canyon and a drier vegetation zone. The sparser vegetation in this eastern area of the park allows better rock exposures, and you will see plenty—Mount Rainier lava flows, granodiorite of the Tatoosh pluton, welded tuffs of the Stevens Ridge Formation, and the contact between the Stevens Ridge Formation and the underlying Ohanapecosh Formation.

Autumn is a particularly good season to examine the geology in upper Stevens Canyon—the crimson leaves of the vine maples can be spectacular that time of year. The Paradise Valley Road and the Stevens Canyon Road are typically closed from the first snowfalls in October until they can be opened in June. In the winter, when the road is closed to automobiles, this area is a favorite spot for alpine skiing. Although it has now been repaired, the Stevens Canyon Road was severely damaged by landslides in three places by the flood of November 2006, when a storm dumped 18 in. (~46 cm) of rain on the park in 36 hours. The status of roads and trails can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Figure B-1. Geologic map for Leg B (two consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.

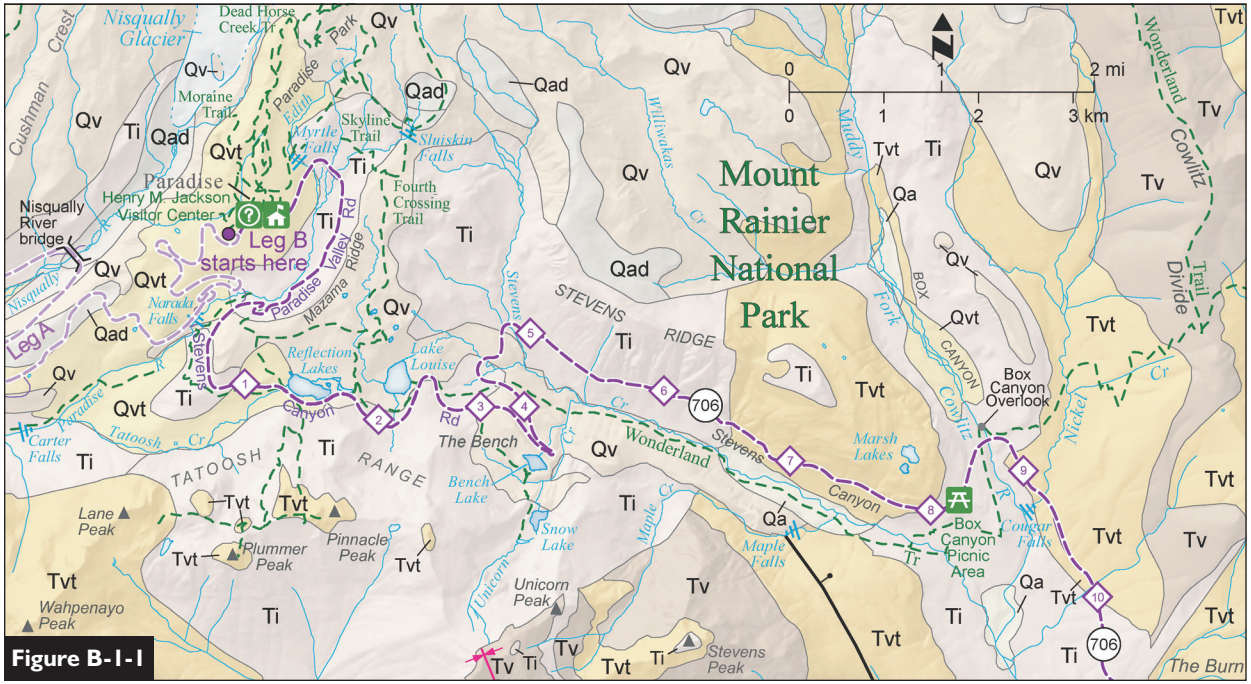


Figure B-1-1

Mileage

0.0 *0.0* Leave the north end of the Paradise parking lot near Paradise Inn and drive down through the beautiful valley of the Paradise River. (This is a one-way road.) An outcrop of andesite with flow banding and breccia is on the left (Fig. B-2).

0.2 *0.3* Outcrop of platy andesite.

0.3 *0.5* Outcrop of columnar andesite.

0.4 *0.6* Edith Creek and Myrtle Falls are contained in a narrow chasm cut in Tatoosh granodiorite of Miocene age.

0.7 *1.1* Paradise River and Fourth Crossing Trail parking area. Tatoosh granodiorite (Fig. B-3) with veining is on the left with the Paradise lahar on top. (See Optional Side Trip, p. 58, for a description of the Paradise lahar.) Geologists such as Donal Mullineaux (1974) and Jim Vallance (2000) of the U.S. Geological Survey have used ash layers preserved in this area and other eastside locations to help interpret the history of eruptions and lahars at Mount Rainier (Fig. B-4).

1.6 *2.5* Glacially smoothed Tatoosh granodiorite is visible slightly before a curve to left. Glacial till crops out upstream. The Paradise lahar deposit near here is draped by about 9 in. (23 cm) of Yn tephra from Mount St. Helens, erupted about 3,500 yr B.P.

1.7 *2.7* Multicolored layers of ash are exposed to the east of the road on top of an unsorted deposit, probably that of the Paradise lahar or of an older one observed by Scott and others (1995) near Sluiskin Falls to the northeast.

1.8 *2.9* Outcrop of Tatoosh granodiorite on the left.

photo by Beth Norman



Figure B-2. Andesite with flow banding and breccia near Paradise. This is the same andesite flow that is exposed at Ricksecker Point.

1.9
3.1 Turnout for the Lakes Trail just before a sharp turn to the right. This 4.8-mi (7.5 km) trail connects with several other trails, including Skyline Trail.

2.2
3.5 An outcrop of Mount Rainier Andesite is on the left (east). Notice the columnar jointing (Fig. B-5).

2.3
3.7 Turn left on Stevens Canyon Road to go to Stevens Canyon and Ohanapecosh. Andesite columns are on the left.

2.5
4.0 More lava columns. The orientation of the columns indicates the flow probably cooled next to a large body of glacial ice.

2.7
4.3 Inspiration Point. This vista point on the right (south) side of the road provides spectacular views of the upper Paradise River valley and Ricksecker Point lava flow to the southwest (Fig. B-6), as well as of Mount Rainier. Across the road to the northeast, a tan tephra deposit contains hornblende, a mineral that is fairly uncommon in Mount Rainier tephras (Fig. B-7). This tephra is overlain by a poorly sorted deposit (lahar or pyroclastic flow?) that is itself overlain by a lava flow older than the overlying Mazama Ridge flow. Sisson and Lanphere (1999) dated the Mazama flow at about 90 ka, and they showed that the age and chemistry of this flow are similar to those of the Bench and

photo by Beth Norman



Figure B-3. A marmot makes its home among boulders of Tatoosh granodiorite.

Stevens Canyon flows of Fiske and others (1963) and, further, that these flows are actually all part of the same flow (see mile 8.8 below.)

3.1
5.0 North of the road are outcrops of the Tatoosh granodiorite.

3.4
5.5 Reflection Lakes (see cover photo). The lakes occupy shallow depressions in a clay-rich deposit that was previously thought to be the Paradise lahar. However, Jim Vallance (USGS, written commun., 2002) believes this to be the older lahar mentioned above and described by Scott and others (1995) at Sluiskin Falls to the north. He determined the date of this lahar to be between 6,400 and 6,200 yr B.P. In order to reach the Reflection Lakes area, the lahar had to spill through a saddle in Mazama Ridge and down Stevens Canyon into the Cowlitz River watershed. Crandell (1971, p. 33) discussed the conditions under which lahar deposits could be left here: "…the lahar moved across Paradise Park and down the Paradise River valley in a single massive transient wave with a height of as much as 800 feet [244 m]. Such a wave must have been generated by a large avalanche of wet, clayey, rock debris from an area high on the south flank of the volcano, or perhaps its summit. Because of momentum, the avalanche-generated wave swept across Paradise Park…the great momentum of the wave, created by a vertical drop of 8000 feet [2438 m], carried it up over the east valley wall [Mazama Ridge]…the bulk of the material

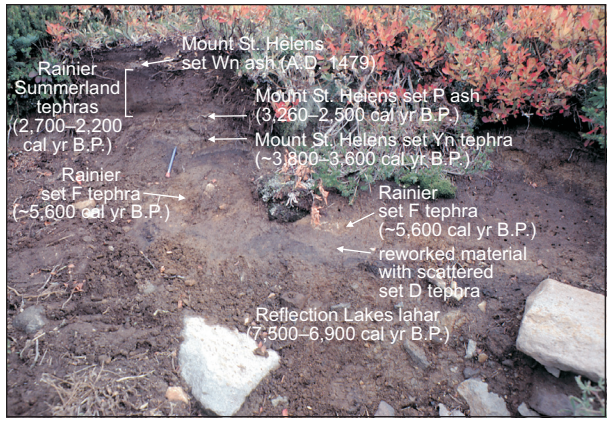


Figure B-4. Ash layers and buried soils overlying a lahar in Paradise Valley near the Fourth Crossing Trail parking area. USGS geologist Jim Vallance suggests that this lahar, which is likely the same one that underlies Reflection Lakes, dates to between 7,500 and 6,900 cal yr B.P., based on the ages of constraining tephra layers (written commun., 2002). Vallance also contributed the interpretations of the various tephra layers shown. He identified four 'exotic' (that is, not from Mount Rainier) tephra layers including Yn (3,800–3,600 cal yr B.P.), Wn (A.D. 1479), and set P (3,260–2,500 cal yr B.P.) tephras from Mount St. Helens. Mount St. Helens X tephra (~A.D. 1500) is present atop the Wn but is not visible in the photo. The blue pencil provides scale.

however, was deflected by Mazama Ridge to the southwest and down the Paradise Valley."

Continue east on Stevens Canyon Road toward Ohanapecosh.

4.2
6.8 MP 2. Sunbeam Creek and waterfall. The creek flows over the Tatoosh quartz monzonite on the south side of the road and into Lake Louise to the north, which sits on a moraine of Evans Creek age (22–15 ka). About 0.5 mi (0.8 km) after the curve past Lake Louise, the road passes an outcrop of the Mazama Ridge lava flow on the right before descending into the canyon of Stevens Creek. The canyon can be spectacular in autumn when leaves of the vine maples turn bright colors (Fig. B-8).

4.5
7.2 Lake Louise parking area. Just past the parking area is an outcrop of platy andesite on both sides of the road at the curve.

4.8
7.7 Pullout on the left with an outcrop of Tatoosh quartz monzonite on the right.

photo by Beth Norman



Figure B-5. An outcrop of Mount Rainier Andesite. The subhorizontal columnar jointing indicates that it may have cooled next to glacial ice. The columns are about 1 ft (0.3 m) across.

5.0 *8.0* Snow Lake Trailhead. Snow Lake (elev. 4600 ft or 7360 m) is a tarn.

5.4 *8.6* Pullout with an outcrop of platy Mazama Ridge andesite on the right.

6.3 *10.1* The Wonderland Trail, which goes around the mountain, crosses the road here.

6.9 *11.0* Stevens Creek. Exposures of Tatoosh quartz monzonite are visible in Stevens Creek and on Stevens Ridge above to the north-northeast. Mazama Ridge to the northwest, capped by a lava flow, is a major drainage divide. Stevens Creek, which drains the last vestiges of Paradise Glacier, flows into the Pacific Ocean by way of the Cowlitz and Columbia Rivers. The Paradise River, on the other side of Mazama Ridge, drains to Puget Sound via the Nisqually River. Ironically, because of glacial retreat, the Paradise River no longer drains the Paradise Glacier.

7.1 *11.4* MP 5. Tatoosh quartz monzonite is exposed from MP 5 to MP 6.

8.8 *14.1* Several small turnouts provide places to observe the Stevens Ridge Formation welded tuff on the north side of the valley and the dacite flow of Mazama Ridge in Stevens Canyon. Fiske and others (1963) inferred that the two lowest benches visible to the south were two separate flows (Fig. B-9). Dave Lescinsky and Tom Sisson (1998), however, showed that these were part of the same flow they mapped at Mazama Ridge. They noted that most of the ridge-capping lavas that Fiske and others proposed had gained their positions through reversed topography probably formed through confinement of a single lava flow to ridge sides and crests by thick valley ice during the Pleistocene (see Fig. 27, p. 30). Curved and chaotic fan-shaped lava columns suggest chilling against ice. Sisson explains (USGS, written commun., 1998): "...in Stevens Canyon, look across the valley and notice the benches in the lava. One lies just upstream of the valley of Unicorn Creek and one lies just upstream of the outlet of Maple Creek. Chemical compositions and four radiometric ages confirm that the Mazama Ridge [see below and at Inspiration Point above], Bench, and Stevens Canyon lavas are all the same flow and do not result from eruptions spaced widely in time and separated by long periods of erosion (previous interpretation).

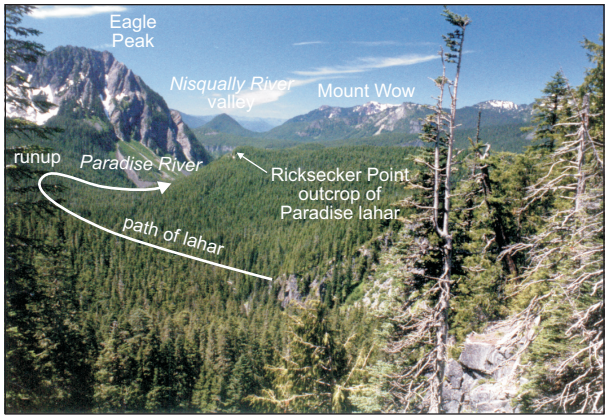


Figure B-6. The view west-southwest down Paradise Valley to Ricksecker Point from Inspiration Point. Ricksecker Point is the toe of a relatively young, fairly thick lava flow from Mount Rainier. That flow, whose age has been estimated at about 40 ka (Sisson and Lanphere, 1999), was probably ponded by glaciers that sat in the Paradise and Nisqually River valleys. The Paradise lahar sloshed through this valley about 5000 years ago, leaving a deposit at Ricksecker Point, some 800 ft (245 m) above the valley bottom (see Fig. A-23, p. 65). Eagle Peak and adjoining peaks of the Tatoosh Range to the west are cored by intrusive granodiorite of the Tatoosh pluton (25.8–14.1 Ma) and capped by older welded tuffs and breccias of the Stevens Ridge Formation.

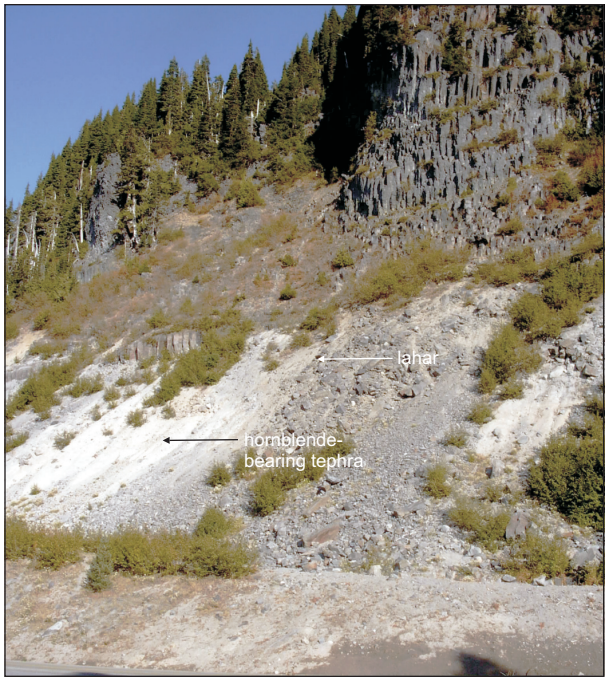


Figure B-7. The toe of Mazama Ridge where the Mazama Ridge lava flow (~99 ka; not shown) caps an older lava flow (columnar joints) over a lahar or pyroclastic flow over a hornblende-bearing tephra that is possibly correlative with the Sunset Amphitheater tephra (~190 ka). It is about 60 ft (18 m) to the base of the older lava flow. View is to the north.

Apparently, lava flowed down Mazama Ridge, bounded on the sides by ice in the valleys of Paradise River and Stevens Canyon. When the lava reached the end of Mazama Ridge it was diverted to the east by running into the Tatoosh Range. The lava proceeded along the margin of the Stevens Canyon glacier (paleo-Paradise Glacier) until it ran into a tributary ice stream in the valley of Unicorn Creek. The lava temporarily stopped and thickened until it melted through the Unicorn glacier, and then it continued down the margin of the main Stevens Canyon glacier until it ran into the tributary glacier in the valley of Maple Creek. The lava was dammed again and thickened until it melted through that ice and continued down a meltwater channel that lay on the margin of the main Stevens Canyon glacier until the eruption ended."

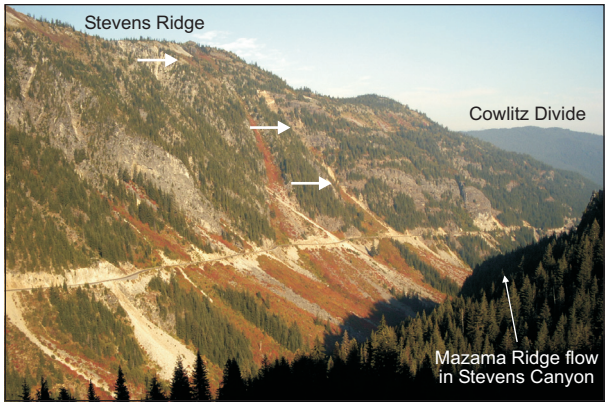


Figure B-8. Stevens Canyon and Stevens Ridge from about 1 mi (1.6 km) east of Lake Louise. Arrows at top and center show the approximate contact of Tatoosh granodiorite (left; 25.8–14.1 Ma) with the welded tuffs of the Stevens Ridge Formation. Notice the differences in the vegetation growing on the respective rock units; the horizontal stripes to the right suggest bedding. Cowlitz Divide is composed of the Ohanapecosh Formation (~37–27 Ma). The Mazama Ridge flow is about 90 ka. View is to the east.

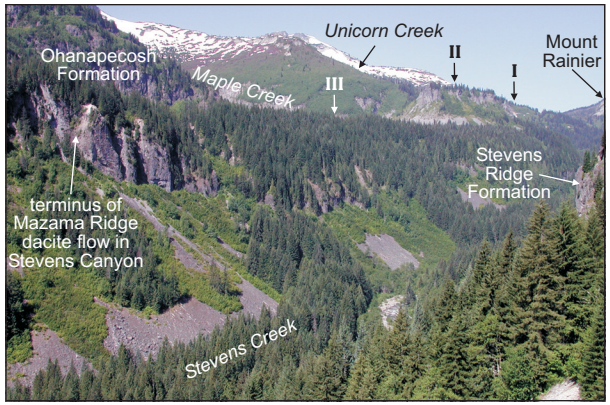


Figure B-9. Stevens Creek canyon from Stevens Canyon Road. The Mazama Ridge dacite flow of Stevens Canyon was dated by Sisson and Lanphere (1999) at about 90 ka. The direction of lava movement was upper right to lower left. Lescinsky and Sisson (1998) concluded that the flow was ponded at successively lower levels by tributary glaciers from the valleys of Unicorn Creek (bench level I, in the distance) and Maple Creek (bench level II) before being deflected and flowing downvalley at a lower elevation (bench level III in center and at left). The uppermost bench level is named 'The Bench'. View is to the west.

The Mazama Ridge dacite flow in Stevens Canyon has been dated at about 90 ka by Sisson and Lanphere (1999).

9.0
14.5 Tunnel through welded tuff. The Stevens Ridge rocks preserve an example of the scale and nature of some volcanic eruptions during the early Miocene in the southern Washington Cascades. The thick welded tuff layers were deposited by ash flows that originated in large eruptions of ash and lapilli. The flows moved as sheets yards (meters) or tens of yards thick flowing outward from the vent. These pumiceous flows were hot enough and thick enough in some places to weld together after they came to rest (Figs. B-10 and B-11). In such eruptions, several to many tens of cubic miles (2.4 mi^3 = 10 km^3) of volcanic debris may be ejected from the magma chamber fueling the volcano—so much that part of the volcanic edifice falls into the void left behind, creating a caldera. The welded tuff is visible for the next mile (1.6 km).

10.3
16.6 Stevens Creek Trailhead.

10.6
17.0 Wonderland Trail. Note the dark-colored sill about 10 ft (3 m) thick at the top of the west portal of the highway tunnel west of Box Canyon. According to Fiske and others (1963), here a Tatoosh sill is cutting a Fifes Peak Formation sill (Fig. B-12).

10.8
17.3 Box Canyon Overlook. The Box Canyon area exhibits spectacular postglacial incision and glacial striations (Fig. B-13). Box Canyon was carved by the Muddy Fork Cowlitz River, which heads at the Cowlitz and Ingraham Glaciers. Although none of the lahars that originated in the Cowlitz River watershed are comparable in size to the largest in other Mount Rainier drainages, the broad flood plain of the Cowlitz River many miles downstream (known as Big Bottom) is underlain by distal phases of many lahars that occurred in the last several thousand years.

At Box Canyon, the Muddy Fork has cut deeply into the volcanic bedrock. The footbridge 0.1 mi (0.2 km) upstream is the best vantage point. The greenish cut stones that line the bridge, walkway, and parking area are blocks of mudflow breccias of the Oligocene Ohanapecosh Formation. The greenish color is due to low-temperature metamorphism.



Figure B-10. Michael Bennett stands at an outcrop of welded tuffs of the upper Miocene Stevens Ridge Formation along Stevens Canyon Road. Note the crude columnar structure of the welded tuff.



Figure B-11. Fiamme, or stretched and flattened pumice (dark, elongate blob on the lower left), in Stevens Ridge welded lapilli tuff along Stevens Canyon Road.

This site is an example of why stratigraphic studies of a volcano must include areas beyond the volcano's base to provide a complete picture of



Figure B-12. Dark-colored sill about 10 ft (3 m) thick at the top of the west portal of the highway tunnel west of Box Canyon. According to Fiske and others (1963), here a Tatoosh sill is cutting a Fifes Peak Formation sill.

lahar magnitude and frequency. Many lahars have passed this point, yet little evidence of them is preserved here. A complete flow record is revealed only in the depositional areas of downstream valleys. Deposits on the volcano itself can be thin and quickly eroded or might be covered by the deposits of later eruptions. Glacial erosion and deposition are added complications. At Mount St. Helens, a series of flood surges that were derived from breakouts of avalanche-dammed lakes did not incorporate enough sediment to form debris flows until they reached a point about 12 mi (19 km) from the base of the volcano. Nevertheless, about 30 km (18.6 mi) from the volcano, one of these debris flows had a peak discharge of 200,000 to 300,000 m^3/s (261,600–392,400 yd^3/s), comparable to the Amazon River at flood stage (Scott, 1988).

11.3 *18.1* Nickel Creek. As the road ascends from here to Backbone Ridge, cuts expose Ohanapecosh Formation breccias overlain by light-colored Stevens Ridge Formation pyroclastic flows for the last 2 mi (3.2 km).

12.2 *19.6* MP 10.

14.0 *22.4* Outcrop of crystal lithic tuff.

14.2 *22.8* MP 12.

photo by Beth Norman

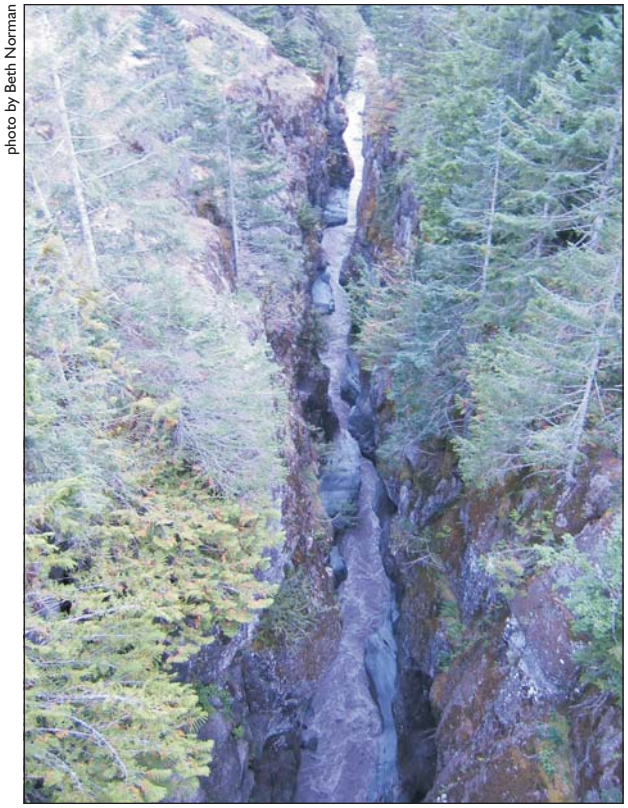


Figure B-13. Box Canyon Overlook. Box Canyon exhibits spectacular postglacial incision in bedrock of the Ohanapecosh Formation. The Muddy Fork Cowlitz River has cut a gorge about 180 ft (55 m) deep and 15 to 30 ft (5–9 m) wide.

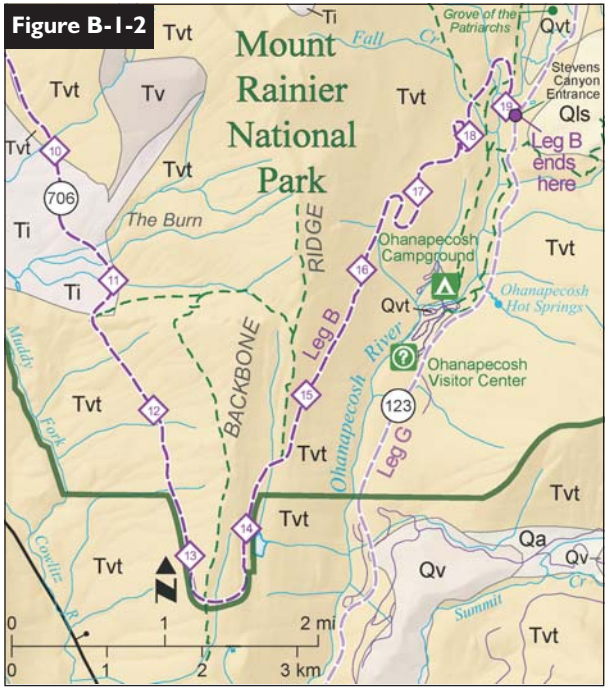
14.9 *23.9* An andesite dike cuts the tuff east of the road.

15.2 *24.5* MP 13.

15.3 *24.6* A turnout on the west side of the road provides a magnificent view of the southeast slope of Mount Rainier with Little Tahoma Peak on the right skyline, Success Cleaver on the left skyline, and Cowlitz Glacier tumbling toward the viewer (Fig. B-14). Outcrops of Stevens Ridge welded tuff across the road to the east are cut by two andesite dikes (Fig. B-15). For the next 2 mi (3.2 km) you will see outcrops of tuffs.



Figure B-14. View of Mount Rainier from the Stevens Canyon Road pullout at Backbone Ridge. The late-afternoon lighting emphasizes the contrast between the volcano's rugged, glacially dissected pre-Holocene rocks and its smooth, youthful summit, Columbia Crest cone. View is to the northwest.



17.3 *27.7* For the next 2 mi (3.2 km), the road descends through Fiske and others' (1963) thickest identified section of the Ohanapecosh Formation. They estimated that the original thickness of the Ohan-

apecosh Formation sediments was as much as 15,000 ft (2.8 mi; 4.5 km). Drive carefully along this stretch of road, which is narrow and has no good places to pull off. Below here are moraines of Evans Creek age and the Pleistocene Clear Fork flow to the southeast (Fig. B-16).



Figure B-15. Dacitic(?) dikes of early Miocene age that cut the Stevens Ridge Formation tuffs exposed at the Backbone Ridge pullout. The left dike is about 4 ft (1.2 m) thick. View is to the east.

Near the top of the ridge within the first 600 ft (180 m) after the sharp turn to the north, scattered 1.6- to 6.6-ft (0.5–2 m) greenish and maroon pods in the rocks (Fig. B-17) are fragments of saprolites that were, along with rocks of the underlying Ohanapecosh Formation, ripped up and incorporated into basal ash flows of the overlying Stevens Ridge volcaniclastic rocks. "Fragments of bedrock, saprolite, stream-rounded pebbles, and bits of macerated wood were swirled upward as much as 50 ft [13 m] into … the ash flow" (Fiske and others, 1963).

20.2 *32.5* MP 18.

20.4 *32.8* Cowlitz Divide Trail crosses the road.

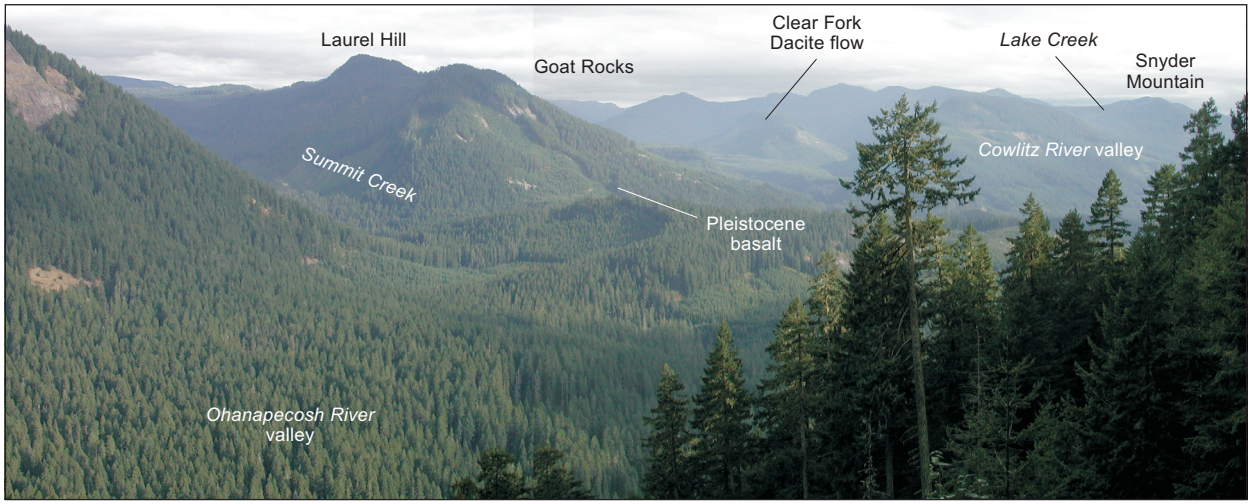


Figure B-16. View from Backbone Ridge to the southeast across the Ohanapecosh River valley at the Clear Fork Dacite flow and Goat Rocks (see Leg H, p. 124). Geoff Clayton (1983) obtained a radiometric age of about 0.65 ka on this flow. Hammond (1989) suggested that the Clear Fork flow may have been ponded by a lobe of ice in the upper Cowlitz River valley. The Pleistocene basalt shown might have been erupted from the Tumac Mountain volcano 10.5 mi (17 km) to the east or from a vent a few miles/kilometers west of Ohanapecosh valley along Summit Creek. Snyder Mountain is cored in large part by a thick pyroxene andesite lava flow erupted from Goat Rocks volcano between 0.78 and 0.14 Ma (Swanson and others, 1997). Swanson and his colleagues noted that the flows filled canyons incised as deep as 1150 ft (350 m) in upper Oligocene volcaniclastic rocks. A large debris avalanche from Snyder Mountain dammed upper Lake Creek to form Packwood Lake; the youngest radiocarbon age on a barkless snag in the lake is 970 yr B.P. (Pringle and others, 1998).

20.7 *33.1* Falls Creek. A tuff crops out on the left (if eastbound).

21.0 *33.8* Grove of the Patriarchs. From the trailhead, a short (50-minute round trip) walk leads to a magnificent old-growth forest of huge Douglas-firs and western redcedars that probably are at least 1000 years old. Their great age and low position on an island in the middle of the Ohanapecosh River indicate that no destructive lahars have originated in this drainage in at least 1000 years. The flood of November 2006, however, did serious damage, destroying the suspension bridge and part of the boardwalk along the trail and depositing as much as 4 ft (1.2 m) of fine sediment on the flood plain that supports the old trees.

21.1 *33.9* Ohanapecosh River bridge.

21.5 *34.6* Junction of Stevens Canyon Road with State Route 123 (see Leg G, mile 10.9). SR 123 passes through the rugged valley of the Ohanapecosh River, tributary of the Cowlitz River. You can turn left (north) here to go to Cayuse Pass and SR 410 or right (south) to go to US 12.

Remember to reset your odometer when you start another leg. ■



Figure B-17. Maroon and greenish pods, between 1 and 2 ft (0.3–0.6 m) across, in the Stevens Ridge pyroclastic flow on Backbone Ridge. These were interpreted by Fiske and others (1963) to be chunks of a soil layer that had developed on the underlying Ohanapecosh Formation. The soil was ripped up and incorporated into the Stevens Ridge flows.

LEG C: SOUTHERN TRANSECT ALONG THE COWLITZ RIVER VALLEY

Interstate 5 to State Route 123 via U.S. Highway 12

by Patrick T. Pringle and Elizabeth S. Norman*

This approach, the western segment of the White Pass Scenic Byway, generally follows the Cowlitz River valley to the east (Fig. C-1), where it meets State Route (SR) 123 (see Leg G). Leg H is a continuation of this route that extends across the Cascades to SR 410, Naches, and Yakima.

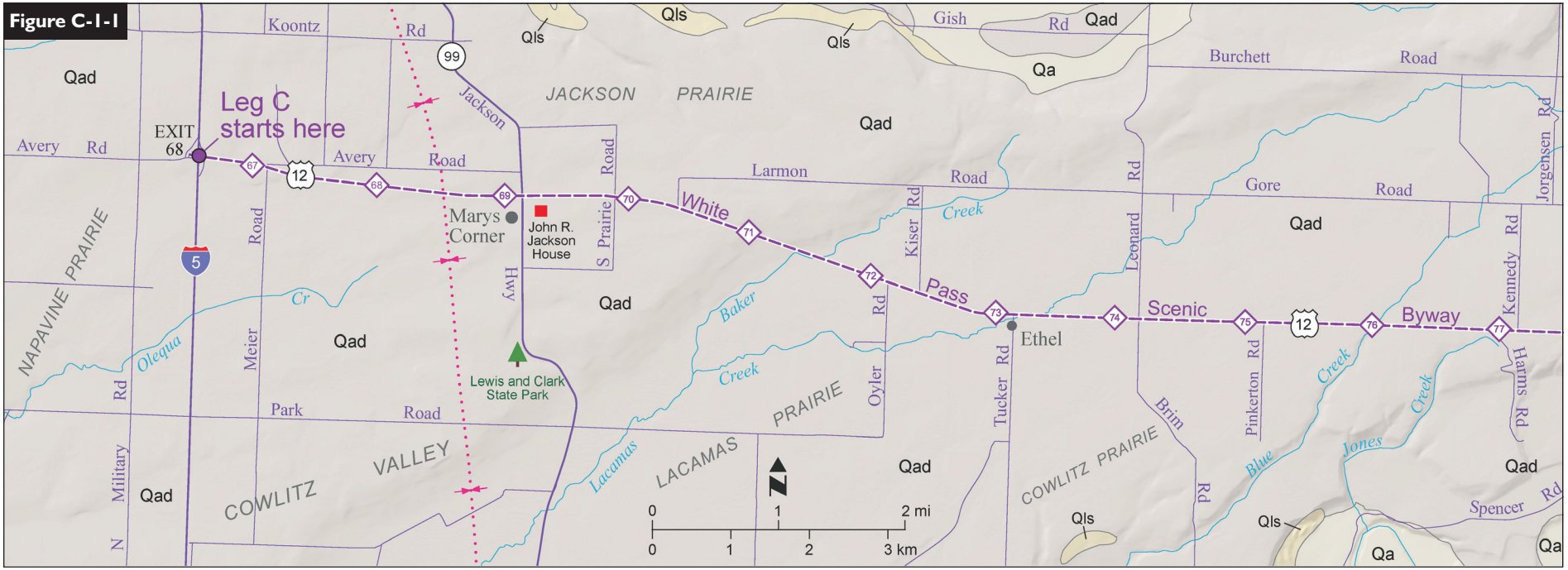
This 71-mi (115 km) route along U.S. Highway (US) 12 begins on Jackson Prairie (underlain by the Pleistocene Logan Hill Formation) and descends a series of progressively younger glacial terraces in stairstep fashion: Jackson, Lacamas, and Cowlitz Prairies or their physiographic equivalents. The older surfaces are at higher elevations and the younger ones are lower because erosion, possibly combined with a minor component of regional tectonic uplift, deepened the Cowlitz River valley before each succeeding episode of deposition. Dethier (1988) evaluated the soil formation on the terraces as related to their age; the deposits will be described en route. Dethier observed that during at least two glacial events, the Cowlitz glacier terminated more than 60 mi (100 km) from Mount Rainier, thus making it one of the longest valley glaciers in the conterminous United States.

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 of Tertiary age crop out along the highway, indicating that you have entered the eroded and folded Cascade Range. Lava flows and fragmental volcanic rocks of this age crop out all along the route.

At Randle, this route accesses SR 131 and Forest Roads (FRs) 25 and 23, which lead to the east side of the Mount St. Helens area as well as to the Cispus River drainage and the north side of Mount Adams. (See Pringle, 2002.) Hummocky glacial deposits (end moraine and ice-marginal deposits) of Evans Creek age (~22,000–15,000 yr B.P.) near here suggest that this is

* See "Contributors", p. ii, for affiliation.

Figure C-1. Geologic map for Leg C (six consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987a,b) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.



the terminal position of the large valley glacier that occupied the Cowlitz River valley.

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful

Mileage

0.0 *0.0* Mileage starts on US 12 at its junction with Interstate 5 (I-5). 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* Milepost (MP) 67.

2.5 *4.0* Marys Corner.

3.2 *5.1* Roadcuts expose the clayey, reddish, deeply weathered top of the Logan Hill Formation. Weathering reaches depths greater than 50 ft (15 m).

3.3 *5.3* MP 70.

4.1 *6.6* Good exposures of red soils of the Logan Hill Formation in a roadcut here.

4.5 *7.2* Descend from Jackson Prairie to Lacamas Prairie, the surface of an outwash plain of middle(?) Pleistocene Wingate Hill Drift. Notice that Lacamas Prairie is flatter than the older Jackson Prairie—it displays relief of only a few feet. Colman and Pierce (1981) estimated the age of Wingate Hill Drift to be about 600 to 300 ka.

7.3 *11.7* On a fine day, there is a good view of Mount St. Helens ahead and slightly to the right. Mount Adams volcano is also visible (east of Mount St. Helens), as is Goat Rocks, a mountainous remnant of an extinct Pleistocene volcano. (For more information on Goat Rocks, see Leg H, p. 124.)

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

11.3 *18.1* MP 78.

11.4 *18.3* Near Salkum, the road descends to a terrace underlain by outwash deposits of Hayden Creek age (~170–130 ka) and then crosses Mill Creek. This terrace is an equivalent of Cowlitz Prairie to the southwest. Till of Wingate Hill age 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 *24.4* Cross Mayfield Lake (a reservoir). MP 82 is on the bridge. The concrete arch dam was completed in 1962. Glacial outwash deposits are visible north of the highway on both sides of the reservoir.

16.6 *26.7* The first outcrops of dark Cascade Range volcanic rocks (Oligocene–Eocene basaltic andesite) begin to appear in roadcuts near here.

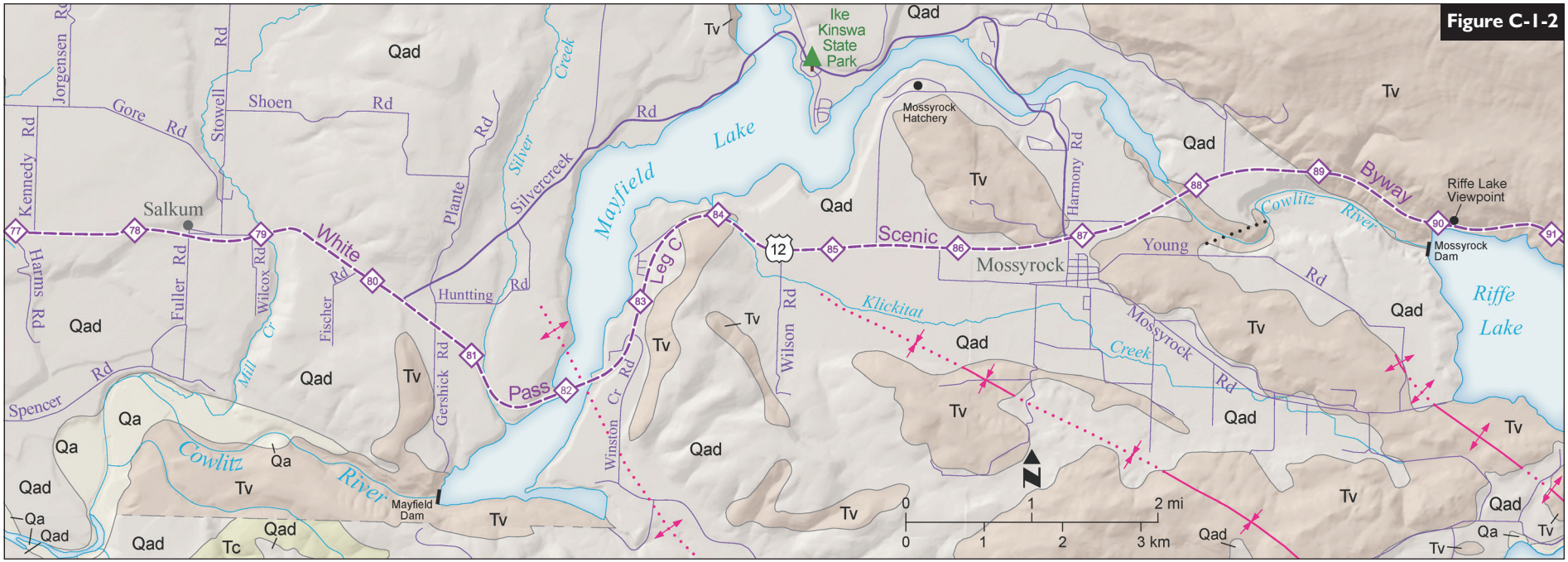


photo by Beth Norman



Figure C-2. Goble Volcanics (Tertiary) 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. The red soil (arrow) was baked by the lava flow that buried it. Note the steeply dipping hyaloclastite beds where lava flowed into water to trigger phreatomagmatic explosions.

17.3 *27.8* There is an outcrop of amygdaloidal basaltic andesite on the right (south) side of the highway, but no place to safely pull over and view it.

19.8 *31.8* Another outcrop of basaltic andesite on the left.

21.2 *34.1* Cross the Cowlitz River.

22.2 *35.7* The cliffs on the left (north of the highway) are more Oligocene–Eocene basaltic andesite.

22.9 *36.8* Landslide with riprap to prevent its moving onto the roadway.

23.3 *37.5* 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 (Fig. C-2). The outcrop north of the highway is mapped as andesite (Schasse, 1987a); however, the rocks contain common ovoid-shaped oxidized remnants of olivine crystals that are more typical of basalt. Beds of fragmental volcanic rocks crop out about 0.5 mi (0.8 km) farther to the east. Note the reddish soils in some places that were baked by the lava or pyroclastic flows that buried them and also the steeply dipping hyaloclastite beds where lava flowed into water to trigger phreatomagmatic explosions. Vugs in the lava contain opal. Opal is composed of amorphous (noncrystalline) 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.



Figure C-3. Riffe Lake (a reservoir) in the glacially carved valley of the Cowlitz River. Rugged peaks of the Mount Margaret wilderness in the distance (above and left of center) are the resistant granodiorites of the Spirit Lake pluton. View is to the south.

South-southeast of Riffe Lake, Mount Margaret and other peaks in the Mount Margaret Wilderness north of Mount St. Helens are composed of granodiorite and granite of the Spirit Lake pluton, whose age has been estimated at 22 to 20 Ma by Evarts and others (1987)(Fig. C-3).

23.7 *38.1* There is a good exposure of hyaloclastite beds on the left (north), but no safe place to get out and examine them.

24.3 *39.1* MP 91.

25.5 *41.0* Viewpoint for Riffe Lake. The outcrop on the left (north) is basaltic andesite.

26.2 *42.1* The road climbs past glacial drift, out of the Cowlitz drainage, and then crosses a drainage divide into the Tilton River watershed.

27.2 *43.7* **OPTIONAL SIDE TRIP:** Short Road Crater View (1.3 mi [2 km] round trip). If the weather is good, this viewpoint near MP 94 affords a distant view of the Mount St. Helens crater, neighboring mountains, and the valley of the Cowlitz River. As you climb Short Road, you'll see Bellicum Peak, a mountain to the northwest that 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.

Remember to compensate for mileage along the side trip.

photo by Beth Norman



Figure C-4. Zone of reddish altered rocks. Slickensides are common on these sheared rocks, although no trace of a fault is visible.

28.2 *45.3* As the road descends into Morton, a zone of reddish altered rocks is exposed on the left (Fig. C-4). Slickensides are common on these rocks. Although no trace of a fault is visible, this may be a shear zone.

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 younger rocks south of Rainey Creek ranges from about 6 to 18 mi (18–30 km), the spacing in the older rocks north of Rainey Creek ranges from about 2 to 6 mi (3–10 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 Fig. 3, p. 4).

31.0 *49.9* Junction of US 12 with SR 7 at Morton. Continue east on US 12.

31.3 *50.3* MP 98.

33.3 *53.5* Slightly east of MP 100, sedimentary rocks of the Puget Group crop out on the south side of the highway (Fig. C-5). These rocks for the most part predate the Cascades, but they do interfinger with the earliest Cascade volcanic rocks. Clevinger (1968, 1969) provided details about the fossils and minerals associated with rocks in this area in his two useful guidebooks (Fig. C-6).

34.6 *55.7* There is an outcrop of volcaniclastic rocks of Tertiary age on the right (southwest), but no pullout.

34.8 *56.0* Junction with Davis Lake Road. This road extends to the north and then loops back to the northwest for a few miles at the base of the foothills before its junction with SR 7 in Morton. Davis Lake and Lake Creek sit in an extension of the same northwest-trending valley occupied by the Tilton River northwest of Morton (see Leg I, p. 77). The orientation of the valley seems influenced by the orientation of nearby folds and faults, many of which trend northwest.

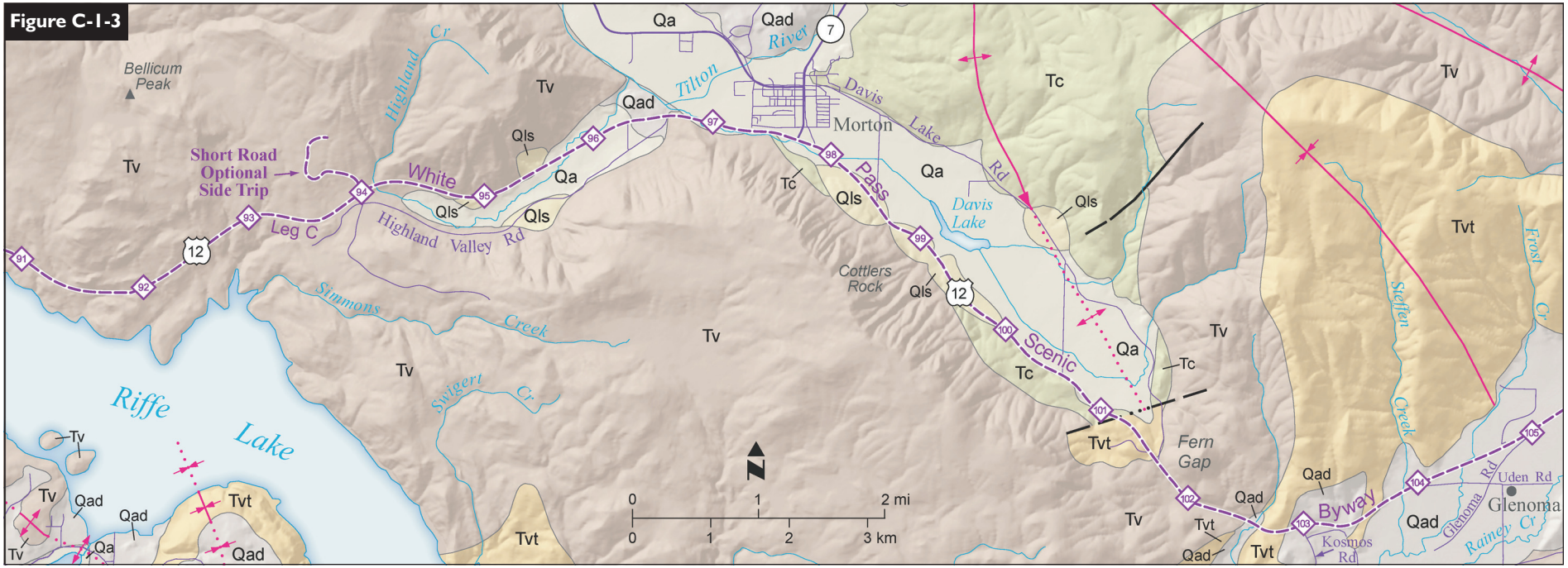
Cathy Whitlock (Barnosky, 1981) developed an extensive record of paleoclimate and environmental change using pollen and plant fossils obtained by coring at Davis Lake and other sites, including Mineral Lake 12.7 mi (20 km) to the north-northeast. Her radiocarbon dates for the Davis Lake core spanned the last 26,000 years and cut through eight recognizable tephra layers. She concluded from the pollen evidence that tundra-parkland vegetation likely existed in this area from 26,000 to 16,000 yr B.P. These cold conditions were followed by warming from 16,000 to 15,000 yr B.P. and then a return to a colder climate until 12,000 yr B.P., when the pollen of several subalpine lowland tree species appeared, representing a shift to warmer, interglacial environment.



photo by Dave Norman

Figure C-5. Geologist Beth Norman examines sedimentary rocks of the Puget Group.

35.2 *56.8* About 4.2 mi (6.7 km) past the SR 7 junction, just past MP 101, the road crosses a northeast-



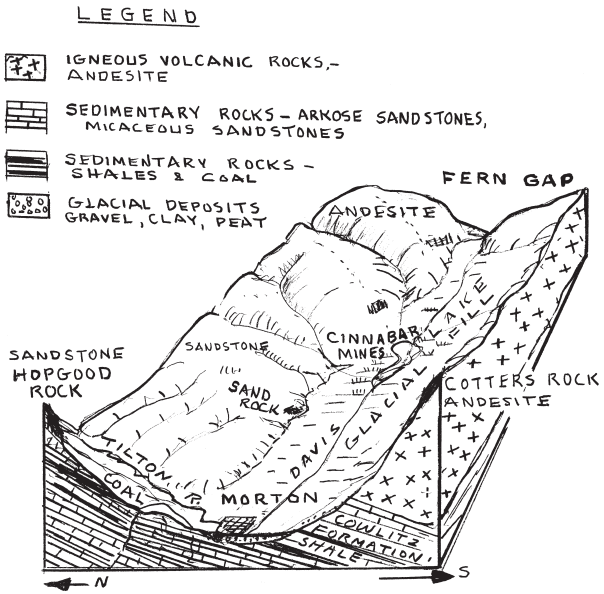


Figure C-6. A block diagram of the geology at Morton, Wash. View is to the east and shows the apparent dip of sedimentary rocks of the Puget Group in the southwest limb of a northwest-trending anticline. The anticline plunges to the southeast. Also shown are the cinnabar mines and selected physiographic features. Volcanic rocks overlie the sediments to the south of Morton. The U-shaped valley was carved during the Hayden Creek glaciation. Modified from Clevinger (1969).

trending normal fault, and you are back in the Goble Volcanics. The fault is not visible in outcrop. Although the fault motion has been interpreted as down-to-the-southeast, the topography appears inverted because the down-dropped rocks now stand higher than those rocks across the fault. If the interpretation of the fault is correct, this situation perhaps resulted because Goble Volcanics are more resistant to erosion than 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.

36.4 *58.5* Light tan to brown volcaniclastic rocks of Tertiary age crop out in the cliff on the left (northeast) side of the highway about 260 yd (240 m) east of Kosmos Road (Fig. C-7).

photo by Beth Norman



Figure C-7. Light tan to brown upper Eocene to Oligocene volcaniclastic rocks east of Kosmos Road. Outcrop is about 30 ft (10 m) high.

36.6 *58.9* A Tertiary lava flow crops out on the inside of a curve on the left (north) side of the road (Fig. C-8).

36.9 *59.4* Basalt flows of Tertiary age are exposed here.

37.3 *60.0* MP 104, Uden Road. Glacial drift exposed here is of Hayden Creek age (~170–130 ka)(Fig. C-9).

37.9 *60.9* Glenoma. The south valley wall along Rainey Creek (the elongated ridge south of Glenoma) is composed of upper Oligocene basaltic rocks, mostly lava flows. These rocks were derived from a volcanic center south of Riffe Lake.

41.0 *65.9* Rainy Creek Road on the south.

41.4 *66.6* Although not readily visible from the highway, deposits of yellowish tephra are common in roadcuts and stream banks near where the road crosses Rainey Creek. This pebble-size pumice is the Yn tephra layer from Mount St. Helens, erupted about 3,600 yr B.P. The deposit of pumice and ash from this eruption extends to the northeast to Alberta, Canada. It was probably the largest volcanic eruption in this region in the past 4000 years. Scientists studying the settlement sites and patterns near this area found that the native peoples moved far away from Mount St. Helens area at about this time and probably stayed away for nearly 2000 years (McClure, 1992).

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

photo by Beth Norman



Figure C-8. Lava flow of Tertiary age.

photo by Beth Norman



Figure C-9. Glacial drift of Hayden Creek age.

photo by Beth Norman



Figure C-10. These cliffs on the north side of US 12 near Kiona Creek are Oligocene andesite flows.

photo by Beth Norman



Figure C-11. Glacial drift of Hayden Creek age (~170–130 ka) exposed on the left (north) side of the highway slightly east of MP 12.

43.0 *68.8* The cliffs on the north side of road are Oligocene andesite flows (Fig. C-10).

43.8 *70.4* Kiona Creek.

44.3 *71.3* MP 111. Junction of US 12 with Savio Road. Continue ahead on US 12. Lake Scanewa (610 acres; 2.47 km^2), a reservoir impounded in 1994 by Cowlitz Falls Dam, lies several miles to the south. It is closed to fishing from March 1 to May 31 to allow out-migration of juvenile steelhead.

45.4 *73.0* Glacial drift of Hayden Creek age is exposed on the left (north) side of the highway (Fig. C-11).

46.6 *75.0* Slightly east of here the highway passes through a terminal moraine constructed by the large valley glacier that occupied the Cowlitz River during the Evans Creek alpine glaciation. South-dipping dip slopes in andesite flows are visible to the north (Fig. C-12).

47.2 *75.9* MP 114. A significant landslide (not shown on map) more than 197 ft (60 m) wide blocked the highway here at about 6:00 p.m. on Nov. 22, 1995, narrowly missing a vehicle (Fig. C-13). During heavy rains, a large mass of rock toppled onto the clay-rich slope to the north, overloading it and causing rock debris and soil to move rapidly downslope some 985 ft (300 m). Inspection of the rock units above revealed a north-trending fault and an associated zone of gouge in the altered rock material along the fault zone—a zone of slippery, clay-rich, and mechanically weak rock debris. The rocks are sandstones and conglomerates of Oligocene age. The landslide deposit is 3.3 to 30 ft (7.5–9 m) thick, and its volume is 150,000 to 200,000 yd^3 (115,000–150,000 m^3). The Washington State

photo by Beth Norman



Figure C-12. South-dipping andesite flows visible north of US 12 about 0.5 mi (0.8 km) west of MP 114. The surface of the flow may have been smoothed by glacial ice in the mid-Pleistocene.

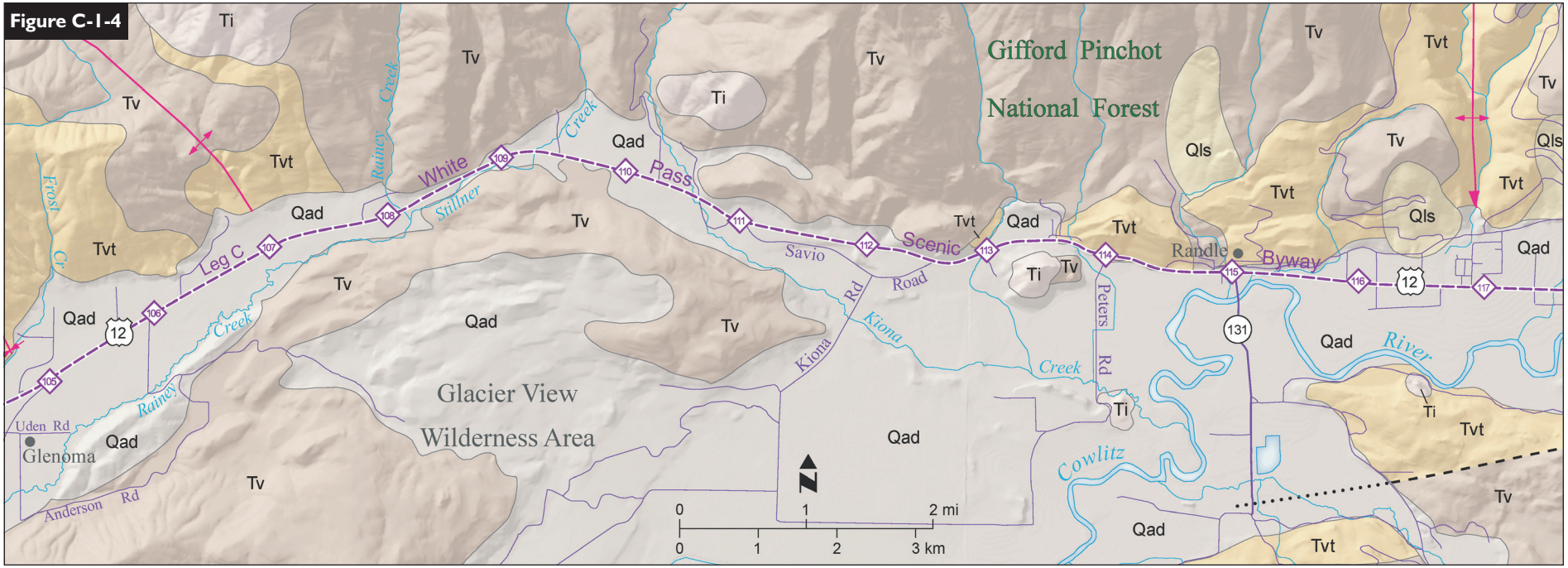




Figure C-13. A landslide complex north of US 12 about 1 mi (1.6 km) west of Randle at Peters Road. The failure occurred in stages at about 6:00 pm on Nov. 22, 1995. One landslide nearly hit a vehicle. This photo was taken in April 1996. During a period when the hillside was saturated, a zone of clayey gouge associated with a north-trending fault here failed when bedrock blocks from the cliff toppled onto upper slopes and overloaded the slippery material. The vertical distance from the topple to the road is about 800 ft (250 m). US 12 now goes around the toe of this slide.

Department of Transportation (WSDOT) removed about 70,000 yd^3 (52,000 m^3) of landslide debris. Several days after the initial slide, the landslide began to flow 20 to 30 ft/day (6–9 m/day). The area had received 16.82 in. (42.7 cm) of rainfall in the previous 42 days, 8.68 in. (22.1 cm) in the previous 22 days, and 1.96 in. (5 cm) in an intense storm two days before the event. WSDOT has stabilized this slide and moved the road away from the base of the slope.



Figure C-14. Flood deposits capping the Cowlitz River flood plain near Randle. These sandy deposits show that since A.D. 1479 more than 13 great floods have inundated this part of the Cowlitz River valley from valley wall to valley wall. The light-colored layer slightly above the trenching tool is a tephra unit known as Wn, which was erupted during a major eruption of Mount St. Helens, probably in late A.D. 1479. The handle of the trenching tool is about 18 in. (45 cm) long.

On a clear day, Mount Adams volcano is visible 33 mi (53 km) to the southeast.

48.3 *77.7* Randle and the intersection of US 12 with SR 131. *Note if you are heading south:* There are no service stations between here and the town of Cougar (~100 mi or 160 km), so make sure you have plenty of fuel.

photo by Dave Norman



Figure C-15. An outcrop of granodiorite near MP 120. View is to the north.

SR 131 accesses the east side of 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.

49.4 *79.5* Cowlitz Valley Ranger Station.

50.0 *80.5* The broad flood plain of the Cowlitz River contains numerous layers of flood silts and sands. USGS geologist Norm Banks located a stack of flood deposits near here that overlie the white pumice layer Wn, erupted from Mount St. Helens in late A.D. 1479 or early 1480 (Fig. C-14). At least 13 flood layers lie on top of the Wn pumice, and the 1996 flood, which was a rain-on-snow event and inundated the valley floor from wall to wall, left the uppermost layer.

51.2 *82.3* MP 118. Cliffs to the left (north) are Miocene diorite and granodiorite intrusions.

54.0 *86.9* Pullout to the right (south). The outcrop on the left is granodiorite with inclusions of andesite (Fig. C-15).

55.1 *88.7* MP 121. The road curves to the left. Note the big scarp visible to the southeast on the face of Castle

Butte (Fig. C-16). Strata of upper Oligocene volcaniclastic rocks are visible in the scarp.

58.8 *94.6* Near MP 125 there are some large boulders near the mouth of the canyon to the south. They might have been carried down by debris flows.

59.1 *95.1* MP 126. Rest area. The hummocky terrain and large, angular to subangular boulders are typical of a landslide deposit, although Swanson and his USGS colleagues Norm Banks and Richard Moore (1997) have mapped this area as 'alluvial fan'. The source area of the debris is Goat Dike, a rock promontory to the south composed of volcaniclastic rocks. Light-gray granules of Mount St. Helens Wn tephra (A.D. 1479) lie atop the debris; however, there is no trace of the 3,500 yr B.P. Yn tephra from Mount St. Helens whose fallout was heavy in this area. Therefore, the age of this hummocky deposit is bracketed by the ages of these two layers.

Studies by Swanson and his colleagues revealed that the area is underlain by bedded volcaniclastic rocks of late Eocene and Oligocene age, mostly laharic units, that interbed with andesite and basaltic andesite lava flows on the south side of the Cowlitz River valley between Smith and Johnson Creeks. Those flows were part of a large shield volcano that was located near Angry Mountain, about 8.7 mi (14 km) to the east-southeast.

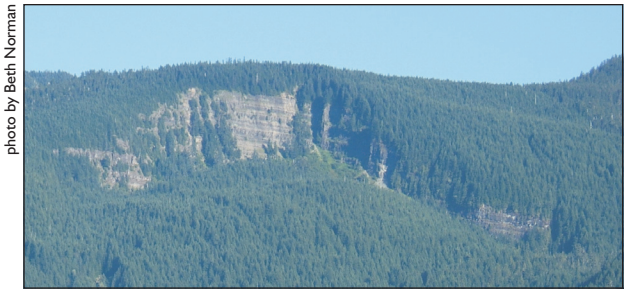

photo by Beth Norman

Figure C-16. The big scarp visible in the distance on the face of Castle Butte is strata of upper Oligocene volcaniclastic rocks.

60.7 *97.7* FR 20. More large rocks south of the highway may also be part of the same landslide noted at the rest area.

61.1 *98.3* MP 128.

61.2 *97.4* More large rocks, these at the mouth of Johnson Creek, were probably deposited by debris flows.

61.5 *98.9* Chambers Lake turnoff and FR 21 to Glacier Lake. For a good view of Mount Rainier on a fine day, you can drive about 1.5 to 2 mi (2.4–3.2 km) up this forest road. Glacier Lake, accessible about 6 mi (10 km) up the Johnson Creek valley and via a vigorous hike, is dammed by a large rock slide–debris avalanche deposit. Bob Schuster dated a subfossil tree exposed in the lakebed upstream of the blockage at about 600 yr B.P., and a provisional tree-ring analysis of one subfossil snag drowned behind the landslide dam indicates that its outermost ring is about A.D. 1453. However, the bark was missing from the tree, so the precise year of its demise is uncertain—it is unclear if there are missing outer rings. The Glacier Lake rock slide may record a significant earthquake, owing to its proximity to two other landslide-dammed lakes and because it is not uncommon for landslides of this type and size to be triggered by seismic shaking. Curiously, Packwood Lake, only about 2.5 mi (4 km) to the northwest of Glacier Lake, is also impounded by a large landslide (Pringle and others, 1998), and

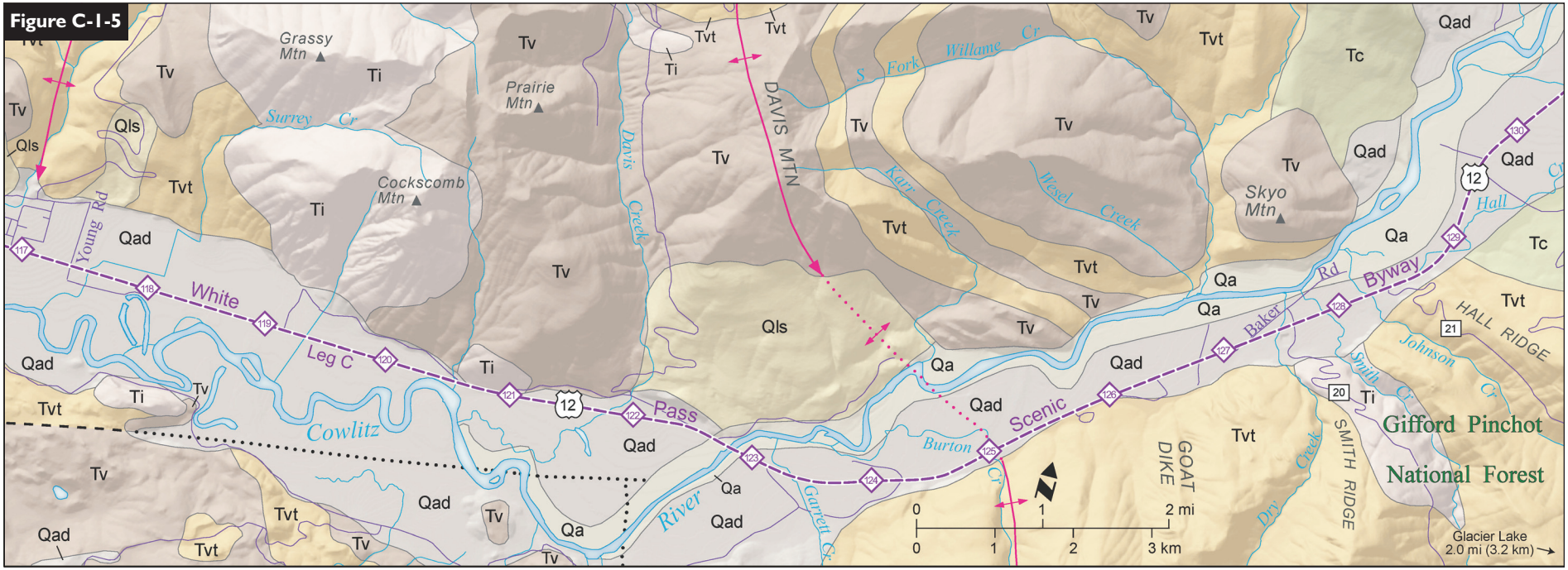




Figure C-17. Private landowner Greg Arkle takes a core sample of a half-submerged tree along the Cowlitz River near Packwood. The trees shown here were preserved by burial, perhaps for centuries, and then exposed when erosion during floods removed part of the bank. View to the southwest (downstream).

Hager Lake, mentioned below, is only about 3 mi (4.8 km) from the others.

Swanson (1995) found no significant evidence of active faulting in this area, although he did identify many small, mostly north-northwest-trending shear zones that cut Tertiary rocks. He constrained the age of most folding in this area to "between 18 Ma (possibly 15.6 Ma) and 12 Ma" based on paleomagnetic data, several K-Ar ages, and field observations.

Remember to compensate for mileage if you take the side trip.

61.6 99.1 Mount Rainier is visible to the left on a clear day.

62.0 99.7 The terrace or bench on the south side of the highway near the curve, slightly after Hall and Johnson Creeks, is supported in part by southwest-trending andesitic dikes. Hager Creek is a 'disappearing stream' that drains into the coarse rocky debris of a large alluvial fan. What could be the source of all this rocky debris? Hager Lake, which lies some 2.4 mi (3.8 km) southeast of the highway up Hager

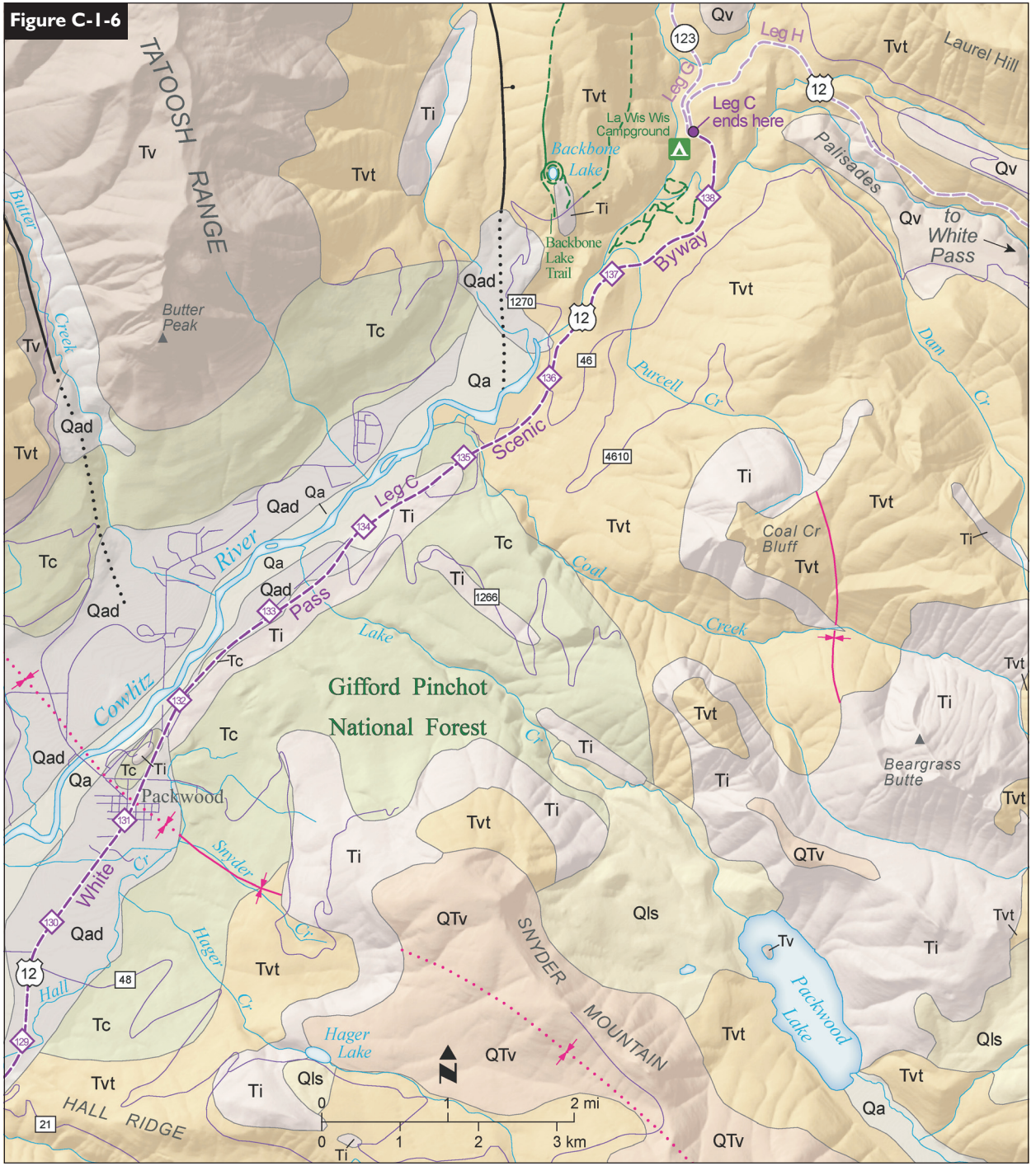




Figure C-18. A subfossil tree near Packwood is buried by about 3 ft (1 m) of sediment. Poorly exposed here near the base of the tree, the Wn tephra, 5 in. (13 cm) thick, was erupted from Mount St. Helens, probably in late A.D. 1479, so the sediments above it have been deposited since that time. The handle of trenching tool is about 18 in. (45 cm) long.

Creek, is dammed by a large landslide from Hall Ridge. USGS Geologist Bob Schuster found standing snags in the lake and suggested it formed within the last several centuries (Swanson and others, 1997). Perhaps partial breaching of the newly dammed lake deposited the bouldery debris of the alluvial fan at the base of the valley wall.

62.1 *99.9* MP 129.

64.1 *103.1* MP 131, downtown Packwood. This small town may be located closer to more volcanoes than any other town in Washington. This location provides easy access to Mounts Adams, St. Helens, and Rainier, as well as the Indian Heaven volcanic field to the south and the White Pass area.

Buried trees and gravel and sand layers rich in Mount Rainier Andesite fragments (Figs. C-17 and C-18) indicate that lahar runouts and volcanic floods from Mount Rainier eruptions have flowed along the valley bottom. The configuration of the



Figure C-19. An Oligocene or Miocene intrusive andesite sill slightly east of Packwood. View is to the north.



Figure C-20. Geologist Beth Norman examines black sedimentary rocks exposed on north side of US 12 slightly east of Packwood. They are lake deposits of Oligocene or Miocene age.

Cowlitz River's upper tributaries at Mount Rainier, however, suggests that other river systems face a higher probability of future lahars than the Cowlitz valley.

Glacial grooves and striations on rocks locally offer further evidence of the huge glaciers that have carved this broad valley during past ice ages.

64.3 *103.5* Depart Packwood heading east. Note landslides visible ahead and slightly to the left, on the south face of Butter Peak, the exposed rocky face to the north that is the southernmost peak of the Tatoosh Range. The Tatoosh pluton was named for the Tatoosh Range by Fiske and others (1963).

64.6 *103.9* The outcrop on left is an Oligocene or Miocene intrusive andesite sill (Fig. C-19).



Figure C-21. Crude columnar joints in an andesitic sill of Oligocene or Miocene age in an outcrop near MP 134 on US 12 east of Packwood. The top of the sill and overlying material has been removed by a glacier of Evans Creek age that filled this part of the Cowlitz valley. The underlying fine-grained sedimentary rocks were interpreted by Swanson and others (1997) as overbank deposits. Leaf fossils shown in Fig. C-22 were found near the hammer (white circle) at the bottom center of the photo.

64.9 *104.4* The black sedimentary rocks that crop out on north side of the road are lake deposits of Miocene age (Fig. C-20). On the south side of road is an andesite sill.

66.6 *107.2* Cross Lake Creek, which drains landslide-dammed Packwood Lake.

66.9 *107.6* MP 134. Columnar-jointed rock exposed south of the road is an andesitic sill of the Packwood complex of Oligocene or Miocene age (Fig. C-21) (Swanson and others, 1997).

67.2 *108.1* Thin shale laminae under the sill are lake deposits that contain some leaf fossils (Fig. C-22).

67.6 *108.8* Grizzly Road. The highway is cut through an andesite sill.

67.7 *108.9* Gray, intrusive andesite of Miocene or Oligocene age.

68.3 *109.9* Coal Creek and Coal Creek Road.

68.4 *110.1* Enter Gifford Pinchot National Forest.

68.7 *110.5* The small outcrop of tuffaceous sedimentary rocks on the right contains fossil wood.

69.0 *111.0* Near MP 136, FR 46 is on the southeast side of the road, and slightly past here, FR 1270 goes to Backbone Lake Trail #164.

69.4 *111.7* Gray tuff on the right (southeast) that overlies a resistant andesitic sill is probably the Purcell Creek tuff of Miocene age, identified by Swanson (1996) in this area.

69.6 *112.0* Green to light-gray tuffs crop out to the right (southeast) of the road.

69.8 *112.3* At a curve to the right slightly before MP 137, note a large cliff of greenish-brown volcaniclastic rocks, possibly Purcell Creek tuff.

70.4 *113.2* Fine-grained tuffs on the right here contain lapilli and larger clasts.

70.6 *113.6* Chain-up area.

71.1 *114.4* La Wis Wis Campground.

71.5 *115.0* Intersection of US 12 with SR 123. You can continue east on US 12 via Leg H or turn left here and follow Leg G (in reverse order) toward Chinook Pass (16.3 mi or 26.2 km). Alternatively, you can intersect the end of Leg B and the Ohanapecosh Entrance to Mount Rainier National Park by going north on SR 123 5.4 mi (8.6 km).

Remember to reset your odometer when you start another leg. ■



Figure C-22. *Metasequoia* leaf fossils in indurated lake beds of Oligocene or Miocene age. These were found under the sill along US 12, about 2.6 mi (4 km) east of Packwood (Fig. C-21). The fragment in the inset photo is about 4 in. (10 cm) long. (Fossil collecting on Washington Department of Transportation land requires permission.)

LEG D: NORTHERN APPROACH

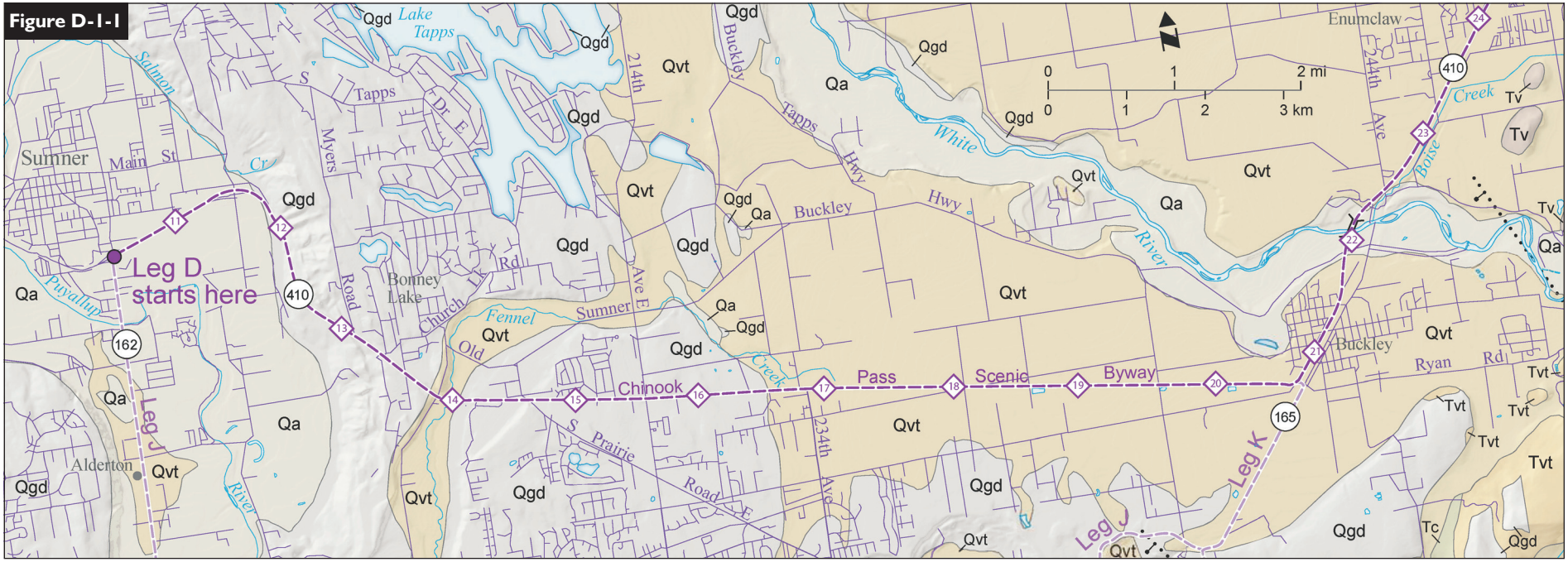
Sumner to Cayuse Pass on State Route 410

State Route (SR) 410 is the Chinook Pass Scenic Byway. This 56-mi (~90 km) leg follows the western portion of the byway, which begins by ascending from the flood plain of the Puyallup River (near Puyallup and Sumner) to cross part of the great Puget Lowland drift plain veneered by glacial sediments (Figs. 2 and D-1). The route enters the Cascade Range slightly east of Enumclaw and leads to the upper reaches of the rugged White River basin, which drains Mount Rainier's east face and the crest of the Cascade Range. The byway follows a part of the historic Naches Trail, traversed by both local tribes and early settlers, and eventually crosses the Cascade Range via Mount Baker–Snoqualmie and Wenatchee National Forests and Mount Rainier National Park to connect with the fertile Yakima River valley (see Leg F, p. 102). Stephen T. Mather, an early 20th century conservationist and first director of the National Park Service, recognized the scenic and recreational value of this area, and in 1928 he suggested special provisions to protect the scenery along this new state highway.

The broad Puyallup and Duwamish River valleys were in large part cut into the surface of the great Puget Lowland drift plain by rivers flowing under the mighty Puget lobe of the continental ice sheet as it surged south between the Olympic and Cascade mountains (see Fig. 6, p. 8). After you climb out of the flood plain of the Puyallup River and as the highway approaches Buckley and Enumclaw, you begin, almost imperceptibly, to traverse the deposits of the enormous Osceola Mudflow from Mount Rainier, which spilled onto the drift plain about 5600 years ago. As the road enters the Cascade Range, it ascends a staircase of Pleistocene-age terraces and crosses the broad glaciated valley of the White River. The valley is floored by a stack of postglacial Mount Rainier lahar deposits—evidence that enormous, sediment-charged slurries from Mount Rainier have sloshed by like swift rivers of flowing concrete.

Radiocarbon dating of recently excavated trees in downstream areas has revealed that during three periods in the past 2700 years, these lahars or lahar runouts

Figure D-1. Geologic map for Leg D (five consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b), Walsh (1987), Tabor and others (2000) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.



caused catastrophic flooding and aggradation in the lowlands. Zehfuss (2005) and Zehfuss and others (2003a) note that deposits younger than the Osceola Mudflow define at least three episodes of clay-poor lahars in the White River drainage. Their inferred history is based on previous work by Crandell (1971), Scott and others (1995), and Pringle (2000) and on their own new results. The oldest of their three episodes of lahars in this area coincided with volcanism of Summerland age (~2,700–2,200 cal yr B.P.) when as many as five eruptions may have occurred (Vallance and Donoghue, 2000). Next came two episodes that correspond to the Deadman Flat assemblage of Scott and others (1995). The name 'Deadman Flat' is no longer used for this assemblage. Instead, the older of these is provisionally called the Twin Creek episode and the younger is provisionally called the Fryingpan Creek episode.

The Twin Creek lahars date at from about 1,700 to 1,350 cal yr B.P., on the basis of the range of three ages on detrital wood and charcoal from deposits along White River. Wiggle-matching of several radiocarbon ages from a single, bark-bearing log exhumed at Kent yielded an age of about 1,500 cal yr B.P. (Vallance and Pringle, this volume, p. 34). The Fryingpan Creek episode occurred about 1,100 yr B.P., as determined from buried stumps at Auburn and Fife (Pringle and others, 1997; Vallance and Pringle, this volume, p. 34). Similarities in the pattern of tree rings of some of the Fife and Auburn trees show they likely died at about the same time.

Here and there on the edges of the valley that you drive along as you head east from Enumclaw, 20- to 30-ft (6–9 m)-wide mounds of rock debris, most of which are made up of Mount Rainier rock, are testimony to the passage of one of the world's largest lahars, the Osceola Mudflow. At Federation Forest State Park, the road sits on top of terraces composed largely of the clay-poor, post-Osceola lahars from Mount Rainier noted above.

As you enter the forest lands past the town of Greenwater and drive toward Cayuse Pass, you will begin to see more exposures of bedded, pastel-colored volcanic rocks, welded tuffs, granodiorite, and landslide deposits—all providing evidence of a dynamic, and at times tumultuous, geologic past.

The highway is closed in winter (typically November to late June) past the Sunrise Road (Leg E) turnoff near milepost 62. The status of roads and trails can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* This leg begins on SR 410 where it intersects with SR 162, just south of the town of Sumner. Set the trip odometer where the road goes under the SR 162 bridge. This arbitrary starting point is about 1.5 mi (2.4 km) east of where you access SR 410 from either SR 512 or SR 167. The broad Duwamish valley was carved during and after the Vashon glaciation. A detailed study of well logs in this valley bottom (Dragovich and others, 1994) confirms that before deposition of the great Osceola Mudflow about 5,600 years ago, an arm of Puget Sound extended from what is now the Port of Seattle to about 6 km (3.7 mi) north of Sumner (at present sea level). Similarly, in the Puyallup River valley, an arm of the sound would have extended southeast to near the west boundary of the city of Puyallup (see Fig. 36, p. 38). Apparently, more than 155 mi^2 (400 km^2) of new land was created by deposition of alluvium (mostly lahar derived) in the Puyallup and Duwamish valleys since before the Osceola Mudflow.

Sandy deposits from Mount Rainier tens of yards (meters) thick, as well as fluvial deposits, now underlie the valley floor, having been deposited mainly by lahars and lahar runouts from Mount Rainier or as a result of the volcanic flooding and aggradation that likely occurred for decades following each volcanic disturbance. One of these, the lahar of about 1,100 yr B.P., probably discharged from the White River canyon to the Duwamish valley at Auburn and branched: one lobe flowed north and sent a major flood of sediment as far as the Port of Seattle, while another flowed south into the present Puyallup Valley and buried forests near Fife. Probably not long after that lahar flooded the lower Duwamish River, the area was instantaneously jerked upward as much as 20 ft (6 m) when the Seattle Fault ruptured in the interval from A.D. 900 to 930 (Atwater, 1999; Zehfuss and others, 2003a).

0.5 *0.8* Milepost (MP) 11.

1.4 *2.3* Begin the climb up along the valley wall on SR 410.

1.6 *2.6* MP 12. Glacial outwash gravels crop out on the east side of the highway.

2.3 *3.7* More Pleistocene gravels crop out on the east side of the road. There is a good view of the valley to the west and southwest. The broad Puyallup River valley south of here and its northward extension, the Duwamish valley, were probably carved by meltwaters at the keel of the advancing Puget lobe of the Vashon glacier between 22 and 15 ka. Although vegetation covers most of the valley walls here, over the years geologists have examined outcrops to try to piece together the geologic history. Deposits of the Vashon glacier typically cap the plateau, and geologists used to think that, in layer cake fashion, the next layer of glacial deposits below the Vashon represented those of the penultimate glaciation. They were in for a surprise! Easterbrook and others (1981) and Westgate and others (1987) confirmed a revolutionary interpretation of the ages of many of the pre-Vashon layers when they dated a layer of coarse tephra near Sumner at about 1 Ma. That layer, the Lake Tapps tephra, sits atop the Salmon Springs deposits that had previously been considered to be only about 75 ka in age! Easterbrook and his coworkers had confirmed that the Salmon Springs deposits were more than one million years old. But why would the events of nearly 1 m.y. (between the Vashon Drift and Lake Tapps tephra) be "missing" from the record?

Recently geologists have begun to reassemble this puzzle. Not only has the Puget Lowland undergone a complicated erosional and depositional history and multiple glaciations, but faults in the upper 30 mi (50 km) of the Earth's crust have ruptured, lifting some areas and lowering others many meters at a time. Large parts of the 'record' have been removed, and much has been 'imported', creating a challenge for geologists. A later development in this fascinating story is that USGS geologist Wes Hildreth (1996) found that the Lake Tapps tephra had a geochemistry nearly identical to that of the pumice erupted from the

Kulshan caldera northeast of Mount Baker, some 110 mi (176 km) to the north!

3.0 *4.8* City of Bonney Lake.

3.5 *5.6* Fennel Creek. About 5600 years ago, a distributary lobe of the enormous Osceola Mudflow surged through this valley. After passing through the Fennel Creek valley, the road continues east across an area of glacial drift known locally as the Enumclaw plateau or plain.

4.2 *6.6* South Prairie Road East.

7.8 *12.6* Begin crossing the Osceola Mudflow deposit. As enormous as this mudflow was, by the time it reached here from Mount Rainier it did not have the volume to inundate the entire plateau area, so it spread out to a critical thinness, much like pancake batter on a griddle, and ponded locally. Where it was confined within valley walls, it continued to flow downstream.

9.2 *14.8* City limits of Buckley.

9.6 *15.4* MP 20.

10.2 *16.4* Junction with SR 165. To access Leg K (p. 87), which describes the geology along SR 165 to Mowich Lake and the Carbon River area, you can turn south (right) here, then go about 0.25 mi (0.4 km) and make another right turn. (Remember to reset the odometer when starting Leg K.)

At the towns of Buckley and Enumclaw, the highway traverses a plain capped by the Osceola Mudflow. Scattered large boulders or mounds deposited by the mudflow are visible on the surface of the plain, but for the most part the terrain is smooth and lacks the mounds commonly visible in localities farther upstream. Within a few miles of this area, an archeological excavation unearthed more than 200 knives, projectile points, scrapers, and other artifacts beneath the Osceola Mudflow deposit (see Fig. 9, p. 12)—evidence of human occupation of the area before and possibly at the time of the mudflow (Williams, 1973; Hedlund, 1976). Hedlund also found artifacts on top of the Osceola Mudflow; these were made of obsidian and jasper not found on the west side of the Cascade Range, whereas the artifacts found under the Osceola Mudflow were made primarily of andesite and basaltic material obtained nearby.

11.0 *17.7* Buckley urban center.

11.5 *18.5* Cross the White River power canal. The graveyard on the east side of the road is probably underlain by lahar deposits of the past 1100 years.

11.7 *18.8* Lahar deposits at the White River bridge at MP 22. The White River drains the east and northeast slopes of Mount Rainier. The upper White River valley was the main pathway for the Osceola Mudflow. Note the enormous 'Osceola' rocks in the river. Deposits of at least three lahars are exposed several hundred yards (meters) downstream of the bridge on the north side of the river.

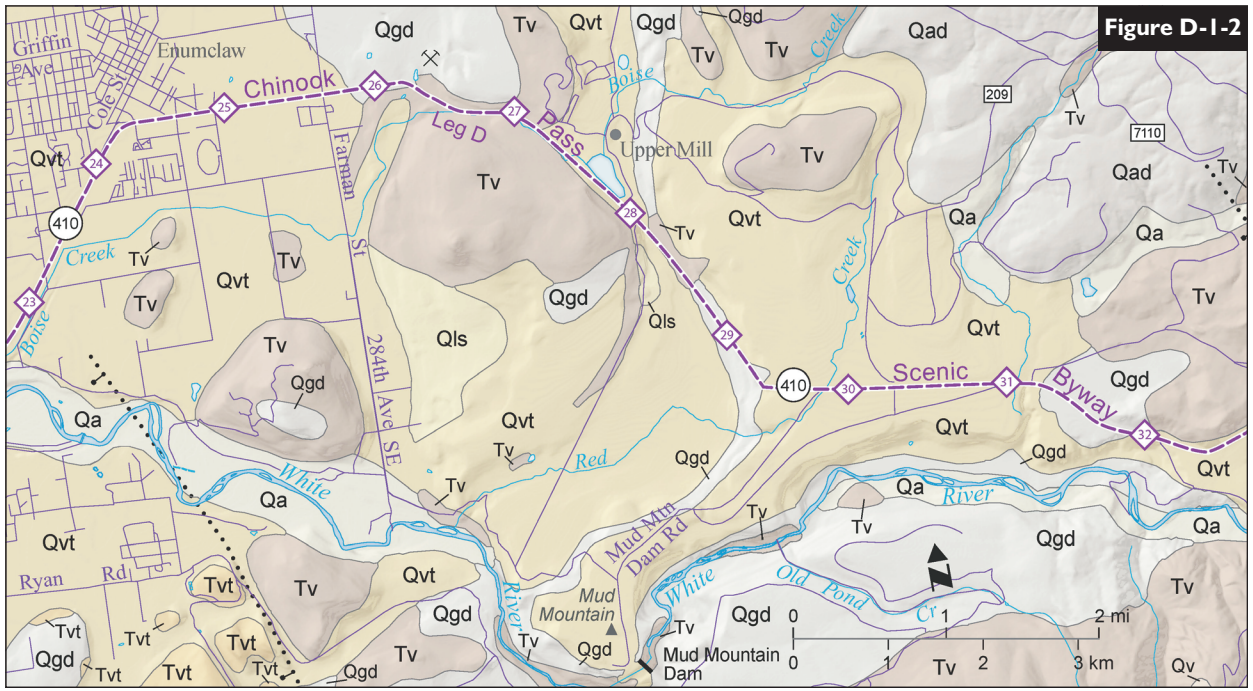
The Osceola Mudflow here is a 9- to 16-ft (3–5 m)-thick cap on the glacial deposits of Vashon age that form the highest (~100 ft or 30 m) terraces near the river. Inset against the high Vashon-age terraces is a 20-ft (6 m) terrace that includes at least two layers of lahars. The lahar deposit that caps the terrace contains rounded grains of set C pumice from Mount Rainier (~2,200 yr B.P.); however, this lahar is likely to correlate with the lahar that buried trees in Auburn and Fife about 1100 years ago and left deposits as far north as the Port of Seattle. It probably picked up the older pumice as it flowed along the White River valley.

Continue east on SR 410 through Enumclaw.

14.0 *22.5* Not far beyond MP 24 and before a curve to the right (if eastbound), notice that the bedrock beds in the mountains ahead seem to dip to the right (~southeast) (Fig. D-2). These are the folded volcanic rocks of the Huckleberry Mountain Formation of Oligocene age studied by Hammond (1963), Frizzell and others (1984), and Tabor and others (2000). The Huckleberry rocks are likely correlative with the Ohanapecosh Formation, whose age was bracketed by Vance and others (1987) by fission-track dating at 36.5 to 28.3 Ma.

14.5 *23.3* Junction of SR 410 with SR 164 and Griffin Ave.

14.7 *23.7* MP 25.



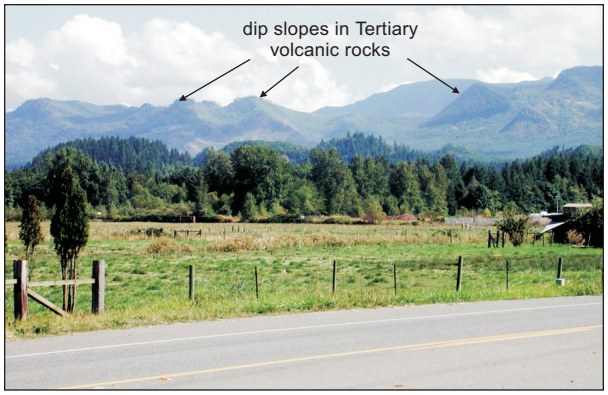


Figure D-2. View to the northeast from Enumclaw showing southwest-dipping beds of folded volcaniclastic rocks of the Huckleberry Mountain Formation (Oligocene) along the Cascade mountain front.

14.8 *23.8* Small U.S. Forest Service and National Park Service offices are on the right side of the road.

15.3 *24.6* Junction of SR 410 with 284th Ave SE (Farman St.). The Department of Natural Resources South Puget Sound Region office is on the right. Stay on SR 410. From here you begin to ascend three terraces situated where the White River valley meets the Puget Lowland. The Osceola Mudflow veneers all three terraces. (See the Mud Mountain Dam stop at mile 19.5.)

16.0 *25.7* Begin ascending the second terrace. You'll see the first (westernmost) exposures of Cascade Range andesites and basaltic andesite of the Fifes Peak Formation along the highway at about mile 16.8 (slightly east of MP 27).

18.0 *29.0* The 410 Quarry outcrop of Fifes Peak Formation andesite is probably about 24 to 23 Ma (Hammond, 1998).

19.5 *31.4* **OPTIONAL SIDE TRIP:** Mud Mountain Dam (slightly west of MP 30) (restrooms and view with exhibit). From the junction of SR 410 and Southeast Mud Mountain Road (there is a large sign at the intersection for the Mud Mountain Dam Recreation Area), you can drive 2.4 mi (3.8 km) on the access road and then a short distance left to the dam viewpoint. A trail winds down to the lower viewpoint (20-minute round-trip walk); however, the upper viewpoint is impressive. A landslide in

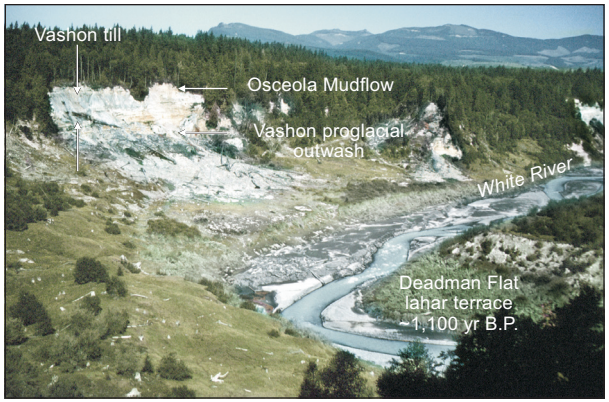


Figure D-3. View northeast from the Mud Mountain Dam overlook showing the Holocene and Pleistocene deposits exposed in the valley walls by a landslide that occurred during the flooding event of February 1996. From the top of the till to the river level is about 350 ft (110 m). The Vashon till was deposited by a re-entrant tongue of Puget lobe ice that pushed its way up the White River valley as much as 4.5 mi (7.2 km) from the east margin of the lowland. The steep canyon walls are quite unstable. This photo was taken in September 1996.

1996 exposed deposits on the valley wall to the north, including hummocky topography of the great Osceola Mudflow (Figs. D-3 and D-4). Vallance and Scott (1997) described the path of the Osceola Mudflow as it cascaded onto the Puget Lowland east of Enumclaw: "When it [the Osceola] encountered a narrow gorge of the White River at Mud Mountain that is only 300 m [984 ft] wide, the Osceola Mudflow spread out over glaciofluvial [and till] terraces of Vashon age that are up to 110 m [361 ft] above the White River...As it continued westward, the mudflow poured over terrace scarps to form a spectacular pair of falls...The upper fall would have formed an arc more than 6 km [3.7 mi] wide and more than 80 m [263 ft] high, and the second would have been more than 3 km [1.9 mi] wide and more than 110 m [361 ft] high."

Mud Mountain Dam was built by the U.S. Army Corps of Engineers solely for flood control in the lower White River basin (Fig. D-5). The earth-fill embankment dam was constructed between 1939 and 1942, although floodgates were not constructed until 1948. Additional information about the dam can be found in Galster (1989a,b).

photo by Beth Norman



Figure D-4. The area in Figure D-3 as it looked in September 2007. An assemblage of deposits comprising post-Osceola Mudflow lahars and lahar-derived sediments caps at least three terraces about 1 mi (1.6 km) upstream of the dam.

photo by Beth Norman



Figure D-5. Mud Mountain Dam. This earth-fill embankment dam was constructed for flood control in the lower White River basin.

The pointed peak sporting a radio antenna and visible to the southeast from the Mud Mountain Dam picnic parking area is the northern end of The Three Sisters, a northwest-trending ridge. The ridge's southeast flank was recently identified as a volcanic vent by USGS Geologist Tom Sisson (written commun., 1998), who noticed cemented spatter with possible feeder dikes and a "…1.5–2-m [2.4–3.2 ft] thick pumice fall that lies between the Tertiary basement and the lava, with pumice lumps to 20 cm [7.9 in.]". He dated the olivine-

bearing basaltic andesites there at about 360 ka (Sisson and Lanphere, 1999). Sisson observed that, although these rocks were erupted about 17.4 mi (28 km) north-northwest of Mount Rainier's summit, they are chemically similar to the basaltic andesites of the Echo and Observation Rocks vents on Mount Rainier's northwest flank.

An assemblage of deposits comprising post-Osceola Mudflow lahars and lahar runouts caps at least three terraces about 1 mi (1.6 km) upstream of the dam (Fig. D-4). One of these flows left a gravelly layer whose top is at about 1200 ft (366 m) elevation, more than 200 ft (61 m) above the river (Fig. D-6).

Remember to compensate for mileage along the side trip.

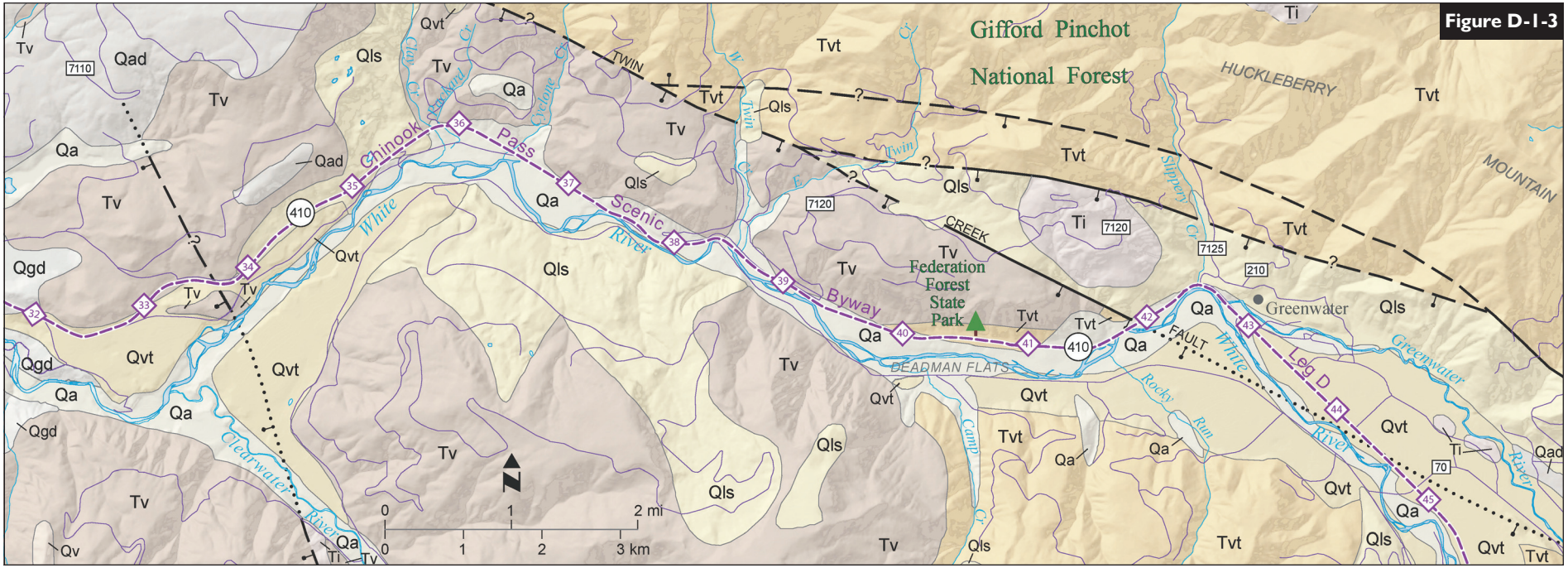
21.5 34.6 Not far west of MP 32, the road cuts a mound in the Osceola deposit; its remnant is south of the road.

21.7 34.9 MP 32.

22.1 35.5 The roadcut on the north side of the road exposes hydrothermally altered Tertiary andesite estimated to be of early Miocene age by Hammond (1980). McCulla (1986) noted two circular areas between the White River valley and Mount Rainier that he interpreted to be shallow intrusive complexes. Zones of alteration that surround these circular features and that bound nearby faults have been dated at 19.0 to 20.3 Ma (Blakely and others, 2007). Several mining districts are associated with these areas of altered rock. (See the "Mining in Mount Rainier National Park" sidebar on p. 90 and the "Mineralization and Mining Northwest of Mount Rainier" sidebar on p. 91.) Along the White River, the altered rock is locally rich in alunite ($KAl_3(SO_4)_2(OH)_6$), a mineral commonly formed in volcanic areas where rocks are altered by solutions containing sulfuric acid. The altered rock serves as a silica resource for the Superior quarry, one of Washington's three silica mines. The silica being



Figure D-6. *(right)* Andy Roth examines a megaclast-bearing lahar runout deposit in the canyon of the White River valley upstream of Mud Mountain Dam. The large boulder is floating in the matrix of the deposit. The reddish-brown blob to its right is a large, fragile chunk of sandy fragmental debris that was picked by the lahar as it flowed downstream—note the bedding within it that dips to the left. Another sandy megaclast is visible behind Andy's left shoulder. These delicate clasts, which probably originated as chunks of alluvium that fell into the moving lahar, suggest that lahars can flow as a plug of sediment moving as a mass. This lahar runout layer extends roughly from Andy's knees to about 3 ft (1 m) over his head. The preservation of graffiti and 'pictographs' on the outcrop made by previous visitors attests to the compact nature of the lahar runout deposit.



Mining in Mount Rainier National Park

by Rebecca A. Christie and Katherine M. Reed

In 1897, the 18th annual report of the U.S. Geological Survey noted that the park boundaries "have been so drawn as to exclude from its area all lands upon which coal, gold, or other valuable minerals are supposed to occur, and they conform to the purpose that the park shall include all features of peculiar scenic beauty without encroaching on the interests of miners and settlers" (Russell, 1898, p. 413). However, Section 5 of the 1899 legislative act that established Mount Rainier National Park extended the federal mineral laws, the Mining Law of 1872 in particular, to lands within the park, perhaps because the act was copied from that for Yellowstone (Catton, 1995). Secretary of the Interior Cornelius N. Bliss asked that Section 5 be repealed because it seemed inconsistent with the purpose of parks. Acting Park Superintendent G. F. Allen was aware that prospecting activity was increasing rapidly—to as many as 165 mineral seekers in 1906. Claim staking then was an informal action, with many locations too vague for proper recording. Claimants were probably hunting illegally in the park and were cutting trails and building crude cabins. A further concern of park officials was how to proceed with permitting timber cutting and road building for developing claims, as well as the effects of water diversions and mills, and of patented mine inholdings. As a result of Allen's concerns and those of a park engineer, by the Sundry Civil Appropriations Act of Congress approved May 27, 1908, staking mining claims was no longer allowed in the park, although existing claims were not affected.

Before 1908, hundreds of claims had been filed, although nearly all were quickly abandoned or invalidated. For example, 41 claims had been filed for land in Glacier Basin on the northeast shoulder of Mount Rainier. (See the "Mining in Glacier Basin" sidebar on p. 98.) The number of active claims declined to about 30 by 1912. Park Ranger T. O. Farrell, who had considerable contact with the miners from 1908 to 1924, alone succeeded in getting 90 of those claims declared invalid.

Thompson (1981) provides a thorough history of these and other mining activities in the park. On the whole, mining was not profitable in the park and beyond its boundaries.

MINING IN THE UPPER NISQUALLY VALLEY

Eagle Peak Copper Mining Company

Mary Gehrett, later Mrs. Baiker Long, filed the Aldula lode claim at Eagle Peak in 1903 (Filley, 1996), and the adjacent Paradise lode claim was filed by her husband and her son, Roy H. Wheelock, in 1906. The Eagle Peak Copper Mining Company, encompassing all of these claims, formed in 1908 and mined copper 1.5 mi (2.4 km) upstream of Longmire on the south side of the confluence of the Paradise and Nisqually Rivers (see Fig. A-1-4, p. 61). Around 1909, they "...installed on the mill site...an oil flotation mill for reducing ores, [an] aerial tramway from the tunnels on the lodes across the river to the mill site, a pipe line to supply water for the mill and domestic use, a tool house, ore bunker, bunk house to house the workers" (U.S. Department of the Interior, 1933). Reaburn (1918) reported that during the winter, the ore was hauled out on sleds.

The claims covered 41.3 acres (16.5 hectares) and produced about 200 tons (~190 metric tons) of ore between 1919 and 1928 (Derkey and others, 1990, p. 148). Thompson (1981), however, noted that in about 1930 a mining inspector indicated that only 45 tons had been shipped in a decade, the total profit being only $455. Huntting (1956, p. 61) reported that the ore assayed at 8.05 percent copper, less than 0.1 ounce per ton silver, and some cobalt. In the 18-ton assay shipment, only 1.87 ounces of gold was found, and it was associated with arsenopyrite. There was also about 0.04 percent uranium (Martin, 1971). The mineralization was in joints in granite or granodiorite just north of an area underlain by the Stevens Ridge Formation.

Tomlinson (1930) quotes a letter: "the last car load taken out some three or four years ago and shipped to a smelter in Tacoma did not contain enough mineral to pay for the freight to the smelter. It was necessary for the company to borrow money to meet the freight bill". No mineral production was reported after 1930 (Martin, 1971).The company managed to do just enough work to keep the claims legal, but the park continued to maintain that use of the mill site could be by park permission only (E. L. Parsegan, Park Ranger, unpublished history, 1966). In a 1932 hearing, a Tacoma commissioner declared the mill site claim null and void, but the company won an appeal in 1933. Filley (1966) wrote "As late as 1955, the company was still proposing developmental plans and insisting that Eagle Rock was a valuable copper claim". Mr. Wheelock continued to seek more development of the Eagle Peak Company property until his death in 1966.

In his 1971 assessment, A. L. Martin, a mining engineer, found that the cost of mining greatly exceeded the average value of the rock. He concluded, "There are no mineral reserves nor indications that the land could ever be used for economic mineral production", recommending that the company be "served through adverse contest proceeding". Park officials bought this property in 1974.

Paradise Mining and Milling Company

Reaburn (1915) noted that tunnels were being developed on the Sherman and Ike Evans claims, adjacent to the Aldula and known as the Paradise Mining and Milling Company workings, also on the south side of the rivers. A 1931 assay showed no gold, a trace of silver, and 13.47 percent copper (Filley, 1996). Huntting (1956, p. 61) noted that 40 tons assayed at 10 percent copper and that the ore was in a "slip plane in andesite". However, little ore was shipped, possibly because the company did not have clear permission to take ore across the Nisqually River, despite having built a tramway. In 1948, the Rainier National Park Company offered to buy the claims from the aging Evans brothers, but the men could not produce a clear title (Thompson, 1981). The property was transferred to the government in 1950—for $6000 in condemnation. A. L. Martin, in the report cited above, commented that this sum may have been the only profit made by the unpatented mine.

A visitor looking at Eagle Peak from the west side of the Nisqually River can discern little evidence of mine tunnels, although the mining practices did cause some scarring of the steep mountainside.

Short Canyon Mining Company

In about 1902, the Hendricks family located several quartz-lode gold claims on the Paradise River above (east of) Longmire springs and the Eagle Peak and Paradise claims. Huntting (1956, p. 61), however, mentions only copper and molybdenum at this property. The claims were developed (shafts, a tunnel, at least two buildings) and worked until 1915, when some Seattle investors bought the claims. Assessment work was not done, and the claims were annulled in 1923 (Catton, 1995).

MINING OPERATIONS IN THE CARBON RIVER VALLEY

The Washington Mining and Milling Company received permission in 1907 to build a road from their 38 lode claims (ore minerals not identified) in the park 6 mi (~10 km) to an existing road near Fairfax; the road was to become federal property on completion. When the road was inspected in the fall of 1907, only the part in the park was complete, the rest being a trail (Thompson, 1981). Large quantities of park timber had been removed, far more than went into road construction. Although some development work was done during parts of the following two years, the company gave up 21 claims in 1909, likely out of fear of adverse proceedings. The remaining claims were relinquished several years later (Catton, 1995), and the company stopped operating in the park by 1913.

In 1908 and 1909, the Hephizibah Mining Company had six claims on Sweet Peak (see Fig. L-1-2, p. 153) and a 5-acre (~2 hectares) mill site claim below the mountain, and they had felled timber around this site. A logging railroad along the Carbon River had by now reached to within a few miles of the claims. Park officials concluded that the mining claims were really an attempt to harvest timber and that the mill site claim was invalid, partly because there was no road on which to haul out the ore. The company objected. Inspection by a General Land Office mineral expert led to the opinion that the claims were valid. However, the Secretary of the Interior Richard Ballinger was unconvinced and proposed further examination. Little further work was done at the mine thereafter, and in 1923 the claims were annulled (Catton, 1995). ■

photo by Beth Norman



Figure D-7. Hydrothermally altered andesite along the north side of SR 410 slightly east of MP 38.

mined was probably deposited along fracture systems in a hot-springs type environment during the late phases of alteration (John and others, 2003). Silica is used for making many products including glass, abrasives, and semiconductors.

22.5 *36.2* Hydrothermally altered andesite crops out on the north side of the highway along a curve.

23.9 *38.5* Emergency pullout on the south side of the road. The wide glacial valley of the Clearwater River, tributary to the White River, is visible to the southwest. Glaciers that carved the Clearwater valley probably headed in the high peaks of the Carbon River stock, a granodiorite intrusion of Miocene age that lies to the south.

24.8 *40.0* Near MP 35 the road reaches the west edge of a large Quaternary landslide that covers about 5.3 mi^2 (14 km^2). Note the irregularities in the roadbed over the next 0.7 mi (1 km) caused by occasional movement of this landslide. The landslide heads along the southeast-trending Twin Creeks fault. Hammond (1980) mapped the fault along the slope to the north of the highway.

Additional zones of altered rock occur along northside roadcuts for the next 5 mi (8 km).

26.8 *43.1* Near MP 37, gently west-dipping columnar-jointed andesite lava flows of Miocene age are visible on the north side of the road.

27.2 *43.7* More andesite crops outs north of the highway.

Mineralization and Mining Northwest of Mount Rainier

by Rebecca A. Christie, Katherine M. Reed, and Patrick T. Pringle

The rocks generally northwest of Mount Rainier in the informally named White River altered area are mostly hydrothermally altered Fifes Peak Formation. The alteration occurred near small plutons and other intrusive rocks and along nearby faults. The alteration in the White River area was dated at 20.3 to 19.0 Ma by Blakely and others (2007).

The White River area altered rocks are largely andesite, basaltic andesite, and dacite flows and breccias; polymetallic veins and epithermal deposits carry copper, silver, and gold. The minerals occur in zones of argillic and propyllitic alteration (John and others, 2003). The distribution of the silica-rich altered rocks was probably structurally controlled. Blakely and others (2007) note, "based on its similarities with Goldfield, [Nevada, the] White River [area] may have potential for concealed precious and/or base metal deposits at shallow depth… Gravity and magnetic anomalies provide evidence for a pluton beneath the White River altered area that may have provided heat and fluids to overlying volcanic rocks. East- to east-northeast-striking extensional faults and (or) fracture zones…may have tapped this intrusion and provided vertical and lateral transport of fluids to now silicified areas", perhaps validating the early 20th century mineral explorations.

In the 1930s and 1940s, the mineralized rocks of the White River area were explored for alunite ($KAl_3(SO_4)_2(OH)_6$), particularly near Enumclaw (see map, inside front cover). Alunite is a source of potash (K_2CO_3), and before this time the United States had relied on German sources of potash that later were embargoed during World War II (Bates, 1969, p. 371). Drilling by Kalunite, Inc. in 1940 indicated nearly 590,000 tons of alunite, but that was likely not enough to pay for erecting a plant to process the ore (Valentine and Huntting, 1960, p. 5). No production was reported.

While exploration for silica in the altered rocks started about 80 years ago, the new understanding of its geology has sparked a renewed interest in this resource. The silica is concentrated as rocks are leached by hydrothermal alteration. At the Superior silica quarry north of SR 410 near Enumclaw, Ash Grove Cement Co. mined about 110,000 tons (~100,000 metric tons) of silica in 2001; the silica was used to make cement. At the Scatter Creek silica quarry, just northwest of the Superior quarry, the James Hardy Building Products Co. mined about 120,000 tons (~109,000 metric tons) of silica in 2001. The silica went to manufacture fiber cement for siding products (Derkey and Hamilton, 2002). Both quarries are still active (2007), but production figures are proprietary. ■

27.8 *44.7* MP 38.

28.0 *45.0* Pullout on the right. The outcrop north of the road is hydrothermally altered andesite (Fig. D-7). The White River is south of the highway.

28.2 *45.4* The road curves to the right. A quick view of the White River, adjacent to the highway, seasonally shows the high turbidity that results from glacial rock flour and other suspended sediments in this glacially fed stream. The road passes over West Twin and East Twin Creeks. Clay-poor lahars of the past 2700 years and the clay-rich Osceola Mudflow are exposed in the West Twin and East Twin Creeks area. USGS geologist Jim Vallance (written commun., 1994) found that the highest exposure of the Osceola Mudflow here is at least 75 m (246 ft) above the White River. To visualize how deep the Osceola must have been in this area, Crandell (1971) noted that 2 mi (3.2 km) farther east along the road, near the Federation Forest State Park campground and south of the highway, a water supply well penetrated the Osceola Mudflow at a depth of 200 ft (61 m)! Thus the actual flow depth of the Osceola in this reach was likely more than 135 m (443 ft)!

28.9 *46.5* Federation Forest State Park boundary.

30.8 *49.5* (~MP 41). The road here is on a terrace composed of sandy, clay-poor lahars of the past 2700 years. The most recent of these has been dated upstream of here at about 1,120 yr B.P. (Scott and others, 1995). The largest lahar in this assemblage was at least 60 ft (18 m) deep at this location.

30.9 *49.7* Entrance (right) to the Federation Forest State Park interpretive center is just south of SR 410.

31.1 *50.0* Scattered mounds or hummocks in the Osceola Mudflow deposit poke up through the fairly flat-topped, younger lahars.

31.4 *50.5* There is a good view of the White River (south) and an outcrop of platy andesite (north).

31.5 *50.7* Picnic area adjacent to the White River along the south side of the road (slightly west of MP 42).



photo by Beth Norman

Figure D-8. Platy andesite lava of the Huckleberry Mountain volcanic rocks is exposed along the road about 0.8 mi (1.3 km) west of Greenwater.

31.8 *51.2* MP 42.

32.0 *51.5* Pullout to the right. Platy andesite lava of the Huckleberry Mountain volcanic rocks is exposed along the road here (Fig. D-8). The age range of about 35 to 25 Ma, similar to that of the Ohanapecosh Formation, was determined by K-Ar and fission-track methods (Frizzell and others, 1984; Tabor and others, 2000).

32.3 *52.0* The rubbly, poorly sorted Osceola Mudflow deposit is exposed on the north side of the road about 0.1 mi (~0.2 km) before it crosses the Greenwater River.

32.5 *52.3* Platy andesite crops out on the north side of the road.

32.8 *52.8* Town of Greenwater (~MP 43). Lahars have left abundant deposits in this area, perhaps because downstream of here the valley is fairly constricted. Upon reaching the narrowed valley, the main pulse of a lahar would have hydraulically ponded somewhat to leave terrace-capping veneers and valley-filling deposits in upstream areas. As a lahar drained, its more watery recessional phase would have quickly downcut into the freshly laid sediments as the White River tried to reestablish equilibrium following each volcanic disturbance.

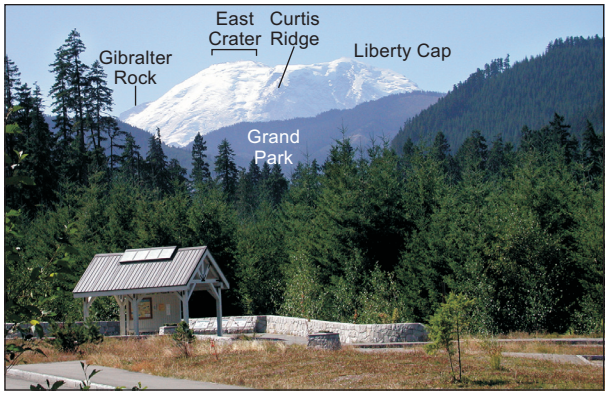


Figure D-9. View of Mount Rainier from the MP 49 viewpoint along Mather Memorial Parkway (SR 410). East Crater, the youngest feature on the volcano's summit cone, is about ~0.25 mi or 0.4 km wide. The summit is about 18 mi (29 km) distant. View is to the south-southwest.

The West Fork White River joins the White River about 2 mi (3.2 km) to the east. This fork drains the northeast slope of Mount Rainier, head-

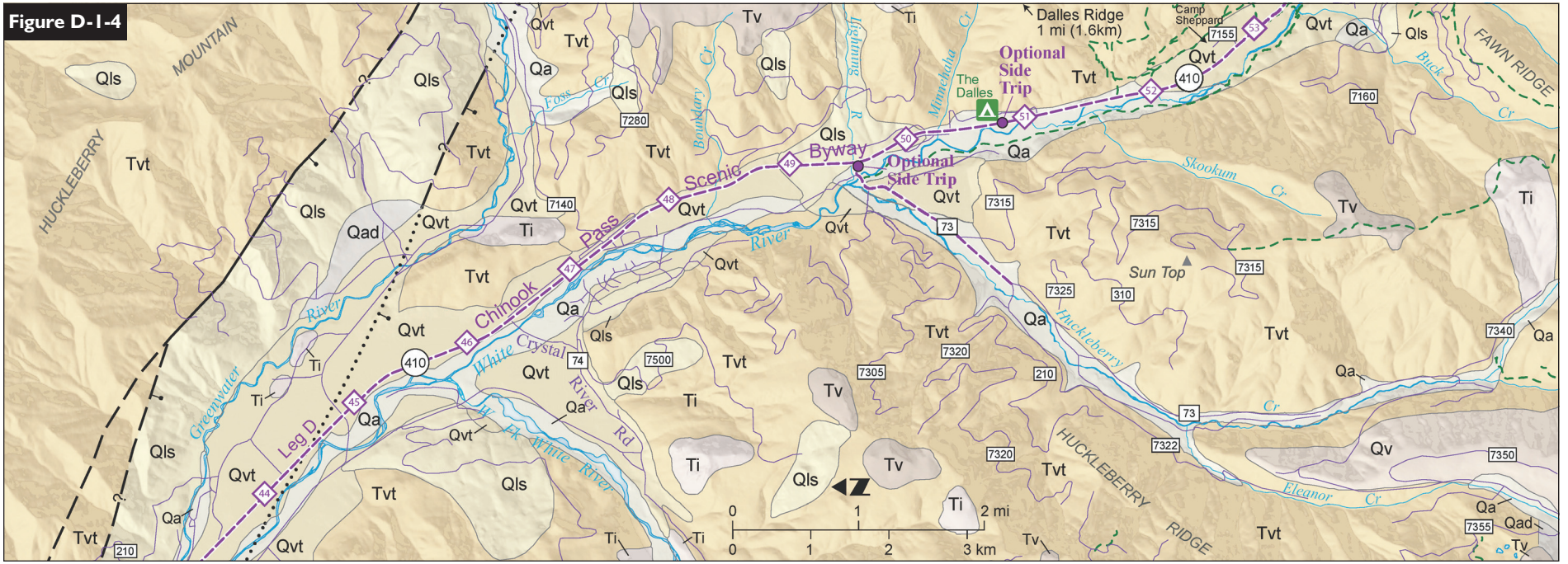




Figure D-10. Crude columnar jointing in a welded lapilli tuff of Miocene age near the Skookum Falls Viewpoint on SR 410. Paul Hammond (Portland State Univ., written commun., 2003) has mapped this tuff as the lowest three or four subunits in the lowest pyroclastic flow of the Sun Top tuff, which occurs along the west face of Dalles Ridge and along the ridge to the west of the White River. Hammond has obtained a radiometric age of about 22 Ma for the Sun Top tuff. This outcrop is about 20 ft (6 m) tall.

ing at Winthrop Glacier. The West Fork valley was one of the pathways of the great Osceola Mudflow.

34.7
55.8
Forest Road (FR) 70 on the north accesses the upper reaches of the Greenwater River and the Naches Pass area. Hiking trails accessible via this road include the trail to Greenwater Lakes, which are dammed by landslides. The easternmost lake contains a submerged forest that can provide clues to the age of the landslide damming it.

36.4
58.5
Pullout at the entrance to Mount Baker–Snoqualmie National Forest. This stretch of road is named the "Mather Memorial Highway" after Stephen T. Mather, the first director of the National Park Service.

37.7
60.7
Mather Memorial Viewpoint at MP 49. From here you can gaze south through the broad glacial valley of Huckleberry Creek to Mount Rainier. The east flank of the young Columbia Crest cone protrudes from the crater left by the great Osceola Mudflow (Fig. D-9).

39.2
63.0
OPTIONAL SIDE TRIP: Osceola Mudflow hummocks via FR 73. The mounds of the Osceola Mudflow deposit are commonly obscured because they are tucked up against the sides of valley walls or back in the trees. SR 410 passes by several mounds, but they are difficult to see. To see them in better exposures, you can turn off on FR 73 (slightly east of MP 50) to the southwest up Huckleberry Creek and follow the gravel road across a bridge at 0.3 mi (0.5 km). At 0.8 mi (1.3 km) you will pass the entrance to the R. Nevan McCullough seed orchard. At 1.3 mi (2.1 km) there is a 'Y' in the road (intersection of FR 7315 and 73). Here bear right, staying on FR73 and continue for another 0.4 mi (0.6 km) to see several large tree-covered mounds (10–20 ft or 3–6 m in height) adjacent to the road. A forest road turn-around point is located 1.8 mi (2.9 km) from SR 410 at the intersection of FRs 73 and 7720.

While being interviewed for the 1996 documentary film "Perilous Beauty", retired geologist Dwight "Rocky" Crandell recounted his early thoughts about the nature and origin of the Osceola Mudflow: "…I came up with the idea that perhaps it had actually flowed into place, like a giant mudflow…and it was just like a light going on over my head, because everything I knew about the deposit fit this kind of origin—that it had…flowed into place, and it had not been formed by a glacier at all. But the question in my mind: if it was a mudflow, then how did it get started, and where did it come from? … I had no idea at all, even though I was standing there on the plain formed by this mudflow, and I could see Mount Rainier in the distance. And I didn't make the connection for a long time…We could hardly believe our eyes when we actually saw a remnant of the same deposit there at the tip of Steamboat Prow" (U.S. Geological Survey, 1996).

Crandell and Donal Mullineaux, another USGS geologist who studied the volcano in the 1960s and 1970s, originally interpreted the mounds as part of an older flow that they called the 'Greenwater lahar'. However, near The Dalles south of MP 50, USGS geologist Jim Vallance found only one lahar unit exposed in each of four test pits that were adjacent to or between hummocks and that were only 200 m (656 ft) west of a gravel pit exposure of Osceola Mudflow (Scott and others, 1995). The hummocks, mainly consisting of rock debris of only one rock type from Mount Rainier, were evidently grounded on the margins of the valley as the Osceola Mudflow ponded in backwater areas. About half the rocks in that Osceola outcrop were from Mount Rainier; others are 'exotic' or non-Mount Rainier rocks, such as intrusive rocks of Miocene age, that were picked up by the lahar as it flowed (Crandell, 1973).

Remember to compensate for mileage along the side trip.

39.3
63.2
MP 50.

40.2
64.7
OPTIONAL SIDE TRIP: The Dalles Campground. For those who have time to explore this campground, there are several features of interest. Geologists have identified many lahar deposits from Mount Rainier near here. Two terraces are not capped by Wn tephra from Mount St. Helens (late A.D. 1479), the white to light-gray, sand-size pumice that is commonly found in the soil layer in the northeast sector of Mount Rainier; hence the lahar deposits here are likely younger than this date. A higher and presumably older terrace is also underlain by Mount Rainier lahar runouts. The campground also has a yet-higher surface with lahars of post-Osceola age underlying it, and Osceola Mudflow deposits are exposed in several places along the river. To access the river, go through campsite 39.

One set of exposed stumps, some of whose tops have been sawed off, are visible near the river. These were buried by a debris flow from

Minnehaha Creek. Judging by the degree of decomposition of the trees, this flow occurred sometime in the last 150 years, but probably much more recently (see Fig. M-4, p. 157).

Fragmental deposits including glacial drift and lahar deposits crop out about 0.3 mi (0.5 km) south of The Dalles Campground.

Remember to compensate for mileage along the side trip.

41.3 *66.4* Skookum Falls Viewpoint. An interpretive sign here discusses rock flour caused by the grinding of glaciers, as well as the Osceola Mudflow. Note the crude columnar jointing in the brownish bedrock across the road to the east (Fig. D-10). This outcrop was mapped by Hartman (1973) as Stevens Ridge Formation welded lapilli tuff. However, Paul Hammond interprets this exposure to be the lower three or four units of the welded Sun Top tuff (Miocene) that he had identified at Dalles Ridge and which Tabor and others (2000) had previously assigned to the Fifes Peak Formation. Hammond (Portland State Univ., written commun., 2003) has dated this tuff at about 22 Ma. The waterfall on Skookum Creek plummets over the same rock unit on the southwest side of the river.

41.9 *67.4* MP 52.

42.7 *68.7* Entrance to Camp Sheppard trailhead (FR 7155) and view of spectacular cliffs of Sun Top tuff up the road. To view the cliffs you must turn up FR 7155.

44.2 *71.3* Buck Creek Recreation Area, FR 7160. For those who are westbound, the imposing cliff straight ahead on the skyline is Dalles Ridge, composed of Sun Top tuff.

45.5 *73.2* FR 7172 and entrance to Alta Crystal Resort on the left.

45.8 *73.3* The dark-colored bedrock outcrops east of the road are Ohanapecosh Formation volcaniclastic rocks of Oligocene age. Large blocks, as much as several feet across, sit above bedded silts.

46.0 *74.0* MP 56.

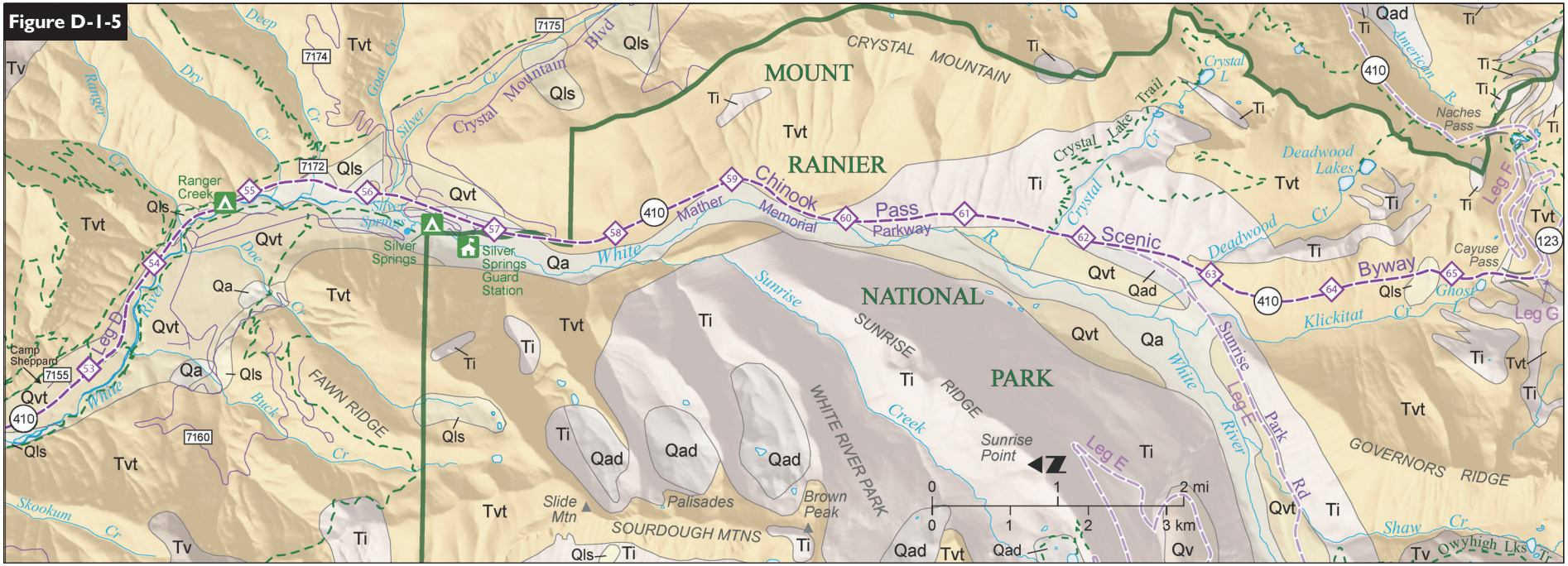
46.5 *75.0* Silver Springs Campground. A water-supply well for a U.S. Forest Service ranger station penetrated the Osceola Mudflow at a depth of about 15 m (48 ft) and was still in it when drilling stopped at 61 m (196 ft). Nearby, the mudflow veneers the valley sides 38 m (122 ft) above the river (Crandell, 1971).

46.8 *75.3* Silver Creek Guard Station and U.S. Forest Service information station (open spring through fall).

47.6 *76.6* Turnoff to Crystal Mountain ski area.

47.7 *76.7* Mount Rainier National Park boundary.

49.3 *79.3* Vertical contact between the Ohanapecosh Formation and Sunrise Point pluton. This is the northern boundary of the Sunrise Point pluton. (See mile 12.9, p. 100.) Oligocene Ohanapecosh Formation lavas and breccias make up the country rocks. The contact slices across contours on either side of the White River, and the Ohanapecosh is only mildly altered, unlike the hornfelsed Ohanapecosh rock farther upstream. The Sunrise Point pluton is a quartz monzonite at this location. Fiske and others (1963), in their pioneering geologic map, showed the basic relations between the upper part of Crystal Mountain—mainly



Ohanapecosh Formation—and the intrusive rocks below. Many sills and dikes cut the Ohanapecosh rocks. Downslope, near the highway, outcrops contain less alkali feldspar and consist of quartz diorite or granodiorite. This is geologically interesting because the dikes and sills are younger (Miocene) than the overlying Ohanapecosh (Oligocene)—the Ohanapecosh rocks are literally the roof of older rocks over the chambers of the magma that later intruded them and are now long solidified.

The west slopes of Crystal Mountain have proven to be of great interest as a location where climate and geologic materials have influenced vegetation. At about 5300 ft (1615 m) elevation, in the basin holding Lower Crystal Lake, naturalists Susan McDougal and David Biek (Tacoma Public Library, oral commun., 2003) have found an extraordinarily rich spot in which there are 13 species of conifers within a 100-m (328 ft) radius. This location may be so diverse because it has rich soils and has endured many climate fluctuations without undergoing a major disturbance. The site is just high enough above the valley bottom that for at least 130,000 years it escaped being overrun by any valley glacier occupying the White River valley (or the great Osceola Mudflow), and at the same time it is just low enough that it was not destroyed by a cirque glacier from the Crystal Lake basin.

51.7 *83.2* Crystal Lake Trailhead.

51.9 *83.5* Sunrise Road veers off to the southwest slightly past MP 62. This road provides access to the Sunrise area of Mount Rainier National Park via Yakima Park Road (see Leg E). It also leads to the White River Campground area and many trails. Stay on SR 410.

52.6 *84.6* About 0.5 mi (0.8 km) south of the Sunrise Road junction, a turnout on the west side of the road allows an excellent view of Mount Rainier and the upper White River valley (Fig. D-11). Be careful of traffic—this can be a busy viewpoint.

53.0 *85.2* Cross Deadwood Creek. Note the rock fragments exposed in a landslide on the north side of the bridge.

53.4 *85.9* At the pullout near here (eastbound), there is a good view into the valley. On the west side of the road, there is an outcrop of granodiorite sills and dikes that cut and alter Ohanapecosh rocks.

54.3 *87.4* Note the rough condition of the road over the next mile (1.6 km); the road is on a landslide (not shown on map) and is constantly being repaired. This large landslide and one slightly to the south are moving westward along west-dipping beds of Ohanapecosh Formation into Klickitat Creek (see Fig. E-8, p. 99).

54.8 *88.2* Cross a ravine that exposes rubble from the large landslide of Ohanapecosh rocks on the south side and bedrock on the north side.

55.1 *88.6* MP 65.

55.4 *89.1* Cross another ravine that exposes rubble from the large landslide of Ohanapecosh rocks on the south side and bedrock on the north side.

There is a small turnout near Ghost Lake and the second large landslide into Klickitat Creek. The parkway crosses the slide by curving around to the right along contour and crosses another ravine that contains large boulders of Ohanapecosh rocks. Ghost Lake is 100 ft (30 m) below the road. Ghost Lake may sit on the landslide—no tree snags are visible in the lake, as could be expected if the lake were upstream of an impoundment. The diameters of two individual lichens (*Rhizocarpon geographicum*) on rocks adjacent to the lake were in excess of 85 mm (3.4 in.). From a calibration curve established by Porter (1981), these measurements suggest an age of at least 180 years for the lichens, and probably more, considering climatic factors. A study of ash layers in the lake could provide a better idea of its age.



Figure D-11. Mount Rainier, Goat Island Mountain (slightly above center), and the glaciated White River valley from a pullout on SR 410 about 0.4 mi (0.64 km) south of the Sunrise Road junction. Note the cirques on the summit of Goat Island Mountain and its glacially faceted flanks.

55.8 *89.8* Cayuse Pass (elev. 4694 ft or 1431 m). Outcrops near the junction with SR 123 are volcanic breccias and andesites of the Ohanapecosh Formation.

At this point, you can choose to continue ahead to Chinook Pass (where you can follow Leg F in reverse) or turn right onto SR 123 to continue on Leg G south toward the Stevens Canyon Entrance to Mount Rainier National Park at Stevens Canyon Road (the end of Leg B) or to access US 12 (the end of Leg C and beginning of Leg H).

Remember to reset your odometer when you start another leg. ■

LEG E: SUNRISE ROAD

State Route 410 to Sunrise

Sunrise Road is one of the most spectacular and scenic drives in the Pacific Northwest (Fig. E-1). The ~15-mi (25 km) road ascends from about 5500 ft (1676 m) elevation to about 6400 ft (1951 m), passing outcrops of lavas and intrusive rocks, rubbly deposits of lahars and glacial tills, tephra layers, and banded layers of silt that were deposited in ice-marginal lakes when glaciers occupied the White River valley. As the road winds around the east end of Sunrise Ridge, spectacular tilted columns of lava attest to the interaction of 'fire and ice'. At the Sunrise Point viewing area, there are broad panoramas from Mount Baker and Glacier Peak volcanoes to the north to Mount Adams in the south. The road then continues west along the surface of the large Burroughs Mountain lava flow to Sunrise and a spectacular view of Mount Rainier volcano. Several trailheads there lead to a multitude of scenic destinations. Glaciers such as the Emmons, the largest in the contiguous 48 states, drape the mountain, their young, sparsely vegetated moraines marking their maximum extent during the Little Ice Age. The smooth, youthful Columbia Crest cone sits in a crater left after the volcano's summit slid away as the Osceola Mudflow, about 5,600 cal yr B.P.

Sunrise Road is typically closed by snow from late October until late June. The status of roads and trails can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Sunrise Road is accessed from State Route (SR) 410, which skirts the eastern edge of Mount Rainier National Park. Sunrise Road turns off to the southwest. Please use care here—the intersection has an unusual acute angle. Oligocene Ohanapecosh volcanic rocks are exposed along the begin-

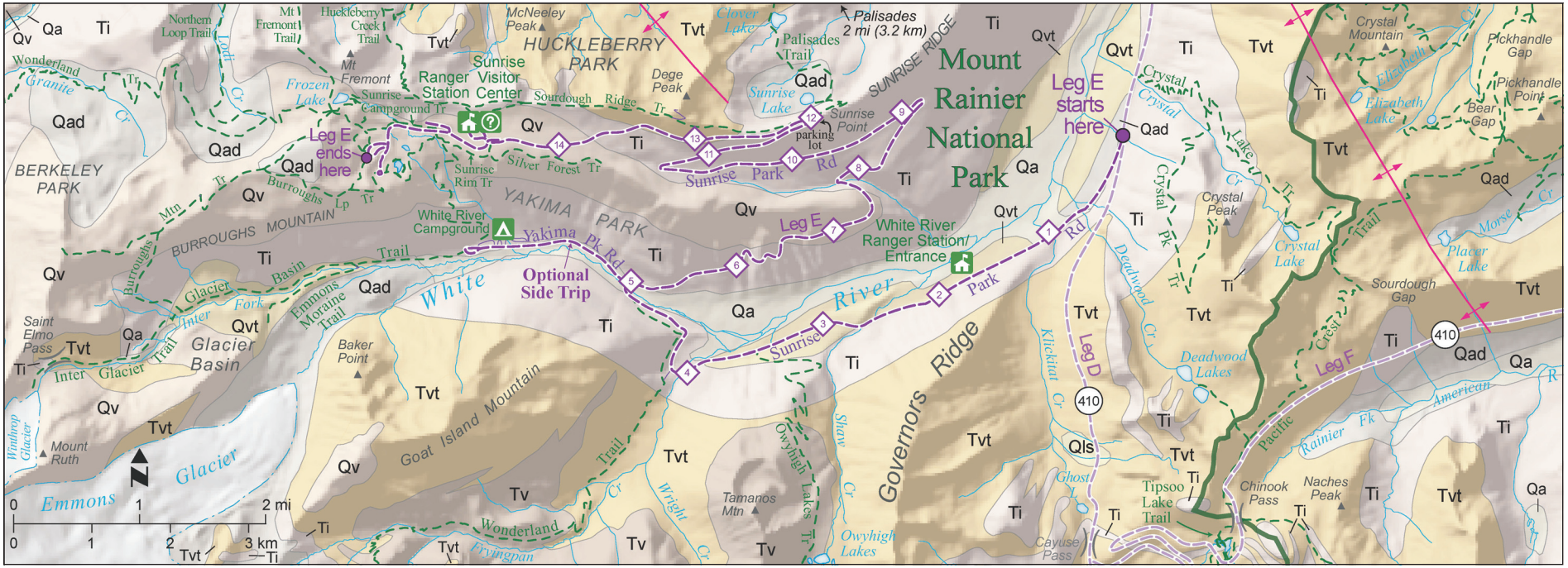


Figure E-1. Geologic map for Leg E. The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on inside back cover.

photo by Beth Norman



Figure E-2. Granodiorite containing inclusions of dark andesite. This outcrop is about 0.4 mi (0.6 km) west of MP 3.

photo by Beth Norman



Figure E-3. Osceola Mudflow deposit near Fryingpan Creek.

photo by Beth Norman



Figure E-4. Avalanche chute and debris fan near White River Campground. View is to the south.

ning of the road as it descends into the White River valley. The view en route is up the White River valley, which heads at Emmons Glacier and drains the east side of the volcano. The White River was a major pathway for the Osceola Mudflow and later lahars. Orange-tinted, poorly sorted diamicts in roadcuts along the valley floor are scattered remnants of the Osceola.

1.3
2.1 White River Entrance. Here are information, restrooms, and water.

2.6
4.2 The outcrop on the left (south) is intrusive Miocene White River granodiorite. Shaw Creek heads at Barrier Peak (due south), which is cored by intrusive rock. Slightly west of Shaw Creek, the Osceola Mudflow deposit is exposed on the right (north).

3.0
4.8 Milepost (MP) 3. Pass an exposure of the Osceola Mudflow deposit here with a layer of cobbles at the top.

3.4
5.4 On the left (south) across from a pullout, granodiorite contains inclusions of dark andesite (Fig. E-2).

3.5
5.6 Trailhead to Owyhigh Lakes south via the east flank of Tamanos Mountain above Shaw Creek. Tamanos Mountain is cored by lava flows of the Ohanapecosh Formation (late Eocene–mid-Oligocene age).

4.2
6.8 West of the bridge over Fryingpan Creek is a parking lot and the Wonderland Trailhead. The Osceola Mudflow deposit is exposed in an outcrop on the north side of the road slightly east of the bridge (Fig. E-3). Geologists found wood in a post–Osceola Mudflow lahar assemblage near here having a radiocarbon age of 1,120 yr B.P., and USGS geologist Rick Hoblitt reported a 1,080 yr B.P. age on charred wood from a lithic-rich tephra overlying that lahar deposit (Scott and others, 1995). While the eruption(s?) that likely produced the lahar and the tephra were probably moderate in size, the laharic floods of this age inundated valleys as far downstream as the Ports of Seattle and Tacoma. Both the Osceola Mudflow deposit and granodiorite of the White River pluton are visible along the road approaching MP 5.

5.3
8.5 Granodiorite crops out near the junction of Sunrise Park Road and the Yakima Park Road to the White River Campground. On the north side of the river, slightly downstream of the bridge, mafic dikes are exposed in stream-polished outcrops of the White River pluton.

OPTIONAL SIDE TRIP: White River Campground and trailheads. The type locality for the quartz diorite of White River is found about 0.3 mi (0.5 km) up the road to the campground (Mattinson, 1977). Mattinson obtained U-Pb ages of 14.1 Ma on two populations of zircons in that pluton. Outcrops between 0.1 and 0.5 mi (0.16–0.6 km) are quartz diorite. The campground ranger station is at 1.0 mi (1.6 km). An avalanche chute and debris fan (Fig. E-4) are visible from loop D at 1.5 mi (2.4 km). Farther up the White River, the hornfels-grade contact between the White River pluton and the Ohanapecosh Formation is exposed. Details on the geology of this pluton can be found in Murphy and Marsh (1993).

For early-season hiking when other alpine areas are still snow covered, consider the Emmons Moraine Trail. This area is in a precipitation shadow, so it commonly gets less snow. Where the Moraine Trail turns south, the Inter Fork Trail continues west and ascends into beautiful Glacier Basin, where limited mining went on in the early 1900s. (See the "Mining in Glacier Basin" sidebar on p. 98.)

Depending on the season or weather conditions, Sunrise Road may be blocked beyond this point. If this is the case, you may still be able to access the Moraine Trail and Inter Fork Trail trailheads. To do this, turn left into the campground and drive to the parking area at the far west end, then walk west from the parking area.

Remember to compensate for mileage along the side trip.

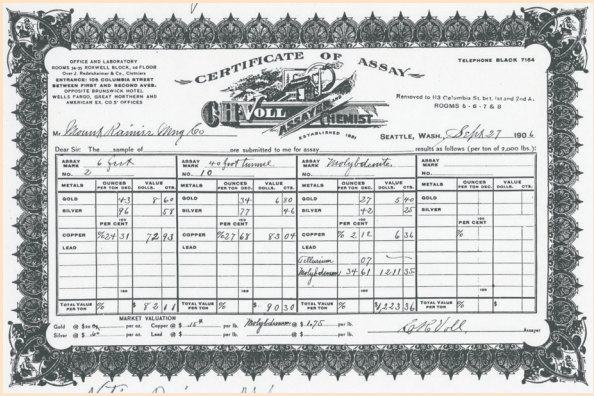
5.4
8.6 The clay-rich Osceola Mudflow overlies debris flow deposits slightly past the road junction.

Mining in Glacier Basin

by Rebecca A. Christie and Katherine M. Reed

Glacier Basin, on the northeast side of Mount Rainier, is in the upper reaches of the White River. The park had an interest in making all sides of the park accessible to visitors, and mining offered a potential way to reach this goal. However, park managers later thought that mining was not in concert with the purpose of the park and gradually acquired mine properties. In the end, miners realized that the return for their efforts was not adequate, but they had prepared the roadways that take today's visitors to Glacier Basin. (See also the "Mining in Mount Rainier National Park" sidebar on p. 90.)

The Mount Rainier Mining Company in Glacier Basin had the most extensive copper and silver workings in the park. Peter Storbo and his associates made 41 claims in 1898 (Filley, 1996), forming their company in 1905. The *Tacoma Daily Ledger* reported that the ore's assayed value was as high as $458 per ton (Martinson, 1966; silver in 1898 dollars was worth about $0.43 per 0.77 ounce, and the average price of copper was 12.03 cents per pound [The Mineral Industry, 1899; Schrader, 1898]).


CERTIFICATE OF ASSAY

Relations between park management and the company were never smooth. In 1911, the Secretary of the Interior concluded that the numerous irregularities (including the fact that no discovery of vein or lode had been made) were enough to start proceedings against the company. The company subsequently (possibly consequently) gave up 32 claims. Eight remaining claims covering about 165 acres (~66 hectares) were patented in 1924.


A 12 x 14 ft shack built in 1948 on the old hotel site. From a 1952 Mount Rainier Mining Company/Storbo report from Douglas B. Evans to the superintendent of Mount Rainier National Park. Photo courtesy of the National Park Service.

By 1930, miners had dug several tunnels and prospect pits, erected a water-powered sawmill, two cabins, a barn, a blacksmith shop (Thompson, 1981), and even a sewer system. Ore was taken out by wagon and pack horses to Enumclaw (at 40 cents per ton [in a November 1915 letter from the Park Supervisor to the Secretary of the Interior]), where it was forwarded to the Guggenheim smelter in Tacoma (Thompson, 1981).

In the interest of increasing tourism, the park allowed the mining company to build a 20-mi (38 km) road up the White River to Glacier Basin (Martinson, 1966). By 1916, a new hotel and boarding house to accommodate 40 people was under construction at the mining site; it apparently was never finished. In addition, the road proved to be too steep for most traffic, as well as of very rough construction (Thompson, 1981), and thus the "hotel" was essentially idle. Not only did the road to Glacier Basin extend across the slippery, clay-rich deposits of the Osceola Mudflow and glacial drift in most of its steep uppermost reaches, it was also adjacent to the Inter Fork of White River in that area. Therefore after rainstorms severely damaged the road in 1926, it would remain quite primitive even with repairs. At about this time, Park Superintendent Reaburn noted that the ore assayed at only $60 per ton, too low to make an interesting profit (if any). As the Park Service was beginning development in the Yakima Park area (1929–1931), it allowed the last three miles of the wagon road to Glacier Basin to revert to a trail (Catton, 1995).


Mill and mine site buildings. Generator building to the left. Safety breaker and ruins of water wheel are on the right.Photo courtesy of the National Park Service.

In the late 1920s, Storbo and his associates were accused of misrepresenting the company and cheating stockholders, and in November 1930, Storbo and another officer were found guilty of fraudulent use of the U.S. Mail to promote stock sales. The trial was widely reported in Seattle and Tacoma newspapers; see, for example, the *Tacoma Daily Ledger* of Nov. 29, 1930. The men served 18 months of hard labor at McNeil Island penitentiary and were fined $1,000 each.

The mine was revived briefly in the late 1940s under the management of Ole (or Tomine) and Thor Oakland; 47 tons of ore was sent to a smelter in Tacoma in 1948. However, costs again exceeded profit. After several years of company offers and government counteroffers, in 1984 the government bought the last remaining inholding of the mining company's land for $55,800, far less than the mine owners thought the claims were worth (Ripp, 1999).

The ruins of the stone cellar walls of the hotel at Camp Storbo, a rock foundation of a cabin, and mine tailings can still be seen in Glacier Basin. ■

Dwight "Rocky" Crandell estimated that the mudflow was at least 700 ft (~210 m) thick here (Schultz and Smith, 1965, p. 28). This would be impressive but for the fact that about 2.5 mi (4 km) upstream of here, USGS geologist Jim Vallance found a runup deposit of the Osceola Mudflow in a small cirque slightly downslope of Baker Point that was 1500 ft (457 m) above the current valley floor!

The Osceola Mudflow is visible in places as a layer less than 33 ft (10 m) thick for about the next mile (1.6 km), with Mount St. Helens tephra layers Yn, C, and Wn visible on top of it in some outcrops.

5.6 *9.0* Another outcrop of granodiorite.

6.3 *10.1* The Osceola Mudflow deposit is exposed at the top of a rock wall on the left near a gravel turnout on the right at a sharp bend to the left (north).

6.6 *10.6* Still more Osceola Mudflow exposed here; note the altered rocks in the poorly sorted layer.



Figure E-5. Geologist Yukio Hayakawa examines tephra layers of Pleistocene age exposed along Sunrise Road about 6.9 mi (11 km) from SR 410. These tilted beds might be part of a slump block. This photo was taken in 1996, and the layers are now covered by slopewash.

6.9 *11.1* Tephra layer about 60 ft (18.3 m) above the road. More tephra is exposed for the next 0.5 mi (0.8 km)(Fig. E-5). Some of these dipping bedded ash layers are likely reworked and are possibly deposited in a basin behind a lateral moraine.

7.0–7.4 *11.2–11.9* Spectacular columns of Mount Rainier Andesite, as well as till, a tephra of pre-Evans Creek age (>22 ka), and beds of fine material (glacial-lake deposits), are visible between miles 7.0 and 7.4.

7.7 *12.4* Exposures begin of the andesite of Burroughs Mountain lava flow.

photo by Beth Norman



Figure E-6. Nearly horizontal lava columns in the Burroughs Mountain flow. They are one of the clues that indicate it was emplaced against glacial ice (Lescinsky and Fink, 2000; see Fig. 27, p. 30). The bounding glacier, which headed on Mount Rainier, must have occupied the White River valley.

7.8 *12.5* Pullout with a sign explaining the formation of horizontal columns. The andesite in the outcrop here has abundant plagioclase crystals (Fig. E-6). This flow is one of the longer intracanyon flows that preceded the main cone-building stage of the volcano. Work by Stockstill and others (2002) shows that as the flow followed the course of the ancestral White River, it likely chilled against a glacier that at one time filled the valley to form the picturesque, nearly horizontal columnar joints exposed in the roadcut. Stockstill and her colleagues also found that the flow is rather large, at 0.8 mi^3 (3.4 km^3), and that the lava is compositionally stratified or zoned. This demonstrated to the researchers that, despite complex magmatic recharge events, Mount Rainier has been capable of developing shallow magma chambers that show compositional zonation, with the less dense, but more explosive felsic magma higher up in the magma chamber—a trait shared by volcanoes that produce explosive ash-flow tuffs.

8.0 *12.8* The layers of fine lacustrine sediments just around the bend from the lava columns are quite impermeable and thus almost always look moist because they are relatively impervious to ground water infiltrating above (Fig. E-7). These sediments likely accumulated in glacial lakes that were dammed up along the margin of a large valley glacier occupying the White River valley. At another turnout slightly farther along there is a diamict, possibly a lahar or pyroclastic flow deposit, overlain by thick tephra.



Figure E-7. Silty beds deposited in moraine-dammed lakes. This outcrop is along Sunrise Road slightly past (northwest of) the nearly horizontal columns of the Burroughs Mountain lava flow.



Figure E-8. Aerial oblique view of large landslides in Ohanapecosh Formation above SR 410. Arrows indicate the direction of flow; the slide in the center of this photo is about 0.3 mi (0.5 km) long and 0.2 mi (0.3 km) across. View is to the southeast from the Sunrise Point area.

11.6 *18.6* An andesite lava flow crops out at the switchback.

12.0 *19.2* MP 12.

12.9 *20.6* Sunrise Point switchback parking lot. This is the type locality of the quartz monzonite of Sunrise Point of Mattinson (1977). The rock is commonly altered. Mattinson (1977) used U-Pb dating of zircons to obtain an age of 24 Ma for these rocks, considerably older than the nearby White River pluton, described above at the optional side trip to White River Campground.

In fine weather, you can see a sweeping panorama of the North Cascades, as well as views of selected peaks in the southwest Washington Cascades and the enormous Mount Adams volcano to the east and south respectively. On the near west-facing ridge to the southeast, several large landslides in the Ohanapecosh Formation rocks move slowly from year to year, creating maintenance problems along SR 410 (Fig. E-8). Blocks of the Ohanapecosh rocks are moving along dip slopes that encourage the masses to slide to the west.

13.8 *22.2* An andesite flow can be seen in this outcrop.

13.9 *22.2* MP 14.

14.0 *22.5* A complex upper and lateral boundary between the Sunrise Point pluton and the Ohanapecosh Formation is exposed here.

14.6 *23.5* Roadcuts to the north (now mostly covered with grasses), across from a turnout on the left (south) side of the road, expose orange Mazama ash, which is overlain by the blocky rubble of layer S (the 'Sourdough rubble') and pumiceous layers from Mount Rainier (Fig. E-9; see also Fig. 34, p. 37). Mazama ash, known as layer O, was produced by the enormous eruption that created Crater Lake in Oregon (7,500 cal yr B.P.).

The tephra once known as the Sourdough rubble or layer S has been reinterpreted by Jim Vallance to be a basal layer of set F, which is associated with the Osceola Mudflow. This layer is visible in this area of Yakima Park as a 6-in. (15 cm)-thick train of sand and angular Mount Rainier rocks that lies about 3.3 ft (1 m) below the ground surface. Mazama ash is exposed immediately underneath the rubbly phase of layer F. The basal layer F rubble is found on Goat Island Mountain (there consisting of much larger blocks) and northward to Huckleberry Park. From the size and distribution of the ejected rocks, Mullineaux (1974) concluded that a laterally directed phreatic explosion deposited this layer. Rocks greater than 20 in. (50 cm) in diameter can be found about 6 mi (10 km) from the Rainier summit! These large rocks are not similar to the Tertiary-age rocks composing the ridge to the north, so it is not likely they rolled downslope to their present location from that ridge. Fresh Mount Rainier rocks exposed in gullies along the Silver Forest Trail (south from Sunrise) could also be part of layer F.

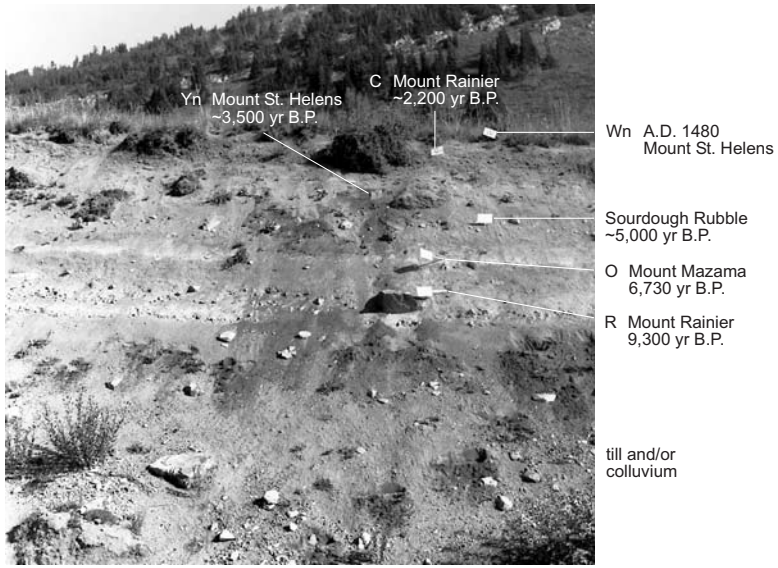


Figure E-9. Tephra layers along Sunrise Road at Yakima Park. The tephra deposits were labeled for the 1965 field trip of the International Association for Quaternary Research; vegetation now covers most of these layers. From the uppermost label to the lowest is about 6 ft (1.8 m). View is to the north, with Sourdough Mountain on the horizon. National Park Service photo.

15.6 *25.1* Sunrise Visitor Center and Ranger Station. (This is a good place to get trail maps.) At the Sunrise parking lot, you can see the great splendor of Mount Rainier's east face. It is a sight that inspires many, as you can see from a photo by Asahel Curtis (see frontispiece). This is one of the best places to see the amphitheater-shaped crater created by the Osceola Mudflow. Remnants of the crater rim are seen at Point Success, Liberty Cap, the uppermost exposures of Willis Wall, and other headwalls. The dark ribs (lava flow levees) that protrude through Emmons Glacier (see Fig. 1, p. 1) were sampled by USGS geologists Tom Sisson and Jim Vallance for their paleomagnetic orientation. They found that these levees have a paleomagnetic orientation similar to that of the rocks of block-and-ash flow deposits in the upper Puyallup River valley that were erupted about 2,450 yr B.P. Thus, this lava flow was likely produced during the same eruptive episode.

Visitors may want to take the optional short hike up the Sourdough Ridge Trail to Sourdough Mountain (0.4 mi; 0.6 km) for additional views or take other trails. A popular and shorter option is to take the Emmons Vista Trail (0.3 mi [0.5 km] round trip; south of the parking area), which leads to several scenic overlooks. From Emmons Vista there are more glimpses of the magnificent east face of Mount Rainier (Fig. E-10).

The 1963 debris avalanche deposit is plainly visible on the surface of the Emmons Glacier, from which the White River can be seen emerging. The deposit, which is made up of at least seven distinct avalanches, originally extended about another mile (1.6 km) downstream to within 0.5 mi (0.8 km) of the White River Campground and had a volume of about 14.4 x 10^6 yd^3 (~11 x 10^6 m^3) (Crandell and Fahnestock, 1965; Fahnestock, 1978). Fortunately, the avalanches occurred in December when the area was deserted. Estimates of flow runup onto the back of a terminal moraine indicated a distal velocity of 80 to 90 mi/hr (35–40 m/sec). High velocities, almost certainly in excess of 70 mi/hr (30 m/sec), increase the risk with this type of event. The avalanches originated from the side of Little Tahoma Peak, possibly triggered by a steam explosion. The flow passed over an old stream gage house, leaving it undamaged, showing that the flow was likely riding on a cushion of trapped air in some places.



Figure E-10. The spectacular northeast face of Mount Rainier from the Emmons Vista overlook, about 100 m (~300 ft) south of the Sunrise parking area. Goat Island Mountain is the erosional remnant at left center on the skyline; it is composed of granodiorite of the White River pluton, as well as volcanic rocks of the older Stevens Ridge and Ohanapecosh Formations. Geologist Jim Vallance found a runup deposit of the Osceola Mudflow in the meadow visible downslope of Baker Point, 1500 ft (457 m) above the present valley floor. Note the amount of recession of the Emmons Glacier terminus from its advance position during the Little Ice Age, which is marked by the lateral and terminal moraine and trimline on Goat Island Mountain. The small lake in the center of the photo is moraine dammed; its volume changes from year to year.

In July 1974 and again on Aug. 16, 1989, similar but smaller avalanches fell from Russell Cliff and traveled 1.2 to 2.5 mi (2–4 km) down Winthrop Glacier. Although the 1989 avalanche was only about 10 percent of the size of the Little Tahoma Peak avalanches, seismic signals generated by it were recorded as far away as 124 mi (200 km) (Weaver and others, 1990). The size and nature of the seismic signal of the Russell Cliff avalanche led a curious USGS seismologist, Bob Norris, to re-check the records from December 1963. He discovered a large signal on December 6 that is tentatively thought to correlate with the avalanches from Little Tahoma Peak (which were previously thought to have occurred on Dec. 13 or 14, 1963) (Norris, 1994).

During his investigations of Mount Rainier in the mid-1990s, USGS geologist Tom Sisson observed localized faults on the flank of Mount Ruth and on the west side of Emmons Glacier that offset a talus slope, with the Emmons side downthrown. He noticed a similar fault that lies on the west slope of Disappointment Cleaver, also downthrown toward the Emmons. It appears that rock masses must periodically spall off these fracture surfaces and slide down the Emmons, and this was likely the cause of the 1963 rockslides.

You can retrace this leg to get back to SR 410 and Leg D, from which you can continue to explore the Mount Rainier area.

Remember to reset your odometer when you start another leg. ■

LEG F: EASTERN APPROACH

Yakima to Cayuse Pass via U.S. Highway 12 and State Route 410

by Wendy J. Gerstel, Paul E. Hammond, Newell P. Campbell, and Patrick T. Pringle*

This 66-mi (108 km) route takes you from the western fringes of the Columbia Basin to the Cascade Range at Chinook and Cayuse Passes, climbing about 3700 ft (1288 m) in 46 mi (74 km) (Fig. F-1). You will follow the valleys of the Naches and American Rivers for most of the trip, and en route you will have the opportunity to see the interior plumbing of a number of dissected Miocene volcanoes. The more ambitious traveler may want to explore roads and trails in Wenatchee National Forest for a more intimate look at these volcanic remnants. Some of these volcanoes may have exceeded Mount Rainier in height and circumference. The Fifes Peaks* and Bumping Lake volcanoes of Miocene age were certainly highly explosive because they produced welded tuffs and expelled such great quantities of magma that the volcanoes collapsed to form calderas.

The Yakima area is a starting point for many geological excursions; however, there isn't space here to describe them all. Those who want to delve deeper can start with Campbell (1998). (See also Norman and others, 2004, along with other sources in "Further Reading", p. 102.) Through the eastern part of this leg, you will pass young lava flows of the Tieton Andesite (Pleistocene) and the Columbia River Basalt Group (Miocene). The Tieton Andesite, best viewed along U.S. Highway (US) 12 at milepost (MP) 199 or about 1 to 2 mi (1.6–3.2 km) west of its junction with State Route (SR) 410, offers dramatic examples of columnar jointing. Visit this locale during the late afternoon for some great photo opportunities!

As you enter and travel the steep-walled reach of the Naches River valley, you parallel the west flank of the largest anticline of the Yakima Fold Belt. (See "The Yakima Fold and Thrust Belt", p. 17). This fold, known as Cleman Mountain, hosts one of the largest landslides along the route, the Sanford Pasture landslide. The landslide extends for about 5 or 6 highway miles (6–10 km) and is best seen from the air because of its scale. This and other huge landslides in the area likely failed along weak layers where fine sediments, including ash, are interbedded with the Columbia River basalt flows. Strong ground motion during past earthquakes could have contributed to movement of some of the landslides. Some portions of these slides are still moving, as indicated by recently tilted trees and cracked and buckled ground.

What formed the curious stone stripes, the strands or branch-shaped arrays of rocks that drape the hillsides in some places along this route and are surrounded by grassy and, locally, scrubby vegetation? Geologists lump these features in a category called 'patterned ground'. The formation of these features, although something of a geologic curiosity, is probably due to frost action in concert with gravity. Depending on the sizes of rocks, elevation, and physiographic factors such as south-facing vs. north-facing slope, and whether the bottom of the talus is deep in its gulley, these stripes can create a cool, shaded, moist microclimate that provides habitat for squirrels, lizards, some frogs, and even a few slug species. Look for greener grass around the stripe edges locally. In the autumn, the dark basalt rocks of the stone stripes provide a stark color and textural contrast to the surrounding golden grassy slopes.

As you approach Chinook Pass, the American River valley with its classic U shape lies to the south. This carved valley is a product of several episodes of alpine glaciation whose source was an ice cap centered at Mount Rainier. Smaller glaciers that fed into this larger ice stream created hanging valleys, many of which host beautiful waterfalls.

This route also takes you through a dacitic intrusive body and past unconsolidated deposits such as glacial till and outwash. Trails throughout the area offer endless opportunities to look at the geology in more detail, with grand and secluded views. Leg O (p. 163) is a short side trip along Bumping Lake Road that features landslides, old mining cabins, volcanic peaks, and glaciated valleys, as well as thick deposits of welded tuff that are locally intruded by dikes.

Note: Because this leg is run from east to west, the map route runs from right to left on each panel. Signed mileposts for the first 16 mi (26 km) refer to US 12, but refer to SR 410 for the remainder of the leg to Cayuse Pass. The highway is sometimes closed in winter, so it is wise to check on road conditions before traveling. Road status can be checked at the Washington State Dept. of Transportation website or by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* This leg begins at the parking lot for the Yakima Greenway at the North 16th Avenue exit off US 12. It is about 1 mi (1.6 km) west of the junction of US 12 and Interstate 82. Cliffs to the north of the highway are composed of the Grande Ronde Basalt of the Columbia River Basalt Group (see Fig. 20, p. 25). Slightly west of the Park and Ride, the Yakima River exits a gorge gradually cut through Yakima Ridge over the millions of years it was being folded or uplifted. Folded rocks and evidence of the faulting that accompanied the folding are exposed within the gorge. The sloped bench above the river is planed on the base of the Vantage interbed; the Vantage sediments overlie the Grande Ronde Basalt. This interbed represents sedimentation dur-

* See "Contributors", p. ii, for affiliation.

* A discrepancy between the name of the Fifes Peak Formation and the landform, Fifes Peaks, is probably the result of a typo. The Fifes Peak Andesite was originally named by Warren (1933), who, although he didn't designate a type section, said that "Fifes Peak, in the northern part of the quadrangle" is one of the most prominent vents. The landform after which Warren was naming the formation is labeled "Fifes Peaks" on the Mount Aix quadrangle map. However, Warren evidently left out the 's'. In his map of the Tieton River, Don Swanson (1978) revised the age of rock unit and called it "Fifes Peak Formation". Although he clearly recognized that the geographic feature is called Fifes Peaks, Swanson did not comment on the discrepancy.

ing a hiatus in lava extrusion. In this unit, plant fossils such as *Ginkgo* leaves can be found. Grande Ronde N_2 flows are below the Vantage interbed. The Frenchman Springs (lower) Member of the Wanapum Basalt is above the N_2 sequence and the Vantage interbed. The Eckler Mountain Member is missing here, either because the flow never reached this area or it was eroded away before the Frenchman Springs flows arrived. The Saddle Mountains Basalt is exposed on the skyline (Reidel and Campbell, 1989).

These Grande Ronde flows are termed 'N' because they have normal magnetic polarity. The crystals or grains of magnetite and other iron-rich minerals in each of these flows are oriented with the Earth's magnetic field of the time of their eruption, just like a compass needle; they would have normal polarity if the flow were emplaced today because they would align with the north magnetic pole. Flows labeled 'R' have reversed magnetic polarity because the Earth's magnetic poles were reversed during that time. That is, a compass needle during 'R' times would align with today's south magnetic pole. The numbers associated with the N or R flows indicate the sequence of their eruption, '1' being erupted before '2'. (See the "Paleomagnetism" sidebar on p. 104.)

Lavas of the Columbia River Basalt Group make up the hillside on the right (north). Some of these flow units were formerly known as the 'Yakima Basalt'; however, geologists discovered that this unit consisted of several distinct flows of the Grande Ronde Basalt (Swanson and others, 1979). Even though these basalts may look the same from a distance, geologists distinguish them on the basis of their geochemistry and texture.

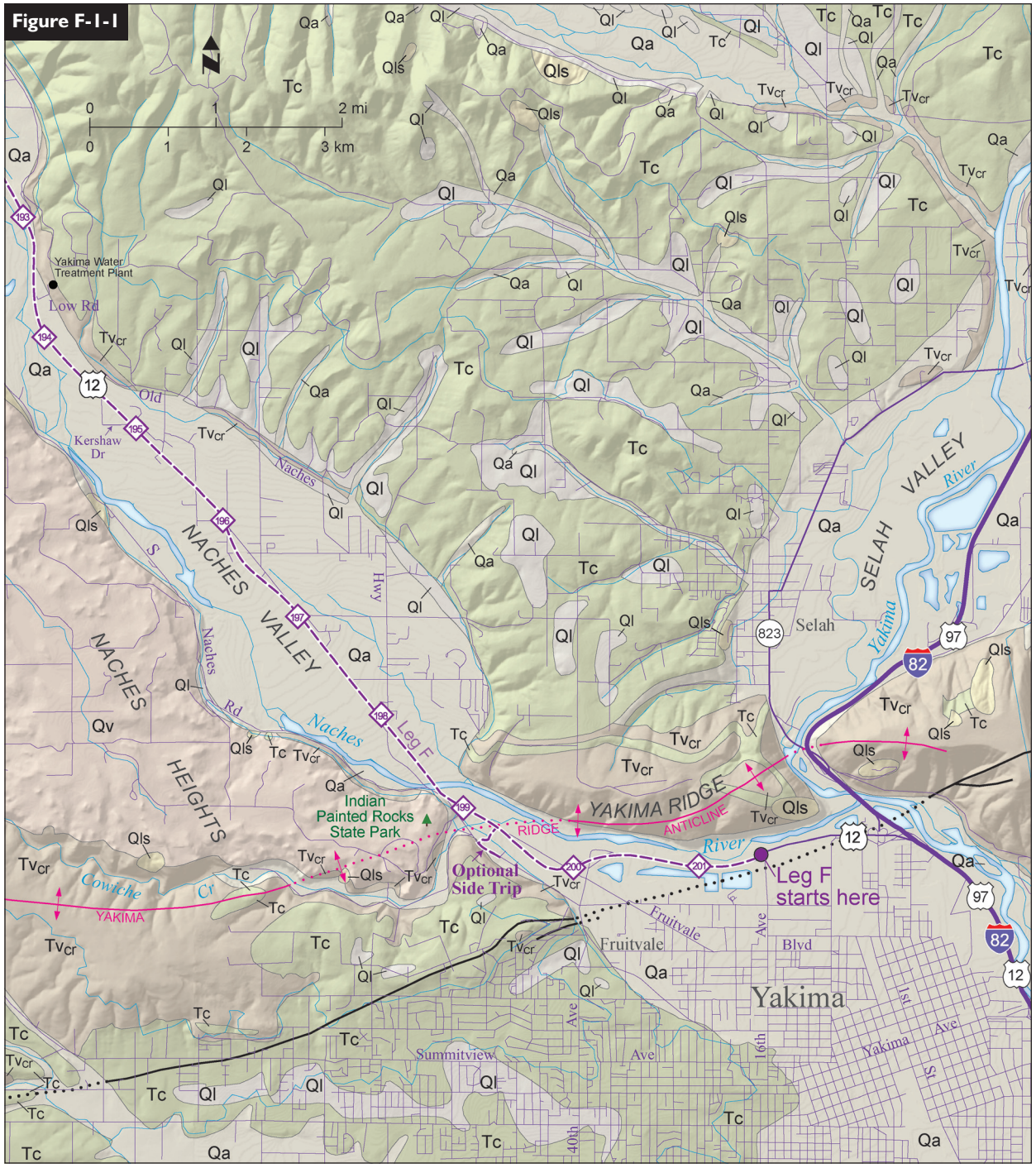


Figure F-1. Geologic map for Leg F (seven consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b), Walsh (1986), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover. *Note:* Because this leg is run from east to west, the map route runs from right to left on each panel.



Figure F-2. A restored pictograph on a column of Tieton Andesite. The pictograph is about 1 ft (30.5 cm) wide. This site is now closed.

1.0
1.6 Near the 40th Street exit, you travel diagonally through the core of the west-southwest-trending Yakima Ridge anticline, a fold that arches the lava beds. The houses on the hillside to the northeast sit on the Wanapum Basalt.

1.5
2.4 MP 200. For about a mile here are some of the famous orchards and vineyards that provide revenue for the Yakima Valley. Agricultural products from here are shipped worldwide. The temperature and general climate of this area help foster a robust agricultural output that includes fruits, wine, and hops. A mere 7 in. (18 cm) of annual rainfall here necessitates irrigation of the orchards. Water demands are intense in the Yakima River valley: more than 97 percent of surface water is used for irrigation (Solley and others, 1998), and as much as 60 percent of the groundwater goes for irrigation (Vaccaro and Sumioka, 2006).

2.6
4.2 **OPTIONAL SIDE TRIP:** MP 199. You can see the terminus of the Tieton Andesite flow by turning south onto Ackley Road for 0.1 mi (0.16 km) and then right on Powerhouse Road for about 100 yd (100 m). The Tieton Andesite flow is the largest lava flow from the Pliocene and Pleistocene Goat Rocks volcano. (See Leg H, p. 132, mile 29.5.) Swallows have taken advantage of fracture pockets in the entablature here to build nests.

On the lava columns are restored pictographs originally painted by some of this area's indigenous peoples (Fig. F-2). However, public access is now closed to protect the pictographs. An informational resource about the art is "Petroglyphs of Central Washington" by Cain (1950). There is no water or restroom at the site.

The Tieton Andesite is noteworthy because it is thought to be the world's longest andesite flow, more than 49 mi (79 km) from source to terminus (Swanson, 1990). Andesite flows are generally too viscous to flow far from their source. The unusual length of the Tieton flow is attributed to its having been confined to a pre-existing stream channel, the ancestral Tieton River canyon. Notice that it now forms a ridge. The deposits that originally confined the flow have since been partially eroded away, and the resulting landscape is described as having 'reversed topography'. Swanson and others (1989) dated the flow to 1 Ma and noted that it was reversely magnetized. Hammond recently dated the flow to 1.64 Ma using Ar-Ar methods.

As you leave this site, you pass through the north limb of the Yakima Ridge anticline, through which the Naches River has cut a notch. *Remember to compensate for mileage along the side trip.*

2.8
4.5 Cross the Naches River. The plateau area to the south dotted with houses is underlain by the

Paleomagnetism—Volcanoes as Tape Recorders

by Patrick T. Pringle and Katherine M. Reed

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. When 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. 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 World War II, the military developed technology for studying the sea floor. The results of that work and the instruments for those studies became available to other scientists in the 1950s for increasingly detailed studies of topography, gravity, seismicity, heat flow, and paleomagnetism. Geophysicists on research ships that were towing magnetometers discovered a pattern of multiple magnetic stripes, each 12 to 18 mi (20–30 km) wide, across the sea floor. The stripes seemed to be parallel to and symmetrical across midocean ridges (see Fig. 7, p. 9).

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', although changing pole positions largely record the movements of tectonic plates. This work shows that Earth's magnetic field has remained normal or reversed for as little as 100,000 years to as much as several million years.

Geomagnetic polarity reversals occur when the Earth's magnetic field reverses, or flips, from one near- axial position to the other, for example from north to south. Figure 20 (p. 25) shows that the Columbia River Grande Ronde Basalt flows termed 'N' have normal magnetic polarity. The crystals or grains of magnetite and other iron-rich minerals in each of these flows are oriented with the Earth's magnetic field of the time of their eruption; they would have normal polarity if the flow were emplaced today because they would align with the north magnetic pole. Flows labeled 'R' have reversed magnetic polarity because the Earth's magnetic poles were reversed during that time. That is, a compass needle during "R" times would align with the south magnetic pole. The numbers associated with the N or R flows indicate the sequence of their eruption, '1' being erupted before '2'. Geomagnetic excursions (denoted as 'E') occur when the Earth's magnetic field drifts dramatically from a near axial position without a complete reversal, and geomagnetic polarity transitions ('T') record orientations of the geomagnetic field that are intermediate between complete reversals.

Geologists studying volcanic rocks in particular have combined the use of paleomagnetism with dating, chemistry and mineralogy, and stratigraphic studies to map distinctive rock units and correlate them with like units over broad areas, as well as to reconstruct the history of rotation of rock units (Beeson and others, 1979; Wells and others, 1998). As noted in Part I of this book ("Lahars, Tephra, and Buried Forests", p. 34), geologists have used secular variation, the drift of the magnetic field over a few centuries, to estimate the age of rocks that were erupted from Mount Rainier within the past few thousand years. ■

Tieton Andesite flow and is known as Naches Heights. This reach of the Naches River is a good apple-growing area because of the well-drained alluvial soils and moderate climate. Notice that the lava flows dip toward us—you are now traveling through the Naches syncline.

3.5 *5.6* Stoplight at Old Naches Highway.

4.8 *7.7* The rounded features in the distant hillside to the left are lava flows with columns arranged like a fan, most likely related to cooling within lava tubes. The highway traverses the lower Naches terrace, an abandoned flood plain.

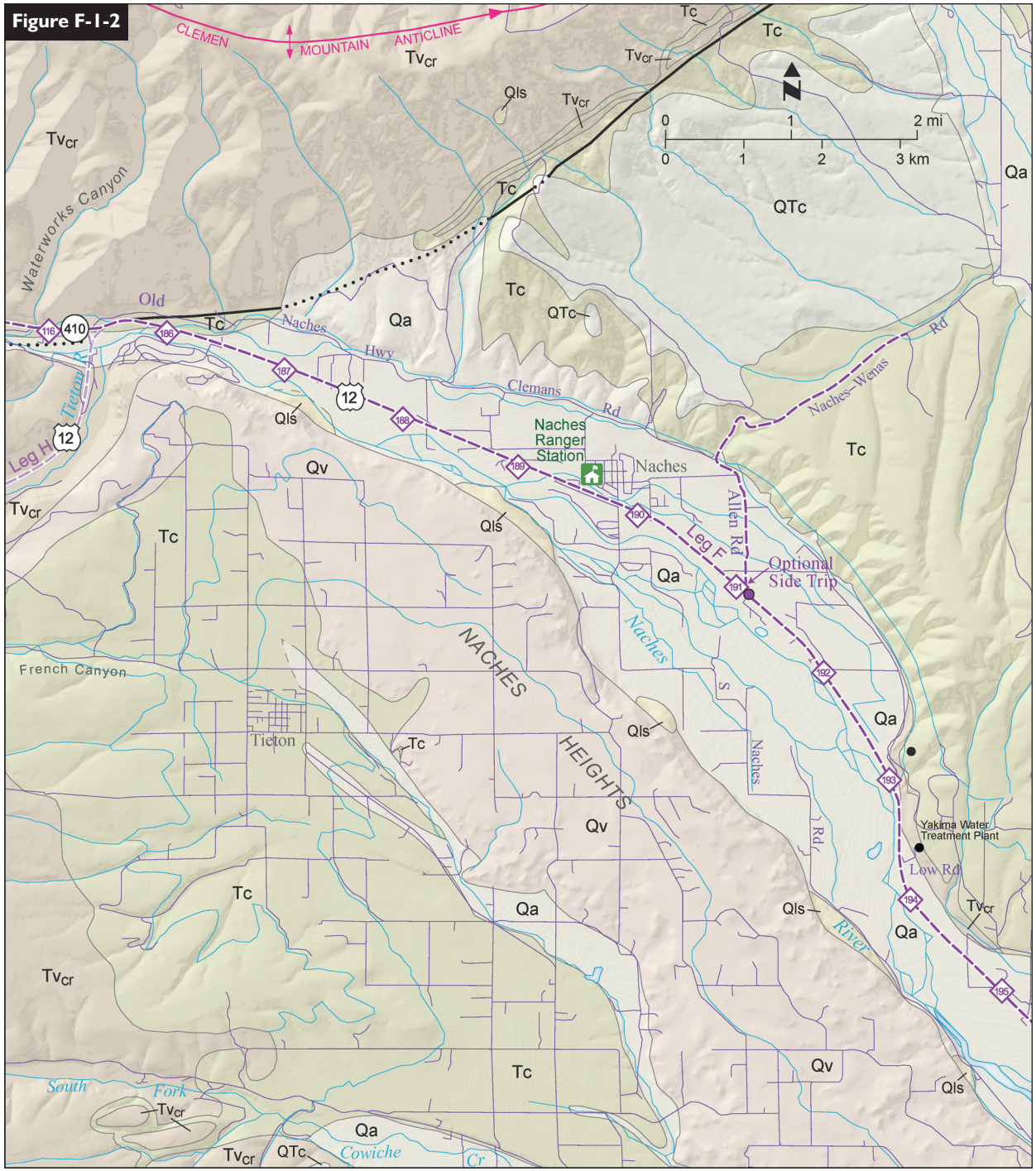
7.0 *11.3* Kershaw Drive. The cliff on the right is made up of the top flow of the Wanapum Basalt of the Columbia River Basalt Group. The youngest unit in the Wanapum Basalt is about 14.5 Ma.

7.8 *12.6* Yakima water treatment plant at Low Road. On the right, sedimentary interbeds lie atop the Roza and Frenchman Springs Members of the Wanapum Basalt and beneath the Pomona Member of the Saddle Mountain Basalt, all parts of the Columbia River Basalt Group.

8.4 *13.5* The water power station here is situated at the westernmost extent of the upper Wanapum flows. Some of the Wanapum flows are invasive into the generally coeval Ellensburg Formation in this area; that is, because of their greater density, they sank into the soft sediments and squeezed between layers. Many of the older Grande Ronde lava flows traveled farther west in this area.

8.8 *14.1* The white horizontal beds in the distant rounded hills on the right are composed of the Ellensburg Formation; the type section is exposed there. Note the shape of hills, which is determined by the softer sediments (Fig. F-3). The Ellensburg Formation here is made up of coarse lahar runouts, conglomerates, and interbedded pumiceous and ashy, stream-worked deposits that were laid down between approximately 7 and 13 Ma. Smith (1988a) reported ages of 7.4 to 13.3 Ma using K-Ar dates from tuff and pumice in combination with stratigraphic relations with other dated rock units. These Ellensburg Formation deposits are the distal or downvalley facies of the lahars produced by Miocene volcanoes. Although the volcanoes them-

Figure F-1-2



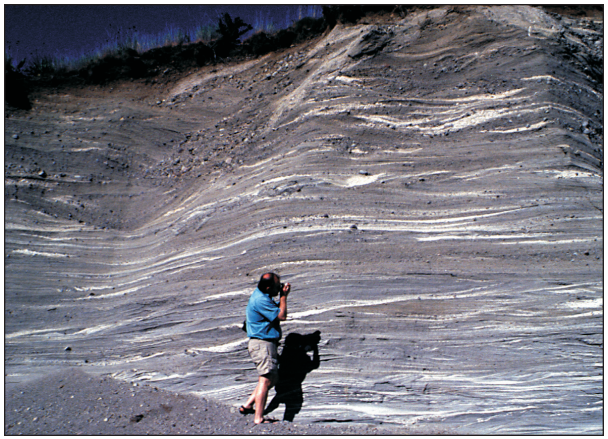


Figure F-3. Geologist Matt Brunengo examines pumice from fluvial deposits of the Ellensburg Formation along Wenas Road north of Naches. The bedded fluvial material sits on several massive laharic units. Whitish discontinuous caliche soils have developed atop these lahar deposits. These Miocene-age lahars were generated by eruptions in the Cascade Range about 12 to 4 m.y. ago. Geologist Paul Hammond has made chemical correlations of likely intrusive bodies with volcanic sediments of the Ellensburg Formation and has identified at least six large dacite plugs in the Cascade Range east of Mount Rainier that are remnants of domes or dome-producing volcanoes that were the sources of Ellensburg. (See Fig. 16, p. 20.)

selves have since been eroded away, these deposits provide important evidence of the past eruptions.

Ahead, an N_2 flow of the Grande Ronde Basalt of the Columbia River Basalt Group caps the Cleman Mountain anticline.

10.4 *16.7* **OPTIONAL SIDE TRIP:** Allan Road/Naches–Wenas Road to volcanic deposits. To see laharic and fluvial deposits of volcanic origin, you can turn right onto Allan Road, then left on Naches–Wenas Rd at 0.8 mi (1.3 km), pass under the old aqueduct (1.1 mi or 1.8 km), and proceed for 0.7 mi (1.1 km) along the type section of the Ellensburg Formation. You are traveling 'up section', through successively younger deposits, as you drive up the grade. The Ellensburg Formation is noteworthy for its assemblages of volcanic deposits, including lahars and lahar runouts whose main lithic component is a hornblende-rich dacite. These deposits were generated by explosive volcanism in the Cascades about 12 Ma, but they

photo by Dvae Norman

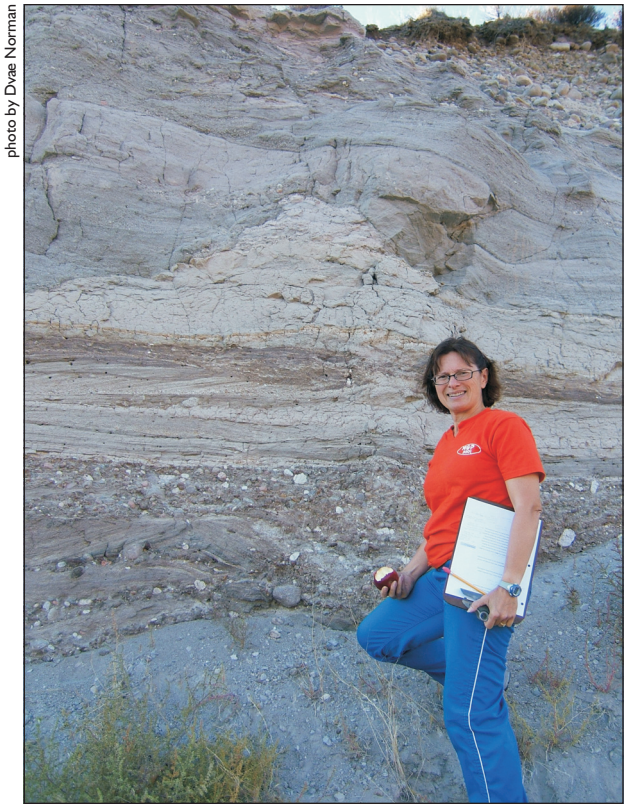


Figure F-4. Ellensburg Formation beds showing classic sedimentary features, such as dish structures, crossbeds, flaser bedding, and graded bedding. This outcrops is located along the Naches–Wenas Road.

are one of the few relics of this volcanism aside from some recently discovered vent areas. The volcanoes that produced these slurries and volcanic floods have largely been eroded away. You can see many classic sedimentary features (such as dish structures, crossbeds, flaser bedding, and graded bedding) in the Ellensburg deposits (Fig. F-4).

Continue to 1.9 mi (3 km) for a safer place to turn around for the return trip to Naches. *Remember to compensate for mileage along the side trip.*

10.5 *16.9* MP 191.

11.0 *17.7* Extensive gravel bars in the river on the left are evidence of large-scale sediment transport. Features such as gravel bars and point bars are continually being modified, especially during years of high river discharge.



Figure F-5. A landslide scarp is visible a little over halfway up the hill behind the house between MP 188 and 187 on US 12.

11.2 *18.0* Entering the town of Naches. The elongate hills and valleys, extending north of here and trending north-northwest, make up the Yakima Fold Belt. (See "The Yakima Fold and Thrust Belt", p. 17.)

11.7 *18.8* U.S. Forest Service Naches Ranger Station on the right.

12.5 *20.1* MP 189. Notice the fan-like arrangement of joints and columns in the lava flows on the slopes across the river to the left. These formed as the lava cooled; they are oriented perpendicular to the arched cooling surface. Ahead is the Cleman Mountain anticline, cored by complex thrust faults (see mile 17.4).

13.0 *20.9* On the left are more fanned columns. These are sometimes informally called 'Mayan Sunrise' features.

13.8 *22.2* A landslide scarp is visible on the left (Fig. F-5).

14.0 *22.5* On the right, note an alluvial fan that emanates from the hills on the north.

16.2 *26.1* Junction of US 12 with SR 410. This marks the end of Leg H, which follows US 12 from SR 123 and over White Pass to this location. Continue west on SR 410.

16.5 *26.4* MP 116.

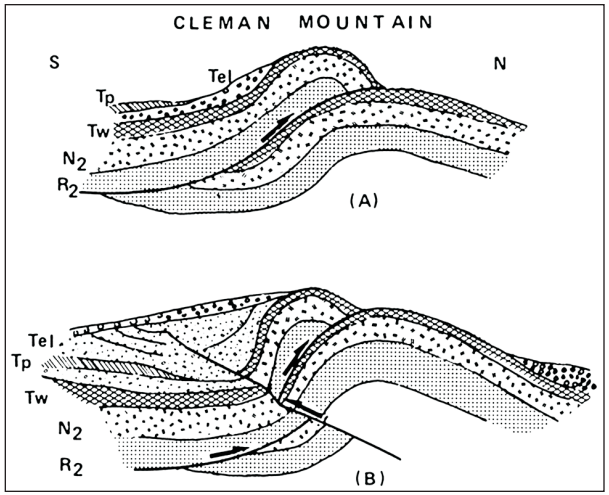


Figure F-6. Generalized cross sections of the Cleman Mountain structure as interpreted by R. D. Bentley and N. P. Campbell. Section A shows a growing anticline in post-Wanapum Basalt time (~14.5 Ma). Section B shows the structure at post-Saddle Mountains Basalt time (~6 Ma). Geologic units shown are Tel, Ellensburg Formation; and the following members of the Columbia River Basalt Group: Tp, Pomona Member of the Saddle Mountains Basalt; Tw, Wanapum Basalt; N_2 and R_2, members of the second normal and second reversed polarity intervals, respectively, of the Grande Ronde Basalt. (See Fig. 20, p. 25, for the stratigraphic position of these units.)

16.8
27.0

The columnar Tieton Andesite flow of Pleistocene age is across the Naches River to the left and a little behind us. Note the fan-like flow features mentioned earlier. These may form owing to differential cooling as water from lava-dammed streams inundates the top of the cooling flow and percolates down into cracks as the lava cools. The Tieton Andesite may have been too viscous to create extensive networks of lava tubes, such as those that form in basaltic lava flows. (Ape Cave at Mount St. Helens is a fine example of a lava tube. It is in basalt.) Caves that formed where parts of columns have fallen away from the exposure were once used by local tribes as shelter and for storage.

Recreational rafters rush to float the Tieton River in the autumn when Tieton Reservoir is lowered in preparation for storage of winter precipitation. They put in about 17 mi (27.4 km) up US 12.



Figure F-7. Ellensburg Formation deposits, including lahars and lahar-derived sediments, are exposed in a quarry. The equipment suggests scale.

17.4
28.0

Here you are entering a canyon cut in south-dipping Miocene Columbia River Basalt. Cleman Mountain is the highest of the Yakima Fold Belt anticlines at more than 600 m (1970 ft) of amplitude. Mapping of the fold by geologists Robert Bentley and Newell Campbell showed that this structure is complexly faulted, both by a south-dipping thrust fault and by a later north-dipping back thrust (Fig. F-6). The south-verging fault, which is along the crest of Cleman Mountain, has been called a 'piggyback thrust' by some workers because it evidently overrode an older thrust that verges to the north (Tolan and others, 1989). The Sanford Pasture landslide probably moved along several weak interbeds that may be made up of sediments, rubbly tops or bottoms of basalt flow layers, or palagonite breccia, basaltic debris partially quenched to glass by cooling in contact with water.

17.7
28.5

The gnarled-looking outcrop on the right is a sheared breccia, part of the folded thrust fault in Cleman Mountain known as the Waterworks Canyon fault.

18.4
29.6

Trailhead to Mud Lake, which sits on the Sanford Pasture landslide. Mud Lake (out of sight above the road) is a sag pond. It is formed in a depression between slide blocks. Rotated blocks of basalt are visible in several places along the roadway. The main body of this late Quaternary slide appears to be stable at present. However, if you look carefully at the hillsides, you may notice smaller, younger slides within the blocks of the original slide.



Figure F-8. Horseshoe Bend dike. This dike-like feature near MP 114 is cemented breccia (caliche) of the Sanford Pasture landslide, which originated on Cleman Mountain behind the viewer. Cougar Canyon is in the background. View is to the southwest.

18.6
29.9

MP 114. An Ellensburg Formation lahar deposit is exposed in a quarry near the bend in the road (Fig. F-7). A thick deposit of alluvium of unknown age cores the prominent terrace adjacent to the river. Also at mile 18.6 is Horseshoe Bend. This curve in the river channel is the only sharp meander along the Naches River. The meander likely became entrenched during the uplift of the Cleman Mountain anticline (Campbell, 1975). The river used to flow east of the highway but is now confined to a channel west of the road. Horseshoe Bend is of historic significance in that it was an obstacle to early foot travel. This meander is controlled by the local geology—the river could cut easily through the unconsolidated landslide deposits, but was forced to turn southwestward where it flowed along the basalt bedrock now exposed in the lower quarry walls.

The large mass of rock across the river straight ahead on the south side of the highway is a dike-like pillar of debris of the Sanford Pasture landslide

that has been cemented by mineral-rich fluids along a fault (Fig. F-8). This fault breccia overlies the entablature of the in-place R_2 flow of the Grande Ronde Basalt and is in lateral contact with a large gravel bar extending eastward into the river channel. The dense patterns of narrow trails, called terracettes, on hillsides on the side of the valley are a result of animals moving along the contour as they graze.

If you look north from here, you can see the easternmost edge of the Sanford Pasture landslide and more fault breccia on the skyline. The breccia is roughly across the valley from the landslide block on the south side of the river.

Notice that the river bed to the right (northeast) is dry. The meander was cut off, probably by the construction of the road. Gravels have been mined out of old river deposits here. The upper walls of the gravel pit expose a terrace of Quaternary age whose origin is still a matter of discussion. The terrace may consist of landslide material of Miocene-age sedimentary rocks overlying the top of an unspecified R_2 flow of the Grande Ronde Basalt. At this location the flow is invasive into the surrounding sediments.

19.3 *31.2* In the next 5 to 6 mi (8–9.6 km), the highway traverses and is cut into deposits of the large Sanford Pasture landslide. Much of the deposit within the valley is composed of basalt blocks and alluvium that slid southward from Cleman Mountain. To appreciate the scale of this landslide, consider that Cleman Mountain, the ridge to the northeast, is the landslide's headscarp as well as the largest anticline in the Yakima Fold Belt (elev. 6000 ft or 1829 m) (Fig. F-6). The landslide likely moved along a weak interbed or interbeds within the Columbia River Basalt flow sequence, or possibly along a thrust fault plane between the R_2 and N_2 lava flow sequences.

19.4 *31.2* A roadcut on the right exposes landslide deposits. Hyaloclastite deposits are present within the landslide debris at the west end of the cut.

21.0 *33.8* For the next 0.5 mi (0.8 km), rubbly basalt and more landslide jumbles are exposed on the right.

22.0 *35.4* Good examples of stone stripes are off to the right (Fig. F-9).

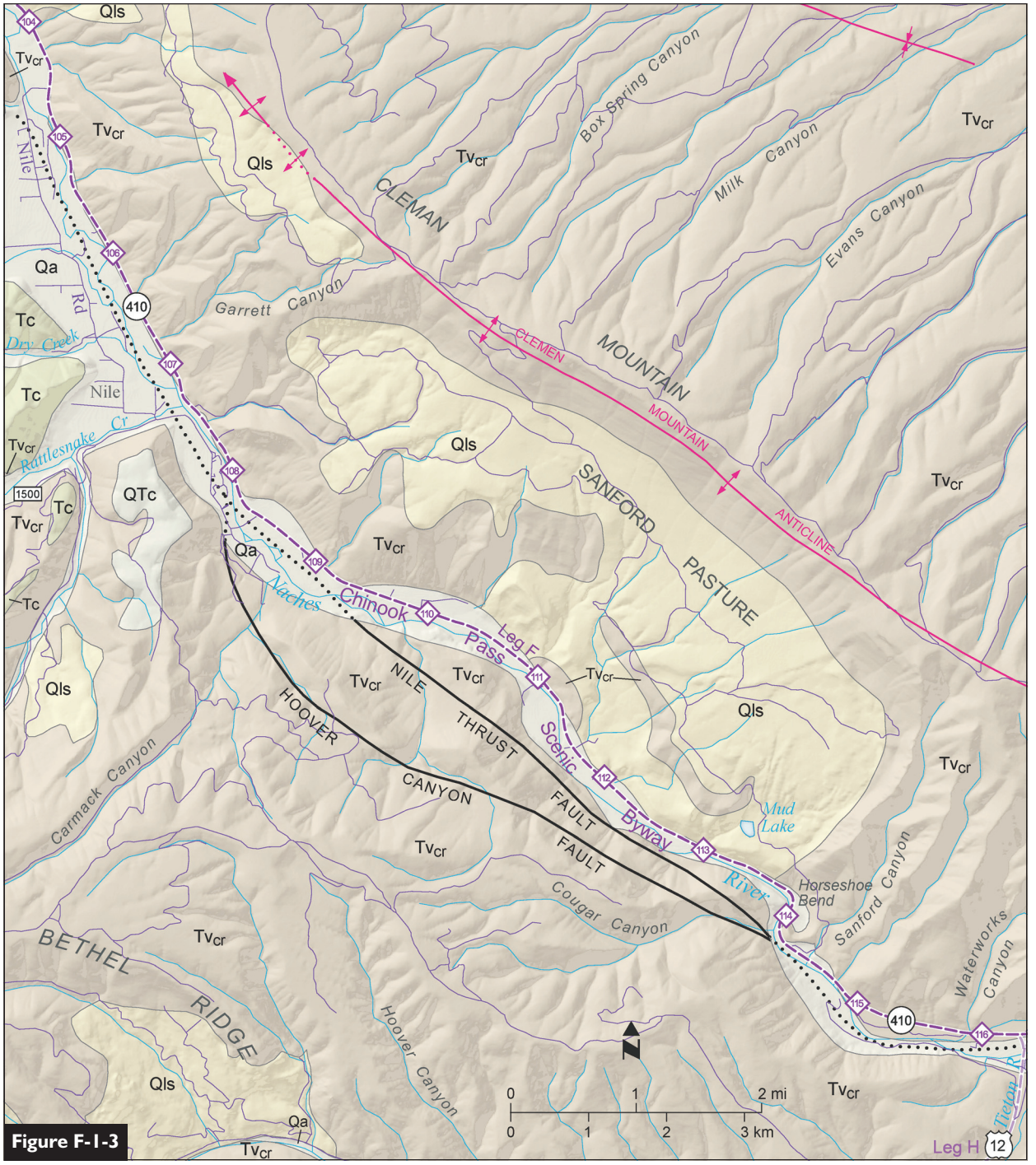


Figure F-1-3



Figure F-9. Stone stripes on a valley wall north of SR 410 near Naches. As with other types of patterned ground, the processes that form them are complex and vary somewhat from location to location. The stripes shown range from about 2 ft to 12 ft (0.6-3.7 m) in width. This photo was taken in the fall, when the color contrast tends to be greatest.



photo by Dave Norman

Figure F-10. An outcrop of blocky basalt with an interbed of river gravels and cobbles near MP 110.



photo by Beth Norman

Figure F-11. Nearly horizontal layers of laharic deposits of the upper Miocene Ellensburg Formation. The bluff is more than 800 ft (245 m) high. View is to the north at the intersection of Nile Road and FR 1500.

22.4
36.0

MP 110. As the road curves to the right, you can see on the right (north) side an outcrop of blocky basalt with an interbed of river gravels and cobbles (Fig. F-10). The clasts of the interbed are imbricated, and a close inspection of the basalts reveals pillow structures, indicating that the lava flowed into water. This outcrop may be in place (not a part of the landslide). Because of the curve and visibility limitations, this location is not a good place to stop.

24.1
38.8

OPTIONAL SIDE TRIP: Nile Road loop. At the intersection with Nile Road (to the west), the synclinal dip of Columbia River Basalt on both sides of the highway is easy to see. Via Nile Road from 0.2 to 0.5 mi (0.3–0.8 km), the basalts are hackly and fractured with several flows evident. About 1.4 mi (2.2 km) west of SR 410, Nile Road intersects FR 1500 up Rattlesnake Creek. Nile Road runs parallel to SR 410 and rejoins it roughly 3.2 mi (5.1 km) west of the FR 1500 intersection, at about mile 27.8 in this roadlog. A good place to view the Ellensburg Formation is from the Nile Library at 0.4 mi (0.6 km) from the 1500 Road junction. A side trip 0.6 mi (1.0 km) up FR 1500 provides views of fluvial sediments and lahar deposits of the Ellensburg Formation across the valley (Fig. F-11). From mile 1.5 to 7.5 (km 2.4–12.0) along Nile Road, you can see excellent examples of both spectacular columns and entablatures (**Fig. F-12**) in the lava flows across the canyon to the northwest. There, an N_2 flow of the Grande Ronde Basalt overlies an R_2 flow. About 9.4 mi (15 km) from the junction of SR 410, you can park in a quarry south of the road. The extensive slope to the east is Devils Table, a southeast-dipping lava flow of Grande Ronde Basalt. At about 10.1 mi (16. 2 km), FR 1502 (gravel) leads to a viewpoint (11.6 mi or 18.6 km from SR 410) where there is a fine view to the west of Rattlesnake Creek basin, Mount Aix, and other features (Fig. F-13).

Remember to compensate for mileage along the side trip.

25.1
40.4

Sediments of the Ellensburg Formation are visible in cliffs across the river to the left. At least 800 ft (244 m) of Ellensburg sediments have been measured in the center of the Bethel Ridge anticline. Near Dry Creek, outcrops in the hillside to the west are Ellensburg Formation; the competent layers are lahar deposits. The upper part of Ellensburg section has leaf fossils in this location. Here landslide material of rubbly basalt overlies Ellensburg sediments. This is the northwest edge of the Sanford Pasture landslide from Cleman Mountain.

A roadcut on the right exposes sediments of an unnamed interbed, about 16 Ma in age, near the base of the Grande Ronde Basalt sequence. The buff-colored silts and sands contain mica, and therefore they may have originated to the north or east, perhaps from highlands near modern-day Wenatchee or from the Okanogan highlands.

25.9
41.7

Continue driving through a syncline. From here to about MP 105, Grande Ronde lava flows of the Columbia River Basalt Group dip steeply to the road on the north side of valley and strike roughly parallel with the valley, whereas the beds on the southwest have a shallower dip (Fig. F-14).

26.2
42.2

MP 106. Note the very steeply dipping basalt columns on the right (north) for the next 0.7 mi (1.1 km) to the west as you drive in the syncline.

27.8
44.7

Junction with the east end of Nile Road on the left. If you took the Nile Road/FR 1500 side trip, this is where you would rejoin the main route of this leg. More basalt is on the right.

28.4
45.7

MP 104.

29.1
46.8

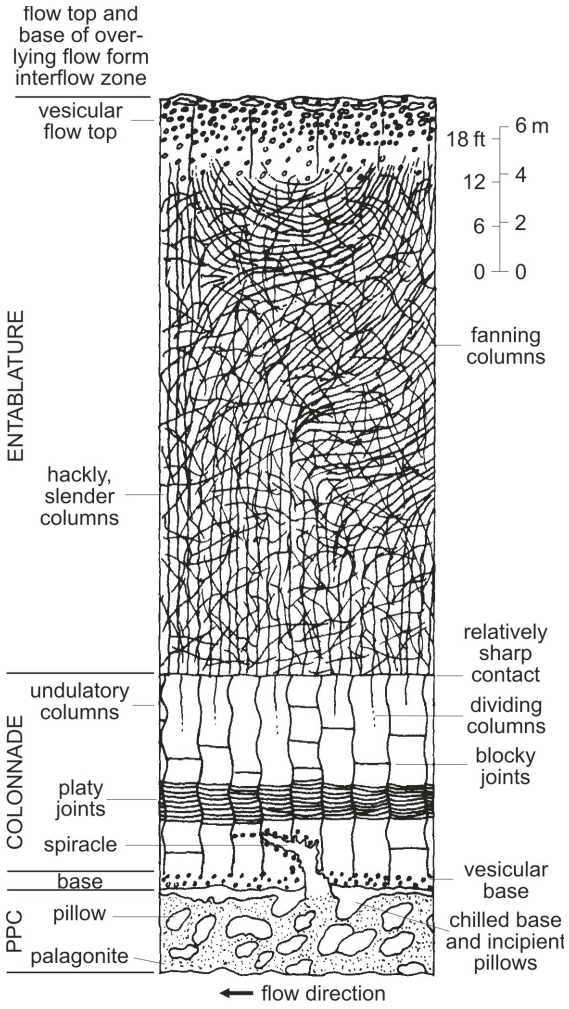
Bald Mountain Road (FR 1701) on the right extends up Benton Creek.

29.2
47.0

Elk Ridge Lodge on the left.

29.6
47.6

Fractured and faulted Grande Ronde Basalt with slickensides is on the right (westbound), as is the contact of the Columbia River Basalt Group with



the underlying Fifes Peak Formation (sandy bed) of upper Oligocene to lower Miocene age (Fig. F-15).

30.4 *48.9* MP 102, Squaw Rock area. FR 1702 (mi 30.1 or km 48.4) on the right leads up Rock Creek near here. A Fifes Peak phyric andesite lava flow and breccia also are exposed along a curve on the right.

31.3 *50.4* MP 101. Eagle's Nest development area. Although this is not a good place to stop, it is worth noting that there are exposures of a poorly sorted (laharic?) deposit of Fifes Peak age overlying weathered pink andesite. A conglomerate overlies eroded lava flows and breccias. The slickensides visible where the conglomerate is in contact with the andesite on the east indicate that these rocks have been deformed (Fig. F-16).

32.1 *51.7* Pinecliff.

32.3 *52.0* MP 100. Enter Wenatchee National Forest; a turnout with information about the Mather Memorial Parkway is on the right.

32.9 *52.9* Slightly past the turnout, on the northeast side of the highway (and slightly south of Cottonwood

Figure F-12. *(left)* Diagrammatic cross section of a typical flow in the Columbia River Basalt Group showing, in idealized form, basal colonnade, jointing patterns, and other structures. PPC is pillow-palagonite (hyaloclastite) breccia complex, which forms where the base of a flow enters water. Spiracles are vents created where steam explosions occur at the base of flows. Columnar jointing generally forms perpendicular to local cooling surfaces; however, formation of these jointing features is complex (see, for example, Long and Wood (1986) and Schaefer and Katterhorn, 2004). Modified from Swanson (1967) and Mangan and others (1986).

Figure F-13. *(below)* Panoramic view from the Mount Aix Viewpoint (elev. 3300 ft or 1006 m), looking west over the Rattlesnake Creek basin. This viewpoint is on FR 1500 about 11.6 mi (18.7 km) west of the SR 410 junction. FR 1500 is accessed 2.3 mi (3.7 km) west of 410 off the Nile Loop Road, its east junction. Timberwolf Mountain is the southern remnant of a large andesite volcano that has associated rectilinear dikes; ages on the volcano are about 25 to 27 Ma. Bismarck Peak (7585 ft; 2312 m) and Mount Aix (7766 ft; 2367 m), the highest peaks of Nelson Ridge, are the highest exposures of Tertiary-age volcanic rocks in the Cascade Range. The east margin of the Mount Aix caldera passes along the east face of Dog mountain. These Wildcat Creek tuffaceous sediments, first described by Swanson (1964, 1978) might be fine-grained equivalents of the Ohanapecosh Formation (Vance and others, 1987).



Figure F-14. Steeply dipping columnar lavas of the Grande Ronde Basalt near MP 106 along SR 410. View is to the northwest.

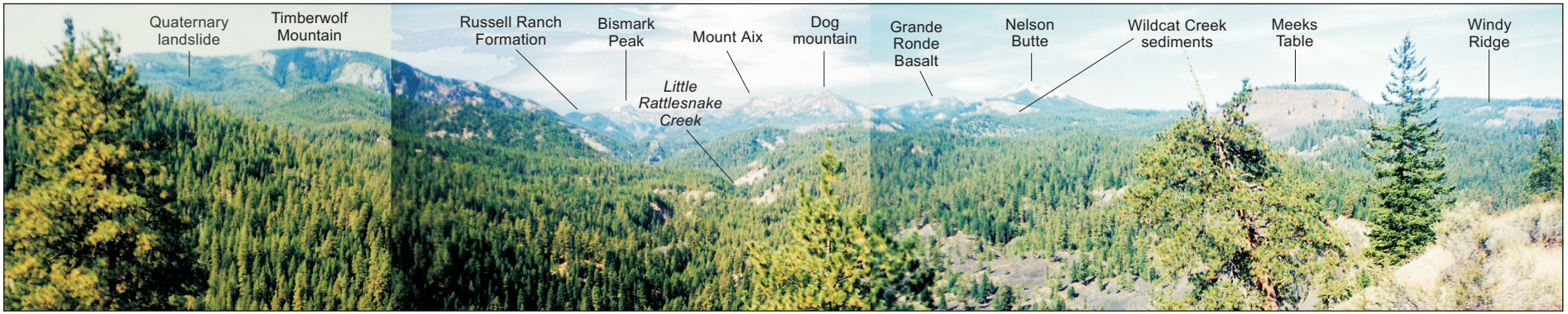




photo by Dave Norman

Figure F-15. Complexly faulted and fractured Grande Ronde Basalt with slickensides and contact (at shoulder level) of the Columbia River Basalt Group with the underlying Fifes Peak Formation (sandy bed) of uppermost Oligocene to lower Miocene age. View is to the north, slightly east of MP 103.

Creek Campground), nearly vertical dikes intrude a Fifes Peak lava flow from Edgar Rock volcano (Fig. F-17). Rocks in some parts of the outcrop have been worn away more than others, possibly because they were weakened by hydrothermal alteration when the volcano was active, as well as being sheared. This might be particularly important because we are near the core of the Edgar Rock volcanic edifice. Scientists studying the rocks in the Mount St. Helens Crater, for example, noticed that rocks there were similarly sheared where mechanical stresses were exerted as viscous magma pushed up through the brittle rock in the throat of the volcano (Swanson and others, 1995). This process weakens the internal strength of a volcano and encourages susceptibility to collapse as well as to erosion. The dikes and sheared rocks were formerly mapped by Carkin as Eocene-age volcanic rocks of Gold Creek. However, Hammond dated one of these dikes near the campground at 27.7 Ma and found that its chemistry is similar to that of the Edgar Rock volcano. This suggests that these Gold Creek rocks are part of an intrusive center that was buried by Edgar Rock volcano and that they represent the oldest part of the Fifes Peak Formation.

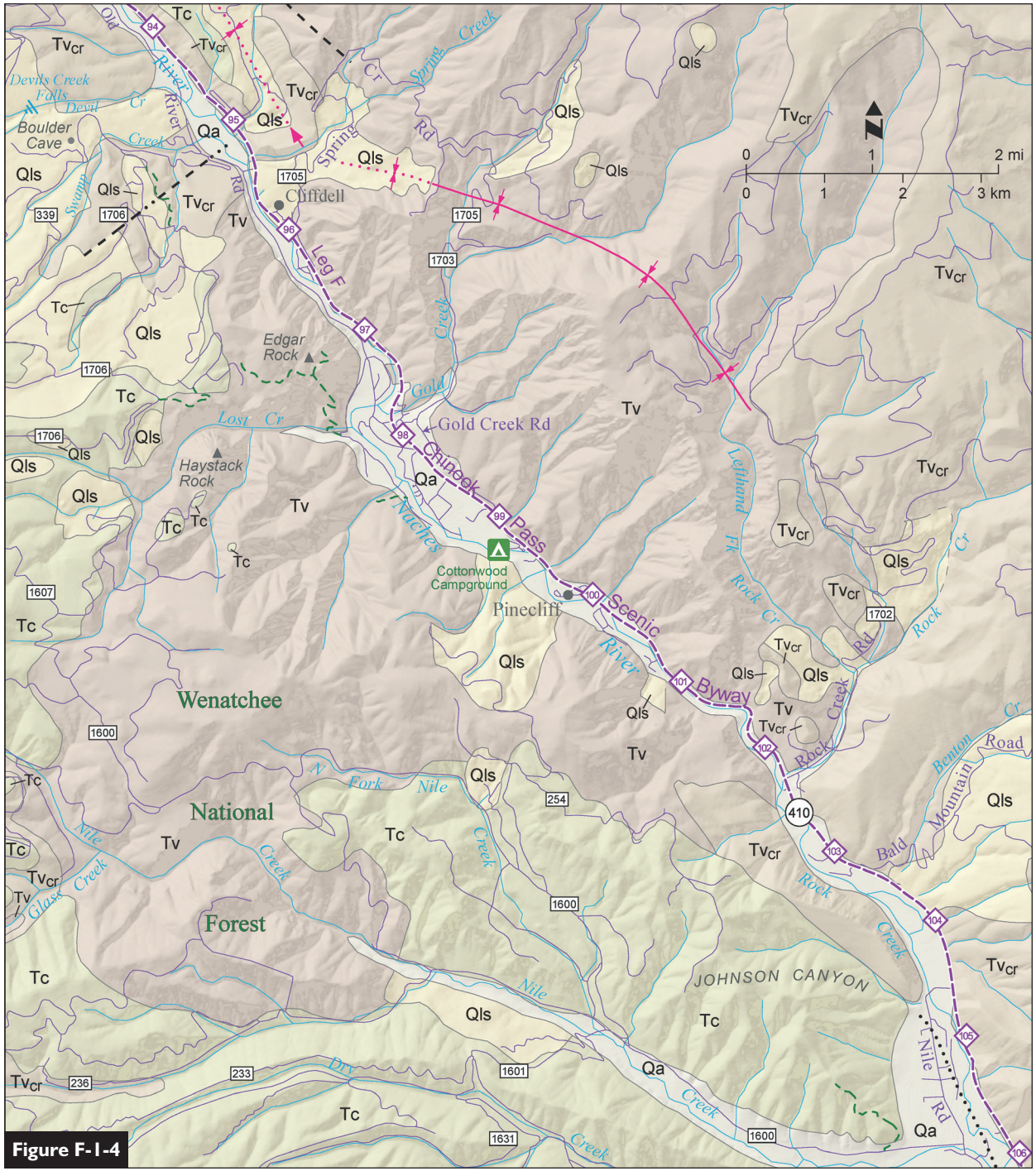


photo by Beth Norman



Figure F-16. Poorly sorted (laharic?) deposit of Fifes Peak age overlying weathered pink andesite. A conglomerate overlies eroded lava flows and breccias.

33.0 *53.1* Cottonwood Campground on the left (westbound).

33.3 *53.6* MP 99. FR 1703 (Gold Creek Road) on the right loops to FR 1705. Many north-trending, nearly vertical dikes cut steeply dipping beds of volcanic breccias here. There are so many dikes that the relation between the steeply dipping bedding planes and dikes is confusing at first glance. Good examples of spheroidal weathering are exposed about 300 ft (~100 m) up FR 1703 from SR 410. These rocks yielded Ar-Ar ages from 30 to 26 Ma and include breccias, conglomerates, and intrusive dikes that have been sheared—there are no other rocks similar to them in the area.

Haystack Rock is composed of andesite of Edgar Rock volcano. An outcrop on the east side of SR 410, slightly south of Cliffdell (at mi 36.0 below), exposes bedded breccias that are interpreted to be part of the compact lava flow and lava breccia, as well as laharic deposits of the volcano. On clear days there are grand views of mountain peaks, including Mount Rainier to the west.



Figure F-17. Dikes intrude the beds of Edgar Rock volcano, one source of the Fifes Peak Formation volcanic rocks, along SR 410 near Edgar Rock. This is near the base of the Edgar Rock deposits. The bedding (arrow) here strikes about 350 degrees and dips 30 degrees to the west. The dikes of a volcano commonly radiate about the center of volcano like the spokes of a wheel; therefore, by evaluating the geometry of the dikes of Edgar Rock volcano, Carkin (1988) was able to estimate the location of the volcano's central edifice to the southwest of here. The dikes range from 1 to 3 ft (0.3–0.9 m) thick. View is to the northeast. Photo by Brad Carkin.

33.7 *54.2* Gold Creek Station and Mercantile. Edgar Rock, a Fifes Peak Formation volcanic remnant of Miocene age, is ahead and lies southwest of the highway (Fig. F-18). Carkin (1988) estimated an age of about 26 Ma for Edgar Rock volcano. He used the orientation of the radiating dikes (Fig. F-17) to infer that the main body of the volcano was to the southwest of the present remnant. The dip of the beds to the northeast may reflect that of the outer flank of the original cone at that location.

33.9 *54.6* Edgar Rock is straight ahead (westbound).

34.0 *54.7* A subhorizontal dike cuts the tilted rocks on the right. Rocks of the Ohanapecosh Formation crop out in Gold Creek about 0.6 mi (1 km) upstream of the road.



Figure F-18. Edgar Rock at Cliffdell. This remnant of the volcano, about 1300 ft (400 m) in height, consists of lava flows and laharic breccias that dip 45 to 50 degrees to the northwest. View is approximately to the west. Photo by Brad Carkin, taken in the late 1980s.

34.6 *55.7* Old River Road on the left. Use great caution here at this blind curve! The turnout on the left at 34.8 mi or 55.7 km (southwest of the highway) is more safely accessed by eastbound travelers. From the turnout there is a view across the river to Edgar Rock. The roadcut on the northeast side of the highway exposes altered volcanic rocks of the volcano that overlie a fascinating mish-mash of volcanic dikes and megaclast-bearing lahar or debris avalanche deposits, the source of which is unknown. Note the cross-cutting relations and sheared dikes. These dikes are likely part of a radial dike swarm of Edgar Rock volcano. The base of the volcano lies slightly to the north. Deposits of the large alluvial fan of Gold Creek cap the cut and have controlled the course of the river and therefore the location of the highway.

35.2 *56.6* Edgar Rock is to the left (westbound) across the river slightly before MP 97. Dikes, flow breccias, hyaloclastites, and a variety of volcanic deposits related to the Edgar Rock volcano are exposed along this stretch of the highway.

35.8 *57.6* FR 1705 on the right connects with the other end of the FR 1703 loop (Spring Creek Road).

36.0 *57.9* Cliffdell. Whistling Jack Lodge and Shell station at mi 36.1 (km 57.8) adjacent to Edgar Rock volcanic rocks.



photo by Beth Norman

Figure F-19. Gravels on top of Grande Ronde Basalt near MP 92 that are likely alpine glacial outwash deposits of Evans Creek age (22–15 ka).

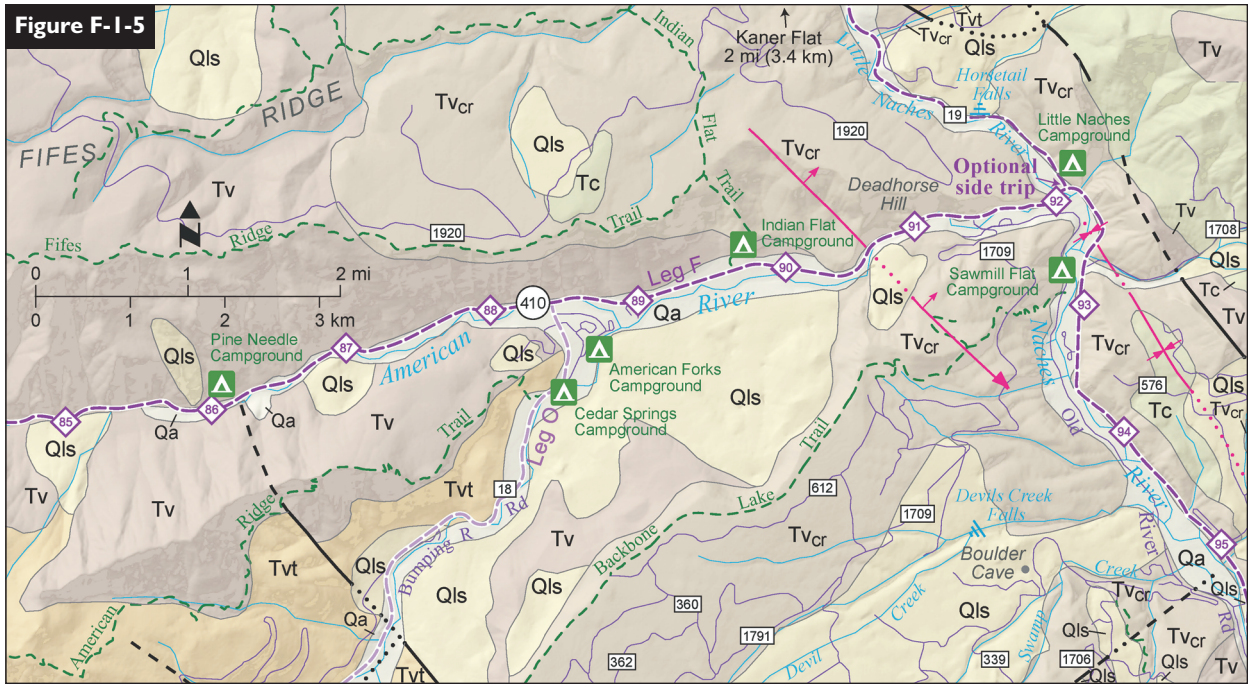
36.8
59.2 Old River Road is on the west (left, if westbound). It accesses Boulder Cave and Devils Creek Falls. On the north are active landslides in Edgar Rock volcanic rocks. Boulder Cave is about 3 mi (4.5 km) to the west on FR 1706-200. Those wishing to hike through the cave, which is now run by a concession, should bring a good flashlight. (Most spelunkers carry back-up lighting as well.) The cave was formed when erosion of interbeds between two Columbia River Grande Ronde Basalt N_2 lava flows created a void and allowed blocks of the overlying flow rock to collapse. The cave is closed from November 1 to April 1 to protect a hibernating colony of Townsend's big-eared bats. Few locations provide the stable environment and lack of disturbance that these bats require for hibernation. Explorers passing through the cave during the winter would waken the bats, causing them to use valuable energy moving around and changing roosts.

38.1
61.3 Grande Ronde Basalt north of the highway exhibits columns with a hackly entablature.

38.3
61.6 MP 94. Grande Ronde Basalt.

38.9
62.6 Sawmill Flat Campground on the left. Here, Grande Ronde lavas define a syncline whose axis runs roughly northwest through the valley.

Figure F-1-5



39.1
62.9 A pullout with information on the Mather Memorial Parkway is on the right (north side).

39.4
63.4 MP 93. This is not a safe place to stop, but note that there are pillows at the base of the Grande Ronde Basalt in the roadcut on the east side of the road. The presence of pillows indicates that, as the flows advanced from the east into higher ground to the west, the lava was flowing into water that may have been ponded. Thus highlands existed here, although as noted in the Introduction, most uplift of the Cascade Range postdates 15 Ma (Reiners and others, 2003). Note that the lava flows to the west across the river dip east.

39.6
63.7 FR 1708 on the right accesses Milk Creek and the 'Devils landslide'. This area may be worth a side trip (not detailed here) on a gravel road to examine a large deep-seated landslide and its badlands topography of jumbled rock debris. The Naches Formation of Eocene age is exposed in the headscarp of the landslide. The Naches Formation rocks consist of micaceous, arkosic sands and abundant volcanic sediments deposited between about 44 and 40 Ma (Walsh and others, 1987). Its lower units comprise lava and rhyolite flows that may have originated from a vent near present-day Mount Clifty. Some of the units yield thunder eggs.

The Grande Ronde flows of the Columbia River Basalt Group exhibit classic columns with overlying entablatures in this area and for the next half mile or 0.8 km (Fig. F-12). Some columns are subhorizontal. Note that the beds dip to the west, so you are now east of the axis of the syncline.

40.2
64.7 **OPTIONAL SIDE TRIP:** Little Naches River and Raven Roost. (Remember to note the mileage and adjust for the distance driven.) The paved forest road (FR 19) on the right (north) extends up the Little Naches River to Little Naches Campground and accesses an optional side trip to the Raven Roost viewpoint area on FR 1902 (off leg map). More landslides are visible en route to the campground and from Raven Roost.

North of Little Naches Campground at Horsetail Falls and farther north, a fish ladder and weir are located in the axis of the syncline in Grande Ronde N_2 basalt. Slightly downstream are placer claims where miners reported finding gold in the



Figure F-20. Geologist Rob Viens examines flattened pumice from a pumiceous rhyolitic lapilli-tuff deposit along SR 410. Note the charred log projecting out of the deposit in the upper right. Carkin (1988) noted a radiometric age of about 20 Ma for the deposit. Samples of this deposit, provisionally named the "tuff of Indian Flat" by Hammond, have yielded K-Ar ages of about 25 Ma.

gravel at its contact with the bedrock. No obvious source for the gold, such as mineralized land in the drainage basin of the river, has been documented. Is it possible that the placer deposits are reworked gold from Naches sandstone, or derived from the abundant silicified and altered rhyolite lava flows in the Naches Formation? At the righthand curve not far after Kaner Flat (2.2 mi or 3.5 km), a roadcut exposes a bed of gravel, possibly correlative with nearby interbeds, at road elevation at the base of the flow.

To help visualize the amount of structural deformation in the last 5 m.y. in the bedrock near here, note that the Columbia River Basalt Group lavas lie in the Naches Valley at an elevation of about 2600 ft (793 m), yet at Manastash Ridge, 5 mi (8 km) to the northeast, those same lavas are

photo by Beth Norman



Figure F-21. Platy jointing in an andesite flow of Fifes Peaks volcano with a thin tan pumice layer sandwiched between flow breccias. This outcrop is north of the highway near MP 87.

exposed at about 6000 ft (1829 m) at the top of a fold—a total of 3400 ft (1037 m) of structural relief, presumably related to a regional combination of faulting and folding. Note also that the northwest alignment of the Little Naches and Naches River valleys is roughly parallel to, and likely controlled by nearby faults and folds, as well as by the Olympic–Wallowa lineament (OWL). Reidel and Campbell (1989) have described the structural features and aspects of this area.

There are no signs for Raven Roost until the turnoff 2.6 mi (4.2 km) north of the highway. To get to Raven Roost, you must drive on an unpaved road for 14 mi (22.4 km) up FR 1902; this road is not recommended for trailers or large campers. From Raven Roost and the radio tower site, there are excellent views of Fifes Peaks, Mount Rainier, and the Cascade crest to the southwest, as well as the valley of Crow Creek into which feed several large landslides. At least one of the lakes in the valley, Crow Creek Lake, was formed by a large landslide and contains a submerged forest (not yet dated). This area is the southern margin of the OWL near where it meets the north-trending Straight Creek fault (see Fig. 14, p. 18), which bisects the North Cascades and is truncated at the OWL (see Fig. 5, p. 7).



Figure F-22. Fifes Peaks from the viewpoint along SR 410. The dark, castle-like mass in the center is an eroded caldera fill of welded volcaniclastic debris; arrows show its approximate contact with the pre-eruption caldera rim (Hammond and others, 1994). View is to the north.

Upon returning to SR 410, remember to compensate for mileage along the side trip.

Cross the Little Naches River. The route now follows the American River. On the right (north) are gravels that likely are glacial outwash deposits of Evans Creek age (22–15 ka) atop a Grande Ronde Basalt outcrop (Fig. F-19). Outcrops for the next several miles are basalt.

40.3 *64.8* MP 92 is at the west end of the Naches River bridge.

40.7 *65.5* FR 1709 on the left leads south up Devil Creek via Old River Road. FR 1709 provides good access to east side of the William O. Douglas Wilderness. Many landslides are exposed along FR 1709 from Boulder Cave to the headwaters of Devil Creek.

41.2 *66.3* For about the next 1.5 mi (2.4 km) Grande Ronde lava columns are oriented nearly horizontally and in places chaotically.

42.0 *67.6* Trailhead for Indian Flat Trail to the right.

42.9 *69.0* Indian Flat Campground on the left.

43.6 *70.2* A cut on the right exposes a light tan pyroclastic flow breccia of Fifes Peak Formation age that con-

tains charred logs and flattened pumice, both preferentially aligned with the direction of the flow (Fig. F-20). Carkin (1988) obtained a date of about 20 Ma on this fragmental deposit, indicating that it may predate the eruption of the Grande Ronde flows. How was such an easily erodable fragmental deposit preserved? Perhaps by being covered by lava not long after being emplaced. The source of the pyroclastic flow deposit is not known, but it could have originated from any one of a number of volcanic centers, such as a dacite plug near Union Creek or other domes near Crystal Mountain.

Along the road, landslide blocks, probably of the upper N_2 flow of Grande Ronde Basalt, have been displaced downslope about 330 ft (~100 m). Many of the bluffs for the next 2.5 mi (4 km) surrounding this basin display headscarps and landslide blocks.

43.8 *70.5* Turnoff for Leg O, Bumping Lake on FR 18/Bumping River Road, an 11-mi (17.5 km)-long route up the glaciated valley of the Bumping River from its confluence with the American River to Bumping Lake reservoir. Fine views of peaks to the south await as you head upstream in the American River drainage. The road passes volcanic and intrusive rocks and the deposits of large landslides originating from surrounding ridges.

44.0 *70.8* Landslide blocks are common near here, slightly east of MP 88.

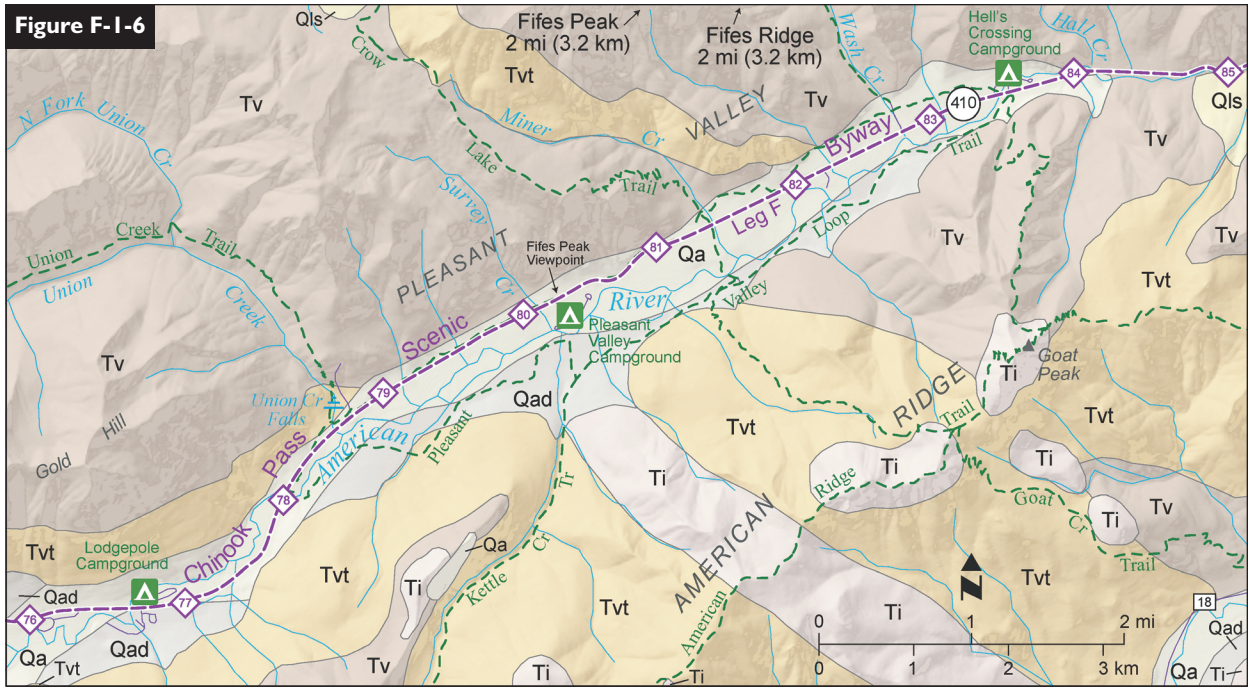
45.1 *72.6* The turnout to the north (right) is in more landslide deposits.

45.3 *72.9* Platy jointing is visible in an andesite flow of Fifes Peaks volcano with a pumice layer sandwiched between flow breccias (near MP 87)(Fig. F-21).

46.0 *74.0* Pine Needle Campground is on the left. There are many breccias of the Fifes Peak Formation over the next few miles. Lava flows and breccias of underlying Goat Peak volcano are also exposed.

46.3 *74.5* MP 86. Till deposits crop out in this area. Campbell (1975) concluded that this represents the "farthest advance of valley glaciers during the Pleistocene". The unconsolidated debris in roadcuts is probably morainal material from those glaciers. There are many landslides between Pine Needle Campground and Hall Creek near mile 48.1.

Figure F-1-6



46.6 *75.0* Note the fragmental volcanic deposits of the Fifes Peak Formation that contain large blocks.

47.0 *75.6* Fragmental deposits, probably of glacial origin, are in cuts on both sides of the road. Subrounded and faceted rocks such as those seen here commonly characterize glacial till and coarse outwash deposits. The house-sized boulder in the river slightly south of the highway is likely part of a landslide deposit.

47.3 *76.1* MP 85. Outcrop of volcanic rocks with possible till deposited over it.

47.9 *77.1* View of Fifes Peaks ahead to the north.

48.1 *77.4* Cross the American River.

48.3 *77.7* MP 84. Till and landslide deposits are visible here.

48.6 *78.2* Hells Crossing Campground on the right (north) and the trailhead for Goat Peak Trail and Pleasant Valley Loop Trail on the left, with a view of Fifes Peaks ahead. The terminal moraine (not on map) of the most recent major alpine glaciation, which is called the Evans Creek glaciation (22–15 cal yr ka) at Mount Rainier, is near this area, but not visible from here.

48.8 *78.5* American River. Hells Crossing Snow Park and Pleasant Valley groomed ski trail system.

49.1 *79.0* Dry wash.

49.3 *79.3* MP 83. Wash Creek and trailhead for Fifes Ridge Trail, which accesses higher country to the north. Note the U-shaped American River valley, carved by multiple glaciations.

50.7 *81.6* Fifes Peaks Viewpoint and trailhead for Crow Lake Way Trail (#953). This spectacular geological viewpoint was constructed by the Washington State Department of Transportation (Fig. F-22). Look for mountain goats on Fifes Peaks.

From this location you get a dramatic look at the caldera margin of the Fifes Peaks volcano. The flows forming the castle-like jagged eastern ridge that rises as high as 6917 ft (2108 m) are a part of the Fifes Peaks caldera-fill deposits.

photo by Beth Norman



Figure F-23. Dikes, chiefly of rhyolite, intrude well-stratified beds of the Ohanapecosh Formation. The dike is at the bottom of the photo, below the hammer handle.

The existence of the 4-mi (7 km)-wide caldera was discovered during detailed mapping of the volcano at Fifes Peaks (Hammond and others, 1994). The mapping produced a detailed stratigraphic section of the Fifes Peak deposits. The caldera is filled to a maximum depth of 2800 ft (~850 m); the fill includes volcaniclastic lakebed deposits, glassy lava flows, lithic-rich surge deposits, and palagonitic beds that provide evidence of water and of phreatomagmatic eruptions. One can imagine that a lake once existed in the caldera before it was filled to the brim with lava flows and debris.

Hammond and his colleagues (2000) made a detailed study to clarify some uncertainty over the source and relations of the lava flows in this area with chemically similar lavas west of here in Mount Rainier National Park. These two groups of lavas were originally thought to have erupted from the same source. However, fission-track and uranium-lead (U-Pb) dating of rocks from both areas showed a significant difference in their ages: 25–24 Ma for the Fifes Peaks area and ~22 Ma for the strata to the west of Dalles Ridge, 18 mi (29 km) northeast of Mount Rainier (see Leg D). This suggests that there must have been a different source area for the two groups of lava flows.

The Bumping River tuff underlies the basal units of the Fifes Peaks volcano. Underlying all of these are the more steeply east dipping lava flows and tuffs of Goat Peak volcano of the Ohanapecosh Formation.

The Crow Lake Way Trail winds up the Miner Creek drainage and along an east–west to north–south ridgeline on Union Creek lava flows of the Ohanapecosh Formation. This trail offers excellent views into the American River valley. From the trail, you can look across the valley to a large landslide (not shown on map) that pushed the American River to the northwest side of valley. In this area, it is not uncommon to see mountain goats or to hear elk bugling in the autumn.

50.9 *81.9* Pleasant Valley Recreational Site and campground on the left. In the late 1980s, road builders straightened curves in this area.

53.1 *85.4* A large glacial erratic sits on morainal deposits north of the highway.

53.3 *85.8* MP 79. A rhyolitic sill exposed in a roadcut just west of the MP is overlain by a poorly sorted deposit or diamict that is probably till. Other deposits here are of fluvial origin or possibly are glacial outwash.

54.1 *87.1* Trailhead for the Union Creek Trail (#956) and the Pleasant Valley Loop Trail (#999), which parallels SR 410 south of the river.

More dikes, chiefly of rhyolite, intrude well-stratified beds of the Ohanapecosh Formation between the #956 trailhead and the American River (Fig. F-23). The graded bedding seen in the Ohanapecosh rocks is common in deposits of sediment-rich streamflow and slurries.

54.3 *87.4* Cross the American River at MP 78.

54.6 *87.9* A quarry on left in the toe of landslide deposits reveals a dacite porphyry intrusive rock with hexagonal biotite phenocrysts. It contains inclusions of Bumping River granite, showing that the dacite intruded the granite. More Ohanapecosh rocks are on the right and at mile 55.1.

55.6 *89.5* Lodgepole Campground on the right. The hills of American Ridge to the south are composed of the Ohanapecosh Formation and multiple dikes.

photo by Beth Norman



Figure F-24. Bumping Lake granite with inclusions of dark andesite slightly east of MP 73.

56.3 *90.6* MP 76. Mesatchee Creek Road. The trailhead for the Mesatchee Creek Trail is on left; ahead is a view of the Cascade crest.

57.1 *91.9* Greenish rock here is part of the Ohanapecosh Formation.

57.4 *92.4* Trailhead for the Bear Gap Trail, slightly west of MP 75.

57.5 *92.5* Cross Morse Creek upstream of the Morse Creek–Mesatchee Creek confluence with the American River. Some gold and copper have been discovered in several prospects in this area, although mining claims were dropped just prior to the designation of the Norse Peak Wilderness area in 1984. The rocks along this stretch of road have been altered by hydrothermal fluids that deposited sulfides such as pyrite (iron sulfide). This mineral-bearing area extends north-northwest to Crystal Mountain and south-southeast into Mesatchee Creek. (See the "Alteration and Mining North and East of Mount Rainier" sidebar on p. 117.)

The hydrothermal fluids that stewed the rocks in this area were associated with the intrusion of several dacite plugs along the north margin of the Bumping Lake pluton.

The Bumping Lake pluton is a giant lozenge-shaped body of granite and granodiorite whose exposed area is about 61 mi^2 (157 km^2). SR 410 passes through the northwest margin of this

Alteration and Mining North and East of Mount Rainier

by Rebecca A. Christie and Katherine M. Reed

Geology of Altered Rocks Northeast of Mount Rainier

The alteration in the Summit mining district was described by Slater (1915), a mining engineer working in the area, although his descriptions are mainly lithologic. There are no published dates on the age of alteration of rocks in this area. Slater, however, did describe the alteration along intrusive boundaries and along a zone of sheared rocks that trends N 50°W, roughly parallel with the fault zones described by Blakely and others (2007), so it is possible some of the alteration is contemporaneous with that in the White River area (p. 89). The altered rocks in the Summit mining district evidently include some pre-Miocene rocks in addition to rocks of the Fifes Peak Formation.

Early Activity in the Summit Mining District

Placer mining was first recorded in the area that later became the Summit mining district in about 1880, particularly near the head of Morse Creek. Placer ground in that area yielded gold nuggets worth as much as $140 each, and $1.50 nuggets were not uncommon (Moen, 1962; gold at that time was worth $20.67 per ounce). Subsequent prospecting in this area for the source of this gold revealed lode deposits that assayed as much as 13 ounces of gold per ton* and as much as 50 ounces of silver per ton, as well as minor amounts of copper and lead. The area around Morse Creek is still popular with gold prospectors, and there are numerous unpatented mining claims in the Mount Baker–Snoqualmie National Forest.

Prospectors filed the first claim at Gold Hill (on the northeast side of Morse Creek) in 1888. Mining for gold and silver exploded in this area during the late 1800s and again in the early 1900s. Much of the gold is very fine and was commonly found free on the ore's surface, owing to the oxidation of iron, or in veins in fractured andesite.

The Summit mining district, organized in 1891, is in the Cascade foothills east of Mount Rainier's summit in the area north and south of SR 410 between Lodgepole Campground and Chinook Pass (Butler, 1934). It covers about 8 mi² (20 km²) in parts of Pierce and Yakima Counties. The Cougar Lake Limited Area (Moen, 1962) covers land in both the Summit and Bumping River districts; it contains the area of the Copper Mining Company's claims.

Numerous mining properties were located in the district. Wernex (1962) reported that an elderly local resident had estimated there were more than 250 claims in the district—probably a low estimate. Hodges (1897) noted there were at least 31 by 1896. There was abundant timber for supporting the roofs of the numerous tunnels and plenty of water. Some of the operations were: Gold Hill Consolidated (36 claims; said to have an "unusually large body of quartz porphyry and quartz veins carrying gold" [P. C. Stoess, unpub. report, 1943]); mines on Pickhandle Ridge and Crystal Ridge (large areas of low-grade ore at the surface); and Manitau Mining and Milling Co. (40 claims on shear zones, veins, contact metamorphism; pyrite and pyrrhotite with associated gold, silver and copper, as well as minor nickel and cobalt). Near the headwaters of Silver Creek were at least three mines that produced more than $1000 before 1945. The bedrock source is likely the Stevens Ridge Formation.

Generally, however, the value of any mined mineral per ton was disappointingly low. Stoess (unpub. report, 1930) wrote, "the average samples taken quite generally showed values from 50¢ to about $4.00 or $5.00 per ton in gold", concluding, however, that "even a casual inspection of the showings on the West side indicate the possibility of large if low grade gold deposits". More details for the district are available in Derkey and others (1990) and Huntting (1956).

Interest in Summit district gold lodes waned, partly because it was not thought to be economical to mill the low-grade ores, partly because the area was difficult to reach (P. C. Stoess, unpub. reports, 1930, 1934). Hodges (1897) had reported that it was more than 50 mi (90 km) by trail up the White River from Buckley and nearly 70 mi (112 km) by horse trail from an outfitting station up the Yakima River. In addition, both the Yukon gold rush and the Great War may have drawn some interest away from this area. Nevertheless, the Works Progress Administration had a crew in the area in 1936 to gather information that might spur development (P. H. Knowles, unpub. report, 1938).

Bumping Lake Mining District

A second area of mining activity, the 175-mi² (~450 km²) Bumping Lake mining district, was organized in 1913. This district is bounded on the northwest by the crest of American Ridge and on the east by the Tieton drainage basin. (The leg maps for Leg O cover some of the district's area.) A district map for that year shows numerous claims and several mines.

At the Copper Mining Company's 42 claims on Miners Ridge, about 3 mi (4.8 km) south of the west end of Bumping Lake, copper, molybdenum, gold (trace), and silver, as well as tungsten (trace) locally, were found in hydrothermally altered rock near granite (Culver and Broughton, 1945). Geologist Paul Hammond has mapped Miners Ridge as Bumping Lake granite, which was dated by R. A. Duncan of Oregon State University at about 24 Ma (Hammond, Portland State Univ., written commun., 2000). Exploration work began in 1906, and in 1934, a 50-ton (45 metric ton) mill was set up to concentrate the ore. During the life of the operation, 22,000 lb (~10,000 kg) of copper concentrate and 650 lb (295 kg) of tungsten concentrate were shipped to the smelter (Moen, 1962). The company was dissolved in 1961 for nonpayment of incorporation fees.

About 1917, $30,000 was spent to open a tungsten mine between Bumping Lake and the Copper City camp, a site that can be reached by FR 162, which follows the drainage of Deep Creek south from Bumping Lake. (This road branches south off FR 1800 beyond the end of Leg O.) The mine proved valueless, however.

Wernex (1962), following an interview with a long-time local resident, wrote: "In 1956, the quest for uranium set off a stampede in the area of Copper City and Bumping Lake, resulting in claim jumping and lawsuits". However, nothing came of this flurry of action. ■

* 1 troy ounce per 2000 avoirdupois pounds = 34.276 milligrams per kilogram.

batholith. Many dikes have intruded the Bumping Lake granite and are therefore younger, ranging from 3.4 to 11 Ma, whereas an average of four $^{40}Ar/^{39}Ar$ ages on biotites of the Bumping Lake pluton is 23.75 Ma. The chunks of Ohanapecosh Formation scattered between dikes are remnants of intruded country rock. The beds in the Ohanapecosh are generally east dipping because they lie in the east limb of the north–south-trending Chinook Pass anticline.

58.8 *94.6* Outcrops of intrusive rock with yellow alteration for the next 0.7 mi (1.1 km).

59.1 *95.1* Bumping Lake granite with inclusions of dark andesite is exposed at a pullout (Fig. F-24).

59.3 *95.4* MP 73.

59.5 *95.7* Yellowish grus is exposed to the north slightly west of MP 73. You are on the northwest margin of the Bumping Lake batholith.

59.7 *96.1* View of Chinook Pass area (for those westbound) ahead and of a glacial hanging valley and cirque(s) to the left.

59.9 *96.4* Well-developed bedding is visible here in the Ohanapecosh Formation. Outcrops from miles 60.0 to 60.2 (km 96.0–96.3) are granodiorite intrusive rocks.

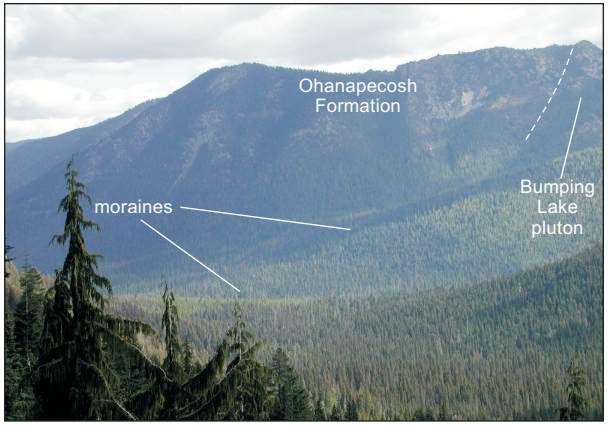


Figure F-25. Recessional lateral moraines in the American River valley at the confluence of the Rainier Fork American River (foreground) and the American River (background). Note the contact between the northwest tip of the approximately 25 Ma Bumping Lake pluton (extreme upper right) and the older (36–27 Ma) Ohanapecosh rocks that make up the southwest tip of American Ridge. View is to the southeast.

60.3 *97.0* MP 72. Riprap has been used in an attempt to stabilize small landslides in an area where colluvium overlies glacial deposits.

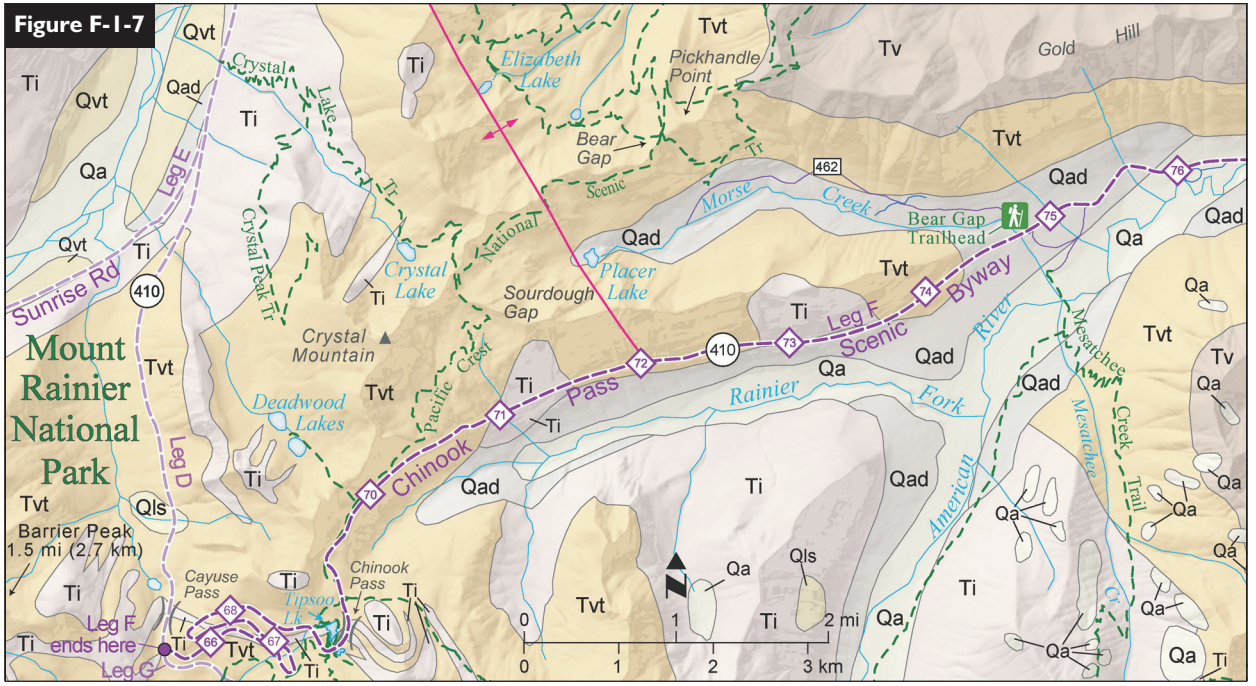
60.4 *97.2* A till is exposed north of the highway near here. Recessional moraines of alpine glaciers that occupied the American River valley are visible in the valley to the southeast from two small pullouts on the south side of the highway (Fig. F-25).

61.3 *98.6* MP 71. At a small pullout about 430 ft (130 m) west of MP 71, an unsorted deposit, probably glacial till, overlies glacially polished bedrock. In the bedrock, a dike cuts an inclusion-bearing intrusive rock. A second larger turnout slightly farther west is also near well-polished bedrock.

61.4 *98.8* A probable till deposit is exposed at a small turnout.

62.0 *99.8* Outcrops of Ohanapecosh Formation volcanic rocks are cut by dikes and sills from here to Chinook Pass. MP 70 is just west of here.

62.8 *101.1* Chinook Pass viewpoint. (There are restrooms here.) This overlook (elev. 5432 ft or 1656 m) offers a beautiful vista to the southeast down a glaciated U-shaped valley of the Rainier Fork American River (Fig. F-26). Ohanapecosh bedrock, including a welded tuff, and many andesite dikes and sills crop out on the north side of the highway at the pass.



63.2 *101.8* Enter Mount Rainier National Park. The Pacific Crest Trail, a National Scenic Trail that stretches from Mexico to Canada, crosses the highway here. Many tephra layers are visible in outcrop on the south side of the highway about 150 ft (46 m) west of the national park boundary. USGS geologist Jim Vallance (written commun., 1999) identified Mount St. Helens layers X (~A.D. 1500) and Wn (A.D. 1479), Mount Rainier layer C (~2,200 yr B.P.), Mount St. Helens layer P (~2,500 yr B.P.) containing an interbedded Mount Rainier ash, Mount St. Helens set Y layers (~3,500 yr B.P.), Mount Rainier layers F, N, D, L, and an unnamed layer and not-yet-named pumice (mostly of the Osceola and Cowlitz Park eruptive episodes; see Fig. 34, p. 37), and the orange Mount Mazama ash that was erupted about 7,500 cal yr B.P. in the great eruption that created the Crater Lake caldera.

63.3 *101.9* The view to the north of Tipsoo Lake and Mount Rainier is spectacular if the weather is clear (Fig. F-27). The craggy peaks visible on the horizon to the southwest are the Cowlitz Chimneys (Ohanapecosh Formation).

63.6 *102.3* Tipsoo Lake parking lot. (There are restrooms here.) The parking lot on the right (westbound) has trails that lead around the lake and connect with several major trails including the Eastside Trail and Pacific Crest Trail. A rhyolite sill 650 ft (~200 m) northwest of the parking area along the highway has been dated at 25.8 Ma by Mattinson (1977). From here to Cayuse Pass are spectacular outcrops of bedded Ohanapecosh rocks cut by dikes and sills.

64.1 *103.1* This small pullout has a view of Mount Adams volcano (south), the Tatoosh Range (southwest), and Sawtooth Ridge, a cuesta of south-dipping volcaniclastic rocks of Oligocene age (southwest).

64.5 *103.8* Welded lapilli-tuff with fiamme, or flattened pumice, near here is cut by nearly horizontal dikes. A similar feature in the Stevens Ridge Formation is

photo by Beth Norman



Figure F-26. Chinook Pass viewpoint offers a beautiful vista to the southeast down a glaciated U-shaped valley of the Rainier Fork American River.

shown in Figure B-11. As the road switches back, you descend through older strata in this section of Ohanapecosh Formation rocks.

64.9
104.4 A cirque is visible to the west on the east face of Barrier Peak, and to the southwest is a view of the Tatoosh Range and Sawtooth Ridge.

65.2
104.9 A dike is visible to the north.

65.7
105.7 Denser rock with slickensides locally—these may indicate right-lateral offset. However, the rock on either side of the fault appears to be the same welded tuff exposed up the road. The nearly vertical joints visible here likely had a role in the failure/creation of the big talus blocks. There is a nice view to the west from this area. Note the nearly vertical dikes that crop out in the cliffs to the north. They appear to dip just slightly west and strike to the north-northeast.



Figure F-27. Mount Rainier from Tipsoo Lake. Cowlitz Chimneys are silhouetted in front of Mount Rainier. View is to the west.

66.0
106.2 This is a fine area to view the mid-lower part of the Ohanapecosh section of rocks, including some thick tuffs and bedded volcanic rocks dipping to the east-southeast (Fig. F-28).



Figure F-28. Volcaniclastic rocks of the mid-lower part of the Ohanapecosh section and a reddish altered zone adjacent to an overlying sill. The view is to the northeast along SR 410, a short distance east of Cayuse Pass.

66.4
106.8 Cayuse Pass (elev. 4694 ft or 1432 m); junction with SR 123. You can continue on SR 410, driving Leg D in reverse, or go south on SR 123 (Leg G) toward the Stevens Canyon Entrance to Mount Rainier National Park or to access US 12 (Legs C and H).

Remember to reset your odometer when you start another leg. ■

LEG G: STATE ROUTE 123

From Cayuse Pass to the Ohanapecosh area and U.S. Highway 12

by Patrick T. Pringle, Paul E. Hammond, and Newell P. Campbell*

This 16-mi (26 km) route descends from Cayuse Pass (elev. 4694 ft or 1432 m) south along Chinook Creek and the Ohanapecosh River to the junction with U.S. Highway (US) 12 (elev. ~1590 ft or 485 m) (Fig. G-1). The Chinook Creek valley is a deep cut into the thick section of Ohanapecosh Formation rocks (late Eocene to mid-Oligocene age) at their type locality. The road passes over Deer, Panther, Laughingwater, and Summit Creeks and crosses at least two large landslides of Ohanapecosh rocks. It is the main route connecting the north, east, and south sectors of Mount Rainier National Park and provides access to many popular hiking trails. Some of the trails, such as the Eastside and Laughingwater Trails, in this part of the national park access spectacular examples of old-growth forests.

This road is closed in winter (typically November to late June) and is subject to closure owing to landslides. SR 123 washed out in four places during the flood of November 2006. Road status can be checked at the Mount Rainier National Park website or by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Start south on State Route (SR) 123 at its junction with SR 410 at Cayuse Pass (elev. 4694 ft or 1432 m). This road accesses the Stevens Canyon Entrance of Mount Rainier National Park (Leg B) as well as US 12 (Legs C and H).

The outcrop on the right is porphyritic andesite.

0.5 *0.8* Milepost (MP) 16. Glacial drift.

0.6 *1.0* A gray diamicton (till?) is overlain by yellowish Mount St. Helens(?) tephra.

0.9 *1.4* Beds of the Ohanapecosh Formation crop out here (Fig. G-2).

1.1 *1.8* Small pullout at a sharp curve to the left. Ohanapecosh beds dip 15 to 20 degrees to the north here and strike east–west. A dike related to the Tatoosh pluton (25.8 to14.1 Ma) cuts welded tuff and lacustrine sedimentary rocks (Fig. G-3).

1.3 *2.1* Another dike. According to Fiske and others (1963), the Tatoosh intrusions are chiefly fine- to medium-grained porphyries that range in composition from diorite to quartz monzonite.

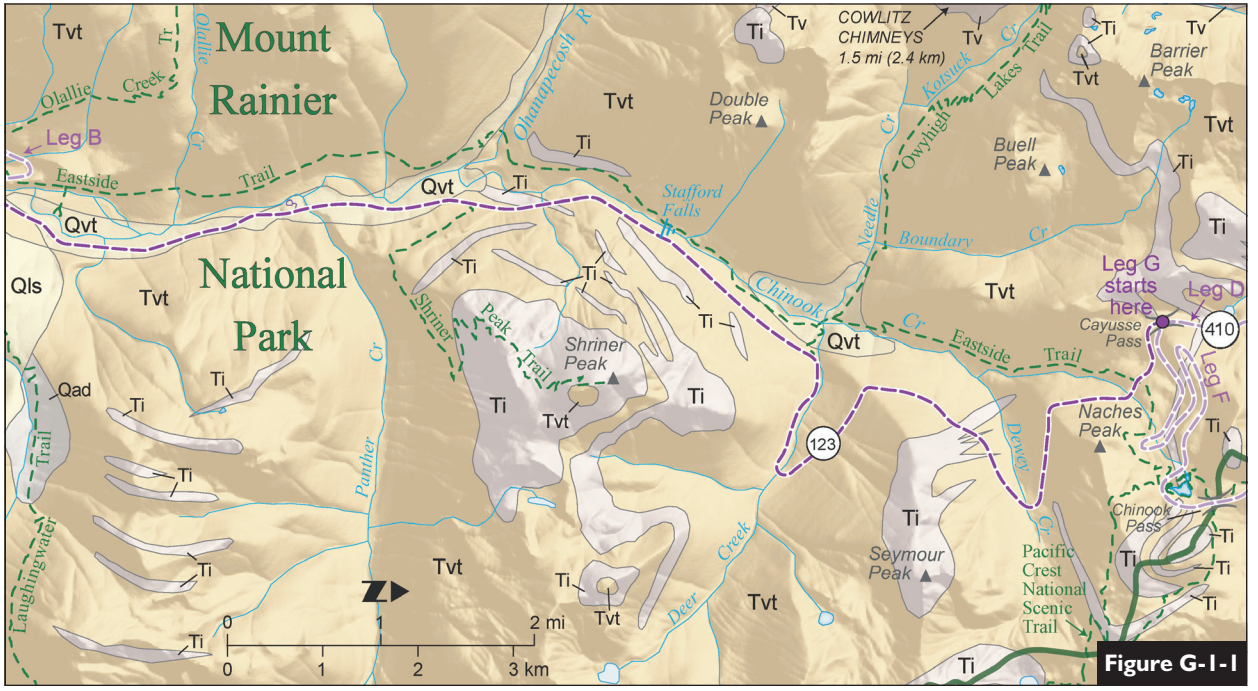
1.5 *2.4* MP 15. Outcrop of Ohanapecosh beds.

1.8 *2.9* Cross Dewey Creek.

2.0 *3.2* Small waterfall and outcrop of Ohanapecosh Formation volcaniclastic rocks (Fig. G-4).

2.1 *3.4* Till on the left.

Figure G-1. Location map for Leg G (two consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover. *Note:* This leg is run from north to south and the map route is rotated and runs from right to left on each panel.



* See "Contributors", p. ii, for affiliation.

2.3 *3.7* The peaks (6198 ft; 1889 m) ahead are rhyolite and andesite volcanic plugs called the Cowlitz Chimneys, a vent area of Ohanapecosh deposits.

2.7 *4.3* Tunnel in the Ohanapecosh Formation (Fig. G-5).

3.0 *4.8* At a pullout to the right, Ohanapecosh Formation tuffs crop out.

3.2 *5.1* Diamict, probably an alpine till, is exposed sporadically in this area (Fig. G-6).

3.4 *5.4* MP 13.

4.0 *6.4* Cross Deer Creek.

4.8 *7.7* Ohanapecosh Formation and Owyhigh Lakes trailhead.

5.3 *8.5* Pullout to the left (east of the road) and a creek. A trail leads down to Deer Creek campsites and the Eastside Trail, which follows Chinook Creek and the Ohanapecosh River.

5.4 *8.7* MP 11.

5.5 *8.8* Ohanapecosh Formation breccias and andesite dike are in the outcrop here.

5.9 *9.4* This steep gully cuts into the Ohanapecosh Formation.

6.1 *9.8* Alpine glaciers polished and smoothed this bedrock of the Ohanapecosh Formation (Fig. G-7).

6.3 *10.1* Turnout on the right. Falls on the left flow over Ohanapecosh breccias. The creek heads on Shriner Peak.

6.4 *10.3* MP 10.

7.1 *11.4* Landslide to the east (not shown on map) developed on Ohanapecosh rocks that are cut by many Tatoosh pluton dikes and sills.

7.3 *11.7* MP 9 turnout.

7.4 *11.9* Trailhead for Shriner Peak Trail on the east.

8.0 *12.9* Exposures of landslide debris and mounded topography for about the next 0.5 mi (0.8 km) in the Panther Creek area.

8.5 *13.6* Cross Panther Creek.

8.8 *14.1* Outcrops of Ohanapecosh Formation for next 0.3 mi (0.5 km).

10.7 *17.2* Ohanapecosh tuff breccias crop out slightly north of the junction of Stevens Canyon Road.

10.8 *17.3* Stevens Canyon Road and Stevens Canyon Entrance to Mount Rainier National Park (elev. ~2208 ft or 673 m) (see Leg B, p. 68). This road heads to Paradise and the Nisqually River Entrance to Mount Rainier National Park.

11.1 *17.9* Trail to Silver Falls (west) and Laughingwater Trail (Fig. G-8).



photo by Beth Norman

Figure G-2. Beds of Ohanapecosh Formation volcaniclastic rocks along SR 123 near Cayuse Pass.



Figure G-3. Dike cutting faulted Ohanapecosh tuffaceous rocks (west or left) and lacustrine beds (east) along SR 123 about 1.1 mi (1.8 km) south of Cayuse Pass. The dike is about 15 ft (4.6 m) wide. View is to the north.

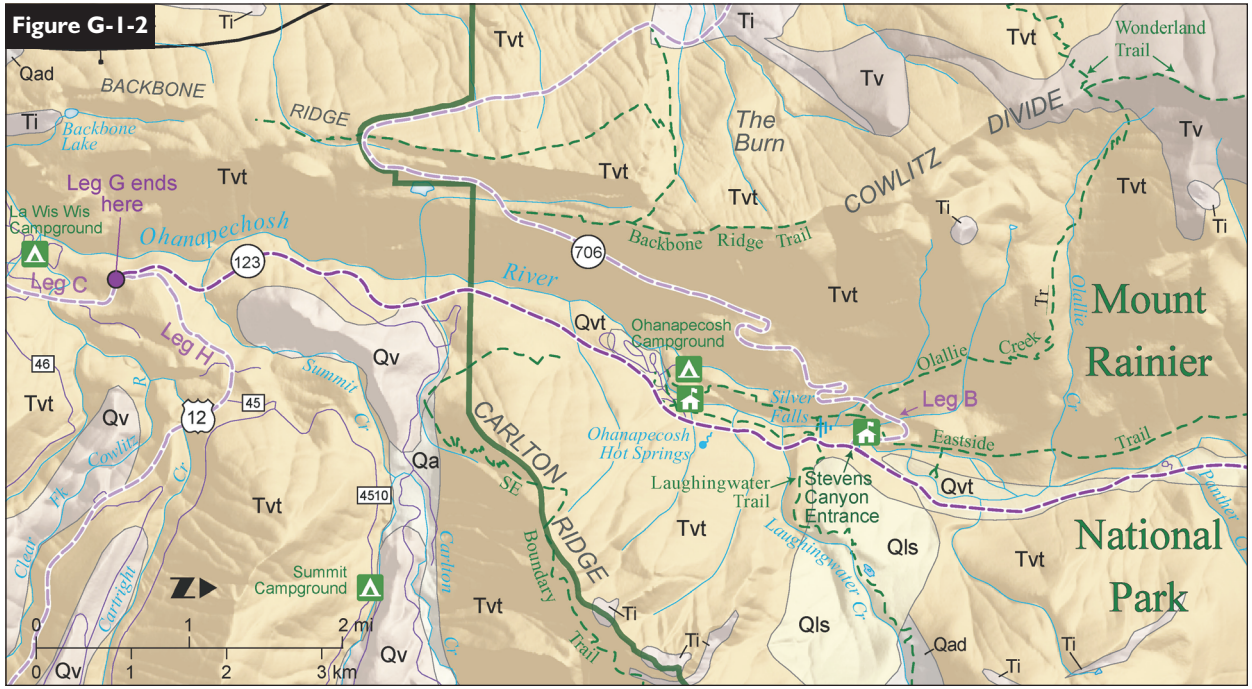


photo by Beth Norman



Figure G-4. Small waterfall and outcrop of Ohanapecosh Formation volcaniclastic rocks about 0.2 mi (0.3 km) past Dewey Creek (southbound).

11.2 *18.0* Landslide on the left and Laughingwater Creek a bit farther (MP 5). The landslide deposit is likely part of the large Laughingwater landslide complex. The landslide evidently dammed the Ohanapecosh River at one time, and this damming may have facilitated deposition of the sediments that compose the flat terrace north of Stevens Canyon Road and west of SR 123. A 6-in. (15-cm) layer of brown pumiceous tephra sits atop the landslide debris adjacent to the road. This light-brown pumice resembles the C layer erupted from Mount Rainier about 2,200 cal yr B.P., which would indicate the landslide deposit was emplaced before that layer was erupted. Yellowish layer Yn pumice from Mount St. Helens, which was erupted 3,800–3,600 cal yr B.P., is not visible, so the landslide may be younger than that pumice. The hummocky terrain of the landslide deposit appears to extend for as much as 1 mi (1.6 km) along SR 123.

11.5 *18.5* Ohanapecosh breccia is exposed on the west side of the highway here.

photo by Beth Norman



Figure G-5. Tunnel in the Ohanapecosh Formation about 2.7 mi (4.3 km) from Cayuse Pass on SR 123.

photo by Beth Norman



Figure G-7. Alpine glaciers polished and smoothed this bedrock of the Ohanapecosh Formation between MPs 10 and 11.

12.6 *20.3* Turn right into the Ohanapecosh Campground. The Ohanapecosh Campground is an excellent 'base camp' from which to explore the trails on the east side of Mount Rainier National Park or in the White Pass area. Travertine mounds deposited by mineral springs are only a short distance up the Hot Springs Nature Trail from the campground (Fig. G-9). (See the "Ohanapecosh Hot Springs" sidebar on p. 123.)

13.5 *21.7* Large boulders on the west side of the road could be glacial erratics or landslide debris.

photo by Beth Norman



Figure G-6. Diamict, probably an alpine till, on the east side of SR 123 slightly north of MP 13.



Figure G-8. Silver Falls, from the Eastside Trail near its junction with the Three Lakes Trail. The falls are about 60 ft (18 m) high and are controlled by a complex interplay of dikes, joints, and bedding. View is to the north.

13.6 *21.9* Outcrops of green Ohanapecosh volcaniclastic rocks for next 0.2 mi (0.3 km) (Fig. G-10). The green color results from chlorite and other clay minerals produced by low-grade metamorphism during burial.

Leaving Mount Rainier National Park; pullout on the right. Ohanapecosh tuffs and breccias are exposed for the next 2.5 mi (4.0 km).

Ohanapecosh Hot Springs

by Rebecca A. Christie and Katherine M. Reed

To Native Americans, Ohanapecosh meant "looking down on something beautiful", "deep blue stream", or perhaps "clear water". (As with many Native names, the original meaning seems to have been lost.) The Ohanapecosh River originates at the inactive Ohanapecosh Glacier (southeast of Whitman Glacier) on the east side of Mount Rainier.

As many as 25 thermal springs in this area feed the river. Reports about the waters differ—some sources note at least one cold spring, while others describe water as hot as 124ºF (51º C)(U.S. National Park Service, 1934?) and flows as great as 250 liters/minute (about 66 gallons/minute) (Graham, 2005). Glover (1936, p. 72) mentioned "The water has a moderate soda and sulphur content."

The hot springs were a popular tourist destination, and after a few years of operation, more than 1000 visitors annually came from afar to camp and partake of the mineral waters. In the early 1900s, access was by way of a 12+-mi (~20 km) trail from Packwood or a somewhat longer trail from Narada Falls below Paradise. There was a tent camp facility at the hot springs by 1913. A Tacoma partnership picked up development in 1925, constructing a road and several buildings, in hopes that the therapeutic reputation of the springs would spread. The springs were just outside the initial park boundary, on Forest Service land. The Park Service had an early interest in acquiring the hot springs land and, in spite of the opposition of local residents, the area was incorporated into the park in 1931. The action was primarily an effort to protect the natural feature, although there was some concern about the activities of the numerous visitors so close to the park.

The Civilian Conservation Corps built a campground at the springs in the late 1930s. Eventually the springs facilities boasted a lodge, as well as bathhouses and cabins. In 1939, one could stay at Ohanapecosh Lodge for $4 a day, and dinner cost $1. In that year, the Ohanapecosh Hot Springs Company increased the number of cabins to 25 and even built a garage. Several more cabins were added in 1941 (Catton, 1995); the resort was privately operated through the 1950s.

Although the springs were now located within the park, the Park Service was ambivalent about how or whether to manage the concession and facilities, finally deciding to close them in 1960. The original buildings have been removed. Today, the Ohanapecosh Campground has about 200 campsites, nature trails, and facilities. The springs remain as wet areas and seeps. ■



Figure G-9. A travertine mound along the Hot Springs Nature Trail near Ohanapecosh Campground. This mound is about 7 ft (2 m) high.



photo by Beth Norman

Figure G-10. Outcrops of Ohanapecosh volcaniclastic rocks are common along SR 123. Note vertical and subvertical joints.



photo by Dave Norman

Figure G-11. Geologist Beth Norman stands next to an outcrop of a poorly sorted lahar deposit exposed east of the road. The hammer is across a hardened cavity created where a rock dropped out of the outcrop; a second cavity is higher and to the left. The lahar has been compacted by the weight of an alpine glacier, now melted away. The outcrop is east of the road, slightly south of MP 1.

14.3 *23.0* Poorly sorted lahar deposit with large rounded blocks.

15.2 *24.5* Poorly sorted Ohanapecosh beds dip ~45 degrees to the west and may be lithified lahar deposits.

15.3 *24.6* MP 1.

15.4 *24.8* A poorly sorted lahar deposit exposed east of the road here has hardened cavities where rocks have fallen from the outcrop (Fig. G-11). These molds are common in fragmental deposits that have experienced what geotechnical experts call 'overconsolidation' due to the ice load from glaciers. Here the deposit overlies Ohanapecosh volcaniclastic rocks, but you can't see them.

15.7 *25.3* Bridge over Summit Creek. This area is part of a post-Evans Creek recessional moraine complex. On the left (west) is an outcrop of Ohanapecosh Formation.

16.3 *26.2* Junction of SR 123 and US 12. From here you could take US 12 east via Leg H toward Naches and Yakima or drive west toward Packwood.

Remember to reset your odometer when you start another leg. ■

LEG H: ACROSS THE CASCADES AT WHITE PASS

Ohanapecosh (State Route 123) to Naches via U.S. Highway 12

by Patrick T. Pringle, Paul E. Hammond, Newell P. Campbell, and Wendy J. Gerstel*

This 46-mi (75 km) leg is the eastern segment of the White Pass Scenic Byway and was featured in Newell Campbell's geologic road guide (1975) (Fig. H-1). The byway passes through one of the most scenic and geologically interesting areas in Washington. There are tens of volcanic centers that range in age from earliest Miocene to Pleistocene. Late Paleozoic/Mesozoic sedimentary rocks and metamorphic rocks, glacial deposits, and large active landslides are also exposed along the way. Begin the journey by ascending from the valley of the Cowlitz River (elev. ~1580 ft or 480 m) through the valley of its tributary, the Clear Fork Cowlitz River, toward White Pass (elev. 4470 ft or 1363 m). En route you will pass west-dipping Ohanapecosh Formation beds (about 36 to 28 Ma, or late Eocene to middle Oligocene age [Vance and others, 1987]) and cross a major fault boundary along the western margin of the Rimrock Lake inlier. The Rimrock Lake inlier is a body of older rocks that pokes up through younger rocks. East of White Pass, you will thread your way through andesitic lavas from Ice Age volcanoes that erupted both north and south of the highway and drive past more outcrops of the pre-Tertiary Rimrock Lake inlier rocks before passing into a section of younger rocks near Tieton Dam. Before arriving at the junction of U.S. Highway (US) 12 with State Route (SR)

* See "Contributors", p. ii, for affiliation.

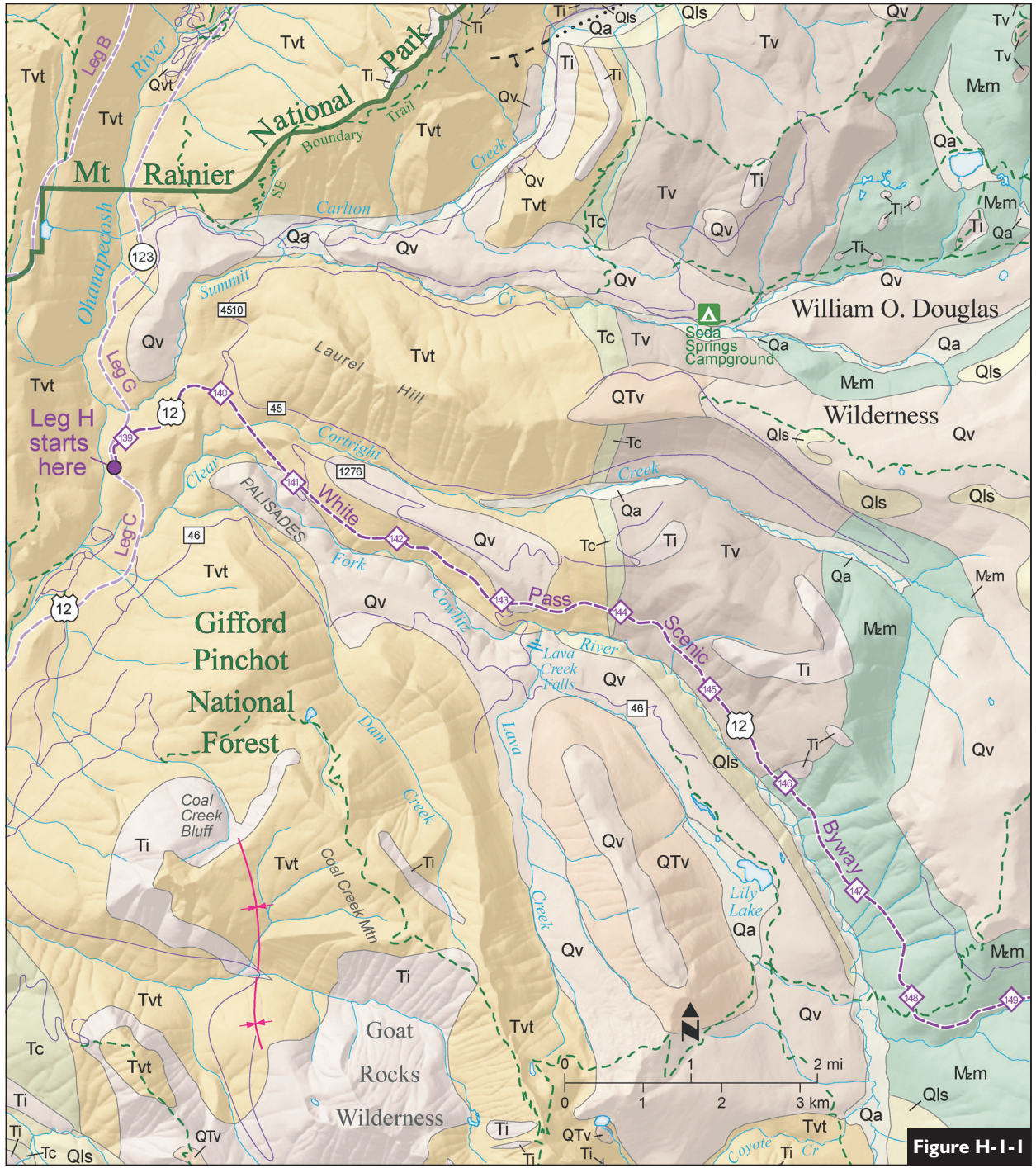


Figure H-1. Geologic map for Leg H (five consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b), Walsh (1986b), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.

Figure H-1-1



Figure H-2. A 6.5-ft (2 m) sill (between arrows) in southwest-dipping beds of Ohanapecosh Formation rocks along the north side of US 12. The beds about 3 ft (1 m) above the sill are gently folded. View is to the northwest.

410 (elev. 1608 ft or 490 m) at the end of Leg H, you will pass some textbook-quality displays of columnar jointing in lava flows and examine a complicated interplay of volcanic deposits and flows buried by younger lavas of one of the world's largest lava flow complexes, the Grande Ronde Basalt. At other locations, invasive flows that entered stream sediments are exposed, and in places river valleys have been displaced or buried by lavas. The distinctive vegetation zones traversed en route have evolved and adapted to both climate and geology.

The highway is sometimes closed in winter, so it is wise to check on road conditions before traveling. Road status can be checked at Washington State Dept. of Transportation via their website or by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Junction of SR 123 and US 12. Sills and pyroclastic flows in Ohanapecosh rocks are visible here. Fiske and others (1963) measured a stratigraphic section of the Ohanapecosh Formation volcaniclastic rocks from Stevens Canyon to the Ohanapecosh River and then to the east along US 12 at 6000 ft (1829 m) thick.

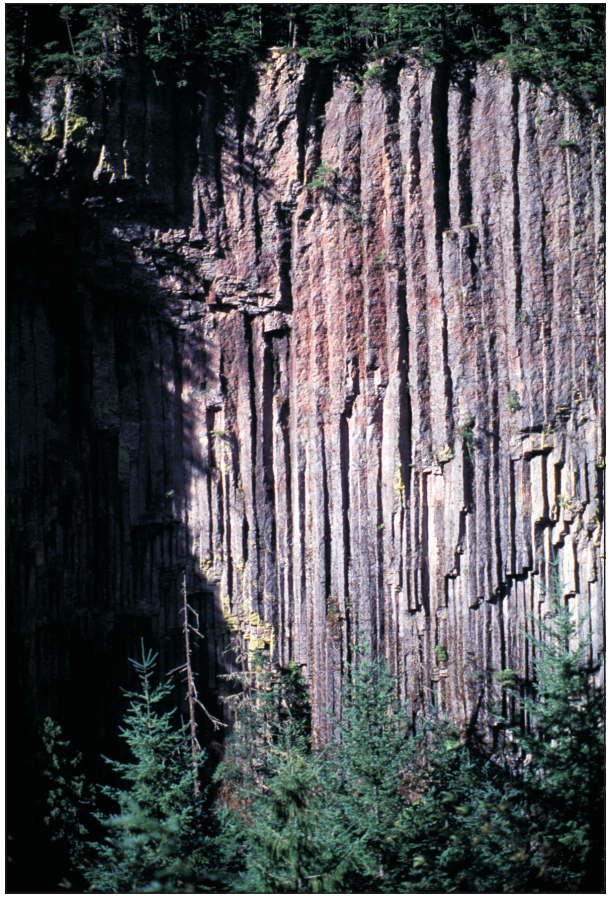


Figure H-3. Towering columns in the hornblende dacite flow on the south side of the Clear Fork Cowlitz River. The columns are about 650 ft (200 m) in height. Geologist Geoff Clayton (1983) obtained a radiometric age of about 0.65 Ma on this lava flow. View is to the south-southwest from the Palisades viewpoint.

0.3 *0.5* Milepost (MP) 139.

0.6 *1.0* A poorly sorted deposit or diamicton here is till of Evans Creek age, 22 to 15 cal yr B.P. Evans Creek is the youngest major episode of alpine glaciation in this area.

photo by Beth Norman



Figure H-4. Outcrop of hydrothermally altered volcaniclastic rocks of the Ohanapecosh Formation north of US 12 near MP 143.

1.2 *1.9* Near MP 140, Forest Roads (FRs) 45 and 4510 lead to Soda Springs Campground. The historic Cowlitz Trail heads at the campground. This route linked local tribes east and west of the Cascade crest, a distance of more than 40 mi (64 km) between settlements. Outcrops of Ohanapecosh Formation volcaniclastics are visible before and after FR 45.

1.9 *3.0* Ohanapecosh sedimentary rocks dip about 30 degrees to the southwest several hundred yards (meters) west of MP 141 (Fig. H-2). The sill is a plagioclase-phyric olivine basalt. Note the gentle 10- to 13-ft (3–4-m) wavelength folds in the rocks above the sill. The deformation likely occurred during emplacement of the sill.

2.3 *3.7* Palisades rest area. Here are some spectacular columns in the Clear Fork Dacite, an intracanyon lava flow of Pleistocene age from a vent near Goat Rocks (Fig. H-3). Clayton (1983) dated the Clear Fork flow at 0.65 Ma.

Why are the columns here wider at the top? The columns develop at different rates as cooling progresses both upward from the base and downward from the top (see Fig. F-14, p. 110). The flow-top rubble at this site has been removed by subsequent glaciation. Hammond has suggested that

photo by Dave Norman

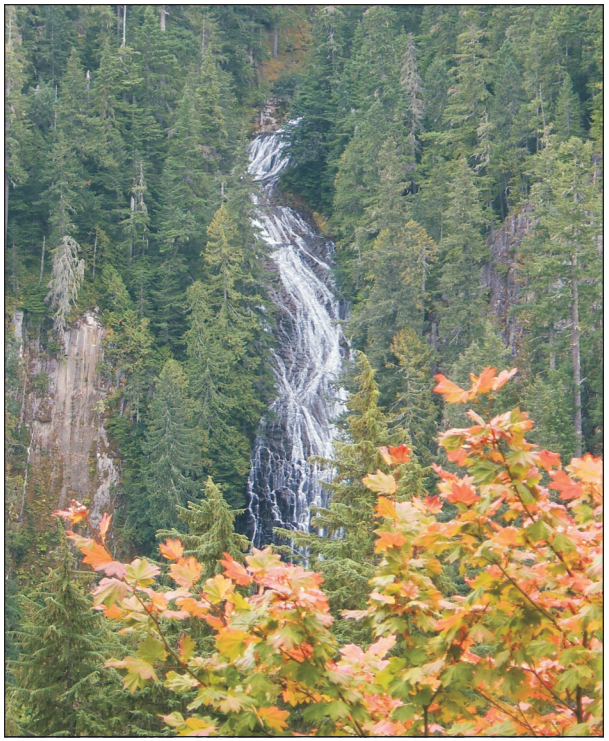


Figure H-5. Lava Creek falls. The wispy nature of the falls is due to the water flowing over and around Palisades columns, some of which are visible on the left.

this same flow may have been ponded by ice in the Cowlitz River valley to the west.

2.5 *4.0* FR 1276.

3.0 *4.8* West-dipping water-laid beds of the Ohanapecosh Formation crop out here.

4.1 *6.6* The sedimentary rocks here dip at least 10 degrees more steeply to the southwest than the rocks 2 mi (3 km) to the west. The beds become steeper over the next several miles and are nearly vertical as you approach the rocks of the pre-Tertiary Rimrock Lake inlier (unit Mzm).

4.2 *6.7* MP 143. Outcrop of hydrothermally altered volcaniclastic rocks of the Ohanapecosh Formation (Fig. H-4). A small amount of coal is exposed at the east end of the outcrop. Also visible in the outcrop is a vesicular olivine basalt flow of Hogback Mountain (Fig. H-1-2) and a flow breccia. This outcrop is continuous to mile 4.5.

4.5 *7.2* Columnar Hogback Mountain olivine basalt is exposed on the north side of the highway. This lava flow originated at Hogback Mountain about 8 mi (12.9 km) to the southeast. Clayton (1983) estimated (by whole-rock K-Ar dating) the age of a lava flow near the top of the Hogback Mountain volcano at about 1.53 Ma; using geomagnetic polarity reversals, he dated the lower part of the volcano at between 2.47 and 3.40 Ma. (See the "Paleomagnetism" sidebar on p. 104.)

4.6 *7.4* The pullout to the right offers an excellent view of Lava Creek falls as the stream goes over the Palisades columns and plunges into the Clear Fork Cowlitz River (Fig. H-5). The river incised its course along the contact between the valley dacite flow and the older Ohanapecosh Formation. Lava Creek was not able to erode the valley dacite flow at the same rate as the river, and as a result the waterfall was formed.

4.7 *7.5* The contact between the Ohanapecosh Formation and the overlying Hogback Mountain basalt flow.

4.8 *7.7* The Ohanapecosh Formation is exposed for about 0.8 mi (1.2 km). Higher up, in cliffs above the roadway, Hogback Mountain basalt can be seen.

5.2 *8.3* MP 144.

5.5 *8.8* Intrusive rocks are exposed on the left near where the road curves to the right (if eastbound). At the turnout slightly past this curve, note the valley slightly east of the high exposure of intrusive rocks, as well as the yellowish alteration in volcanic rocks adjacent to the intrusive body. The intrusion evidently altered and weakened the surrounding rocks.

6.0 *9.7* This stretch of the road passes through colluvium as you approach the margin of the pre-Tertiary rocks.

7.0 *11.2* The inferred fault contact between the Russell Ranch Formation and Ohanapecosh Formation is near here. Although the fault itself is not visible, the east block is up relative to the west block, which places black carbonaceous shale of the Russell Ranch (east) against light-colored andesites of the Ohanapecosh on the west. This faulting causes chronic landslide problems here (Fig. H-6).

photo by Beth Norman



Figure H-6. Roadwork along an unstable slope where altered volcanic rocks adjacent to an intrusion (right) frequently collapse onto the highway. This outcrop is slightly east of MP 144 on the north side of the highway.

7.1 *11.4* MP 146 area. Hammond (1980) described the steeply west-dipping beds of Summit Creek sandstone here that overlie shattered and sheared argillite rocks of the Russell Ranch Formation. The Summit Creek deposits are arkosic sandstone that underlie the Ohanapecosh Formation in this part of the Cascade Range and thus predate the onset of Cascade volcanism. The Summit Creek rocks are older than the 36 Ma fission-track age on overlying volcanic rocks and younger than the 55- to 44-Ma fission-track ages for the unnamed volcanic rocks below the sandstones (Vance and others, 1987). There are some intrusions exposed here in the Russell Ranch Formation that also cut, and thus are younger than, the rocks of Summit Creek.

The Russell Ranch Formation mostly consists of sheared, fine-grained oceanic sedimentary rocks that were buried and weakly metamorphosed; the rocks include argillite and arkosic sandstone along with tuffs and radiolarian cherts. The argillite is highly shattered in this area, and Hammond and others (1994) interpreted this shearing as a result of faulting along the west margin of the pre-Tertiary Rimrock Lake inlier.

photo by Dave Norman



Figure H-7. The pre-Tertiary Russell Ranch Formation (to the right of geologist Beth Norman) near MP 148. The crude high-angle layering to the left is part of a talus cone exposed by road excavation.

8.1 *13.0* Intrusive andesite with large hornblende and biotite crystals crops out here.

8.2 *13.2* The first good outcrops of the Russell Ranch Formation.

8.9 *14.3* The pullout to the right has a good exposure of the Russell Ranch Formation (Fig. H-7).

9.1 *14.6* Scenic vista points near here (MP 148) offer views of Goat Rocks to the south-southwest (Fig. H-8), Mount Rainier to the northwest (Fig. H-9), and the shattered Russell Ranch Formation across the road to the north (Fig. H-10). The Clear Fork Dacite flow is visible to the west.

9.6 *15.4* Russell Ranch Formation is exposed for next 0.4 mi (0.6 km).

10.6 *17.1* Note the hummocky landslide surface in the forest south of the road between here and Knuppenburg Lake.

10.7 *17.2* Knuppenburg Lake to the right is dammed by the rockslide–debris avalanche that originated from the north flank of Hogback Ridge, due south of the lake. Radiocarbon ages for the submerged subfossil forest in the lake will reveal the approximate age of the landslide (Fig. H-11). A few hundred yards (meters) upstream of the lake, debris-flow deposits of the last few decades have partially buried the trees growing adjacent to Millridge Creek.

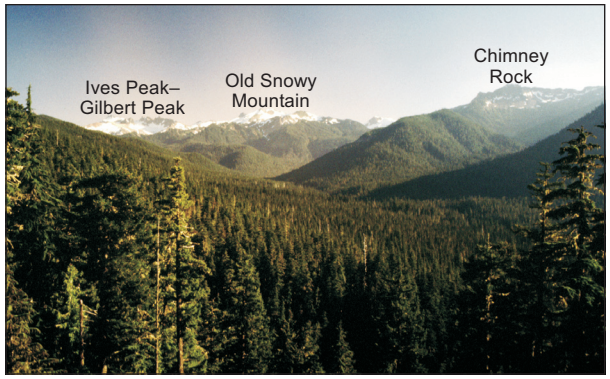


Figure H-8. Goat Rocks Wilderness. The mountains are erosional remnants of Goat Rocks volcano of Pliocene to Pleistocene age. View is to the south-southwest up the Clear Fork Cowlitz River.



Figure H-10. Shattered rock of the pre-Tertiary Russell Ranch Formation is exposed near MP 148 along US 12. The Russell Ranch unit includes marine sedimentary and volcanic rocks that are at least in part of Late Jurassic and Early Cretaceous age (~145–130 Ma). The complex consists mainly of sandstones and mudstones with minor conglomerates, reworked water-lain tuffs derived from volcanic-arc volcanoes, and pillow lavas (altered to greenstones) that likely formed at an oceanic ridge (Miller, 1989).

Hogback Ridge is the source of the Hogback Mountain olivine basalt, which overlies shattered and landslide-prone clastic rocks of the Russell Ranch Formation. According to Swanson and Clayton (1983), the late Pliocene and early Pleisto-



Figure H-9. Mount Rainier from near MP 148 along US 12. The snow-covered Tatoosh Range is low on the horizon to the south (left) of Mount Rainier. The tooth-like rock to the right of Mount Rainier's summit cone is Little Tahoma Peak, an erosional remnant of Mount Rainier. View is to the northwest.



Figure H-11. Ghostly subfossil trees in Knuppenburg Lake were drowned when a landslide from Hogback Ridge blocked the valley. The small delta of Millridge Creek is visible in the upper left corner of the photo. Radiocarbon dating of the trees will provide an approximate age for the event, which may have been triggered by an earthquake. View is to the southeast.

cene Hogback Mountain shield volcano was 3 mi (5 km) wide and 2300 ft (700 m) high. Some of its more than 200 lava flows, which are intercalated



Figure H-12. Tumac Mountain tephra cinder cone. Geologist Geoff Clayton (RH_2 Engineering Inc.), who conducted detailed studies in this area, noted that a crater is hidden in the trees on the west flank of the cone. He estimated the age of the Tumac Mountain volcano at 20 to 30 ka. View is to the southeast. Photo from Clayton, 1983.

with those of the Pliocene to Pleistocene Goat Rocks volcano, poured as far as 18 mi (30 km) down valleys. Clayton (1983) suggested that, during its youth, Hogback Mountain volcano might have looked similar to the Tumac Mountain complex. Tumac Mountain (Fig. H-12) is a late Pleistocene basaltic volcano located 1.8 mi (3 km) north of Spiral Butte. Clayton estimated its age to be 30 to 20 ka.

11.0 *17.7* Leech Lake on the north. Here is another outcrop of shattered Russell Ranch Formation rocks.

11.6 *18.7* FR 1284 and entrance to a Department of Transportation maintenance facility.

12.3 *19.8* White Pass, elevation 4470 ft (1363 m). Andesite crops out on the north side of road, and the Russell Ranch Formation is exposed on the south side. Spiral Butte is ahead to the northeast (Fig. H-13).

12.7 *20.4* Boundary between Gifford Pinchot (west) and Wenatchee (east) National Forests.

12.9 *20.7* The Pacific Crest Trail crosses the route here.

13.2 *21.2* This roadcut is in Spiral Butte dacite (Fig. H-14).

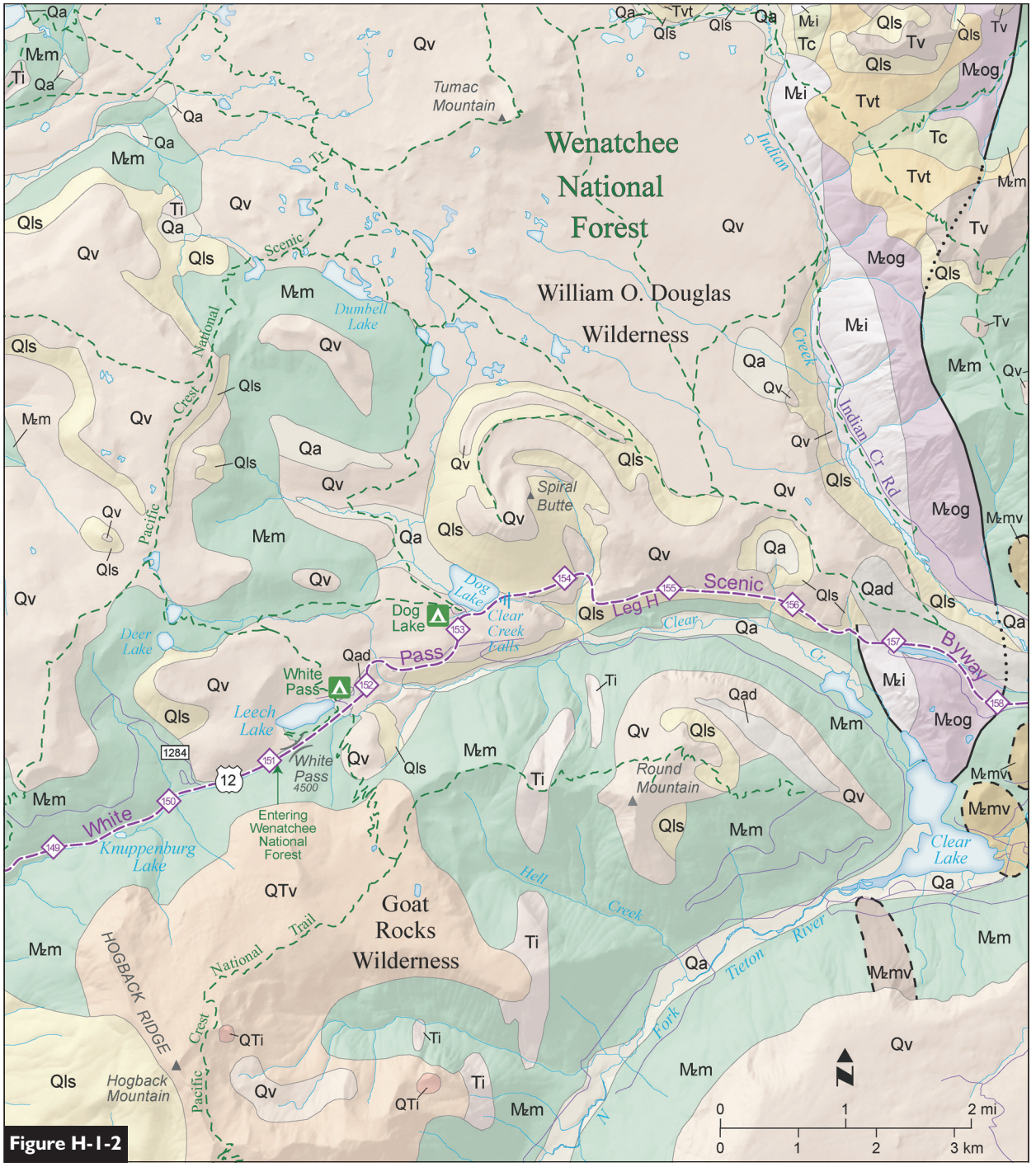


Figure H-1-2

photo by Beth Norman



Figure H-13. Spiral Butte is a Pleistocene dacite lava dome.

photo by Beth Norman



Figure H-14. Platy jointing in Spiral Butte dacite along the north side of US 12 near MP 152.

13.7
22.0

Spiral Butte lavas. Spiral Butte is a dacite dome of Pleistocene age (Fig. H-15). Clayton (1983) inferred that during the most recent Ice Age advance of alpine glaciers (~22–15 ka), Spiral Butte may have partially dammed the ice that moved south from the Tumac Mountain plateau. This obstacle would have concentrated the flow of ice in the Clear Creek valley. Erosion by the ice would have exposed the fragmental deposits at the summit of Spiral Butte and created the cliffs that have now raveled to form the talus slopes seen northeast of Dog Lake. Alternatively, an earlier thick ice cap centered on the Tumac Mountain plateau could have diverted the thick lava flow of Spiral Butte to the southeast into the Clear Creek valley. There the lava may have cooled against ice, as Lescinsky and Sisson (1998) have suggested for flows at Mount Rainier (see Fig. 27, p. 30). Tom Sisson and Marvin Lanphere (USGS, written commun., 2004) reported an $^{40}Ar/^{39}Ar$ age of about 102 ka for Spiral Butte lava.

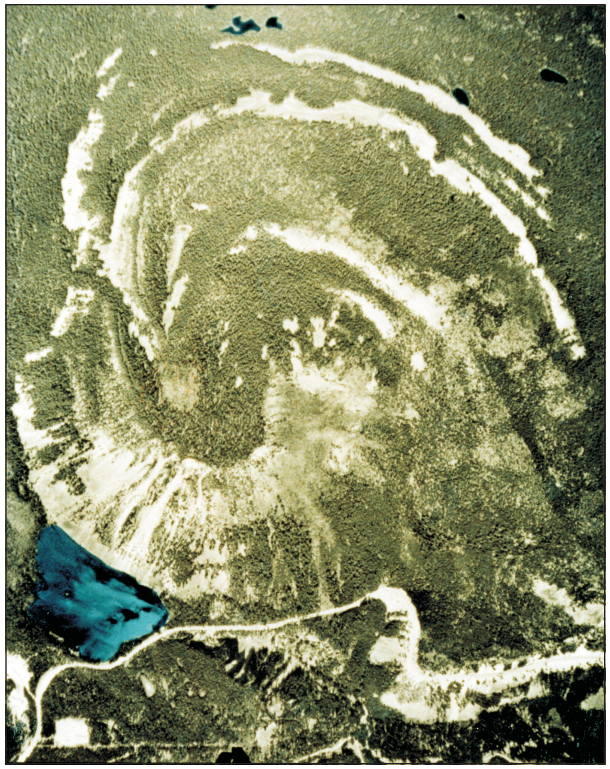


Figure H-15. Aerial view of the Spiral Butte dacite dome. The sparsely vegetated spiral arms at the top are talus-draped margins of a lava flow levee. The lava flowed north and then spiraled clockwise along the eastern side of the volcano, possibly channeled by ice. According to geologist Geoffrey Clayton, Dog Lake (lower left) is dammed between a hornblende-andesite lava flow from an unnamed peak near Deer Lake to the west and rocks of Spiral Butte. Spiral Butte dome is about 2 km (1.2 mi) in diameter. North is to the top. Photo from Clayton (1983).

14.4
23.1

Dog Lake North Campground.

photo by Beth Norman



Figure H-16. Clear Creek falls. A silicic andesite lava flow forms the falls. A short trail affording views of the falls begins at the pullout at mile 14.8.

14.8
23.8

The turnout on the south side of the road has a scenic view of Clear Creek falls (Fig. H-16), a view down Clear Creek valley to the southeast, and restrooms (except in winter). Clayton (1983) mapped the silicic andesite lava flow that forms the falls. It was erupted from a vent area about 3 mi (5 km) farther west. The flow overlies a basalt flow that Clayton dated at 0.65 Ma.

15.7
25.2

A broad turnout on the south side of US 12 at a pronounced curve about 0.5 mi (0.8 km) past MP 154 offers a panoramic view of the local terrain (Fig. H-17): Round Mountain to the south-southeast and the Clear Creek valley and Rimrock Lake to the east. *Note:* this turnout may be inaccessible owing to rockfall hazards.

16.0
25.7

Platy andesite crops out for the next 1.5 mi (2.4 km).

16.3
26.2

MP 155.

17.6
28.3

At this curve on the left, the contact between Indian Creek Gneiss (to the east), about 154 Ma, and the sheared rocks of the Russell Ranch Formation (>144–146 Ma) is exposed (Clayton, 1983; Miller, 1989). Till deposits of alpine glaciers are extensive in this area.

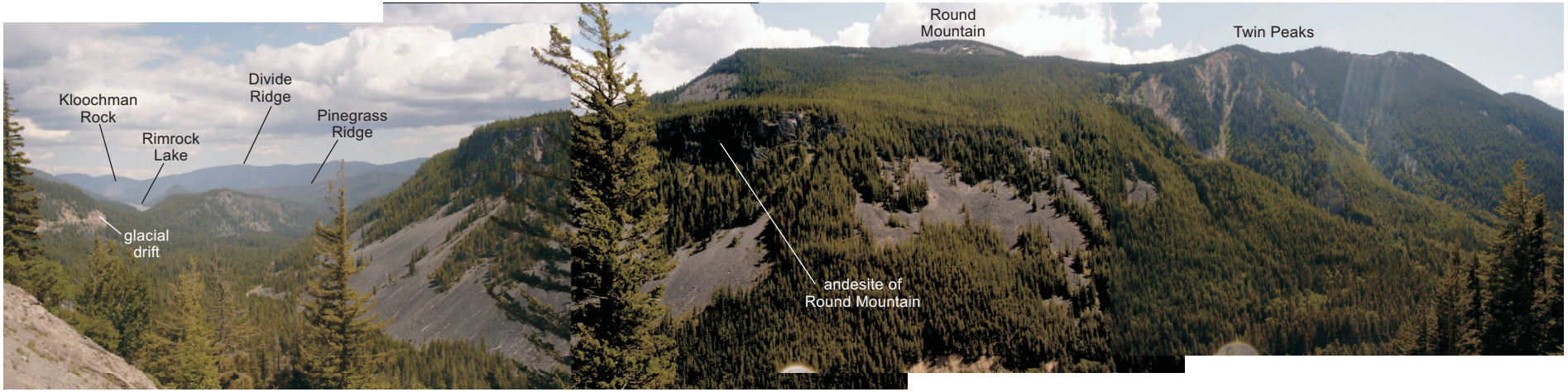


Figure H-17. Panoramic view across the valley of Clear Creek from a turnout near MP 154 on US 12. The view spans the distance from Divide Ridge (on the skyline to the east southeast) to Twin Peaks (south-southwest). Twin Peaks is composed largely of the Russell Ranch Formation with a spine of Tertiary dacite, whereas Round Mountain produced an andesite flow dated by Clayton (1983) at 0.8 Ma. Pinegrass Ridge is underlain by the Tieton Andesite flow (~1.64 Ma) from Goat Rocks volcano (12 mi [19 km] to the southwest of this viewpoint) and several other Pleistocene lava flows. Divide Ridge exposes more than 1700 ft (518 m) of the Grande Ronde Basalt and interbeds. Swanson (1967, 1978) noted that the upper part of this sequence at the west end of Divide Ridge is at an elevation of 6888 ft (2100 m), whereas undeformed coeval flows near the northern and eastern part of the Columbia Basin are at about 2394 ft (730 m). Assuming the latter areas represent a stable datum, Divide Ridge may demonstrate 4429 ft (1350 m) of absolute uplift (Swanson and others, 1989). Hogback Mountain is just out of the photo to the right. View is to the southeast.

17.9 *28.8* Indian Creek Gneiss with amphibolite crops out in this roadcut (Fig. H-18). The rocks are highly sheared and deformed by high-temperature metamorphism. Pegmatite dikes intrude the outcrop.

18.9 *30.4* An outcrop of greenstone of the Russell Ranch Formation is on the south side of road slightly west of MP 158.

19.3 *31.0* More greenstone of the Russell Ranch Formation.

19.9 *32.0* Tieton Road–Clear Lake area turnoff.

20.1 *32.3* Campbell (1975) noted that a small outcrop on the north side of the highway here is the terminus of the olivine basalt flow from the Tumac Mountain cone, about 6 mi (10 km) to the northwest. While some earlier researchers thought that the youthful-looking Tumac cinder cone was Holocene in age, Clayton (1983) carefully studied the evidence for glaciation at Tumac Mountain and concluded the volcano predated the most recent episode of major alpine glaciation of about 22 to 15 ka.

20.3 *32.7* Indian Creek. MP 159. The type locality of the Indian Creek Gneiss, one of the units in the Indian Creek complex, lies about 4 mi (6.5 km) to the northwest. Those who want to further explore the rocks of the Indian Creek complex via foot trails and nearby roads can find information in Miller (1985) and Northwest Geological Society (1991).

20.7 *33.3* Indian Creek Campground.

20.9 *33.6* Silver Beach resort.

21.7 *34.9* Heritage Marker for the Russell Ranch that was flooded by the reservoir.

22.3 *35.9* Steeply dipping beds of the Russell Ranch Formation are exposed north of the highway.

22.7 *36.5* Rest area south of road (not marked). Chert beds north of the highway.

23.2 *37.3* MP 162. Sheared sedimentary rocks north of the highway include turbidites of siltstone, sandstone. and shale (Fig. H-19). Faulted greenstone and cherts are below the turbidites. Radiolarian cherts in the Russell Ranch Formation were found near here by Miller and others (1993). They noted that the radiolarians in the cherts are compatible with a Late Jurassic to Early Cretaceous age. For the next 1.5 mi (2.4 km), you are in sheared metasedimentary rocks and basalts of the Russell Ranch Formation.


photo by Beth Norman

Figure H-18. Indian Creek Gneiss and amphibolite crop out north of the highway in this roadcut between MPs 157 and 158.

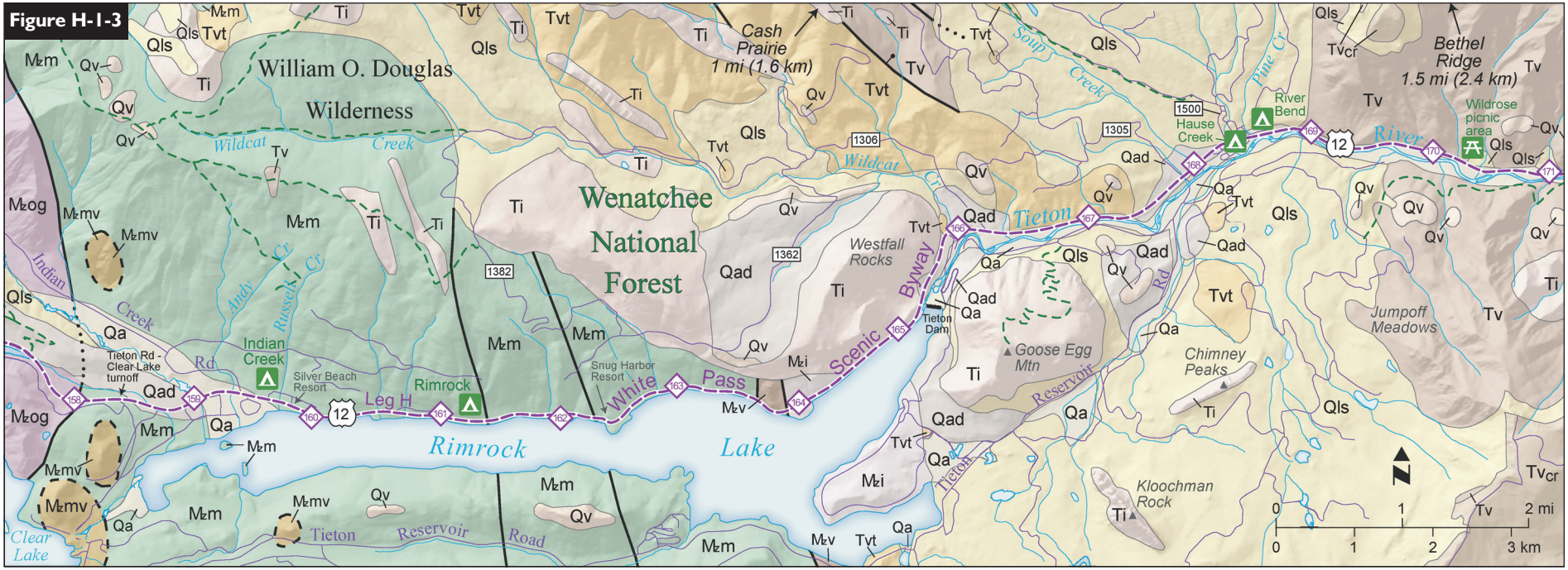




photo by Beth Norman

Figure H-19. Sheared sedimentary rocks north of the highway near MP 162 include turbidites of siltstone, sandstone, and shale. Faulted greenstone and cherts are below the turbidites.

23.3
37.5 An outcrop of sheared shale and greenstone with slickensides is north of the highway. The greenstones include remnants of pillow basalts.

23.7
38.1 Snug Harbor resort.

25.0
40.2 The sheared intrusive rock exposed along the highway here is mapped as the "trondhjemite" of the Indian Creek pluton of Jurassic age (Swanson and others, 1989). The name for this type of low-potassium granitoid rock originated at Trondhjem, Norway.

25.3
40.7 Rounded boulders of probable glacial till can be seen north of the road at MP 164. Note the slickensides in an area of sheared intrusive rocks near here.

26.3
42.3 MP 165. Swanson and others (1989) pointed out that there is a dark margin of hornfelsed Oligocene Wildcat Creek lapilli tuff in contact with the Pliocene/Oligocene Westfall Rocks here. They described the Westfall Rocks as a 'micro' diorite because of its small crystals. The heat of the Westfall Rocks intrusion along this contact has largely recrystallized the tuff along the dark margin.

26.6
42.8 Exit Tunnel. Tieton Dam was constructed between the masses of shallow intrusive diorite at Goose Egg Mountain (east) and Westfall Rocks

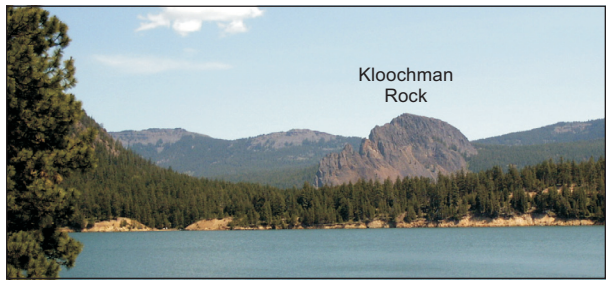


Figure H-20. A view southeast from US 12 near the east end of Rimrock Lake shows the extreme south end of Goose Egg Mountain (far left) and Kloochman Rock with Divide Ridge, composed of many flows of Grande Ronde Basalt, in the background. The area of low relief behind Kloochman Rock largely consists of large, deep-seated landslides from Divide Ridge. Yellowish forested exposures on the opposite lake shore are Quaternary glacial drift overlying rocks of Jurassic Indian Creek complex.

(west)(Fig. H-20) that Hammond has dated at 25.7 and 26.1 Ma respectively using Ar-Ar dating. The dam was built between 1917 and 1925, chiefly for irrigation purposes. In the next 0.1 mi (0.1 km),



Figure H-21. Wildcat Creek sedimentary rocks on the north side of US 12 near MP 167. These Oligocene rocks, which contain laharic deposits (between the white arrows), could be correlative with the Ohanapecosh Formation. This exposure is about 20 ft (6 m) in height.

there are exposures of the Westfall Rocks diorite. Straight ahead in the distance are Pleistocene lava flows of olivine basalt. These flows originated from a vent to the northwest and moved down Wildcat Creek (Campbell, 1975). Hammond notes Ar-Ar dates of 1.38 and 1.31 Ma on the flows.

27.2 *43.8* Rimrock Grocery store on the right. Gabbroic rock crops out on the left side of road, then you cross Wildcat Creek (Fig. H-1-3).

27.3 *43.9* MP 166.

27.4 *44.0* Wildcat Creek Road and FR 1306 are on the left.

28.0 *45.0* The light greenish, mostly fine-grained volcanic sedimentary beds that crop out north of the road near here are the Wildcat Creek tuffs. Vance and others (1987) obtained dates on these rocks that range from about 34 to 30 Ma. Hammond (2005) recently revised the age to 34 to 29 Ma from work reported in Vance and others (1987) and Landers and Swanson (1989). The beds include laharic deposits and tuff beds (Fig. H-21) and might be correlative with the Ohanapecosh Formation. In fact,

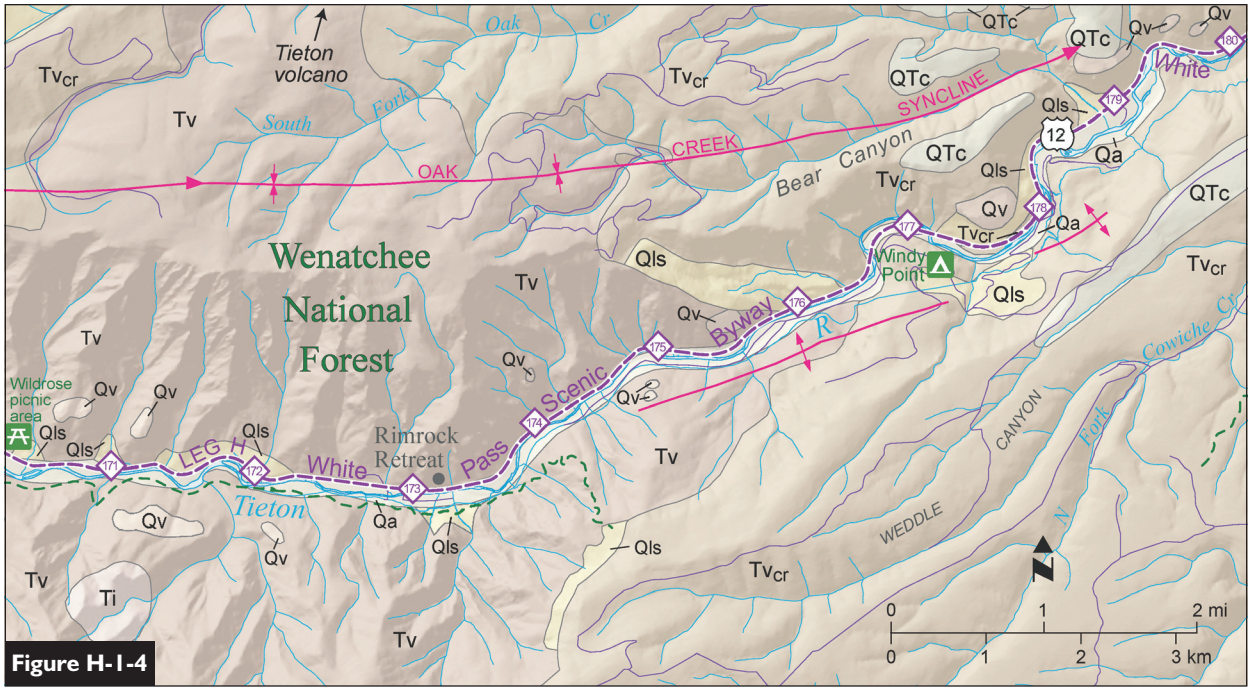


Figure H-1-4

Vance and others (1987) interpreted these as the distal equivalent of beds in the upper part of the Ohanapecosh Formation. You'll pass outcrops of tuffs for the next 0.7 mi (1.1 km).

29.1 *46.8* Junction of US 12 with Soup Creek Road (FR 1305) northwest of highway) and Tieton Road (east end of Tieton Reservoir Road, FR 1200).

29.5 *47.5* Bethel Ridge Road (FR 1500) on the north. The forest road accesses the summit of Bethel Ridge, one of the westernmost folds of the Yakima Fold Belt in this area. Cash Prairie, a bedrock bench west of Bethel Ridge (not visible here), is composed of the Cash Prairie rhyodacite tuff erupted at about 25 Ma from the Mount Aix caldera (Hammond and others, 1994).

You will see many outcrops of volcaniclastic deposits and lava flows related to Tieton volcano (Oligocene–Miocene) on the ridge as you go east on Highway 12. Swanson described the Tieton volcano as a large stratovolcano having a basal shield more than 200 m (656 ft) thick and overlain by 1500 m (4922 ft) of tuff and breccia (Swanson, 1964). Many of the layers of fragmental debris have the steep dips that overall describe a composite volcano (stratovolcano). Swanson and others (1989) described at least 300 m (984 ft) of gently dipping volcanic debris flow deposits, lava flows, and pyroclastic flow deposits "that can be traced nearly continuously into the cone." These deposits likely formed part of an apron at the foot of the volcano. The center of the Tieton volcano lies about 4 to 6 mi (6.5–10 km) east of the summit of Bethel Ridge. Shultz (1988) obtained an age of 26 to 25 Ma for the volcano. Hammond (unpub. data, 2003) confirmed the chemical similarity of its lavas to those of the older Fifes Peak Formation, whose source volcanoes, in order of decreasing age, are Fifes Peaks, Tieton volcano, Timberwolf Mountain, and Edgar Rock.

Bethel Ridge may be cut by a fault. A ridge-top trench several meters in depth and evidence of recent landslide movement, including tilted trees on its north and south slopes, could indicate a sackung. Those adventurous enough to take a side trip up along the forest road can look for the tilted trees of a 'drunken forest' near the top of the ridge.

photo by Beth Norman



Figure H-22. Flow breccias of the Tieton volcano exposed along the north side of US 12 slightly east of MP 169.

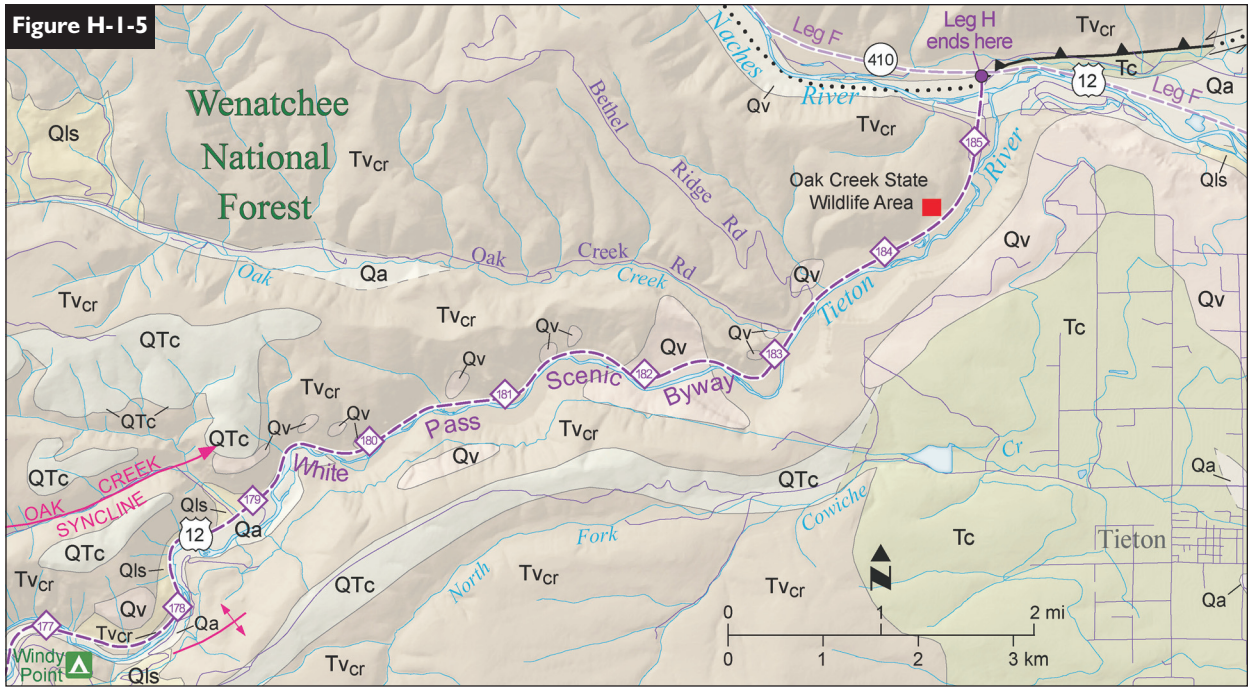
photo by Beth Norman



Figure H-23. Pillow lava (gray, center) in palagonite breccia on the north side of US 12 near MP 177. The breccia is associated with the Columbia River Basalt flows. A rock hammer shows scale.

Note that the road to the top is rough, and four-wheel drive vehicles are advisable.

30.5 *49.1* Outcrop of flow breccias of the Tieton volcano (Fig. H-22). Blocks of andesite as much as 30 in. (0.9 m) in diameter crop out in a buff-colored pumice matrix.



31.0 *49.9* An overhanging rock outcrop of flow breccia and andesite is slightly west of the Wildrose picnic area and MP 170.

33.9 *54.5* Enter Rimrock Retreat (elev. 2250 ft or 386 m). This is a popular put-in site for rafters on the Tieton River.

36.1 *58.0* Diamict with angular rocks on the north side of the road likely is the toe of a large landslide from Bethel Ridge. Large landslides are mapped on both sides of the road near here, yet they go almost unnoticed by the casual viewer. Many radial dikes (not shown at map scale) of the Tieton volcano have intruded the rocks of this area. The dikes crop out on both sides of the valley here. Rounded river cobbles and gravels of Quaternary age sit atop the volcaniclastic rocks of the volcano.

37.0 *59.5* Pillow basalts and basalt columns west of MP 176.

37.4 *60.2* Another of the andesite or basaltic-andesite dikes of the Tieton volcano.

37.8 *60.8* Cross the Tieton River. The road cuts through a pillow palagonite breccia (Fig. H-23) that likely formed when part of a lava flow of the Columbia River Basalt Group flowed into impounded water—the flow probably dammed east-flowing streams. Slickensides on the south side of the highway show that the pillow breccia is cut by a fault. However, the fault has not been traced farther than this road cut (Swanson and others, 1989).

38.2 *61.5* MP 177. Cross the Tieton River a second time (if eastbound).

38.6 *62.1* Windy Point Campground. Near here Swanson (1978) mapped 12 distinct flows of the Grande Ronde Basalt of the Columbia River Basalt Group (Fig. H-24). The lower three flows belong to magnetostratigraphic unit R_2 and the upper nine flows are N_1. (See the "Paleomagnetism" sidebar on p. 104 and Fig. 20 on p. 25.)

39.7 *63.9* On the south side of the highway is a viaduct taking irrigation water from a diversion dam west of Rimrock Retreat to agricultural lands in the Yakima River valley. Big blocks on the north are probably part of a landslide deposit.

photo by Beth Norman



Figure H-24. Flows of the Grande Ronde Basalt of the Columbia River Basalt Group near Windy Point Campground.

40.2 *64.7* Eastern boundary of Wenatchee National Forest and the west boundary of the Oak Creek Wildlife area at MP 179.

41.2 *66.3* Landslide deposit (not mapped) near MP 180. Exceptionally well developed jointing in the Tieton Andesite is visible at on the right (Fig. H-25).

42.7 *68.7* Stone stripes, a type of patterned ground, are draped on the hillside here (see Fig. F-9, p. 109).

43.3 *69.7* About 0.4 mi (0.6 km) east of MP 182, there is a good view of the valley-filling Tieton Andesite lava flow overlying Columbia River Basalt.

43.4 *69.8* A micaceous sandstone and siltstone layer between two N_2 flows of Grand Ronde Basalt (Swanson and others, 1989). Swanson (1967) suggested that the metamorphic and plutonic minerals in these interbeds here indicate a northern source area for the stream that deposited them in Grande Ronde time. The mica in these sedimentary rocks, therefore, could be interpreted to be from the ancestral Columbia River or a major tributary. The location of the paleo-Columbia River channel here at the western edge of the Columbia Basin makes geologic sense in that previous researchers have suggested the river was pushed to the margin of the province by the basalt flows. About the sediments, Swanson and others (1989) also noted: "Mixed with the metamorphic and plutonic suite [of minerals] is a pyroclastic suite, including …glass shards, and glass-rimmed plagioclase and mafic minerals." This suite provides clear evidence of explosive activity from Cascade volcanoes during Grande Ronde time 16.5–15.6 Ma (Campbell and Riedel, 1991; see Fig. 20, p. 25).



Figure H-25. Huge columns of the Tieton Andesite flow of Pleistocene age exposed along US 12. The ridge on the horizon is about 580 ft (177 m) above the Tieton River.

44.2 *71.1* On the left at a tight (dangerous) curve to the left, upper entablature and well-developed lower colonnade (columns) of Tieton Andesite sit on rubbly, cobble-rich fluvial deposits of the ancestral Tieton River (Fig. H-26).

44.6 *71.7* Entrance to Oak Creek State Wildlife Area. Note that the exposure on the northwest side of the highway shows the Tieton Andesite only a few meters above river level. Swanson and others (1989) suggested that this implies the base level has not changed much in the approximately 1 m.y. since the andesite was erupted, so little or no downcutting took place—except through the lava flow. Hammond recently redated the flow using Ar-Ar to 1.64 Ma.

45.6 *73.4* Well-developed columns of Tieton Andesite to the south.

46.4 *74.7* Cross the Naches River. This is slightly upstream of its confluence with the Tieton River.

46.6 *75.0* Junction of SR 410 and US 12. From here you can drive east or west on Leg F, joining this leg about 16 mi (26 km) west of where it begins. Reset your odometer if you are proceeding on Leg F. ■

photo by Wendy Gerstel

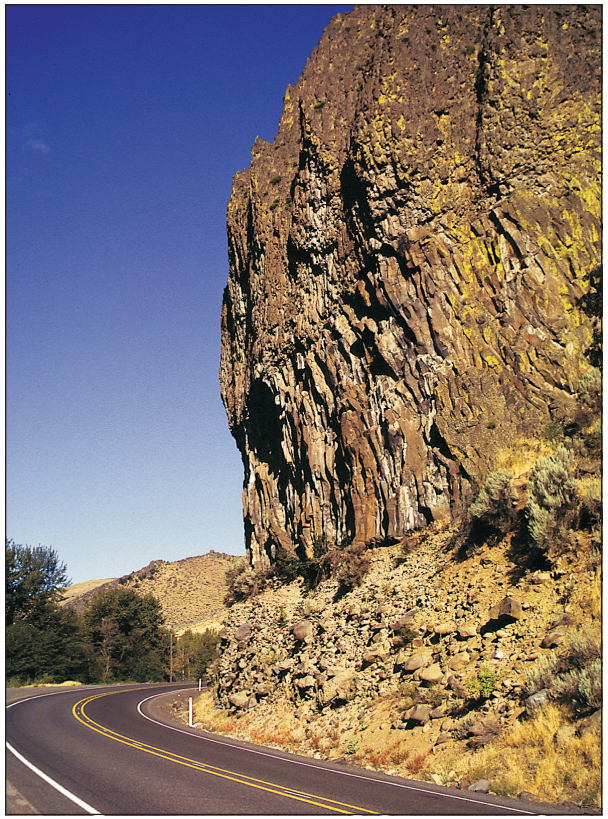


Figure H-26. Tieton Andesite overlying coarse fluvial gravels. View is to the west along US 12.

LEG I: ALTERNATE SOUTHERN APPROACH

From Interstate 5 to Morton via State Route 508 and to Elbe via State Route 7

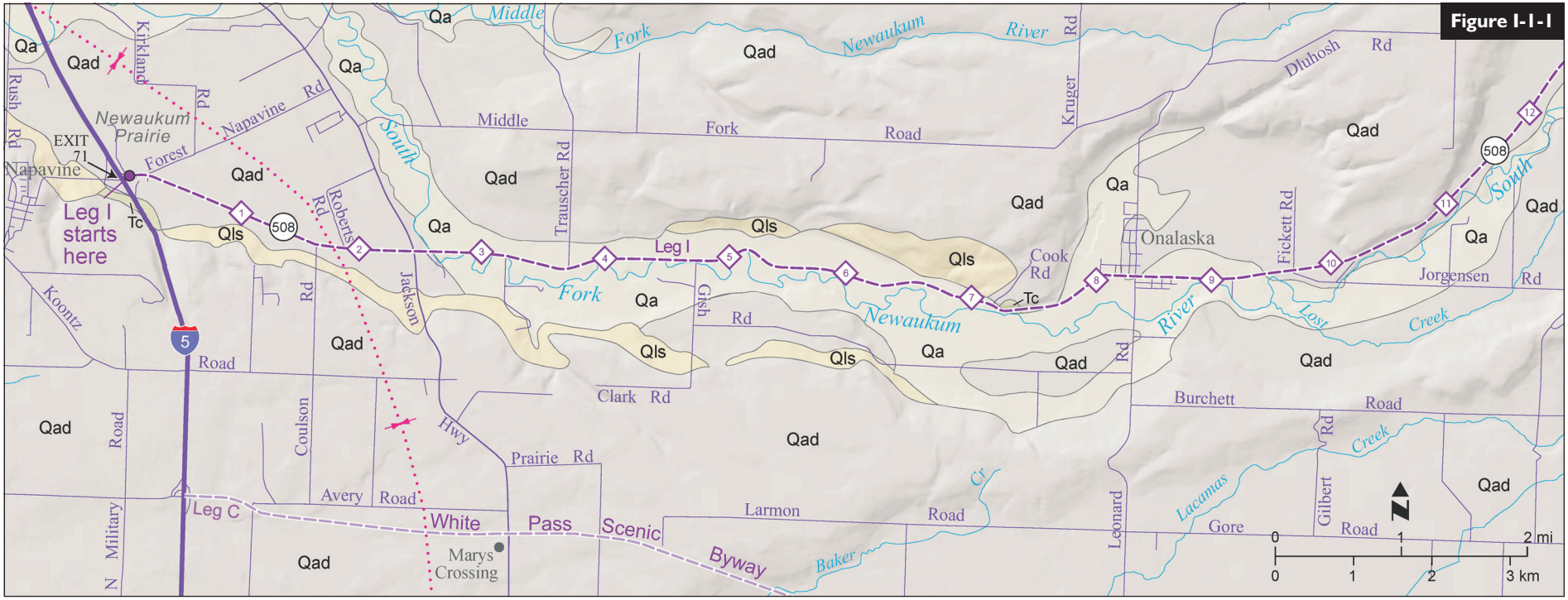
This 49-mi (78 km) leg starts at the junction of Interstate 5 (I-5) and State Route (SR) 508 (Exit 71) in the southern Puget Lowland at the town of Napavine (elev. ~210 ft or 133 m). SR 508 begins on the Newaukum Prairie, composed of gravelly glacial outwash, and winds to the east and upstream along the South Fork Newaukum River, which drains into the Chehalis River (Fig. I-1). Between the towns of Alpha and Cinebar, the road crosses a low drainage divide into the Mill Creek watershed, which drains into the Cowlitz River, a major tributary of the Columbia River. Not far beyond Cinebar, the road enters the Cascade Range physiographic province and the Tilton River watershed. To the north and east rise the faulted, folded, and eroded, mostly andesitic rocks of the hills near Bald Mountain and The Rockies. This pile of lavas is a relic of the Eocene Northcraft volcano, one of the Cascade Range's founding members! Hammond (1998) has concluded that the Northcraft eruptive center was located roughly 12 mi (20 km) northwest of Morton. The Northcraft rocks are probably about 40 million years old because they sit above the middle Eocene sedimentary rocks of the McIntosh Formation and below the sedimentary rocks of the uppermost middle Eocene Skookumchuck Formation.

Older rocks of middle Eocene age, such as the McIntosh Formation, are exposed locally where anticlines have warped the rocks upwards or where faults have shoved older rocks up. Conversely, synclines, or downward folds in the rocks, have exposed younger, later late Eocene sedimentary rocks (Skookumchuck Formation) and still younger volcaniclastic rocks of probable Miocene age. Mining areas of historic interest sprang up where past igneous activity concentrated metalliferous minerals or other deposits of economic value.

The Tilton River area was covered by alpine glaciers about 140,000 years ago during the extensive Hayden Creek glaciation in the southern Washington Cascades. The huge glaciers of that and earlier glaciations carved out the broad valleys we see today.

At Morton, the leg joins SR 7 and heads north through a dissected anticlinorium that exposes sedi-

Figure I-1. Geologic map for Leg I (four consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987a) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.



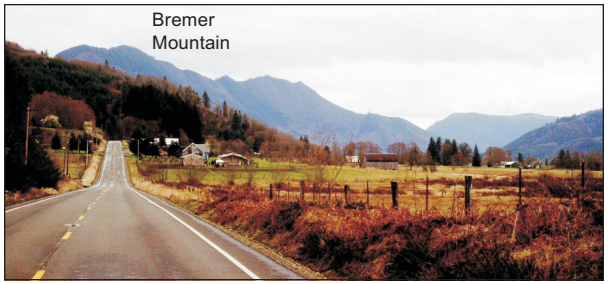


Figure I-2. Glacially carved rocks of the Cascade Range as seen from the Tilton River valley near MP 20 along SR 508. The flat-lying valley bottom is composed of glacial outwash, probably of Hayden Creek age (~140 ka). View is to the east.

mentary rocks of the Eocene Puget Group. En route you will pass small bodies of intrusive dacite. The rocks have been tightly folded and faulted throughout this area, and many large landslides are testimony to the fact that tilted, altered, and fractured fragmental and (or) weak rocks are highly susceptible to gravitational failure. A short distance south of Elbe, you will leave the Tilton River drainage at a low divide (elev. ~1760 ft or 537 m) and enter the watershed of the Nisqually River, which flows into Puget Sound.

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Note: There are a limited number of outcrops on this leg.

Mileage

0.0 *0.0* Intersection of I-5 and SR 508 (Exit 71). Start mileage on the west side of the freeway. You will be crossing an alpine glacial outwash plain for the next 2.5 mi (4.0 km).

1.7 *2.7* Coulson Road.

1.9 *3.1* Roberts Road (stop sign).

2.4 *3.9* Intersection of SR 508 with Jackson Highway.

2.6 *4.2* Cross the South Fork Newaukum River, which heads in volcanic and sedimentary rocks of Eocene age. The highway will be on the flood plain for the next 2.5 mi (4 km).

Cinnabar

by Rebecca A. Christie and Katherine M. Reed

In western Washington, cinnabar (HgS), the primary ore of mercury, is found in pods or lenses and breccia zones in Eocene Puget Group sedimentary rocks. Its presence may be related to nearby volcanic activity (Huntting, 1956). At some localities, it occurs as bright red needle-like crystals.

In 1913 (the year is disputed), Edward Barnum noticed cinnabar in a seam of coal near Morton. Within the next year, retorts were operating, and soon several mines were producing in the area about 2 mi (3 km) southeast of the town. Two notable mines north of Davis Lake were the Roy and the Barnum-McDonnell. Production from 1929 to 1940 was $509,717*; the peak year was 1929 (Mackin, 1944). Clevinger (1968, p. 20), however, mentioned that between 1927 and 1931 more than 5000 flasks were produced; the total value exceeded $1 million. The Morton area was Washington's most significant producer of mercury.

The Depression years saw low mercury prices and little mining activity in the area. After about 1940, no more high-grade ore was found. A large flotation mill built in 1940 near one of the Barnum-McDonnell tunnels was dismantled in 1943; remains are still visible. When the price of mercury spiked in the late 1950s and early 60s to more than $570 per flask, there was some leasing activity in the Morton area. A minor amount of cinnabar was produced in the 1950s at the Royal Reward mine in Green River Gorge State Park, King County, about 2.5 mi (4 km) south of Black Diamond, where coal was mined until recently.



Massive cinnabar. Photo courtesy of R. Weller/Cochise College.

Land in the Morton area is for the most part now privately owned. No mining is going on in this area at present (2008). The Washington Department of Natural Resources and Department of Ecology sampled water at the inactive mines in 2001 and found that it was suitable for drinking (Wolff and others, 2001). The mined area now supports hemlock and Douglas-fir trees.

Cinnabar gives its name to the town of Cinebar, the small town on SR 508 near its intersection with Cinebar Road. ■

*Mercury prices are quoted per 76-lb (34.5 kg) flask. The average annual price fluctuated considerably during this period, from $57.93 in 1932 to $176.86 in 1940. To convert to dollars/kg, multiply by 0.029008. Values from http://minerals.usgs.gov/minerals/pubs/commodity/mercury/430798.pdf.

3.0 *4.8* The meandering river is still south of the highway. The rolling bar and swale topography common on flood plains is evidence of migrating meanders. The core of ridges or swells is generally composed of bars of sand or larger particles, and depressions (swales) are sloughs filled with silt and clay.

4.3 *6.9* Note the two terraces visible to left (north), one 20 to 23 ft (6–7 m) in height, the other 33 to 40 ft (10–12 m) in height. The lower terrace is younger. Deposits from landslides that head in the Pleistocene Logan Hill Formation are common along the margins of the north valley wall (Schasse, 1987b). Dethier (1988) speculated that the Logan Hill Formation is between 0.63 and 1.7 Ma, that it could correlate with the 840 ka Salmon Springs Drift dated by Easterbrook and others (1981), and that it is associated with marine isotope stage 22 (see Fig. 25, p. 29).

7.2 *11.6* Ascend a small alluvial terrace before the road begins to make some curves. Where trees have been cut, you can see more terraces to the north. There is a small outcrop of the Wilkes Formation (Miocene) on the north side of the road (left if eastbound) slightly before where the road curves to the left. The Wilkes Formation includes semiconsolidated nonmarine sediments, as well as lignite and some tuff (Roberts, 1958). Yancey and Mustoe (2007) recently obtained a provisional radiometric age of 11.6 Ma on tuff deposits in the Wilkes Formation at Toledo, about 10 mi (16 km) west-southwest of this location. This age is similar to that of some volcanic deposits of the Ellensburg Formation described in Part I and in Leg F.

8.1 *13.0* The road ascends a 10-ft (3 m)-high terrace of Hayden Creek Drift (~170–130 ka) as you enter Onalaska.

8.4 *13.5* Leonard Road, Onalaska. Descend the Hayden Creek terrace to the flood plain of the South Fork Newaukum River.

8.6 *13.8* More bar and swale topography for the next 0.3 mi (0.5 km) indicates that you are once again in a flood-plain environment.



Figure I-3. North-dipping, carbonaceous sedimentary rocks of the Puget Group along SR 508 east of Bear Canyon. Some small fault offsets are exposed in the outcrop. The rock hammer (lower right center) is 13 in. (33 cm) long. View is to the north.

9.6 *15.4* Ascend yet another terrace (composed largely of sand), about 7 ft (2 m) in height.

10.1 *16.3* The highway runs right next to a 20- to 23-ft (6–7 m)-high grass-covered terrace of the Logan Hill Formation to the north of the highway.

12.6 *20.3* The Cascade Range lies dead ahead and to the northeast.

13.3 *21.4* Centralia–Alpha Road.

13.6 *21.9* Cross a bridge over the South Fork Newaukum River.

14.0 *22.5* Jagged peaks of folded, faulted, and eroded Cascade Range rocks loom ahead.

14.3 *23.0* The highway enters a broad, glaciated(?) valley with mountains on the north and south. The gently rolling topography of the valley floor is underlain by glacial outwash deposits of Hayden Creek age (~170 to 130 ka).

16.4 *26.4* Intersection of Johnson Road (south) and Van Hoesen Road (north). Continue straight ahead on SR 508.

18.1 *29.1* Milepost (MP) 18. Cinebar Road and town of Cinebar. The reddish mineral cinnabar (HgS), the most important ore of mercury, is associated with veins in volcanic rocks and is found along fault zones in the sedimentary rocks of this area. It has also has been found in the East Fork Tilton River basin, north and east of Morton. Most production was southeast of Morton. (See Fig. C-6, p. 78, and the "Cinnabar" sidebar on p. 136.)

18.3 *29.4* Cross over Mill Creek, then ascend a low terrace.

18.4 *29.6* Cinebar post office.

19.5 *31.4* Cinnabar Creek. North of here, a southeast-trending normal fault uplifts Eocene sediments on the southwest and down-drops lavas of the Eocene Northcraft Formation on the northeast (Walsh and others, 1987). The Northcraft Formation is poorly exposed along the north side of the highway near MP 20, about 0.4 mi (0.6 km) east of here.

19.7 *31.7* The mountains ahead (east) have steep scarp slopes on their south sides that are the result of chiseling by Pleistocene glaciers (Fig. I-2).

20.0 *32.2* The highway ascends a terrace next to a valley on the right. The terrace surface may be Logan Hill Formation.

21.3 *34.3* The road curves to the north (left) into Bear Canyon.

21.5 *34.6* The road curves within and crosses a high bridge over Bear Canyon. The storm of November 2006 triggered a 160,000-ft^2 (~14,800 m^2) landslide that affected or threatened a 500-ft (152 m) section of road here. The bulk of the landslide material is composed of glacial deposits that evidently became saturated and moved downslope into Bear Canyon Creek.

Slightly east of the canyon on the north side of the highway is an outcrop of north-dipping middle Eocene sedimentary rocks (shales and sandstone) of the Puget Group (Fig. I-3). Glacial sediments of Hayden Creek age are exposed on the south side of the road, and farther to the east are more lavas of the Northcraft Formation—also dipping to the north in an area of tight folds. Rugged peaks called "The Rockies", about 4.5 mi (7 km) northeast of this location, are situated roughly at the center of the Northcraft volcanic pile; they are apparently locally covered by younger (Miocene?) rocks (Walsh and others, 1987).

22.3 *35.9* The Tilton River valley opens up from here to the east. South of the highway at this location is a remarkably flat landform some 200 ft (61 m) above the river level. This surface probably is a glacial outwash or kame terrace (see Fig. 24, p. 29). The highway drops closer to river level over the next several miles as it heads east.



Figure I-4. Glacial outwash of Hayden Creek age exposed along the Tilton River near mile 28.5. Raveling from the exposed face contributes to formation of riffles in the stream. This exposure is about 40 ft (12 m) high.

22.7 *36.5* Cross over the west branch of Alder Creek, which drains a debris fan extending from an unnamed peak to the northeast.

23.0 *37.0* Cross the east branch of Alder Creek, which also heads on the unnamed peak composed of sedimentary rocks of the Puget Group.

25.0 *40.2* The road crosses the Tilton River slightly past MP 25. Outwash deposits of Hayden Creek age are exposed in the bank, slightly upstream of the bridge (Fig. I-4). The name Hayden Creek was assigned to the deposits of an extensive episode of alpine glaciation in the Cascade Range. This glaciation is

now thought to be associated with the global period of intense glaciation between about 170 and 130 ka and recorded in "stage 6" of the global climate record interpreted from oxygen isotope ratios (see Fig. 25, p. 29). During the Hayden Creek glaciation, enormous valley glaciers from nearby mountains covered all but the highest peaks in this area. (See more on the Hayden Creek glaciation on p. 27.)

Andesitic rocks of the Northcraft Formation, representing one of the earliest episodes of Cascade volcanism, are exposed about 0.5 mi (0.8 km) west of a long eastward bend in road.

25.5 *41.0* The road follows the river. Mountains to the north of the valley are andesitic lavas of the middle and upper Eocene Northcraft Formation, which is locally exposed along the highway for about 5 mi (8 km) east of here. To the south are younger basaltic andesites (about 36 Ma) (Walsh and others, 1987).

27.2 *43.8* The fan-shaped landform at the base of the south valley wall at the second junction of Dodge Road on the right (south) originates on a landslide.

27.6 *44.4* Pass coalescing fans of rock debris from Bellicum Peak on the right (south) for the next 0.2 mi (0.3 km). The ridge is composed of andesitic lavas.

27.9 *44.9* Gray amygdaloidal volcaniclastic rocks of andesitic composition crop out in a borrow pit on the south side of road. There are additional exposures for about 0.3 mi (0.5 km).

28.5 *45.9* Cross the Tilton River about 0.4 mi (0.6 km) upstream of its confluence with the North Fork Tilton River.

28.9 *46.5* The many boulders of sedimentary and igneous rocks in the streambed attest to the long history of erosion that has cut through the great thickness of rocks here. More than 10,000 ft (3048 m) of strata are exposed in the Morton area. Rock collectors have found specimens of chalcedony, petrified wood, geodes, zeolites, agates, calcite crystals, fossils, and more. Clevinger (1968, 1969) described the geology of the Morton area and collecting locales.

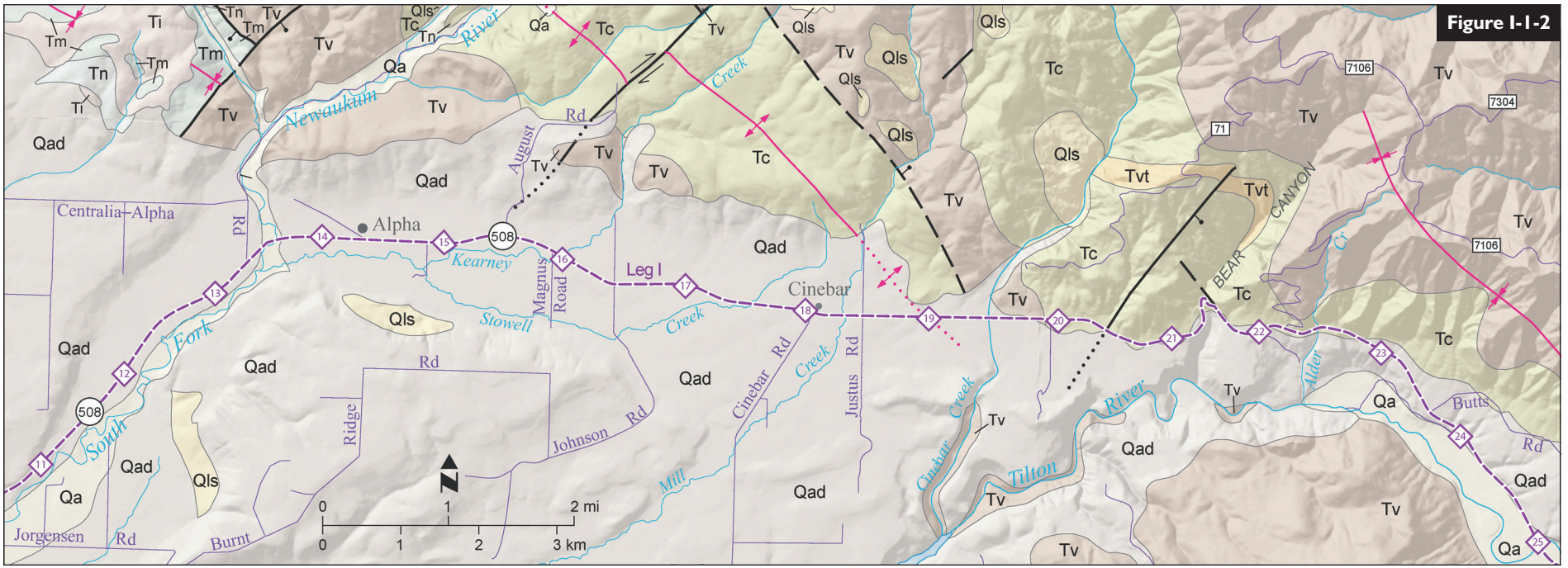
29.0 *46.7* Ascend a terrace composed of drift of Hayden Creek age. Hayden Creek Drift mantles the lowermost 400 ft (122 m) of the north valley wall here.



photo by Dave Norman

Figure I-5. At Gust Backstrom City Park, a waterfall created by a ledge of resistant sandstone of the Puget Group offers an interesting place to play. Note the potholes and smoothed surface of the rock caused by the scouring action of entrained sediment during higher flows of the Tilton River.

29.8 *48.0* In this stretch of road, look for Northcraft Formation exposures here and there on the left side of the road from about MP 29.5 to 30.7 and for oxi-



dized, or rusty, cobble gravels from the Hayden Creek Drift in the left bank of the river. The Northcraft rocks here have a K-Ar age of 38.3 ±1.9 Ma (Schasse, 1987b).

30.4 *48.9* A dike intrudes the Northcraft Formation volcanic rocks on north side of the highway.

32.3 *52.0* Cross the Tilton River again. Gust Backstrom City Park, which can be reached by a turnoff about 500 ft (150 m) southeast of this bridge, has access to the river (Fig. I-5). Clevinger (1969) described the geology at this site, including a waterfall created by a ledge of resistant sandstone of the Puget Group. Petrified wood and fossils have been found among the well-polished cobbles and boulders composing bars near this site.

32.5 *52.3* As you enter the central area of Morton, you climb a 20- to 23-ft (6–7 m)-high terrace that is locally capped by till of Hayden Creek age. Morton is a good place to take a break for lunch.

32.8 *52.8* Intersection of SR 508 with SR 7; mile markers for SR7 begin here. Continue northward on SR 7 to its junction with SR 706 at Elbe. Note that Leg C, on US 12, passes on the south side of Morton and continues east. The junction with US 12 is about 0.5 mi (0.8 km) to the south.

32.9 *52.9* Intrusive rock (not shown on map) on the southeast side of road has been mapped by Schasse (1987b) as a diorite of Miocene or Oligocene age.

34.4 *55.3* An outcrop of Puget Group sandstone is on the right (east) on a curve to the east, slightly north of MP 2.

34.8 *55.7* On the right (east) as the road curves is an outcrop of Puget Group sandstone. A railroad bridge is visible west of the road.

35.6 *57.3* Cross the East Fork Tilton River.

35.8 *57.6* Coarse, cobbly material, possibly an alluvial fan from the east, is exposed along the right side of the road.

37.3 *60.0* The road crosses an alluvial plain for the next 0.4 mi (1.1 km).

37.7 *60.3* The road starts to ascend a grade on Hayden Creek Drift.

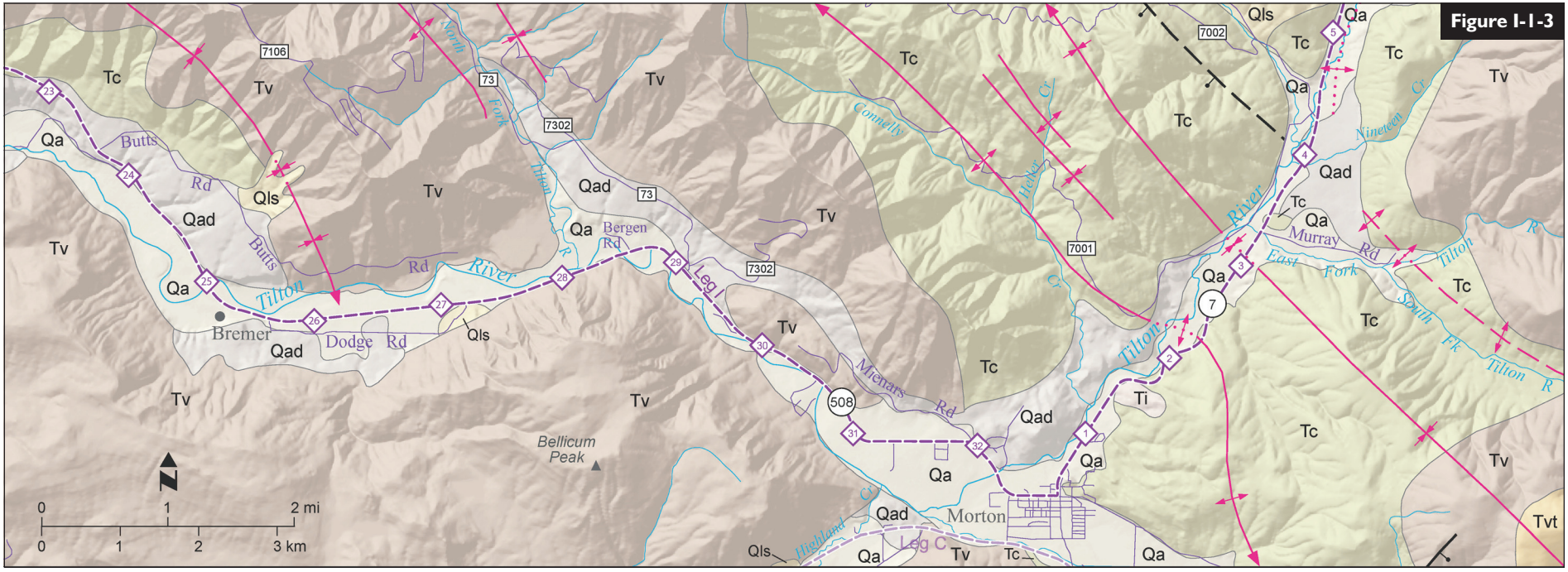
38.4 *61.8* Slump scarps and outcrops along the west side of the highway near MP 6 locally expose volcanic ash and pumice layers. The yellow pumice seen most commonly is the Yn tephra from Mount St. Helens. This tephra was ejected in an eruption about 3600 years ago that produced an estimated 1 mi³ (~4 km³) of pumice and ash. Winds carried the plume of ash and pumice north and then east into Canada. The eruption had a profound effect on the local indigenous peoples, many of whom undoubtedly perished in the eruption (McClure, 1992). The great volcanic disturbance also had long-lasting effects on the settlement patterns in this area.

38.6 *62.1* Landslide deposits are on the west side of road for the next 0.3 mi (0.5 km).

38.9 *62.6* Talus or landslide deposits composed of the Puget Group are on the west side of the road.

39.0 *62.7* Outcrops of Miocene–Oligocene diorite for 0.1 mi (0.1 km).

39.2 *63.0* MP 7.



41.7 *67.1* Cross Summit Creek. You are now in the Nisqually River watershed. Summit Creek drains into the Nisqually via Roundup and Mineral Creeks.

42.3 *68.0* MP 10. Rubbly deposit on the left (northbound) is an alluvial fan.

45 0 *72.4* FR 74 is on the west side of the highway. When the weather is clear, from this prairie area there is a grand view of the rugged southwest face of Mount Rainier 23 mi (36.8 km) to the northeast.

45.5 *73.2* Mineral Road South. Mineral Lake, about 1.5 mi (2.4 km) to the northwest along this road, sits on deposits of Hayden Creek drift. The town was named for the abundant mineral deposits in this area. The remodeled Mineral Inn was once a sanitarium (Kirk and Alexander, 1990). (See "Gold and Arsenic in the Park Junction and Mineral Areas" sidebar.)

45.7 *73.5* Drive through a bedrock notch (fault controlled?) between the Northcraft Formation on the southwest and undifferentiated andesitic rocks of Tertiary age to the northeast.

45.9 *73.9* Outcrops of basaltic andesite flow breccias are on both sides of the road on a curve.

46.3 *74.5* The road descends into the large, broad, U-shaped, glacially carved Nisqually River valley.

48.3 *77.7* Mineral Hill Road (west). Lahar deposits and big boulders indicate that you are once again on the flood plain of a river that drains Mount Rainier.

48.8 *78.5* Nisqually River, then the intersection of SRs 7 and 706. If you continue on SR 7, you will reach Olympia/Tacoma. SR 706 will take you to the Longmire entrance to Mount Rainier National Park.

Remember to reset your odometer when you start another leg. ■

Gold and Arsenic in the Park Junction and Mineral Areas

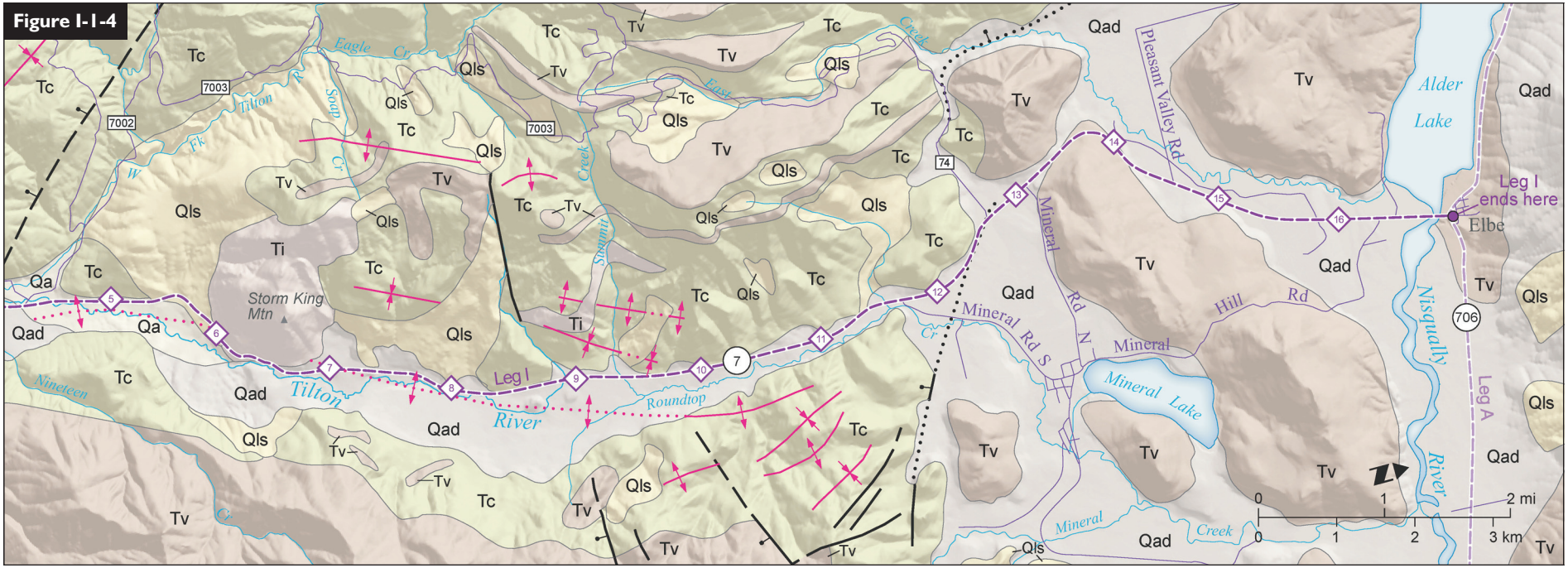
by Rebecca A. Christie and Katherine M. Reed

Mineral Creek flows into the Nisqually River less than a mile (~1 km) southwest of Park Junction, about 2.5 mi (4.0 km) west on SR706 (Leg A). Mining for gold and arsenic took place along the creek for several years between 1892 and 1922.

In 1892, the Eureka Mining Company of Tacoma issued a prospectus that described Mineral Creek as the new "Eldorado of Washington". The company's claims covered about 40 acres (16 hectares), and each claim contained "a very large vein of gold bearing quarts [*sic*], about 100 feet [30.5 m] wide, running the entire length of the same" (Eureka Mining Company, 1892). Despite the company's efforts, this area had no significant yield of gold.

The Mineral Creek Mining and Smelting Company, whose operations site was 5 mi (8 km) southeast of the town of Mineral, mined realgar (AsS), from which arsenic is extracted. A surface vein of rich sulfide ore (sphalerite, galena, and realgar) was discovered in 1900 and worked until 1922. Huntting (1956, p. 23) noted that 1000 tons (900 metric tons) of arsenic ore were reported to have been produced here in 1903, less in the following years. The mine closed when a smelting process was developed that recovered arsenic as an inexpensive by-product during the recovery of other metals, making operation of the mine unprofitable (Huntting, 1956; Filley, 1996). ■

Figure I-1-4



LEG J: APPROACH TO THE CARBON RIVER AREA

Through Orting and South Prairie Creek valley via State Route 162

This 17-mi (27 km) scenic route takes you upstream in the broad Puyallup River valley past its confluence with the Carbon River, and it then continues up the valley of South Prairie Creek (Fig. J-1). This leg begins near Sumner (elev. ~75 ft or 23 m), follows State Route (SR) 162 south through the city of Orting, and then curves east-northeast to the junction with SR 165 (elev. 692 ft or 211 m) via the town of South Prairie. SR 165 is the gateway to the northwest entrances of Mount Rainier National Park (see Legs K and L). This area is close to where the thick Puget lobe glacial ice flowed against the resistant rocks of the Cascade Range near the end of the Ice Age (~16 ka).

A nexus of glacial meltwater channels cuts the landscape near here. Some of these channels were likely carved by floods when large ice-marginal lakes burst their ice dams. Later, after the ice had receded farther north, rivers of glacial meltwater flowed southward into a deep ice-dammed lake, called glacial Lake Puyallup, at the location of the modern Puyallup Valley, filling the whole valley to the brim with water. Crandell (1963b) characterized this lake by carefully mapping a delta complex that formed where sediment-laden outwash streams emptied into it. He noted three different elevations for the tops of those deltas, at 460, 400, and 360 ft (140, 122, and 110 m, respectively). Because the delta tops are close to the level of the lake into which they are built, he inferred that those surfaces mark three levels of glacial Lake Puyallup, each controlled by the lowest available spillway at a given time. The surface of the oldest of these lakes was more than 400 ft (122 m) above that of the modern Puyallup River valley at Orting.

Troost (2007) has suggested that the intensive scouring of meltwater channels that cut across the glacially fluted landscape to the west, flood deposit gravels that lap onto drumlins truncated by those channels, and kettles left by blocks of stagnant ice and multiple terrace levels along those channels all indicate a sequence of glacial outburst floods or jökulhlaups from glacial Lake Puyallup. The lake eventually emptied to the north when the Puget Lobe had melted far enough back.

About 5600 years ago, prior to the Osceola Mudflow, the postglacial (and post-Lake Puyallup) Puyallup River terminated in Puget Sound between the cities of Sumner and Puyallup (see Fig. 36, p. 38). It was tributary to the White River, which flowed through the valley of South Prairie Creek until the enormous Osceola Mudflow from Mount Rainier aggraded its channel and cut a new "shortcut" channel for the White River farther north between Enumclaw and Auburn.

The Puyallup River valley has a long agricultural history—the fertile silty, sandy soils are rich in Mount Rainier Andesite fragments and crystals. There is a diversity in agriculture—berries, vegetables, and nursery stock—that thrives on the sandy loam of the lowermost (more northern) valley near Puyallup, Sumner, and Alderton (Fig. J-2). However, as the highway goes south past McMillin, the clay-rich, rocky, and extensive Electron Mudflow deposit crops out at the surface. The mudflow is more difficult to till than the sandy loam, and so vegetables give way to pasturelands. This great lahar flowed into place about A.D. 1500, burying the old valley floor by as much as 16 ft (5 m) at the present site of Orting, probably within one hour after it began on the

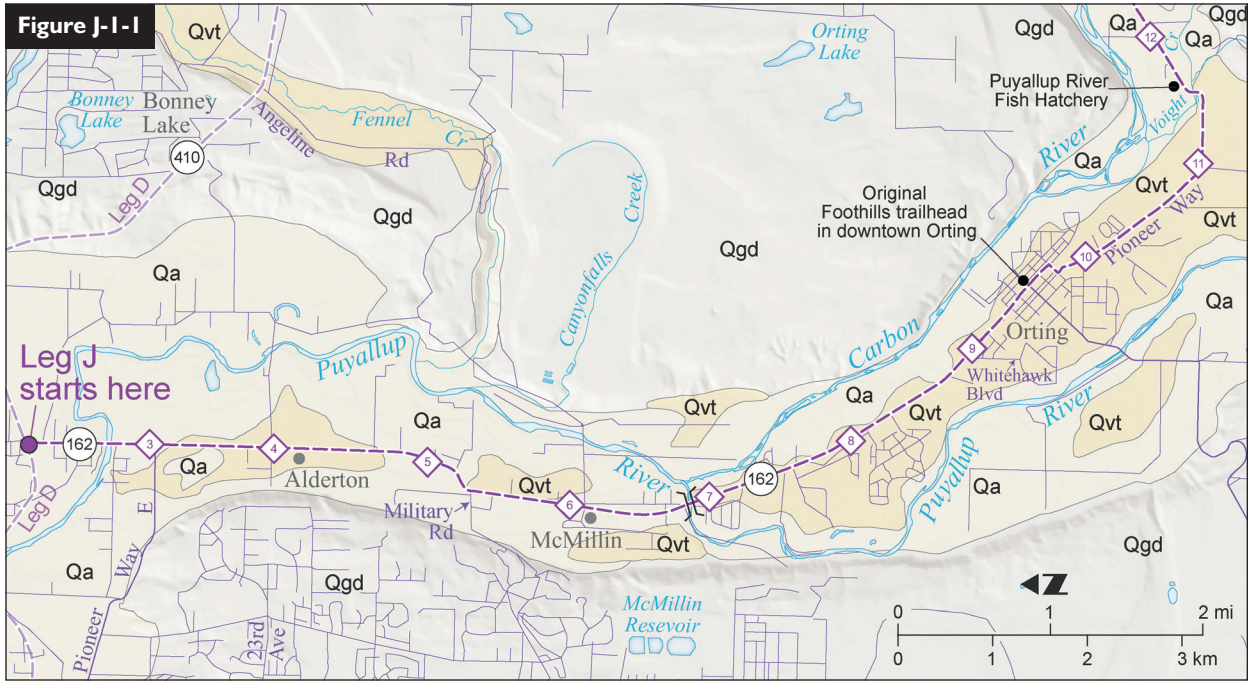


Figure J-1. Geologic map for Leg J (two consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Walsh (1987), Tabor and others (2000), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. Check the north arrows for map orientation. The map explanation is on the inside back cover.



Figure J-2. This produce exhibit by the McMillin Grange at the Western Washington State Fair in Puyallup in the early 1990s demonstrates the fertility of the soils in the Puyallup River valley. At McMillin and points downstream of Orting, a silty sandy loam commonly overlies the Electron Mudflow deposit. Upstream (south) of McMillen, the clay-rich Electron Mudflow is commonly exposed at the surface, and there, dairy farms prevail.

upper west flank of Mount Rainier. The lahar flowed at least as far as the east outskirts of Puyallup. Planning for future use of the valley bottom, including residential and commercial development in the valley and associated infrastructure, includes discussions of the potential for lahars, flooding, liquefaction during earthquakes, and preservation of farmlands, as well as other issues. The population density of the valley bottom has already made efficient evacuation to higher ground via automobile a near-impossibility, so these issues will no doubt continue to appear in local headlines!

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Junction of SR 410 and SR 162. Go right (south) on SR 162.

0.5 *0.8* Bridge across the Puyallup River. The farthest downstream outcrops of the Electron Mudflow (channel-fill deposit) and the Osceola Mudflow are here. The top of the Osceola deposit is about 22 ft (7 m) lower than this bridge. Studies of drilling logs of the Osceola mudflow by Dragovich and others (1994) have shown that the topography of the southern Puget Lowland has changed significantly within the past 5600 years. At the time of the Osceola Mudflow, the highland area now occupied by the modern cities of Federal Way, Milton, Edgewood, and Des Moines was nearly a large island in Puget Sound except for being attached by a narrow neck of land to the Puget Lowland near Sumner (see Fig. 36, p. 38). The delta of the Puyallup River at Puget Sound was located near the present City of Puyallup, and the delta of the ancestral White River in Puget Sound was located about halfway between Sumner and Auburn.

During the magnitude 7.1 earthquake of 1949, many eyewitness accounts of 'sand volcanoes' documented spectacular liquefaction in this area (Chleborad and Schuster, 1998). Black sands composing the sand volcanoes had originated in lahar-derived deposits from Mount Rainier (Palmer and others, 1991; Pringle and Palmer, 1992).

0.7 *1.1* Milepost (MP) 3. Pioneer Way.

1.2 *1.9* Enter Alderton. Lower(?) Pleistocene laharic deposits of the Alderton and Puyallup Formations of Crandell and others (1958) are exposed in the valley walls near Alderton. The two units are separated by the Stuck Drift of Crandell and others (1958); all are reversely magnetized (Easterbrook, 1994) and thus were deposited during a time when the Earth's magnetic field had reversed; this period is called the "Matuyama reversed magnetic polarity chron" (0.8–2.6 Ma). (See the "Paleomagnetism" sidebar on p. 104.)

2.9 *4.7* Military Road.

3.6 *5.8* MP 6, McMillin. There are scattered dark gray to black boulders along the roadside (Fig. J-3). Many of these are volcanic bombs that were erupted about 2,450 yr B.P. and deposited in a thick fan of pyroclastic debris on the west flank of Mount Rainier. They were picked up by the Electron Mudflow, about A.D. 1500, and carried to this location.

Danner (1966) described tufa interbedded with gravel on a steep bluff near where Canyon-falls Creek intersects McCutcheon Road, slightly northeast of McMillin. Tufa is a spongy, porous deposit of calcium carbonate deposited by a spring or seep.



Figure J-3. Andesite volcanic bombs near McMillin and Orting commonly display a 'breadcrust' texture. These rocks were probably erupted about 2,450 yr B.P. during Mount Rainier's Summerland eruptive period and deposited in pyroclastic flow deposits in the upper South Puyallup River. They were then picked up by the Electron Mudflow in about A.D. 1500 and carried to this location. The bomb in the foreground is about 18 in. (0.45 m) wide. (See Fig. A-11, p. 60.)

4.4 *7.1* Another Puyallup River bridge. The Carbon River enters the Puyallup River about 0.2 mi (0.3 km) downstream of this bridge.

4.5 *7.2* Trailhead for the Foothills Trail, a 'rail trail' built on an abandoned railroad bed that parallels the highway.

5.7 *9.2* Enter Orting.

5.8 *9.3* Village Green subdivision. Many tens of buried trees were exhumed during the excavations for



Figure J-4. A aerial view to the southeast of the Puyallup River valley near Orting, some 30 mi (50 km) flow distance from Mount Rainier. The valley is underlain by a thick stack of lahar deposits from Mount Rainier. The youngest lahar is the Electron Mudflow of about A.D. 1500. It originated on the upper west flank (right side) of Mount Rainier and flowed down the Puyallup River valley. At Orting, it covers the entire valley floor to a maximum depth of about 16 ft (5 m). The buried stump shown in Figure J-5 was found during excavations located in the lower left corner of this photo. Photo by Steve Brantley, U.S. Geological Survey, 1992.

this subdivision. The trees were buried in place or carried to this location from Mount Rainier by the Electron Mudflow. The oldest tree found had 457 annual growth rings (counted about 6 ft (~2 m) above the roots), thus it had begun to grow some time before about A.D. 1045.

6.1
9.8 Small turnout on the west. In good weather, Mount Rainier can be seen straight ahead to the southeast.

6.4
10.3 Ptarmigan Middle School. The tree stumps on the lawn were exhumed during construction of the school and are members of the buried forest mentioned above. The inevitability of future lahars in the Puyallup River valley and the installation of acoustic flow monitors in the upper Carbon and Puyallup River valleys by the U.S. Geological Survey (USGS) in cooperation with Pierce County have changed the emergency preparedness practices of citizens in this valley, including that of the schools. Students now learn about the history of lahars and how they are monitored, and they practice evacuations via bus and walking to high ground. A project called "Bridge for Kids" initiated by local citizens has acquired preliminary funding for planning and development of a pedestrian bridge that would allow citizens of Orting to walk to higher ground on the east side of the Carbon River if a lahar is detected. (See http://www.bridge4kids.com.)



Figure J-5. One of the many large subfossil trees unearthed in 1993 during excavations for a sewer line at a new subdivision in Orting. This Douglas-fir was rooted about 16 ft (5 m) below the present land surface. Its average breast-height diameter was more than 9 ft (2.8 m). Tree-ring matching tells us that it was about 360 years old when it was buried by the Electron Mudflow from Mount Rainier at about A.D. 1500. The Electron began when a massive part of the upper west flank of Mount Rainier collapsed and began to flow as a wet, thick slurry at high velocities down the Puyallup River. While the average speed of the flow was about 30 mi (48 km) per hour, in the upper reaches of the river it flowed significantly faster. The lahar likely reached this area about one hour (or less) after it had been initiated at Mount Rainier. It was probably more than 100 ft (30 m) deep when it exited the Cascade Mountains near the present town of Electron, and likely flowed through the site of Orting as a surge about 30 ft (9 m) deep.

6.5
10.5 White Hawk residential subdivision. This area was inundated by the Electron Mudflow in about A.D. 1500 (Fig. J-4). Beginning in 1993, excava-

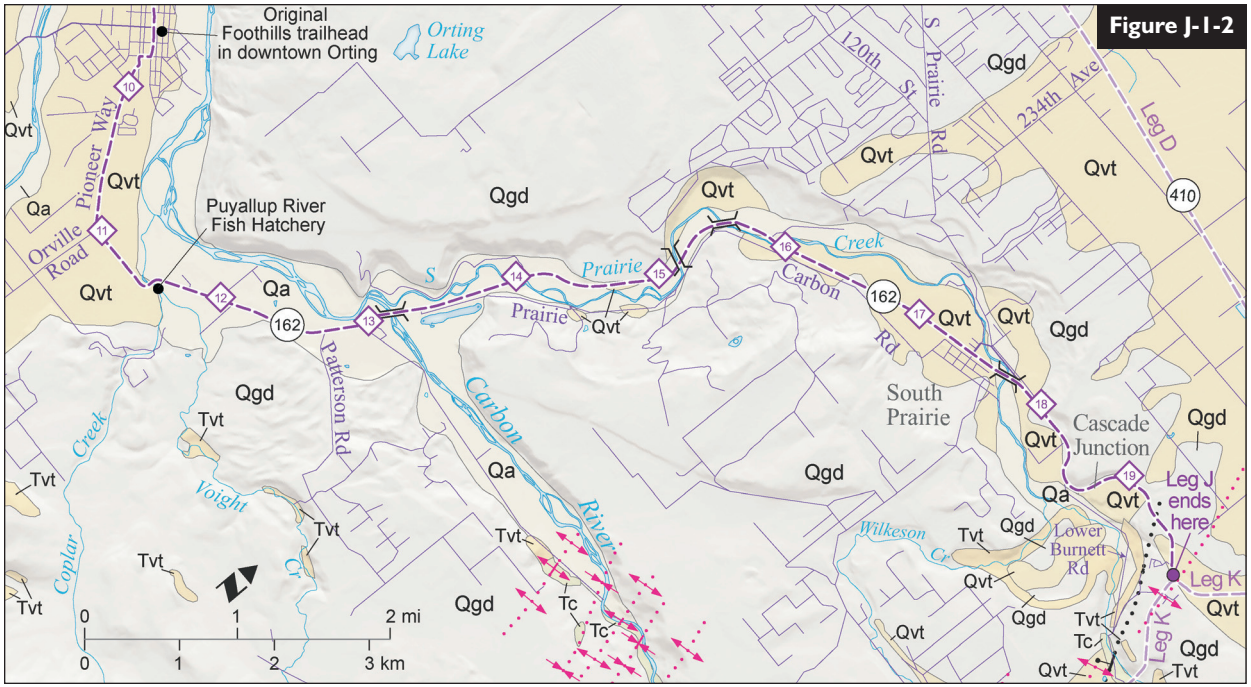


Figure J-1-2

tions on the west side of the highway have exposed remnants of a buried old-growth forest (mostly Douglas-fir) that was preserved within the clay-rich mudflow (Fig. J-5). Some of the excavated snags are lying on the surface, and several in-place stumps stick up in the storm-water retention pond north of the subdivision entrance (now mostly obscured by vegetation in the pond). The 16-ft (5 m)-long chunk of andesitic volcanic breccia, on the left (southeast) side of White Hawk Boulevard (up 0.1 mi [0.1 km]), was excavated here.

7.1 *11.4* Downtown Orting (Calistoga Street).

7.6 *12.2* MP 10.

8.1 *13.0* The warning siren slightly east of the highway is part of the lahar warning system that uses acoustic flow monitors to detect the approach of a lahar from Mount Rainier. The USGS installed the monitors in upper reaches of the Puyallup and Carbon Rivers in 1998 in a cooperative arrangement with Pierce County and the Washington Emergency Management Division of the Washington Military Department (Lahusen, 1996).

The west flank of Mount Rainier, the source of the Puyallup River, has been identified as being particularly susceptible to failure because of the concentrations of altered rock composing its upper flanks. (See "Stewing in Its Own Juices", p. 39.)

8.5 *13.7* MP 11. Orville Road. About 0.8 mi (1.3 km) south of here, USGS geologist Dwight "Rocky" Crandell described another huge boulder 32 ft (10 m) in diameter that had been rafted from Mount Rainier by the Electron Mudflow.

9.1 *14.6* Puyallup River Fish Hatchery at Voight Creek.

9.5 *15.3* MP 12.

10.3 *16.6* Patterson Road. Note the lahar evacuation sign. This road leads out of the lahar inundation zone.

10.5 *16.9* MP 13. Railroad bridge. The new Carbon River bridge replaces the old trestle bridge that was partly undermined and made unsafe by flood erosion in 1990.

10.6 *17.0* You have reached the Carbon River, which heads at Carbon Glacier and drains part of the north flank of Mount Rainier. This is where South Prairie Creek enters the Carbon River. Despite its present size, South Prairie Creek valley is a remnant of the much larger ancestral White River valley that drained the north slope of Mount Rainier. The canyon is wider than that of the Carbon River and is eroded through the bedrock of the Puget Group (Eocene), here formally subdivided into the Carbonado (oldest), Northcraft, and Spiketon Formations.

Both river beds contain abundant rocks from Mount Rainier, but they also include Tertiary igneous bedrock of the Cascades and sandstones, shales, and coal fragments from coal seams of the Puget Group. Along bars and shores of the lower Carbon River, one can find abundant black, gray, and tan petrified wood from the Northcraft Formation. Pieces as large as 1.5 ft (0.5 m) in diameter and 3 ft (0.9 m) long have been found. Farther downstream in the Orting area, the fragments of petrified wood are generally smaller.

11.4 *18.3* MP 14. Bridge over South Prairie Creek.

12.6 *20.2* Another bridge over South Prairie Creek.

13.4 *21.6* An Osceola Mudflow deposit, a massive, poorly sorted, concrete-like layer, is exposed in the left bank of South Prairie Creek under vegetation on the downstream side of this bridge.

15.0 *24.1* Fire station in the town of South Prairie.

15.1 *24.3* Yet another bridge over South Prairie Creek.

15.4 *24.8* The road ascends a terrace.

15.9 *25.6* Lower Burnett Road. Glacial outwash is exposed slightly east of here in a roadcut and continues for half a mile (0.8 km).

17.2 *27.7* End of SR 162 at the intersection of SR 165. Here you can join Leg K (at mile 1.6 of that leg) to the Mowich Lake area. Leg L, the Fairfax Forest Reserve Road to the Carbon River Entrance to Mount Rainier National Park, can be reached from SR 165.

Remember to reset your odometer when you start another leg. ■

LEG K: STATE ROUTE 165—THE MOWICH LAKE ROAD

by Patrick T. Pringle, Timothy J. Walsh, and David A. Knoblach*

This is the most direct access to Mount Rainier National Park from Seattle. The 27-mi (43 km) route begins in the Puget Lowland at Buckley (elev. ~720 ft or 220 m) in the White River drainage basin and, after crossing South Prairie Creek at Burnett and Wilkeson Creek at the historic mining town of Wilkeson, it winds south and east up the Carbon River valley via its spectacular gorge (Fig. K-1).

A short distance after you cross the Fairfax Bridge, you ascend outwash terraces, cross into the Voight Creek drainage basin, and then after about 11 mi (17.5 km) finally reach the Mowich River valley. As you enter Mount Rainier National Park, the road climbs to Mowich Lake, a beautiful tarn at 4929 ft (1502 m) elevation. The Mowich Lake area provides access to several main trails in the national park, including one to scenic Spray Park.

From the beginning of this leg to a short distance beyond its intersection with State Route (SR) 162, you travel along a glacial outwash channel of Pleistocene age, remaining on the Osceola Mudflow deposit and older lahars that underlie the flood plain for nearly the entire stretch. You then ascend a series of terraces in glacial deposits and enter the bedrock highlands of the Cascade Range. Once on the Cascade rocks, you pass folded, faulted, and intruded sedimentary rocks of the Eocene Puget Group, generally finding progressively younger rocks as you proceed up section through a tilted mass of layered rocks (Fig. K-2). You'll then drive past the overlying beds of the younger Ohanapecosh volcanic rocks and some sedimentary interbeds of Oligocene age and dikes and sills of an extensive intrusive complex of Miocene age before finally arriving at Mowich Lake.

This road is closed in winter (typically November to late June) near Milepost 0. Road and trail status can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Junction of SR 410 with SR 165. Take SR 165. This valley was carved by glacial meltwaters about 15,000 years ago. The bottom of the valley is underlain by lahars from Mount Rainier that flowed here through the White River valley.

0.2 *0.3* Milepost (MP) 21.

0.4 *0.6* On a clear day, there is a splendid view of Mount Rainier to the left.

1.2 *1.9* MP 20.

1.6 *2.6* Junction of SR 165 with SR 162. Stay on SR 165.

2.1 *3.4* View of jagged peaks of Carbon Ridge ahead, about 9 mi (15 km) to the southeast, as you enter Burnett near MP 19. Carbon Ridge is composed of granodiorite of the Carbon River stock of Miocene age. This intrusion yielded K-Ar ages of 17.1 and 19.4 Ma (Tabor and others, 2000).

2.3 *3.7* Bridge at Burnett.

3.2 *5.1* MP 18.

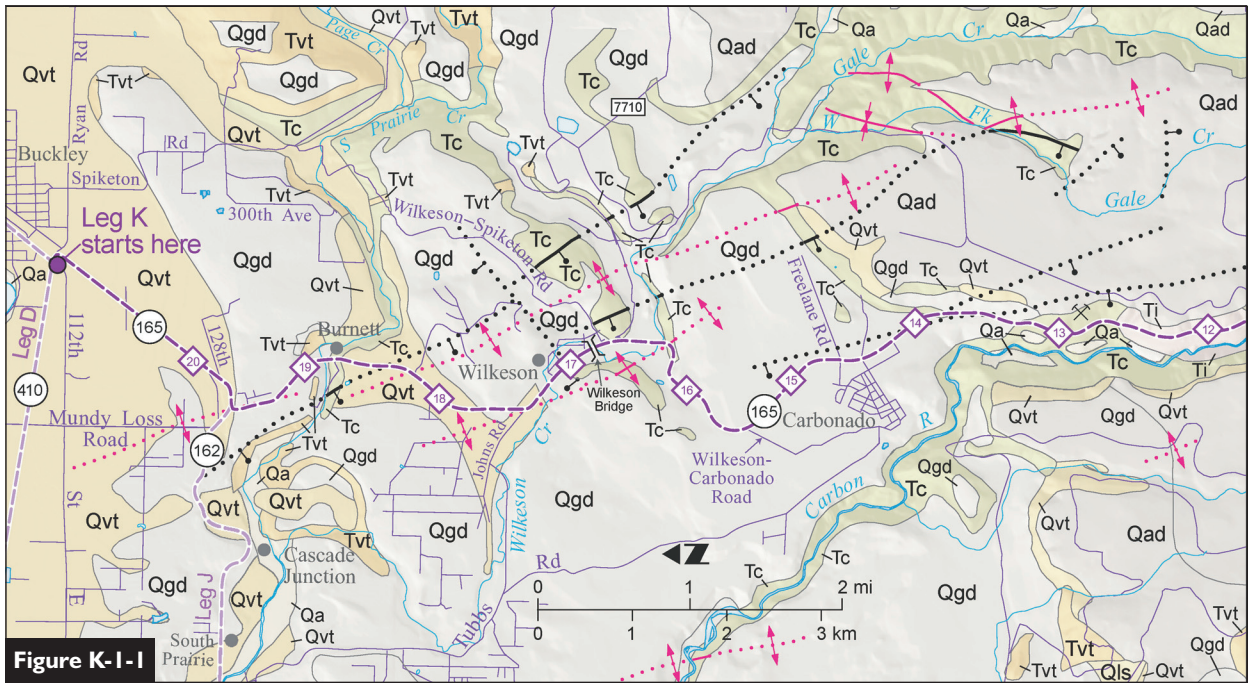


Figure K-1-1

Figure K-1. Geologic map for Leg K (three consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Walsh (1987), Tabor and others (2000), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.

* See "Contributors", p. ii, for affiliation.

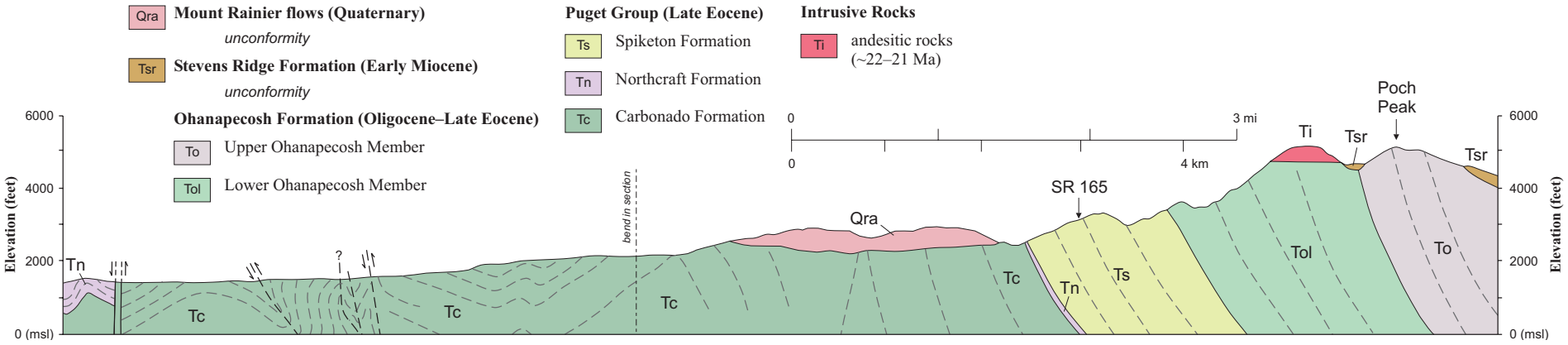


Figure K-2. The structure of faulted and folded bedrock of the Eocene Puget Group and Oligocene Ohanapecosh Formation and Stevens Ridge Formation west-northwest of Mount Rainier. Also shown are a Mount Rainier lava flow (unit Qra) and the recently identified Mowich Lake sill complex (unit Ti) of Hammond (1999) and Hammond and others (1999). Deposits of Quaternary glaciers and rivers are not shown. Modified from Buckovic (1974).



photo by Dave Knoblach

Figure K-3. The Wilkeson sandstone structure at Wilkeson before it was damaged by the 2001 Nisqually earthquake. The new structure was rebuilt in 2004 using the same sandstone blocks. View is to the north.

3.4 First of two turnoffs to Carbonado.
5.5

3.7 Ascend a terrace.
6.0

3.9 Wilkeson Cemetery on the left (east).
6.3

4.2 A sandstone monument marks the entrance to the
6.8 Town of Wilkeson (Fig. K-3). The original monument, built in 1925 for $2000, bore a sign reading "Wilkeson—Gateway to the Carbon Glacier" for those entering Wilkeson and "Remember Wilkeson" for those leaving (Hall, 1980). The original structure was damaged in the Feb. 28, 2001, Nisqually earthquake (magnitude 6.8). The earthquake shifted the sandstone blocks of one of the columns about 4 in. (10 cm) and tilted the structure slightly. Many of those blocks were used in constructing the new monument, which was completed in 2004.

4.6 Turnoff on the left (east) to Wilkeson School, con-
7.4 structed in 1913 of Wilkeson sandstone (Fig. K-4). Wilkeson sandstone was also used to construct the buildings on the Washington State Capitol Campus in Olympia, including the Capitol itself; construction there began in 1912. This sandstone is the uppermost member of the Carbonado Formation of the Puget Group of Eocene age. (See "A Sandstone Industry" sidebar on p. 147.)

The Wilkeson sandstone, part of the middle to upper middle Eocene Carbonado Formation, likely was deposited in a deltaic and flood-plain environment by streams that originated to the east (Fig. K-5). The Wilkeson sandstone also marks the stratigraphic top of the historically productive coal seams in the area. In this vicinity, lahars of the Northcraft volcano flowed into local drainages and thus are interbedded with Wilkeson deposits. Sedimentary rocks of the Spiketon Formation, in turn, overlie and are interbedded with Northcraft laharic deposits. These sandstones, siltstones, and coal in the Spiketon are similar to those in the Carbonado Formation; however, the rank of the coal is lower. Collectively, these Eocene terrestrial sedimentary rocks are known as the Puget Group. The great thickness (>8,500 ft; ~2,600 m) of the Puget Group rocks suggests they were deposited in slowly subsiding tectonic basins (Gard, 1968).



Figure K-4. Wilkeson School, constructed in 1913. The building stone, Eocene-age Wilkeson sandstone of the Carbonado Formation, was quarried and dressed nearby. It was also used to construct the Washington State Capitol buildings.

Coal was discovered in this area in the 1870s, and a railroad reached the mines in the late 1870s. By 1885, the Tacoma Coke and Coal Company had constructed 160 coke ovens here (Kirk and Al-



Figure K-5. These well-preserved ripple marks on a *dip slope* of folded Carbonado Formation sandstone record wave movements on an Eocene beach. A rock hammer is shown for scale.

exander, 1995). The sixty that remain today can be seen near the road to the east of Wilkeson School and are on the National Register of Historic Places. There are more coke ovens at the bottom of the gorge near Carbonado and also near Crocker, located about 4.5 mi (7.2 km) west of Carbonado along SR 162 (Leg J). More than 500 were in use in this area in1921. Coke production here ended by about 1937.

The McKay coal seam lies immediately below the Wilkeson sandstone. In the late 1800s, coal miners believed that the stratigraphy at Wilkeson was similar to that of other coal regions in western Washington, such as along the Green River and at Black Diamond in King County to the north. However, because coal beds are folded and faulted throughout this area, it was (and still is) impossible to correlate coal seams between King County and Pierce County. Nonetheless, the uppermost significant coal seam found anywhere in either King County or Pierce County was commonly, but incorrectly, called the McKay seam.

Local lore states that at one time a person could walk the nearly 9 mi (14 km) between the towns of Burnett and Fairfax entirely underground through the system of mine tunnels. This story is untrue because of the folding and faulting noted above, but it does suggest the abundance of mined tunnels in this area.

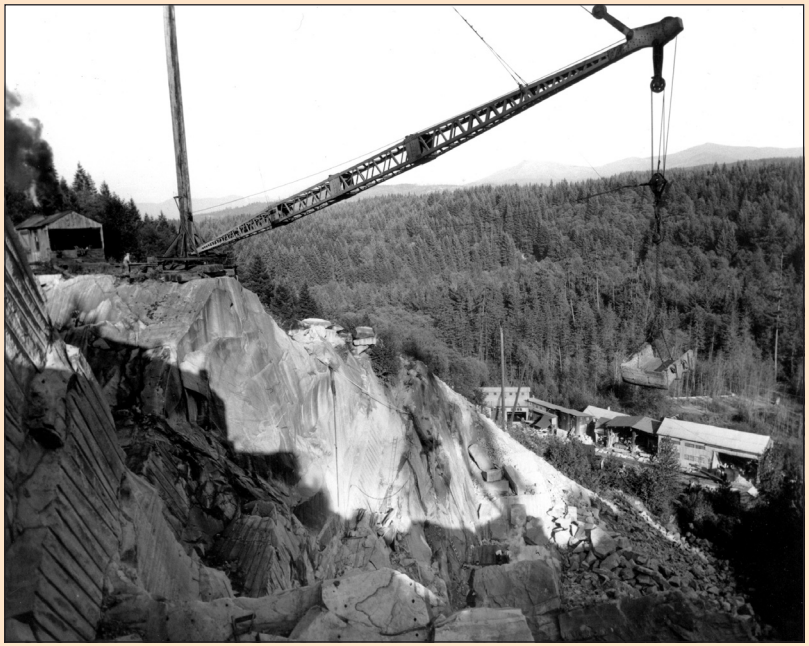
A Sandstone Industry

by David A. Knoblach and Rebecca A. Christie

Part of the Carbonado Formation of the Puget Group, the Wilkeson sandstone is a thick, buff to tan, medium-grained sandstone (Moen, 1967; Knoblach, 1994). The stone has about 10 percent porosity and needs no waterproofing, making it a high-quality building stone. A 1917 newspaper article quotes a building stone expert: "The sandstone from the Wilkeson quarry...is the best in the entire country. It has great strength, stands heat, and is nearer waterproof than any other sandstone I know. It is so hard that if the Germans had the Wilkeson stone they would be using it for bullets" (*Tacoma Daily Ledger*, 1917).

During the 1870s, the Northern Pacific Railroad removed material from outcrops of this stone for ballast in the construction of its railroad lines along the Pacific coast. In 1883, the builders of St. Luke's Episcopal Church in Tacoma were the first to use Wilkeson sandstone for construction (Knoblach, 1993). Demand for stone for commercial buildings and homes increased in the 1890s following several devastating fires in large cities in Washington and around the nation. The early railroad quarry opened officially in 1886 (Hall, 1980). In time, several quarries worked in the stone, prominent among them, the Walker-Wilkeson quarry. Another quarry in this formation was worked near the town of Burnett (about 4 mi [7 km] north of Carbonado).

Many civic, business, and residential buildings in Washington and Oregon are faced with this sandstone. About 15,400 tons (~15,000 metric tons) of Wilkeson sandstone went into the dome of the current Washington State Legislature building, completed in 1928. It is one of only two solid stone domes in the nation (*The Northwest*, 1968), probably the last dome of its kind constructed anywhere in the world. Dressed and carved stone from this quarry went into the Cathedral of St. John the Evangelist in Spokane, built between 1926 and 1954. Stone cutting was a well-paid, men-only profession.



Walker-Wilkeson quarry in the late 1920s. A derrick that can move both equipment and rock rubble in the quarry lifts a container. The gang saws were in the shop buildings at the base of the slope. View is to the northeast. Photo courtesy of Tacoma Public Library.

With the development of concrete as a building material and improved bricks, stone use declined. Most major quarries had folded after the Depression. Bucking this trend, the Walker-Wilkeson quarry was in continuous production from 1904 until bankruptcy closed it in 1982. Total stone output from the Walker-Wilkeson quarry from 1911 to 1969 was estimated at 353,265 tons (~320,000 metric tons) (Knoblach, 1994). Orders totaling at least $250,000 were left unfilled at its closure (*The Olympian*, 1982). Products from the quarry, once the largest cut-stone plant west of the Mississippi River, included ashlar (hewn or squared stone), hearths, sills and coping, patio stone, special cut pieces, and sculpted stone (*Tacoma Daily Ledger*, 1932). Knoblach (1993) reported that the quarry (under another ownership) sold rock for pilings and rockeries, as well as architectural miniatures; today, as the Wilkeson Sandstone Quarry, it once again offers cut stone. The sandstone is still occasionally used to repair historic buildings and for preservation purposes. ■

Although perhaps not aesthetically pleasing in design, the subsurface coal mines in Washington are some of the most significant construction projects in the history of the Pacific Northwest. For

example, in the 1890s, a mining inspector noted that more than 1000 pieces of timber were used for every 400 tons of coal mined—more than anywhere else in the world. The main reason local mines were so complex, and the extraction of coal so difficult, was that many coal seams were in places steeply dipping to vertical. Coal mining in the Fairfax area upstream of here was abandoned because the density of faults increased as mines approached Mount Rainier, making the coal extraction uneconomic, even though the rank increases closer to the mountain.

Many Wilkeson area coal mines now pose hazards to construction and recreation in the area. Some collapsed tunnels are visible from the air, appearing like parallel grooves or scratches upon the local topography.

The last active coal mine in the Wilkeson area closed in 1968, mainly because underground bituminous to subbituminous coal mining was no longer profitable. Open-pit mining could be considered here in the future here; however, environmental concerns such as acid mine drainage and habitat disruption would have to be addressed. Some of the local sedimentary rocks have been drilled for their coal-derived natural gas reservoirs, although no economically feasible deposits have been found.

Geologist Bailey Willis, who had mapped the coal seams in the Wilkeson–Carbonado area in the 1880s, was the one of the first Europeans to hike to the Carbon Glacier area along the north side of the Carbon River through the Fairfax Bridge area. The route was known for many years as the Bailey Willis trail. Coal miners recognized Willis by naming a coal town in the Wilkeson area South Willis. The town no longer exists, but it was about 1 mi (1.6 km) east of Wilkeson. The Willis Wall on Mount Rainier also is named after him. Willis later worked for the U.S. Geological Survey in California and recognized the earthquake potential of that region. He was one of the first to push to improve local building codes there because of the earthquake risks. (See the "Bailey Willis" sidebar on p. 149.)

4.8 *7.7* Cross Wilkeson Creek and ascend several terraces of glacial drift. About 16 ka, the Puget lobe of the continental ice sheet reached the mountainous terrain of the Cascade Mountains near here. It blocked rivers and creeks draining the Cascades, forming ice-marginal lakes. As the glacial ice receded, lakes would empty and subsequently become dammed by ice at successively lower elevations. When the Puget lobe had melted back and streams established channels, great kame deltas that had been deposited in the ice-marginal lakes remained perched along the former location of the ice margin as ghostly reminders of the ice dams and lakes. (See Fig. A-3, p. 55, and Figs. N-3 and N-4, p. 161.)



Figure K-6. Geologist Tim Walsh examines a thick hydrothermally altered andesite sill near MP 13 along SR 165. View is to the south.

5.3 *8.5* MP 16.

6.4 *10.3* The gravel pit on the left exposes stream-laid glacial deposits that are probably of Evans Creek age (~22–15 ka) and represent the outwash of the most recent Pleistocene alpine glacier in the Carbon River valley.

6.7 *10.8* Main Carbonado turnoff. Remain on SR 165.

8.3 *13.4* Gorge of the Carbon River. One result of a clearcut operation here was the discovery of a thrust fault (unmapped) and fold visible to the north-northwest in the gorge (toward Carbonado). The trees have since grown back, and the fault is not visible now. The outcrop to the left is intrusive andesite of Oligocene or Miocene age.

8.5 *13.7* Outcrops of folded Carbonado Formation sandstone and shale of the Eocene Puget Group with bituminous coal interbeds here dip to the east-northeast. Visible in these outcrops is a shear zone with thrust offset in a thin coal layer.

8.6 *13.8* Outcrops of folded Carbonado Formation sandstone

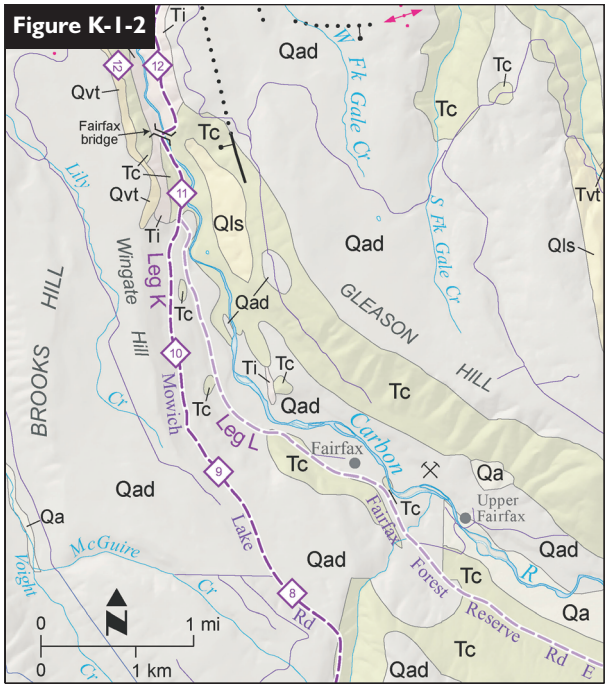
8.8 *14.2* The complexly jointed rock on the left (east) is intrusive andesite of Oligocene or Miocene age.

9.1 *14.6* The blocky outcrops in this stretch were originally mapped by Gard (1968) as quartz diabase, an intrusive rock similar to diorite, but they might more appropriately be described as hydrothermally altered or propylitized andesite sills (Fig. K-6). This rock has been sheared, and there are quartz veins visible in a pull-apart or extensional structure. The sill intrudes the Puget Group, which locally dips at steep angles. Geologists have not yet determined an age for this andesite, which is compositionally similar to Miocene intrusive rocks found in the Puyallup and Nisqually River basins 9 mi (14.4 km) and 21 mi (33.6 km) to the southeast respectively. It intrudes rocks ranging in age from Eocene through lower Oligocene, hence it is younger than those rocks.

The sill made this location a potential dam site. However, the area contains many significant underground coal mines, located both within the valley and below the river. The dam project was abandoned because unknown mine tunnels could become conduits for water after the reservoir was filled. Although the significant mines are mapped, others that were worked before the 1890s and during the depression of the 1930s have no record. This sill also has been considered as a potential quarry for crushed rock.

9.4 *15.1* Joints in the intrusive rocks likely contribute to minor slope instabilities near here by providing both failure planes and pathways for moisture. Notice that many joints have a nearly vertical orientation.

9.7 *15.6* Fairfax Bridge spanning the Carbon River gorge. Heat from the intrusions that fueled Cascade volcanoes affected coal seams both regionally and lo-



cally. In general, the rank of Eocene coal increases from lignite and subbituminous at shallow depths west of the Cascade Range nearer the Puget Lowland to anthracite (hard coal) closer to the volcanic centers and intrusive bodies and Mount Rainier (Walsh and Lingley, 1991).

It is widely accepted that Eocene coal seams in the Roslyn area north of Interstate 90 on the east side of the Cascade Range are the upstream equivalents of those in the Wilkeson–Carbonado area. However, Roslyn lies on the north side of the Olympic–Wallowa lineament, and rocks in that area are separated by faults from the rocks of this area. A similar increasing rank with proximity to volcanoes and intrusive centers applies there.

10.2 *16.4* Siltstone, mudstone, and sandstone with coal are exposed here. Beds dip to the west.

10.3 *16.6* Junction of SR 165 (Mowich Lake Road) with Carbon River Road (Fairfax Forest Reserve Road). To visit the Ipsut Creek Campground area and Carbon Glacier, bear left on Carbon River Road to follow Leg L. Bear right to stay on SR 165 to continue on this leg.

Bailey Willis (1857–1949)

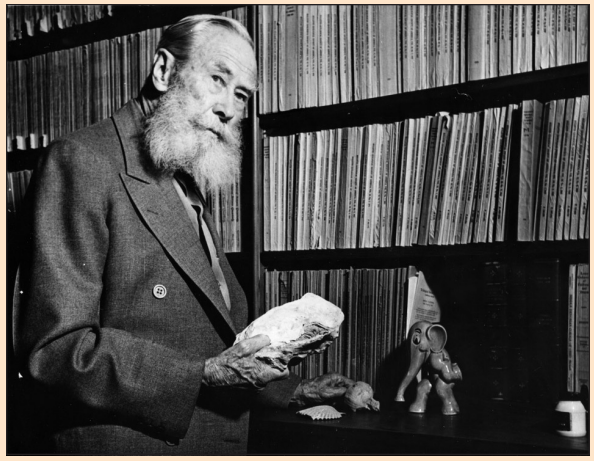
by David A. Knoblach, Katherine M. Reed, and Rebecca A. Christie

Bailey Willis, working as a survey geologist for the Northern Pacific Railway, mapped the coal seams in the Wilkeson–Carbonado area in the early 1880s. He was the first European to hike to the Carbon Glacier along the north side of the Carbon River through the Fairfax Bridge area. The route from Ashford to Fairfax, whose construction he supervised in 1883, was known for many years as the Bailey Willis (or Grindstone) trail. The trail enabled tourists to visit the north side of Mount Rainier. Willis worked with many others to have the mountain area set aside as a park (in 1899); he named Mountain Meadows, Spray Falls, Tolmie Peak, and Liberty Cap. The Willis Wall at the head of the Carbon Glacier is named after him. Coal miners recognized Willis by naming a coal town in the Wilkeson area South Willis; that town sent much of its coal production to California but faded away in about 1920 when California's oil and gas prices became lower than the cost of the 'imported' coal.

Willis joined the U.S. Geological Survey in 1884. His interest in the Puget Group continued, however; he published papers on the subject in 1897 and 1898. His career led him to study geologic structures worldwide. Oreskes (1999, p. 305) noted: "Those who thought [continental] drift plausible faced the criticism of Bailey Willis, who argued that the [continental] fits were *too* good, because faulting during breakup and subsequent coastal erosion would surely have modified the continental outlines!" He was later generally known as the 'father of structural geology'.

During his California years, he recognized the earthquake potential of that region. "It will be well for architects to respect His Majesty, the Earthquake, in making their designs" (Geschwind, 2001, p. 79). He was one of the first to push to improve local building codes there because of the earthquake risks. His efforts were not welcomed at the time. "[If scientists don't] stop their talk about the earthquake problem [in California] I for one am going to see what I can do about stopping the whole seismological games" said a real estate promoter in the early 1900s, who later organized a builders association to halt efforts to improve building codes in California, and to publicly humiliate and discredit Bailey Willis and other geologists (Geschwind, 2001, p. 89). Today the West Coast benefits from his work in having the Universal Building Code seismic zonation to guide construction.

Willis became the head of the Stanford University Geology Department in 1915. During his lifetime he presided over several professional societies and received numerous awards, including the gold medal of the Société Géographique de France (1910) and the Penrose Medal of the Geological Society of America (1944). He died in Palo Alto, California. ■



Geologist Bailey Willis (1857–1949) conducted pioneering investigations in the Mount Rainier area in the late 1880s. His lengthy career as a geologist included stints as the President of Seismological Society of America, as the head of two divisions of the U.S. Geological Survey, and as Chairman of the Geology Department at Stanford University. Willis was also an influential advocate for the establishment of Mount Rainier National Park. Photo courtesy of Stanford University Archives.

10.7 *17.2* On a clear day, there is a nice view of Mount Rainier and the Carbon River valley here.

11.0 *17.7* A large mound to the left (east) of the road could be morainal debris. However, similar mounds have been identified in volcanic debris avalanche deposits (see below).

12.0 *19.3* End of pavement.

12.2 *19.5* MP 9.

12.4 *20.0* A clearcut here in 2002 revealed abundant subangular boulders of andesite scattered on the landscape in this vicinity. Although this area was mapped by Crandell and Miller (1974) as glacial drift, these subangular andesite boulders are more indicative of a lahar or volcanic debris avalanche deposit. The boulders might not be obvious because trees have reestablished on the site.

13.6 *21.9* A poorly sorted, matrix-supported deposit exposed on the right (west) here contains subangular ande-



Figure K-7. Cross beds and some ripple marks exposed in rocks of the Puget Group on the north side of SR 165 between MPs 2 and 3. Marker pen (5.5 in. or 14 cm) is for scale (lower right center in circle). The cross-bedded rocks are tilted nearly vertically owing to extreme folding of the Puget Group rocks. These cross beds probably indicate sand movement in transverse bars of a braided stream, possibly at the onset of Ohanapecosh volcanism. A similar sort of sediment transport has occurred downstream of Mount St. Helens in ash-choked rivers.

site boulders and may be correlative with the similar boulders mentioned above. This deposit appears to postdate the Hayden Creek drift of about 170 to 130 ka.

13.5 *21.7* The roadcut on right exposes a glacial deposit with rounded boulders and cobbles.

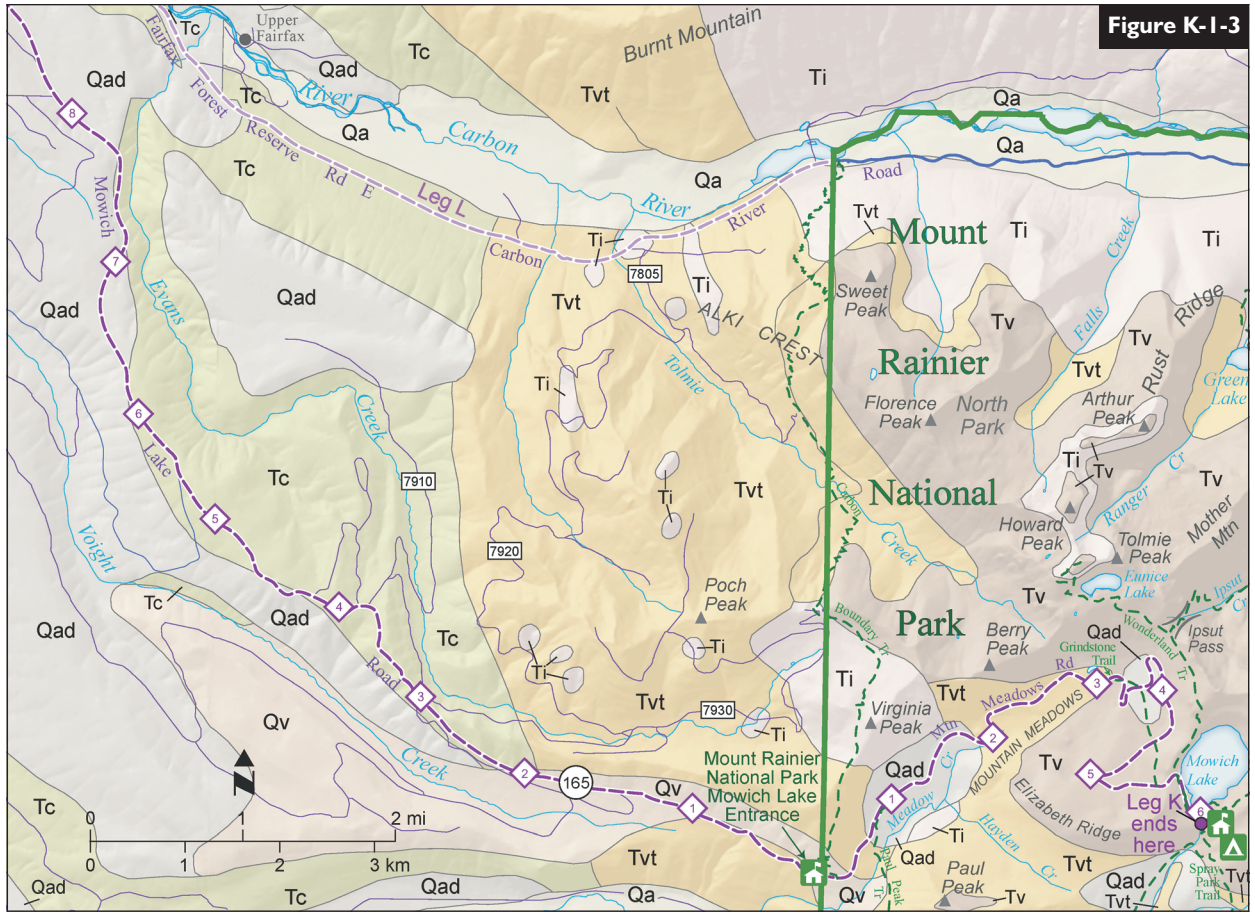
14.7 *23.6* A panoramic view to the southwest across the Mowich and Puyallup River valleys through a clearcut; it will soon be blocked by a young forest.

16.6 *26.7* Pullout to the right. Altered massive Puget Group sandstone crops out here.

16.9 *27.2* Sandstones on the east side of the road are interbedded with carbonaceous shales.

17.3 *27.8* More Puget Group sandstones are visible here, as are views of Mount Rainier through the foliage.

18.2 *29.3* MP 3. Evans Creek ORV (off-road vehicle) area. Carbonaceous siltstones with plant fragments are interbedded with sandstones. On a fine day, a spectacular view of Mount Rainier is nearly straight ahead.



18.6 *29.9* Note the cross beds (and possible ripple marks?) in sandstones of the Puget Group. The bedding of the rocks is oriented nearly vertically and strikes about north-northwest. If the beds were unfolded, the dip of the cross beds would indicate a generally westerly streamflow (Fig. K-7). For the next 0.5 mi (0.8 km) there are good outcrops of sandstone.

19.1 *31.7* More thin-bedded sandstone with local interbeds of carbonaceous material. These dipping beds contain fragments of volcanic debris and may have been deposited near the onset of Oligocene Ohanapecosh volcanism.

19.7 *31.7* If the weather is good, there is a fine view of the west face of Mount Rainier here.

20.2 *32.5* MP 1.

20.3 *32.6* Till from an advance of an alpine valley glacier overlies bedrock exposed in the quarry on the left (north). This quarry is overgrown with alder and behind a dirt berm, so it is difficult to see.

20.7 *33.3* A rainstorm during the winter of 1995/96 triggered a landslide in glacial drift and underlying colluvium that took out the road at this curve. Geologists from the Washington State Department of Transportation designed an engineered structure called a 'geosynthetic wall' to secure the repaired road from future failures (Moses and Jenkins, 1998). The concrete barriers along the south edge of the roadway mark the top of the wall.



Figure K-8. A thick sill of the Mowich Lake sill complex, a talus slope, and autumn foliage along SR 165 about 2 mi (3.2 km) west from the end of the road at Mowich Lake. Hammond (2000) noted that this sill complex covers an area of about 21 mi^2 (60 km^2) and has exposed thicknesses as great as 0.6 mi (1 km). View is to the north.



Figure K-9. Mowich Lake and Mother Mountain. Castle Peak, on the left skyline, is composed of the dikes and many sills of the Mowich Lake andesite sill complex (Hammond, 1999). View is to the northeast.



Figure K-10. Mount Rainier and the two flank vents, Echo Rock and Observation Rock. These vents, both of Pleistocene age, produced the basaltic-andesite flows that underlie Spray Park. View is to the southeast from near the Wonderland Trail at Spray Park.

21.0
33.8
A large outcrop of Ohanapecosh volcaniclastic rocks here includes a massive lapilli tuff. This is the first appearance of these greenish volcaniclastic rocks along this road. These rocks are significant because they are one of the older layers to show evidence of Cascade volcanism.

21.1
33.9
This former quarry exposes a nexus of near-vent dikes that is part of the sill complex described below at mile 21.6. If you pull off on the south side of the road, you'll have a nice view of the northwest face of Mount Rainier, the North and South Mowich and Edmunds Glaciers, and the upper Mowich River valley.

21.2
34.1
MP 0. SR 165 ends here and the National Park Service road begins. The road is gated here in winter.

21.5
34.6
Mount Rainier National Park (sign). Rocks here strike N35°W and dip about 55 degrees to the northeast. One of the units is a poorly sorted volcaniclastic bed that might be a lahar deposit.

21.6
34.8
Just inside the national park boundary, thin-bedded Ohanapecosh rocks are cut by dark, fine-grained intrusions. The beds of the Ohanapecosh strike about N50°W and dip about 70 degrees to the northeast, whereas the dikes strike about N30°W and dip nearly vertically. These intrusions are part of the Mowich Lake sill complex previously designated as Fifes Peak Formation (Hammond, 1999). According to Hammond, the dikes have yielded $^{40}Ar/^{39}Ar$ ages of about 22 to 21 Ma and are distinctly different in composition from the rocks of the older Fifes Peak Formation farther to the east. This sill complex covers an area of some 21 mi^2 (60 km^2) and is predominantly porphyritic augite-hypersthene andesite and microdiorite in composition. Hammond and his colleagues speculate that these intrusive bodies fed lava flows along the White River that have a similar petrologic composition.

21.7
34.9
More alpine till is exposed here and at scattered outcrops between here and Mowich Lake.

21.8
35.0
A sill crops out on the right

22.1
35.5
Trailhead for the Paul Peak Trail. Intrusive rocks of the Mowich Lake sill complex crop out on the north side of the road, and a massive lapilli tuff of the Ohanapecosh Formation is not far to the west. The Paul Peak Trail accesses the Wonderland Trail, which circumnavigates the volcano.

22.5
36.2
Outcrop of intrusive andesite on the left.

22.6
36.4
Outcrops of fragmental rock to the left here are hydrothermally altered and (or) sheared Ohanapecosh rocks. The alteration likely is related to the nearby Miocene intrusions noted above.

22.9
36.8
Ohanapecosh volcanic breccia is exposed here.

23.5
37.8
"Diorite porphyry" with crude columnar jointing mapped here by Fiske and others (1963) probably represents another exposure of the above-mentioned Mowich Lake sill complex described by Hammond (1999) and Hammond and others (1999). Till nearby is overlain by Mount St. Helens Yn tephra (3.5 ka).

24.2
38.9
Greenish rocks exposed on both sides of the stream crossing are Stevens Ridge Formation volcaniclastic rocks (~25–21 Ma).

24.5
39.4
Grindstone trailhead is to the right after a hairpin curve. This trail extends south from the Mountain Meadows area to the north flank of Elizabeth Ridge and does not connect to the Wonderland Trail.

25.0
40.2
A prominent sill of the Mowich Lake sill complex is visible in a big cliff to the east at Ipsut Pass (Fig. K-8).

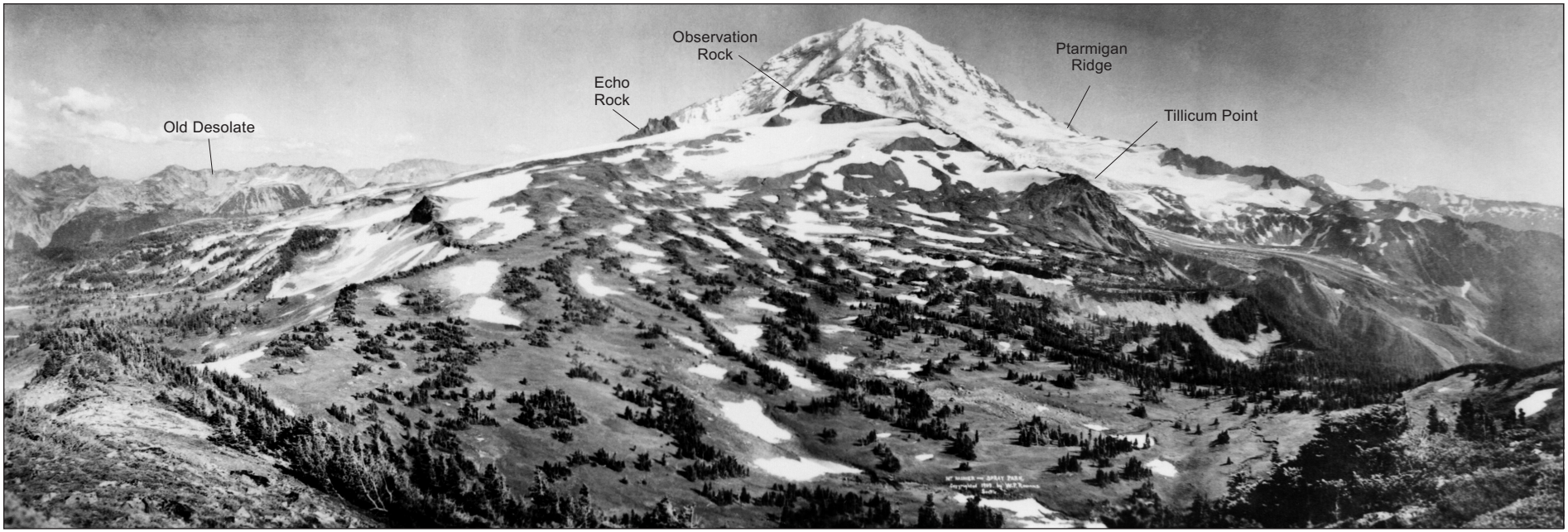


Figure K-10. "Mt. Rainier and Spray Park", a 1903 photo by W. P. Romans. This broad view is to the southeast and may have been taken from Mount Pleasant or another ridge-top location northwest of Spray Park. The smooth, partially snow-covered landform in the upper left center is the basaltic-andesite 'mini-shield' produced by Pleistocene eruptions at Observation and Echo Rocks. Old Desolate is made up of Miocene intrusive rocks and Mt. Rainier andesite. Photo copyrighted 1903, used with permission of the Washington State Historical Society; annotation added by the authors.

25.1 *40.4* Yellowish Stevens Ridge Formation(?) volcaniclastic rocks are exposed here.

25.3 *40.7* Outcrops of Stevens Ridge volcaniclastics and Fifes Peak andesites for next 1.3 mi (2.1 km).

25.9 *41.7* There can be a good view of Tolmie Peak to the north at a hairpin turn to the left at 4800 ft (1464 m) along the north flank of Elizabeth Ridge. Tolmie Peak and its adjoining ridge consist of Mowich Lake sill complex rocks with local granodiorite intrusions of early Miocene age.

27.0 *43.4* Parking area for Mowich Lake (Fig. K-9). Mowich Lake is a tarn and the largest lake in Mount Rainier National Park at 122.6 acres (~50 hectares); its measured depth is 190 ft (58 m)(Wolcott, 1961). The Spray Park Trail, accessible from the parking area, leads to beautiful Spray Park and views of Mount Rainier and two basaltic-andesite satellite vents—Observation and Echo Rocks—both of Pleistocene age (Figs. K-10 and K-11).

You will have to retrace this route to access other legs. ■

LEG L: CARBON RIVER ENTRANCE VIA CARBON RIVER ROAD

The short (~8 mi or 12 km) Carbon River Road (or Fairfax Forest Reserve Road) diverges from State Route (SR) 165 (Mowich Lake Road) at about 1400 ft (427 m) elevation, roughly where the latter leaves the Carbon River canyon and the valley widens (Fig. L-1). After about 2 mi (3.2 km), it approaches the town of Fairfax. Fine deposits near here indicate that the area was inundated by a sequence of temporary glacial lakes that were formed when receding ice of the Puget lobe of the continental ice sheet blocked the Carbon River (Fig. L-2).

The road enters Mount Rainier National Park and passes through a forest of spectacular Douglas-fir trees before reaching Ipsut Creek Campground. However, much of this 5-mi (8 km) stretch of road in the park was destroyed in the flood of November 2006. The National Park Service is considering not rebuilding this road segment because the river, whose bed has aggraded, is a constant threat. Those who drive the primitive road from the national park entrance or who walk or bike in can access the network of trails that traverse the park, including one only 3.2 mi (5.2 km) long that leads to the terminus of Carbon Glacier, the largest glacier on Mount Rainier. The maps for this leg stop at the Carbon River Entrance to the park although the road log continues as far as Ipsut Creek Campground. You will need a trail map if you wish to hike or bike past the entrance.

Note: The status of roads and trails can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any of the optional side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Junction of SR 165 (Mowich Lake Road) with Carbon River Road (*aka* Carbon Glacier Road and Fairfax Forest Reserve Road). From southbound SR 165, bear left onto Carbon River Road.

0.4 *0.6* If the weather is good, there are views of Mount Rainier from this area.

1.6 *2.6* On Feb. 2, 2003, the road at about this location suffered a collapse that was later attributed to possible subsidence of a coal mine. This type of subsidence is a concern in this area because of the numerous subsurface mines. Walsh and Logan (1989) summarized the extent of coal mining in Washington and provided an overview of the subsidence problem.

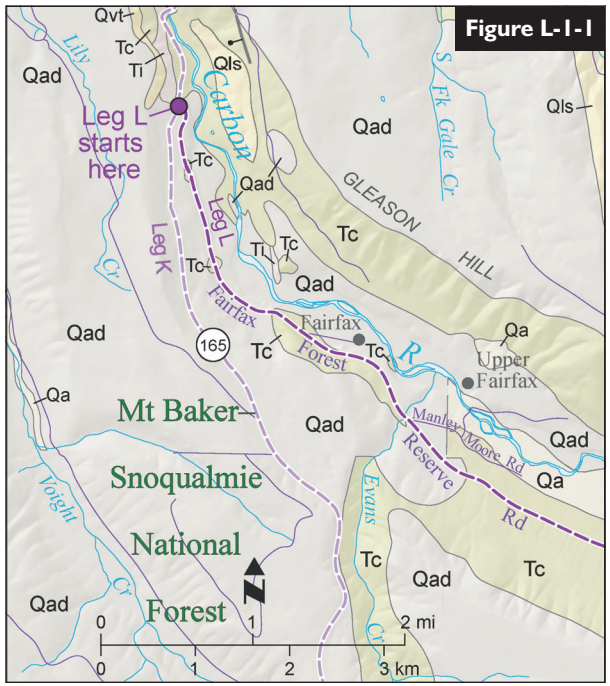
1.9 *3.1* Lacustrine deposits, part of the ice-margin lakes mentioned above, were mapped by Crandell and Miller (1974) near here, but are now covered by vegetation.

2.9 *4.7* Bridge over Evans Creek, near the type locality of the Evans Creek Drift (~22–15 ka). Manley Moore Road is about 100 ft (30 m) past the bridge.

5.6 *9.0* Note the large boulders in Poch Creek that were carried here by a debris flow during a rainstorm in November 1995. Residents in the house just west of the creek heard intense rumbling as the debris roared down the channel. Poch Creek heads on Poch Peak, about 2.8 mi (4.4 km) south-southeast of the here. The peak is composed mostly of Oligocene Ohanapecosh Formation.

5.8 *9.3* This tributary to Poch Creek contains large boulders, also of debris flow origin.

6.1 *9.8* Cross Tolmie Creek, which heads about 3.4 mi (5.4 km) southeast of here at Tolmie Peak in Mount Rainier National Park. That peak is near where William Fraser Tolmie made his observations of Mount Rainier in 1833. (See "Historic Accounts of Activity at Mount Rainier", p. 13.)



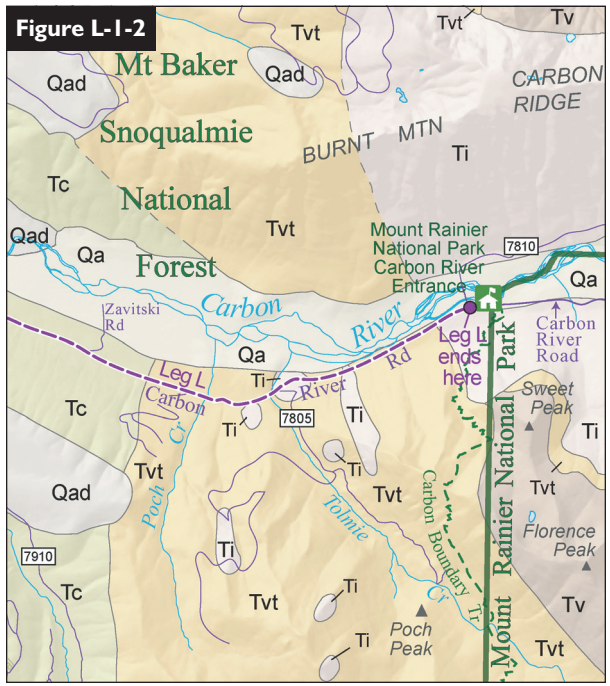
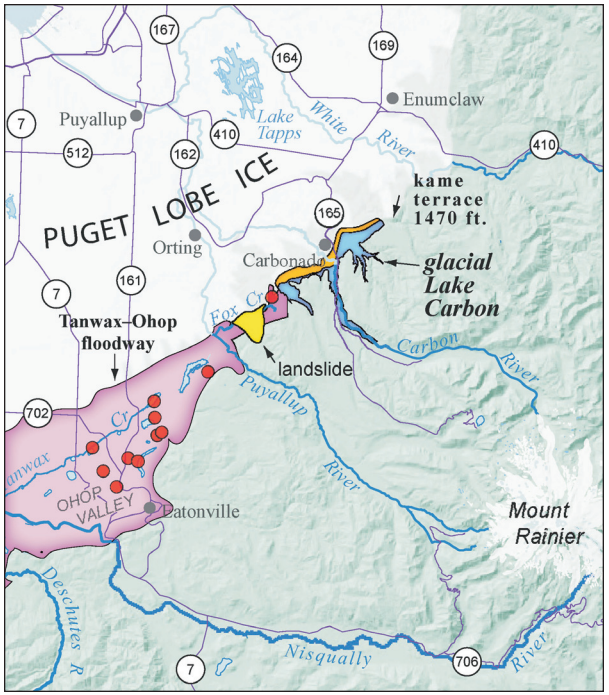
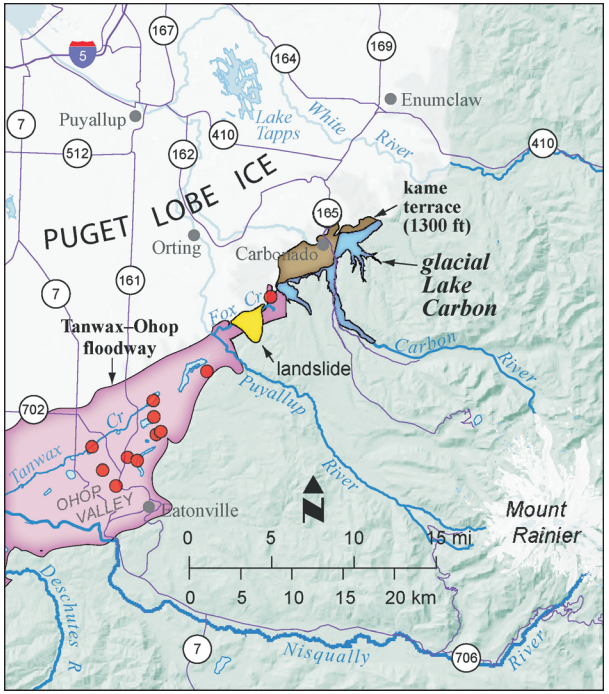


Figure L-1. Geologic map for Leg L (two consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Walsh (1987), Tabor and others (2000), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The map explanation is on the inside back cover.





6.4 *10.3* Massive andesite bedrock is exposed on the right.

6.9 *11.1* The road descends to the Carbon River.

7.6 *12.2* One-lane logging bridge over the Carbon River.

7.7 *12.4* Mount Rainier National Park, Carbon River Entrance, 1880 ft (573 m) elevation. The road is closed here. You can proceed on foot or by bike.

Figure L-2. *(left)* Diagrams showing portions of two stages of lakes that interconnected with glacial Lake Carbon (blue). Two kame terraces, orange (stage 1; elev. 1470 ft or 448 m) and brown (stage 2; elev. 1300 ft or 396 m), are inferred to have formed at the respective lake levels. The pink area is part of the floodway downstream of the lake. The flood inundated areas along the ice margin and probably merged with meltwaters from the Puget lobe near Rochester about 18 mi (29 km) south-southwest of Olympia. The landslide (bright yellow), which consisted of Pleistocene Lily Creek Formation and Wingate Hill Drift, likely blocked the meltwater channel during drainage, and thus enhanced the flood wave when the dam was breached. Some of the debris carried away by the flooding was deposited downstream as the lag of big boulders (red dots). The network of interconnected lakes was probably more extensive than that shown. Parts of some roads are shown. (See Fig. A-3, p. 55, for a more regional view of the flood area.)

10.5 *16.9* Falls Creek picnic area.

10.7 *17.2* Green Lake Trail trailhead. This trail ascends through some fine old Douglas-firs to Green Lake, a tarn.

11.1 *17.9* Chenuis Falls Trail. Mother Mountain is visible from the parking area. The mountain is part of an andesitic sill complex with an average age between 23 and 21 Ma. It is lithologically and temporally distinct from the older andesites of the Fifes Peak Formation (Hammond, 2000).

11.9 *19.1* Ipsut Creek Campground. The Carbon Glacier Trail is accessed from the far (south) end of the campground. It is about 0.5 mi (0.8 km) along the trail to Ipsut Falls, 3.2 mi (5.2 km) to a cable bridge that crosses the Carbon River, and 3.4 mi (5.5 km) to the Carbon Glacier terminus, a worthwhile destination (Figs. L-3 and L-4). At 3500 ft (1067 m), the terminus of the glacier is the lowest in the lower 48 conterminous states (Driedger, 1986). Those who choose to explore the area near the glacier's terminus should use caution because of the common rockfalls in that area.

You must retrace this route to access other legs. ■

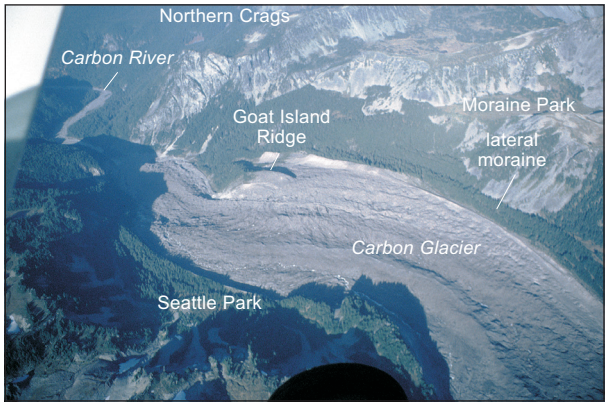


Figure L-3. Aerial-oblique view of the terminus of the Carbon Glacier taken in October 1999. The surface of the glacier in its terminal reach is almost entirely covered with rock debris. The Carbon River exits the snout of the glacier. The Wonderland Trail follows the righthand side of the right lateral moraine. View is to the north-northwest; an airplane strut is in the upper left.



Figure L-4. The rock-covered terminus of the Carbon Glacier with Mount Rainier in the background. The snout of glacial ice is visible in the center of the photo, the bed of the Carbon River in the foreground. Echo Cliffs borders the river on the right side of the picture. View is to the southeast from the cable bridge over the river on the Wonderland Trail. Photo taken August 2004.

LEG M: WESTSIDE ROAD

With an extended trip to Round Pass, the Puyallup River, and Klapatche Point via hike or mountain bike

Although infrequently visited, roads and trails in the western areas of Mount Rainier National Park reveal some of the most beautiful vistas of the mountain. About 1 mi (1.6 km) east of the Nisqually Entrance to Mount Rainier National Park (elev. 2000 ft or 610 m), the short Westside Road leads north up the valley of Tahoma Creek to Round Pass (elev. ~3800 ft or ~1160 m), where it begins the descent into the valley of the South Puyallup River (Fig. M-1). For the first several miles, the road is bounded on the west by spectacular Mount Wow, composed of fragmental volcanic rocks and lava flows of the Oligocene Ohanapecosh Formation. The peak towers more than 3500 ft (1067 m) above the valley floor, and during the rainy season, graceful waterfalls cascade from its abrupt buttresses. An active fault likely passes between Mount Rainier's summit and the older rocks of Mount Wow (Crosson and Frank, 1975), and this may explain why huge landslides have tumbled down its slopes in the past. Note the enormous landslide blocks of Ohanapecosh Formation near the road.

Vehicle access to the western part of Mount Rainier National Park has been limited since about 1988 due to intermittent jökulhlaups, or glacial outburst floods, that have destroyed Westside Road on multiple occasions (Walder and Driedger, 1993, 1995). These sudden torrents of water from the South Tahoma Glacier have incorporated huge quantities of boulders, sediment, and organic debris from glacial moraines, the Tahoma Creek stream channel, and nearby terraces to swell into damaging debris flows. Numerous killed and injured trees and abundant lobes of bouldery debris are testimony to the fury of these flows. Aggradation of the debris fan and frequent channel changes in response to these events have also caused damage (Walder and Driedger, 1994). The November 2006 floods triggered a debris flow(s?) and major channel changes to the area once again.

Visitors can hike or bike from the Mount Wow debris cone area to points farther along Westside Road that are inaccessible to vehicles. A good map is important for keeping track of landforms en route. Useful trail maps are available online and at visitor and information centers within the park.

Debris flows can happen at any time, so it is important for hikers and bikers to be aware of the possibility of sudden debris flows and be able to get upslope to safety away from a potential channel if they hear the rumble of an approaching flow. Erosion and deposition will probably continue to cause dramatic changes in the streambeds in the future, so the trail route may change again.

During the winter season (typically November through April), the road is gated near the entrance road used by skiers, about 1 mi (1.6 km) east of the Nisqually entrance to Mount Rainier National Park. Cross-country skiers should be mindful of severe snow avalanche hazards. Road and trail status can be checked at the Mount Rainier National Park website or by contacting the park by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any of the optional side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

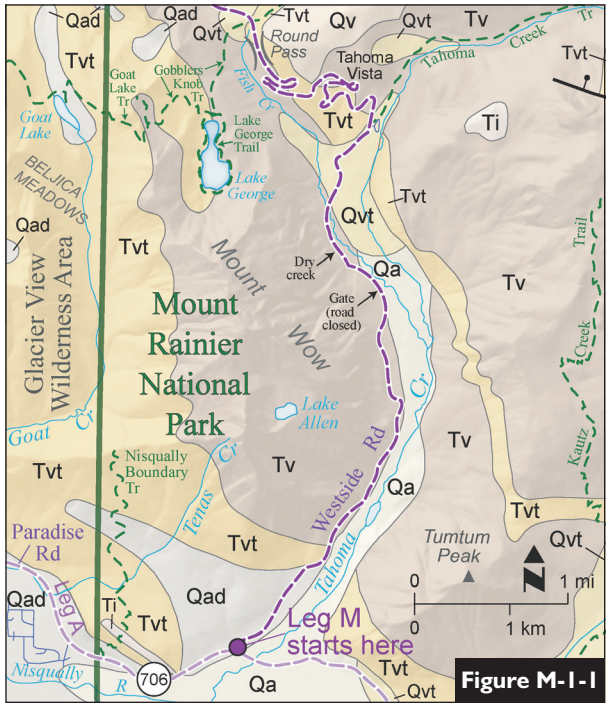


Figure M-1-1

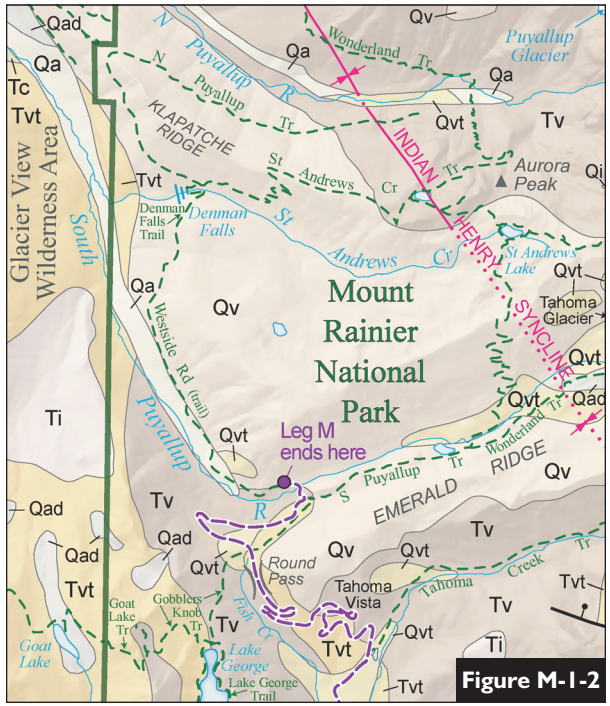


Figure M-1-2

photo by Beth Norman



Figure M-2. Dark-green to gray Ohanapecosh lavas from the Mount Wow complex of flows, a probable center of Oligocene volcanism.



Figure M-3. Historical photo of a debris fan from Mount Wow taken by Asahel Curtis, June 4, 1928. The car is crossing the small bridge over "Dry creek", the local name for a bouldery gully that drains the north margin of another debris fan whose deposits are exposed by the road excavation (left and right foreground). The buried trees shown in Fig. M-4 was about 150 ft (45 m) southeast of Curtis when he took this picture. Note the gently northeast-dipping volcanic rocks of the Ohanapecosh Formation (~36–28 Ma) exposed on Mount Wow on the skyline. View is to the northwest. The debris fan deposits are not shown on the geologic map (Fig. M-1). Washington State Historical Society Photo 53995.



Figure M-4. Trees buried in the toe of a debris fan from Mount Wow were exhumed by the debris flows of 1986. The leaning tree is about 40 ft (12 m) tall. The rubbly deposits of the fan consist chiefly of poorly sorted debris of the Ohanapecosh Formation. This location is about 3 mi (4.5 km) up Westside Road. The roadbed is visible at top of the outcrop on the extreme left. View is to the north on May 23, 1990. The road was repaired and protected by riprap after later flows eroded farther into the landslide deposit and removed the tree.

Mileage

0.0 *0.0* Turn onto Westside Road from Paradise Road. Dark-green to gray outcrops west of the road for the next 2 mi (3.2 km) are Ohanapecosh lavas from the Mount Wow complex of flows, a probable center of Oligocene volcanism (Fig. M-2).

0.1 *0.2* Pavement ends.

1.7 *2.7* Pass an outcrop of Ohanapecosh lavas.

2.4 *3.8* Good view (if the weather is clear) of Tahoma Creek with standing dead trees and erosion from the 2006 floods and previous debris flows.

2.5 *4.0* Large outcrop of volcaniclastic rocks is on the left with a shear zone.

3.2 *5.1* Tahoma Creek area. The road is closed here. From this point you can see the Mount Wow debris cone complex, lahar deposits, and deposits left by and the effects of the 1986 to 1992 glacial outburst floods and the great November 2006 flood. Much of Westside Road has been closed intermittently since November 1988 because portions of it have been destroyed by debris flows and flooding. Although destructive, these events also have exposed previously unseen older deposits for geologists to interpret. Some visitors may choose to walk or bicycle farther up Westside Road. (See "Optional Route for Hikers and Bikers along Westside Road" on p. 157.)

Note the large, rocky, largely unvegetated debris fan that heads on Mount Wow (Fig. M-3). Crandell (1969b) mapped this as an "alluvial cone"; however, the large size of most of the boulders combined with the morphology of the fan and the wedge-shaped headscarp indicate that this fan could have been deposited in large part by one or more catastrophic rock slides. Some of the large blocks were carried down by snow avalanches.

At a location along the Westside Road approximately 0.2 mi (0.3 km) south of "Dry creek", the local informal name for a rocky gully slightly south of the debris cone shown in Figure M-3, some large subfossil trees were exhumed by the debris flows of 1986 (Fig. M-4). These trees had been buried in another debris-fan deposit from Mount Wow. One of the trees, a large Douglas-fir, protruded about 16 ft (5 m) above the deposit in 1986. Using a graph by Cline and others (1980) of decomposition rates of Douglas-fir in the Oregon Coast Ranges (Fig. M-5), I first estimated that the tree died between 150 and 200 years ago. Later I was able to crossdate its tree rings with those of old living trees, which revealed that the tree may have been injured about A.D. 1821 to 1824; it is not clear if a catastrophic rockfall avalanche buried the tree and killed it at that time, or if it was killed by a rapid progradation of the toe of the Mount Wow debris fan within a few years after being injured (Fig. M-6).

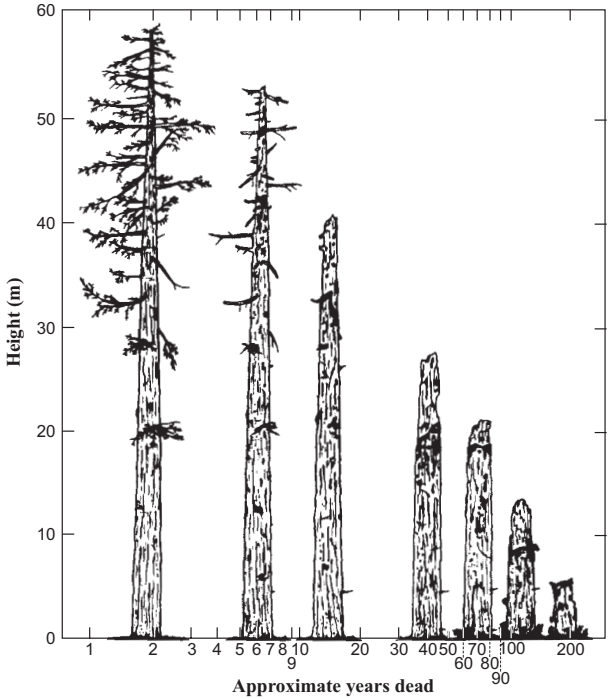


Figure M-5. Progression of decomposition of a Douglas-fir tree in the Oregon coast range over a 200-year period. Trees of this species at Mount Rainier decompose at about the same rate. Dramatic examples of the relative rates of decomposition for different species can be seen at Kautz Creek (see Leg A), where a forest was partially buried by a debris flow in 1947. There, Douglas-firs and hemlocks have undergone rapid decay, whereas western redcedars are relatively well preserved (and identifiable by their narrow, pointed tops). Modified from Cline and others (1980).

The deposit that partially buried the tree is a monolithologic breccia of Oligocene Ohanapecosh Formation rocks from Mount Wow. This breccia is visible in roadcuts and streamcuts here and in the bed of Dry creek that is incised into the Dry creek fan.

OPTIONAL ROUTE FOR HIKERS OR BIKERS ALONG WESTSIDE ROAD. Leave the Mount Wow debris cone complex and go north on Westside Road. At Fish Creek, a debris fan shows where debris flows and floods have traveled along the right of way of the road or have cut across it farther upstream to enter Fish Creek. This area is constantly changing as Tahoma Creek's channel wanders from one side of the valley to the other, occasionally escaping its channel to flow into Fish Creek. All mileages from here on refer to distance traveled on foot or by bicycle, unless the road is reopened and you can travel by car.

Walk or bike about 0.9 mi (1.4 km) up the road from the parking area near Dry creek to the old picnic ground to see deposits of the Tahoma lahar and debris flows that have flooded this area since 1986. A trail links the segments of the Westside Road washed out by floods. About 0.3 mi (0.5 km) of Westside Road north of Fish Creek was damaged by the floods of November 1990. This stretch was partially filled in by a debris flow on Nov. 6, 1991. The road was partially destroyed again by an event on Sept. 8, 1992, and subsequently has been closed and reopened, depending on the activity and depositional patterns of the debris flows and Tahoma Creek. The channel changes caused by the November 2006 floods in Tahoma Creek were probably the largest since the 1988 events here.

Older deposits of many kinds have been exposed by recent floods and debris flows. One of these deposits, that of a lahar, is a poorly sorted, clay-rich, yellowish layer exposed in the streambed at the site of the picnic ground mentioned above. This may be the same deposit that caps the terrace adjacent to Westside Road slightly north of Fish Creek. Farther upstream, the lahar deposit sits on top of Mount St. Helens ash layer Wn, which was deposited about A.D. 1480 (Yamaguchi, 1983, 1985). USGS geologists thought that the lahar was likely correlative with a layer mapped by Crandell (1971) and visible on the right bank of Tahoma Creek 1.2 mi (2 km) upstream of this site (Scott and others, 1995). Trees overwhelmed by the lahar were rotted to the ground surface, indicating at least 200 years of weathering. It's possible this lahar is correlative with the Electron Mudflow of about A.D. 1500. Another grayish, sandy lahar deposit is visible underneath the lahar locally. Fragments of an organic soil horizon containing Mount St. Helens tephra Wn found on top of the gray unit suggest that it was deposited prior to 1480 A.D.

The debris flows since 1986 almost certainly began as outburst floods (jökulhlaups) from South Tahoma Glacier, about 3.5 mi (5.6 km) upstream

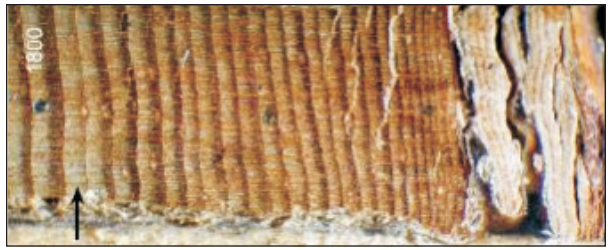


Figure M-6. Photomicrograph of the outer annual growth rings (to the right) in a 0.2-in. (5 mm)-diameter core sample of the partially buried Douglas-fir tree shown in Fig. M-4. Pencil dots mark decade rings. The narrow rings and abundant resin canals (not visible at this magnification), both potential signs of stress, suddenly appear about A.D. 1821 to 1824; the tree died shortly thereafter. This stress, and ultimately the death of the tree, was likely caused when the tree was partially buried, thus the tree rings allow an interpretation of the timing of burial. Notice the faint or missing latewood in the 1801 'light ring' (black arrow). Light rings are low-density rings that denote unusually cool summers (Yamaguchi and others, 1993). Light rings are easily recognized in Douglas-fir and other species growing above about 2000 ft (600 m) elevation and are useful as marker rings for cross dating. Many low-density rings have been correlated with very large volcanic eruptions (for example, Tambora in 1815) that injected enough sulfurous aerosols into the stratosphere to cause significant global cooling (Briffa and others, 1998). The 1801 light ring has not been confidently associated with any volcanic event to date.

of here to the northeast. The fact that most have occurred during clear weather indicates that a source of water other than precipitation was responsible for their initiation. That source was water stored inside or underneath the glacier (Walder and Driedger, 1993). Outburst floods have eroded two zones of stagnant ice that provide much of the sediment for the debris flows. The upper stagnant-ice zone is glacier ice overlain by a veneer of rock debris, whereas the lower zone consists of complexly layered glacier ice and rock debris.

A typical debris flow along Tahoma Creek moves a few tens of thousands of cubic yards (meters) of sediment. Between 1986 and 1994 there was as much as 10 ft (3 m) net aggradation of bouldery deposits over a reach about 2.5 mi (4 km) long (Walder and Driedger, 1994). Fine sediments carried by the watery recessional phase of debris flows have moved as far as the bridge on the main road between the park entrance and Longmire,

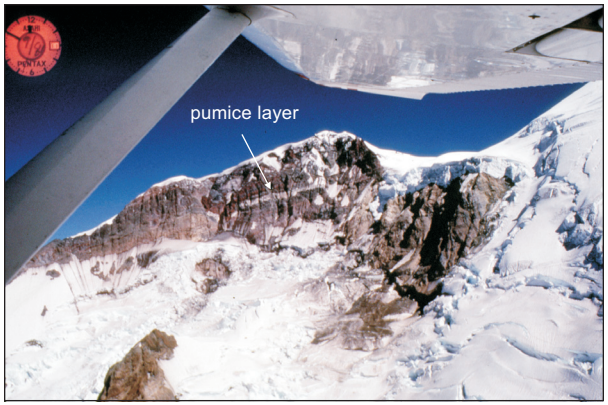


Figure M-7. Sunset Amphitheater, showing the approximately 65-ft- (20 m)-thick pumice layer (at arrow) that extends many tens of miles to the west-northwest. The pumice was dated by geologists Tom Sisson and Marvin Lanphere (1999) at about 190 ka; the same pumice was found in fluvial deposits on Ketron Island in southern Puget Sound by Walsh and others (2003). Tahoma Glacier can be seen cascading off Columbia Crest cone at the far right; at the far left is the uppermost portion of Puyallup Glacier. Contained in the Sunset Amphitheater section are layers that record multiple periods of volcanic eruption and hydrothermal alteration punctuated by glacial erosion. Photo by USGS geologist Rick Hoblitt, 1981.

and some have reached the Nisqually River about 0.6 mi (1 km) downstream of the main road. However, nearly all sediment transported by debris flows remains within the Tahoma Creek drainage basin.

The evidence for outburst floods is largely circumstantial. Crandell (1971) and Scott and others (1992) described erosion of glacier ice near the terminus of Tahoma Glacier by water emerging from the glacier near the base of an icefall. Walder and Driedger (1994, 1995) suggested that rapid input of meltwater or rainwater to the glacier bed triggers release of water stored in large cavities between ice and bedrock to initiate these floods.

5.0 *8.0* Round Pass. Here you can see the volcano's chiseled west flanks. On a clear day there are fine views of the lava flows, breccias, pyroclastic flow deposits, and tephra layers that make up the mountain, and of some of the noteworthy glaciers, such as the Mowich, Puyallup, Tahoma, and South Tahoma, that are actively carving it. All demonstrate that Mount Rainier has formed by multiple periods of volcanic eruption, hydrothermal alteration, punctuated by glacial erosion and mass wasting.

The Round Pass mudflow (2,600 yr B.P.) described by Crandell (1971) crops out on the west side of the road. About 2.1 mi (3.5 km) to the northwest, outside the park, deposits of the mudflow can be found as much as 820 ft (250 m) above the South Puyallup River. At that location, 2 mi (3.2 km) northeast of Round Pass, is at a reentrant tributary valley draining the west side of Mount Wow. There, exposed trees that were killed by the mudflow lean northeast toward the South Puyallup valley, an orientation that indicates the Round Pass mudflow may have run up over Mount Wow—a vertical distance of more than 1476 ft (450 m)—and flowed north on the west side of Mount Wow before overrunning the trees and reentering the South Puyallup River valley.

The Marine Memorial Airplane Crash Monument at Round Pass is a good place to observe the upper west flank of Mount Rainier and Sunset Amphitheater (Fig. M-7). A yellowish deposit lying near the glacial terminus is the rubble of a large avalanche that came to rest there at about 1900 (Crandell, 1971). This memorial was dedicated to the 32 U.S. Marines who died when their plane crashed on South Tahoma Glacier on Dec. 10, 1946, and who are still buried within the glacier.

8.4 *13.5* Well-exposed block-and-ash-flow deposit in the South Puyallup River (Fig. M-8). Tom Sisson and Jim Vallance (USGS, written commun., 2003) note an approximate age for this deposit of 2,500 yr B.P. based on secular variation and the similar paleomagnetic signature of young Mount Rainier lavas exposed in the Emmons and Winthrop Glaciers. Correlative lahar-derived deposits extend as far as Puyallup, more than 42 mi (70 km) downstream (Pringle and Palmer, 1992).



Figure M-8. Block-and-ash flow deposits along the Westside Road slightly north of where the road crosses the South Puyallup River. The photo shows two or more separate pyroclastic flow units. Note the 3-ft (1 m)-diameter volcanic bombs (blocks) that have radial jointing patterns and the pocket knife for scale at the base of one flow unit (see Fig A-11, p. 60). The outcrop is about 50 ft (15 m) high. View is to the north.

The road log ends here, but you can hike farther up the road. Otherwise, you can retrace the route and access another leg. ■

LEG N: ALTERNATE WESTERN APPROACH TO MOUNT RAINIER

Yelm to Eatonville via State Routes 507 and 702

This approach, which starts from the city of Yelm about 16 mi (~26 km) southeast of Olympia, is an alternative to parts of Leg A and can be accessed from Interstate 5 (I-5) via State Routes (SR) 507 or 510 near Olympia (Fig. N-1). With excellent views of Mount Rainier, the 27-mi (43 km) leg crosses the Nisqually River and follows an historic wagon road route (SR 702) as it rises and descends over topography streamlined by movements of the Puget lobe of the Vashon glacier during the last Ice Age. Not far east of SR 7, andesite boulders and southwest-trending valleys that cut into the drift deposits mark the passage of at least one large late-glacial flood caused by the emptying of a network of ice-dammed lakes near the Carbon River valley (see Fig. A-3, p. 55). Near Eatonville, you begin to see outcrops of Cascade Range bedrock. The trip leg then rejoins SR 7 at its junction with SR 706, about 5 mi (8 km) northwest of the town of Elbe.

Distances along the route are given in miles, followed by kilometers in italics. If you take any of the optional side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Mileage

0.0 *0.0* Yelm city center. Junction of SR 510 with SR 507. Proceed east on SR 507.

1.0 *1.6* Bald Hill Road intersection. Stay on SR 507. Between here and the Nisqually River, note the piles of grayish andesite cobbles and some boulders that landowners have stacked near fence rows. These rocks, most of which originate in the Cascade Range near Mount Rainier, may be downstream deposits of the late-glacial Tanwax Creek–Ohop Valley flood or a subsequent late-glacial flood caused by the sudden draining of an ice-dammed lake during recession of Puget lobe ice some 16,000 years ago. While the Puget lobe glacier itself did carry a minor component of andesite rocks, its deposits are typically characterized by diverse lithologic types that include abundant metamorphic and intrusive rocks picked up by the glacier as it moved south from Canada and across the igneous and metamorphic rocks of the North Cascades and other northern terrains. The fact that most surface boulders in this area are andesite indicates that the flow that deposited them likely originated in the Cascade Range.

2.4 *3.8* Nisqually River at McKenna. Several postglacial lahars or laharic floods from Mount Rainier have reached this area and extended as far as the Nisqually River delta, about 21 mi (34 km) flow distance north-northeast of here. A tree buried in deposits of andesitic sand in the Nisqually River flood plain upstream of McKenna yielded a radiocarbon age of 585 yr B.P. (Scott and others, 1995). Sandy deposits that may be lahar-derived sand have been documented in the modern Nisqually delta; those sediments contained buried wood that yielded radiocarbon ages of about 2,320 and 540 yr B.P. (Barnhardt and others, 2000).

The low area adjacent to and north of the river in this area was severely flooded by the Nisqually River rain-on-snow flood in the winter of 1996.

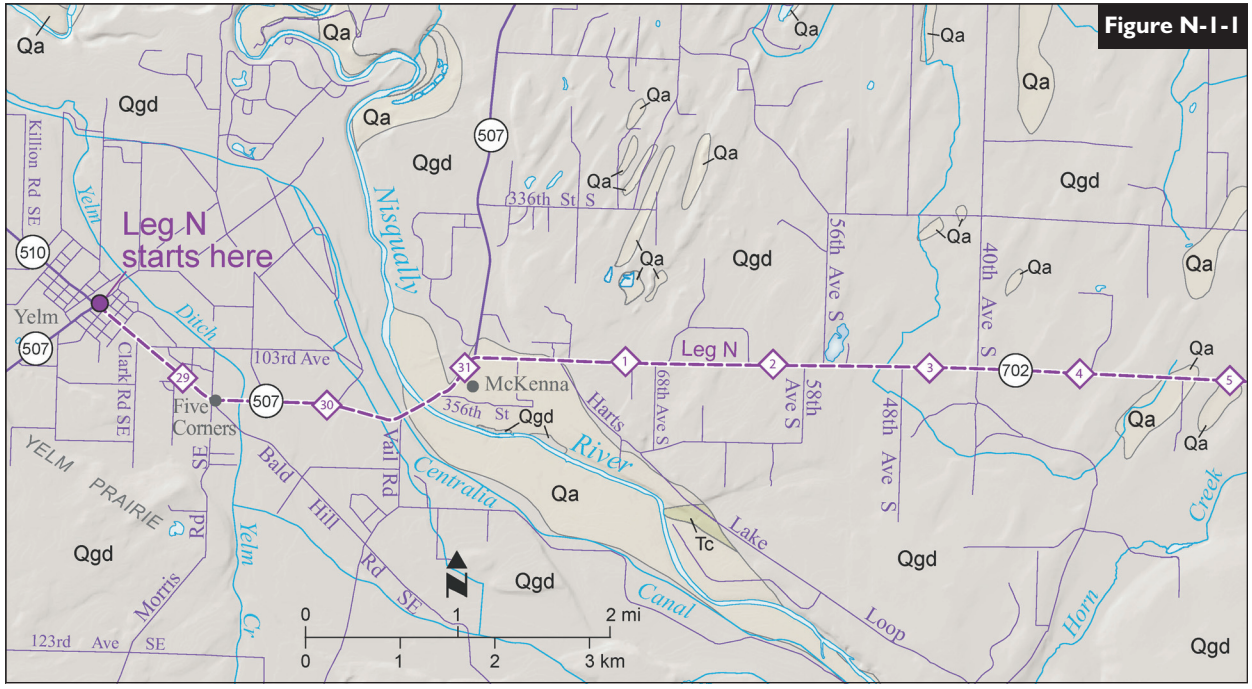


Figure N-1. Geologic map for Leg N (four consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987a) and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The numbers in diamonds indicate mileposts. The map explanation is on the inside back cover.

2.8 *4.5* Milepost (MP) 31.

2.9 *4.6* Junction of SR 702 with SR 507. Go right onto SR 702. Excavations into this flat surface in 2002 exposed a sandy, 3-ft (1 m)-thick lahar-derived deposit that may be correlative with lahars as old as 2.5 ka that are exposed near the town of National farther upstream.

3.8 *6.1* MP 1. Small area of Mima Mounds north of the road. The causes of these mounds have long been a subject of intense interest and scientific debate. Washburn (1988) wrote an excellent compilation that describes the Mima Mounds of the Puget Lowland area and summarized various hypotheses about their formation. The classic example of a mounded prairie, as well as interpretive information, can be found at Mima Mounds Natural Area, administered by the Washington State Department of Natural Resources. The preserve is located about 10 mi (16 km) south of Olympia, several miles west of I-5 on SR 121.

From here to SR 7, the road follows the undulating surface of some classic glacially fluted topography. The north-northeast-trending hills are drumlins, streamlined landforms created by the passage of glacial ice over fragmental material. From the air, or as viewed on a shaded relief map, they are dramatic evidence of the direction of glacial movement (Fig. N-2). Near the terminus of a glacier, even low topographic irregularities will guide the ice flow. Thus, not all drumlins are oriented north–south, the main flow direction of the Puget lobe. The drumlins have as much as 33 ft (10 m) of vertical relief (Booth and Goldstein, 1994). Also note the many glacial erratics throughout the area.

12.1 *19.4* Junction SR 702 with SR 7. Continue with this leg by carefully going straight ahead, then bearing right on Eatonville Cutoff Road. You are now entering another floodway of the Tanwax Creek–Ohop Valley late-glacial flood (Pringle and others, 2000a).

Alternatively, you can begin Leg A here by turning right onto SR 7. Remember to adjust your odometer if you do.

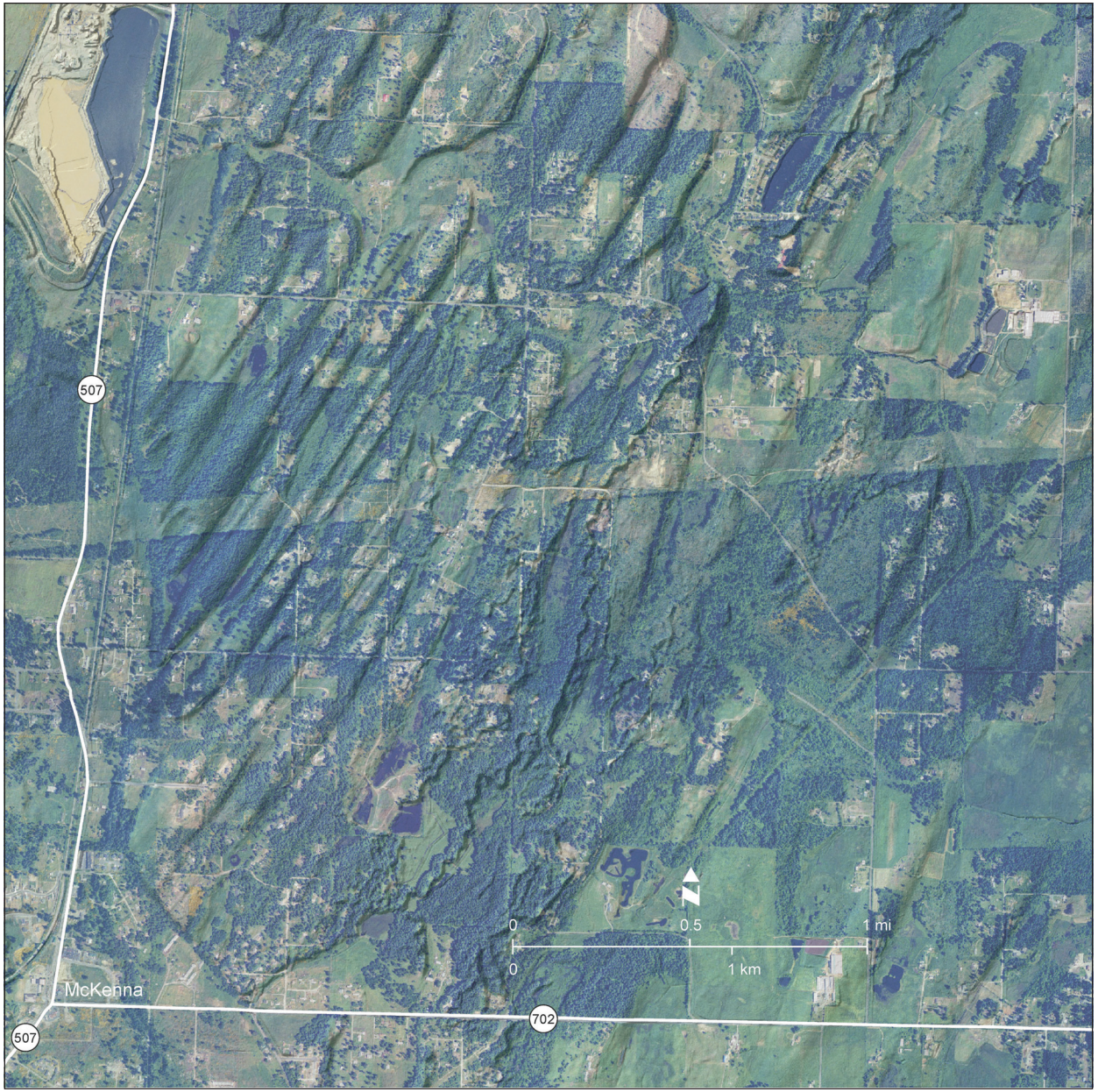


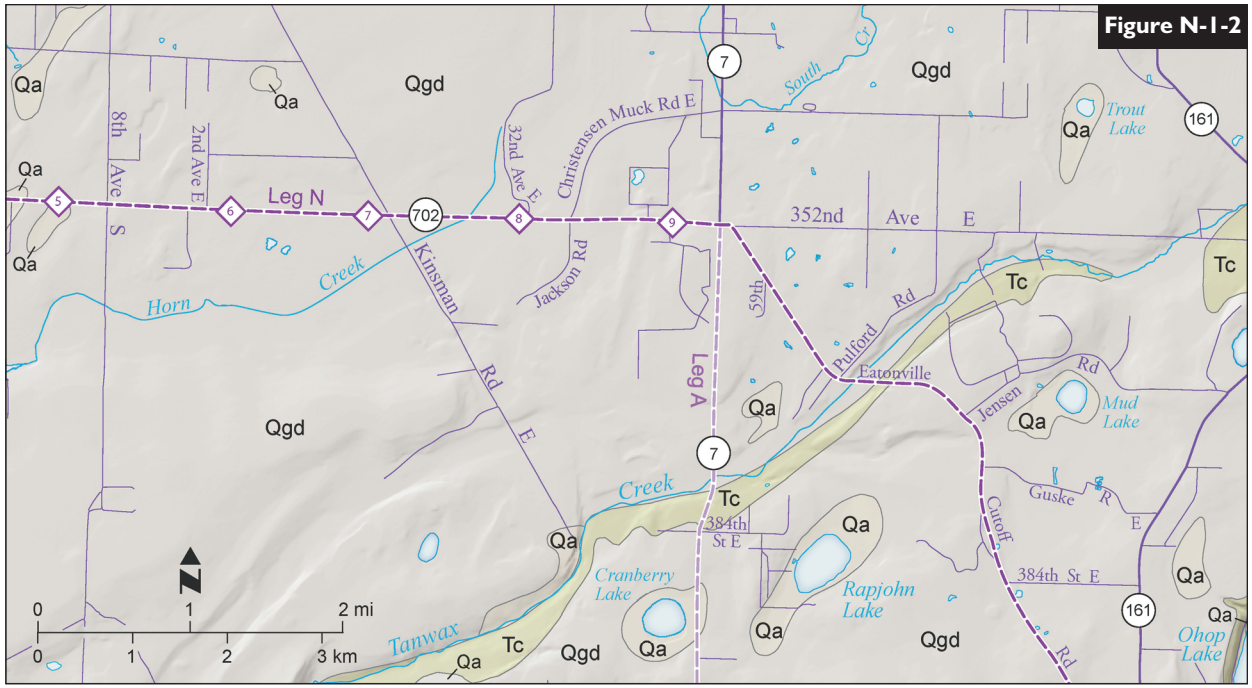
Figure N-2. Dramatic drumlinoidal topography shaped by passage of the Vashon Glacier, as seen on a shaded relief map. These streamlined, elongate hills of glacial drift are built and (or) shaped under flowing glacial ice. The axis of individual drumlin features is parallel with the direction of ice movement.



Figure N-3. Megaripples? 6 to 9 ft (2–3 m) high in gravelly soils along Eatonville Cutoff Road slightly west of Tanwax Creek. They are oriented approximately perpendicular to the flow direction. The megaripples were probably deposited by the Tanwax Creek–Ohop Valley flood, which likely resulted when an ice-dammed lake in the Cascades breached its dam. View is to the northeast.



Figure N-4. Lag deposit of large boulders (to 6 ft [2 m] in diameter) in the valley of Tanwax Creek that was deposited by the late-glacial (~16 ka) Tanwax Creek–Ohop Creek valley flood, a jökulhlaup (see Fig. A-3, p. 55, and Fig. L-2, p. 154). This flood(s?) resulted from the partial draining of glacial Lake Carbon, which was dammed by the Puget lobe ice about 17 mi (~27 km) northeast of here (Pringle and others, 2000a). The rocks consist mostly of andesites and some granodiorites that likely originated in rivers draining Mount Rainier or in deposits of the Lily Creek Formation and Wingate Hill Drift. Both of the latter units are rich in andesite rocks because they originated in the Cascade Range near the present location of Mount Rainier. View is to the northeast toward the source area of the late-glacial flood.



13.3 *21.3* Possible megaripples deposited by the Tanwax flood are on the northeast side of the highway slightly west of Tanwax Creek (Fig. N-3).

13.5 *21.7* Cross Tanwax Creek. Note flood-deposited boulders in the valley bottom in the distance to the left (Fig. N-4).

16.9 *27.1* Junction of Eatonville Cutoff Road with SR 161. Turn right and continue south on SR 161.

17.1 *27.5* Mount Rainier viewpoint at Dogwood Park. If the weather is clear, this is a good place to see the west face of the volcano, some 26 mi (~42 km) to the east (Fig. N-5). A historical marker at this site incorrectly claims the three peaks of Mount Rainier are cinder cones. The youthful Columbia Crest cone, the middle peak, is capped by two craters. Liberty Cap, the northern peak, and Point Success, the southern peak, are erosional remnants of the large crater created about 5600 years ago by the eruption that produced the Osceola Mudflow.

18.0 *29.0* MP 5. Miocene Mashel Formation sediments are exposed on the north side of the road along this curve as you descend into the Ohop valley. The valley is a late-glacial spillway of the Puget lobe of the Vashon Glacier. The Mashel Formation consists of poorly consolidated fluvial and lacustrine



Figure N-5. Chiseled west face of snowclad Mount Rainier with Cascade Range foothills in the foreground from Dogwood Park along SR 161. View is to the east from about 26 mi (42 km) west of the volcano.

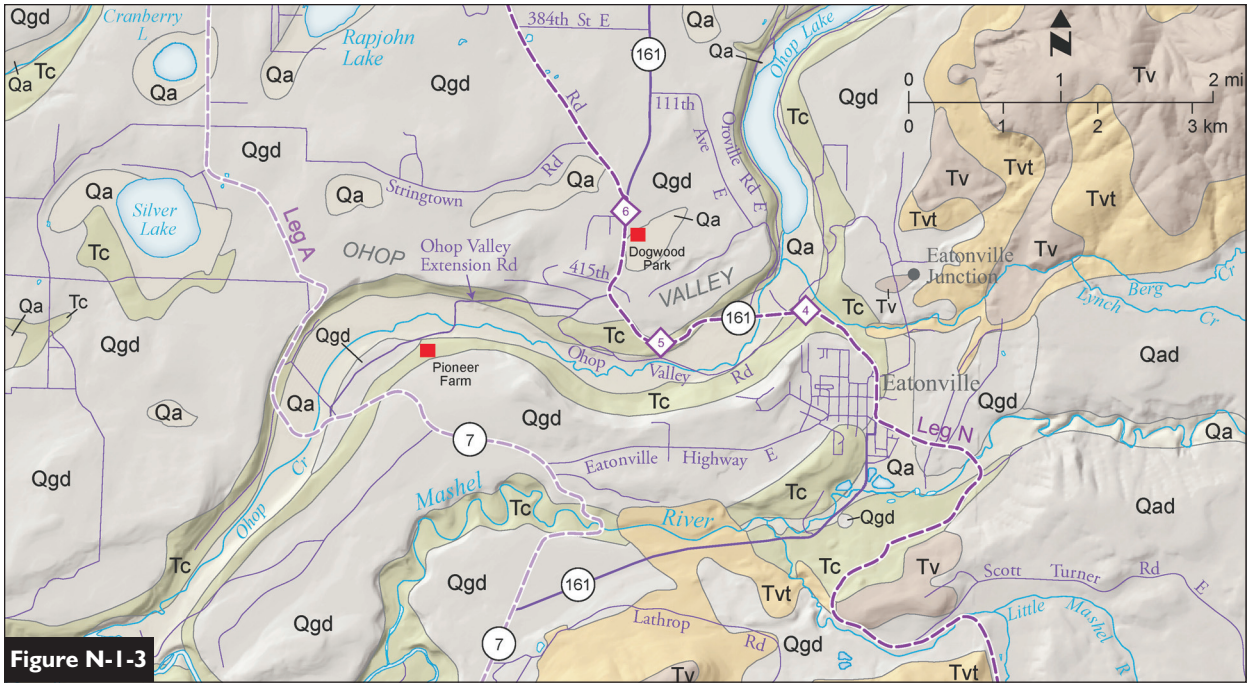


Figure N-1-3

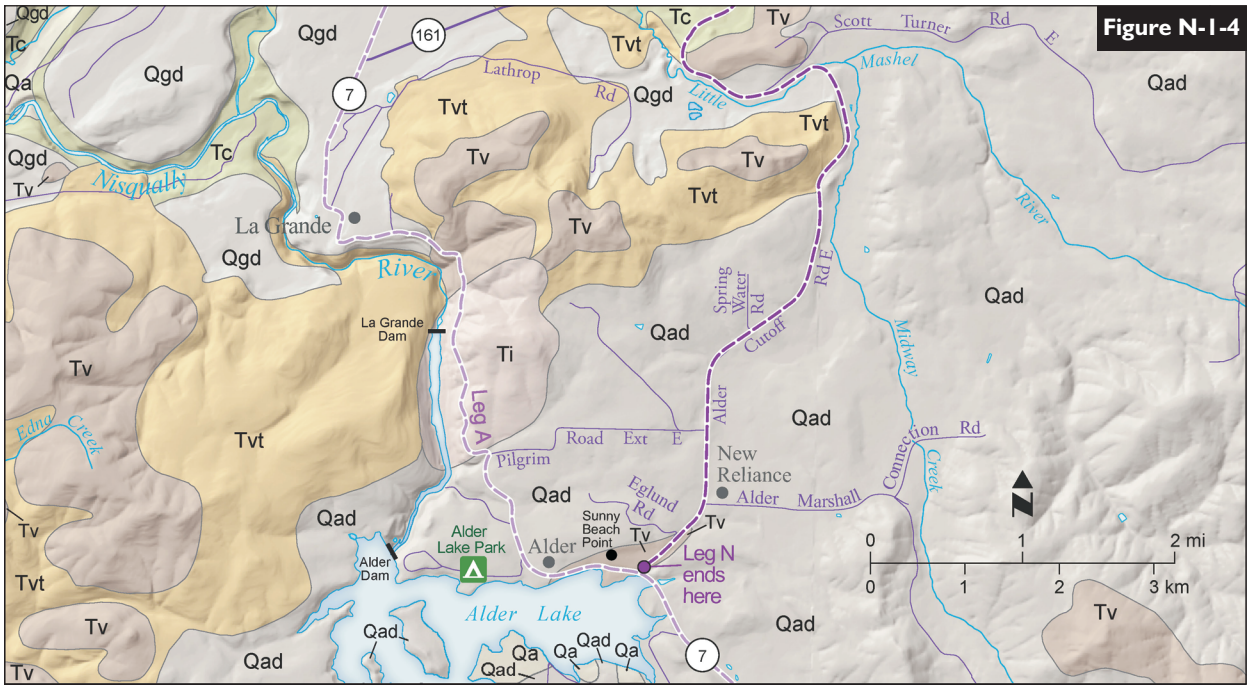


Figure N-1-4

sediments that in many places contain dacite clasts.

18.7 30.1 Cross Ohop Creek, a puny remnant of the great river of glacial meltwater that flowed through this valley about 16,000 years ago.

19.9 31.8 City of Eatonville. Turn left on to Center Street at the junction of SR 161/Center Street/Washington Street with Eatonville–Alder Cutoff Road in the center of town. (SR 161 continues straight ahead for about 3 mi (4.8 km) to SR 7.)

20.6 33.0 Cross the Mashel River, whose headwaters drain a portion of the Cascade Range foothills between the Puyallup and Nisqually River basins.

22.1 35.5 Slightly after the railroad bridge there is a pullout to the right. An outcrop of Oligocene or Eocene basaltic andesite is on the left. Snavely and others (1958) believe that these rocks are likely correlative with those of the Northcraft Formation farther to the south.

22.8 36.7 Scott Turner Road on the left.

23.0 37.0 Cross over the Little Mashel River.

23.3 37.5 An outcrop of red and black tuffs of Oligocene/Eocene age is on the left.

26.7 43.0 Pass an outcrop of glacial drift, Wingate Hill Drift, on the right (west). The great extent of the Wingate Hill deposits shows that it was one of the most extensive alpine glaciations in the southwest Washington Cascades. Dethier (1988) estimated its age to be 600 to 300 ka; thus it could have been deposited during the extensive marine isotope stage 12 glaciation, about 450 ka (see Fig. 25, p. 29).

27.0 43.4 Andesite of Oligocene/Eocene age crops out on the right.

27.1 43.4 Junction of Eatonville–Alder Cutoff Road with SR 7. Here you can turn left to continue east on SR 7 (Leg A) and connect with SR 706 to Mount Rainier National Park. This is a dangerous intersection, so please use caution.

Remember to reset your odometer when you start another leg. ■

LEG O: BUMPING LAKE ROAD

From State Route 410 to the Bumping Lake Area

by Wendy J. Gerstel, Paul E. Hammond, and Patrick T. Pringle*

Bumping Lake Road (Forest Road [FR] 18) extends about 11 mi (17.5 km) up the valley of the Bumping River from its confluence with American River to the Bumping Lake area (Fig. O-1). This broad glaciated valley cut into volcanic and intrusive rocks yields views of Cascade peaks to the south. Campgrounds and hiking trails are accessible, and rough gravel roads allow the adventurous to visit several areas of historic mining activity. (See the "Alteration and Mining North and East of Mount Rainier" sidebar on p. 117.) In winter, cross-county ski enthusiasts visit this area.

As along other roads through the heart of the Cascade Range, the geology visible here includes volcanic and intrusive rocks, glacial deposits, large landslides, and more. Deposits of the Bumping River tuff are exposed en route. This tuff was created in great eruptions that produced the Mount Aix caldera about 25 Ma. Hammond and others (1994) estimated the total volume of the caldera at as much as 100 km^3 (~24 mi^3), about 100 times the volume of the 1980 eruption of Mount St. Helens. (The approximate location of the caldera is shown in Fig. 16, p. 20.) Many of the descriptions of the geology along this leg are from Hammond and others (1994) and ongoing work by Hammond as part of an intensive mapping project in this area.

The highway is sometimes closed in winter, so it is wise to check on road conditions before traveling this leg. Contact the Washington State Dept. of Transportation via their website or by phone. (See "Websites and Phone Numbers", p. 176.)

Distances along the route are given in miles, followed by kilometers in italics. If you take any of the optional side trips, you'll have to keep track of and add those miles to all the remaining mileages in the leg. Having a pencil and paper handy, and even a calculator will be helpful.

Note: There are no mileposts on this road.

Mileage

0.0 *0.0* Junction of Bumping Lake Road (FR 18 or 1800) with State Route (SR) 410. Turn south onto FR 18.

Fifty feet (15 m) from the junction you cross the American River. Poorly sorted deposits on both sides of the river are of glacial and landslide origin. Large blocks of columnar-jointed basalt are exposed at the intersection. These likely originated in the landslide from the ridge of Miocene Grande Ronde Basalt to the southwest (see Fig. 20, p. 25).

0.5 *0.8* Cedar Springs Campground on the left.

0.7 *1.1* American Ridge Trail (#958) is on the right. The large blocks of columnar basalt here are similar to those exposed along SR 410 at the Bumping Lake Road turnoff. The basalt blocks are likely from the Grande Ronde Basalt of the Columbia River Basalt Group, which caps the ridge to the north and likely capped rocks of the Fifes Peak Formation (~27–22 Ma) to the southwest of here. These blocks are part of a large landslide complex southeast of the road that extends for nearly 3 mi (4.5 km) along Bumping Lake Road from SR 410 to Fifes Creek and for at least 2 mi (3 km) to the east along the south side of SR 410 to the east end of Indian Flat Campground. Given the large size of the landslide mass, more than 3. 5 mi (5.6 km) long from northeast to southwest and as much as 1.4 mi (2.2 km) wide, it may have temporarily dammed the Bumping and (or) American Rivers.

0.8 *1.3* A poorly sorted deposit, possibly till, is exposed in the terrace on the left. This debris may be part of the extensive landslide complex described above.

1.1 *1.8* An outcrop on the right (northwest) side of the road here is worth examining. There is a small pullout about 0.1 mi (0.2 km) farther on the left (south) side of the road for those returning northbound. The outcrop is mapped as Bumping River tuff (Schasse, 1987b). A reddish zone visible at the base of the tuff is a soil that was baked by the heat of the tuff when it was deposited. The entire exposure appears to be part of a landslide deposit (**Fig. O-2**). Nearby, the deranged orientation of trees ('drunken forest') is evidence of a history of landsliding.

1.4 *2.2* More blocks of columnar basalt.

1.6 *2.6* Pullout to the left. More columnar basalt of the Grande Ronde formation is exposed on the right. Deposits across the river to the southeast show telltale evidence of landslide activity: tilted trees, large masses of out-of-place Fifes Peak volcanic rocks and Grande Ronde Basalt, and poorly sorted deposits exposed in the riverbank.

2.3 *3.7* FR 1802 to Upper Fifes and Cedar Creeks. The rubble exposed southeast of here is likely a part of the landslide complex described earlier. Ahead you get a fleeting glimpse of Old Scab Mountain and the cirque on its north face.

2.6 *4.2* Fifes Creek. The large landslide along whose northwest margin you have traveled since leaving SR 410 ends about here against a northwest-trending normal fault whose motion was down to the northeast.

2.7 *4.3* View of the cirque on Old Scab Mountain is straight ahead.

2.8 *4.5* Colluvium and an unconsolidated deposit, possibly that of a lahar associated with eruption of the Bumping River tuff, are exposed on the right.

3.4 *5.5* The Bumping River tuff is exposed on the northwest side of the road (Fig. O-3). There are some places to park about 0.1 mi (0.2 km) to the north, but be alert to traffic here. The following description for the site is paraphrased from Hammond and others (1994) and from an informal field guide written by Paul Hammond for the 1997 field trip sponsored by the Geological Society of the Oregon Country: An outcrop of Bumping River tuff is on the west side of the road, Bumping River along the

* See "Contributors", p. ii, for affiliation.

east side of the road. This roadcut exposes about 100 m [381 ft] of the Bumping River tuff. The sequence approaches its greatest thickness (as much as 1000 m [3281 ft]) at this location. The source vent for this material lies approximately 20 km (12 mi) to the south at Bismarck Peak in the Mount Aix caldera. At least five separate flow units can be seen in this exposure, each representing a separate pyroclastic flow event. A 2- to 3-m- [6–10 ft] thick basalt sill separates a lower massive unit from thinner units above. While samples from this section have been fission-track dated at 26.6 ±3.6 Ma and 27.7 ±5.0 Ma (Vance and others, 1987), recent dates by Hammond (2005) indicate a K-Ar radiometric age of 24.7 Ma for the tuff.

The sequence of pyroclastic flows suggests a period of caldera collapse during eruption. These deposits are overlain by lahar and pyroclastic surge deposits. Exposed at road level, underlying the deposits of the Bumping River tuff, are deposits of older, weathered volcaniclastic strata known informally as the Wildcat Creek beds.

A sill is exposed at the south end of the outcrop. In the winter of 1995-96, a large chunk of the sill slid down along a fracture plane onto the slopes below.

4.0 6.4 On the right is an olivine basalt feeder dike for the sill in Bumping River tuff mentioned above.

4.1 6.6 The Bumping River welded tuff is exposed in a quarry on the right. Thick hot ash flows commonly cooled as one or more flow units and became welded. Note that the rocks in individual flow units display little, if any, bedding because the hot volcanic debris flowed into place essentially en masse (Fig. O-4). Cooling joints can develop as thick layers of welded fragmental material cool from above and below, just as similar jointing develops in a cooling thick basalt flow (see Fig. A-11, p. 60).

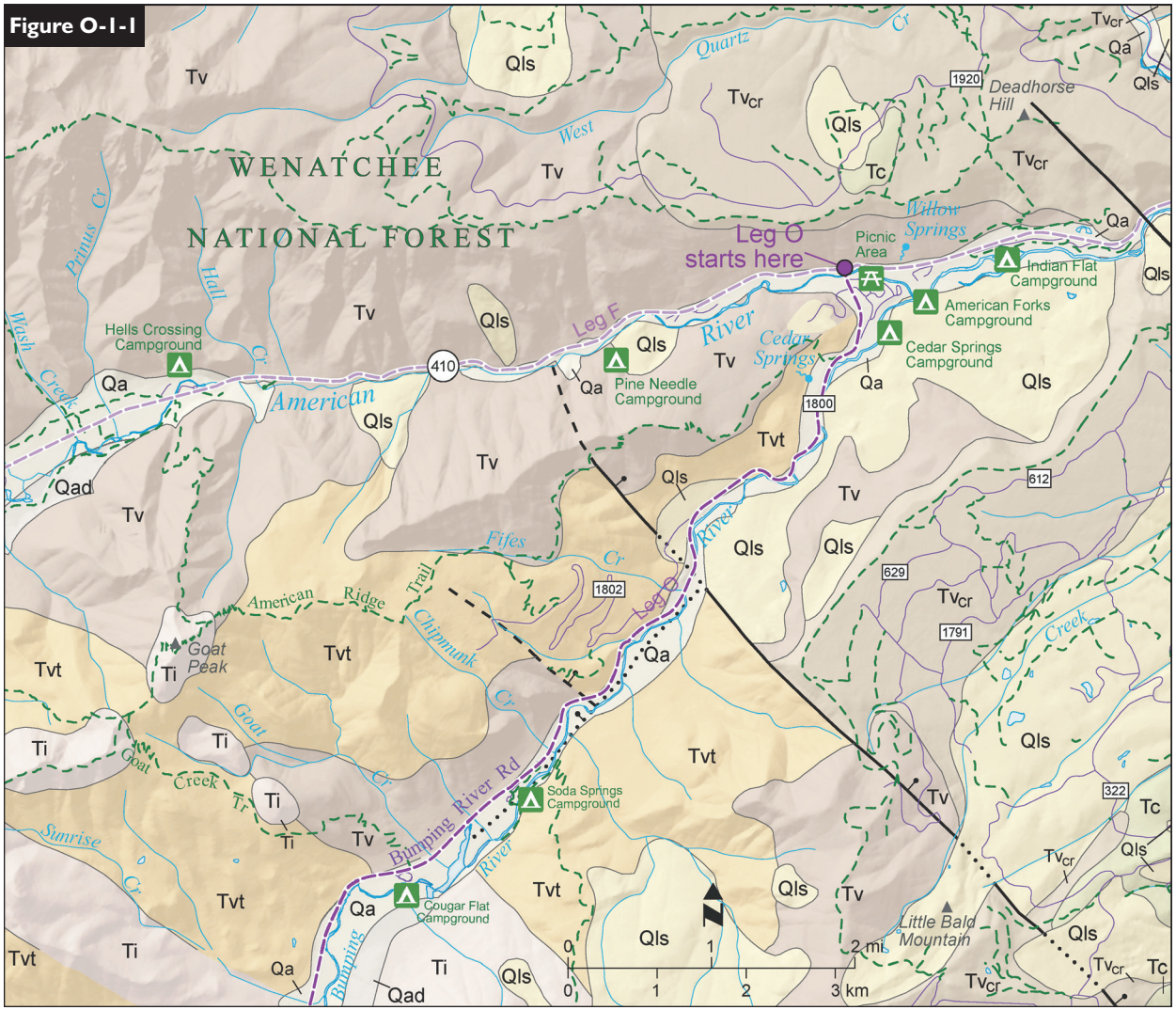


Figure O-1. *(left)* Geologic map for Leg O (two consecutive panels). The geology was adapted from 1:100,000- and 1:500,000-scale digital versions of Schasse (1987b), Walsh (1986), and Schuster (2005) and has been draped over a shaded relief image generated from 10-m elevation data. The leg maps were constructed using source-map data whose scale is smaller than the leg map scale, thus minor exposures may not appear on leg maps. The map explanation is on the inside back cover.



Figure O-2. Geologist Wendy Gerstel examines a reddish baked zone under Bumping River tuff along Bumping Lake Road about 1.1 mi (1.75 km) from SR 410. The entire outcrop is part of a landslide mass. Note the crude columnar jointing in the tuff deposit (top center). View is to the north.

photo by Beth Norman

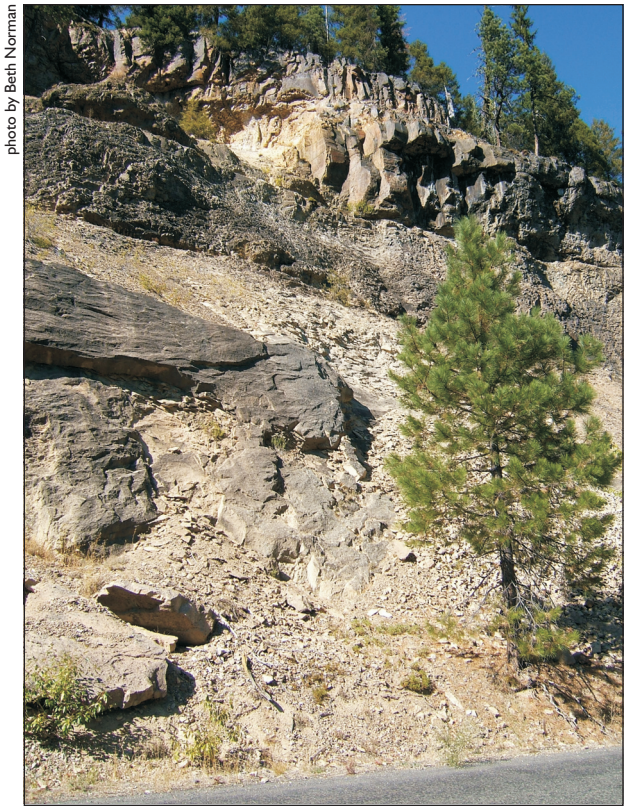
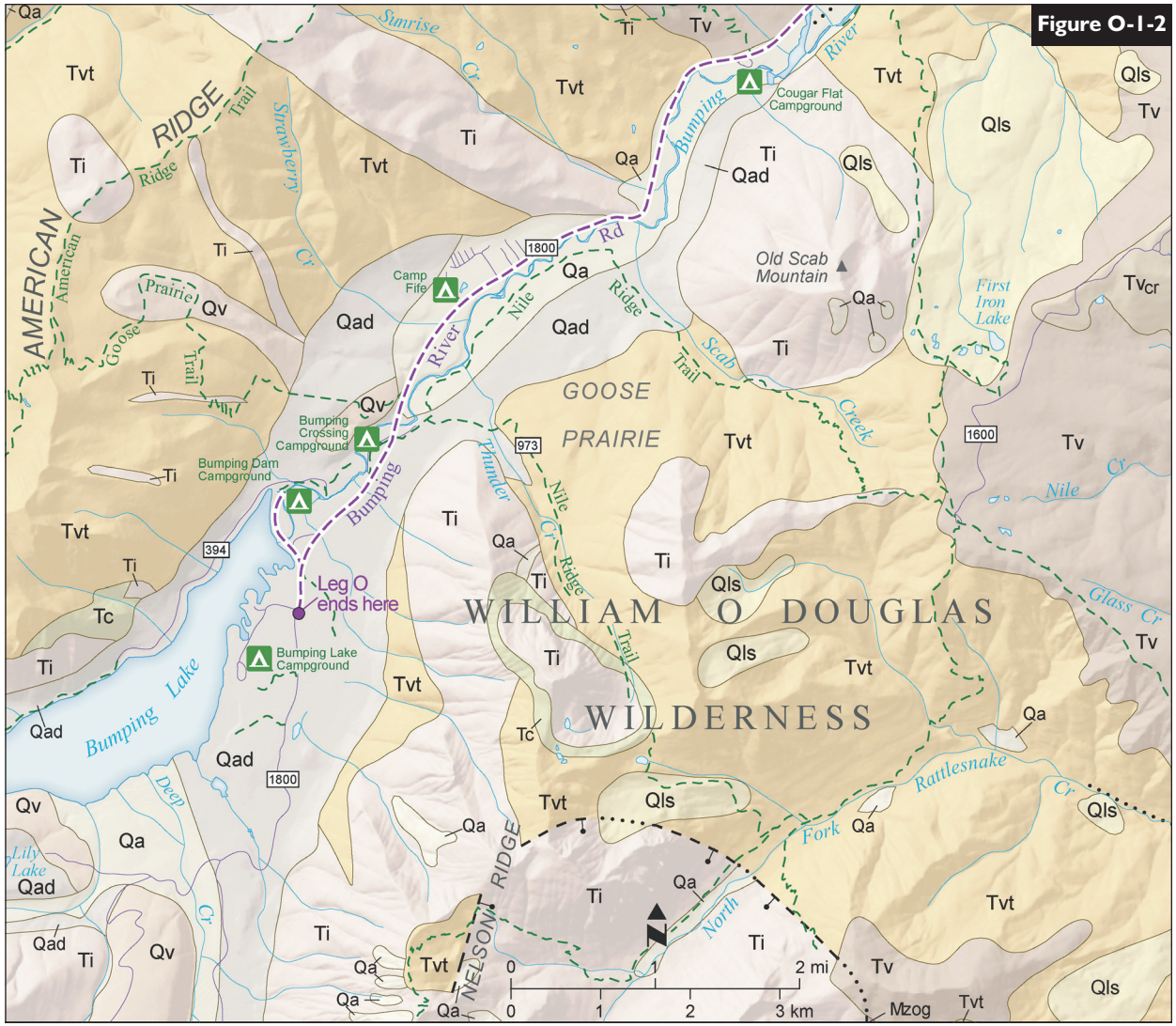


Figure O-3. Cooling joints in the Bumping River tuff. There are at least five separate flow units of the tuff in this exposure (top of section) in this photo. The bottom of the basal breccia is just above the center of the photo, and its contact dips to the right. A large area of unweathered (yellowish brown) rock near bottom of photo was exposed when a large chunk of the bedrock slid down along a fracture plane (not visible in this photo) during the winter of 1995-96. This outcrop is almost 400 ft (122 m) high.

4.9 *7.9* Soda Springs Campground.

5.0 *8.0* Glacial drift exposed here may be ablation till or outwash. On the right (west) side of the road (to mile 5.3 and farther) is a pre–Evans Creek drift (older than 22,000 cal yr B.P.).

5.3 *8.5* The debris-flow deposit on the right (west) is probably from a 1996 flood event in Goat Creek.



5.7 *9.2* Goat Creek Trail (#959) on the right. The gully exposes fragmental rock debris as the road ascends and crosses an alluvial fan.

5.8 *9.3* Cougar Flat Campground on the left.

6.1 *9.8* West of the road, the poorly sorted deposit, or diamicton, that is only slightly weathered and contains rounded clasts may be glacial drift of Evans Creek age (22 to 15 cal yr ka).

6.4 *10.3* Another view of Old Scab Mountain, an intrusive complex that is a likely source for the rock in the upper Ellensburg Formation in this area (Humphrey, 1996). (See Leg F for a discussion of the Ellensburg Formation.)

7.4 *11.9* Dacite sill. Smith and others' (1989) radiometric age of about 8.8 Ma for this 20-m (66 ft)-thick sill closely matches that of the top of Old Scab Mountain obtained by R. A. Duncan (Oregon State Univ., written commun., 2003). Note the hexago-

nal biotite crystals. Overlying the dacite sill is glacial drift of Evans Creek age containing rounded cobbles.

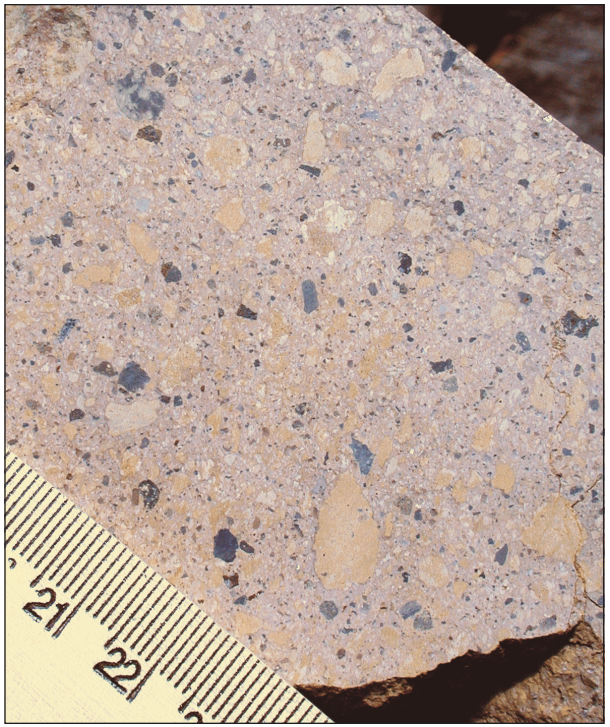
8.3 *13.3* Goose Prairie area, elevation 3266 ft (996 m); store, homes, cabins for rent. This is the former summer home of Chief Justice William O. Douglas, whose 1950 book "Of Men and Mountains" includes descriptions of his adventures in this area as a youth. Note the broad valley bottom here; bedrock constriction downstream and probable damming by moraines caused glacial outwash infilling of a valley.

8.4 *13.5* Camp Fife, a Boy Scout facility.

9.4 *15.1* Goose Prairie Trail (#972).

9.5 *15.3* The columnar-jointed outcrop on the right is hornblende andesite of Bumping Crossing, which was erupted from a large cinder cone north of here. Its age is roughly 300 to 25 ka, making it one of the few exposures of Quaternary-age volcanic rocks near here (Hammond, unpub. mapping, 2004).

Figure O-4. Close-up of the texture of a sample of Bumping River tuff that has been cut with a diamond saw. The scale is in centimeters. The light tan shapes are pumice fragments that have been somewhat flattened. Also visible are lithic fragments (dark clasts) and crystals, all in a welded ashy matrix.



9.6 *15.4* Cross the Bumping River. The Evans Creek terminal moraine here has nested recessional moraines and ground moraine upstream of it.

9.7 *15.6* Bumping Crossing Campground. Trails #973 and #974 are within 300 ft (90 m) of the river. More till and possible outwash deposits are exposed on both sides of the road.

10.8 *17.4* Junction of the road to Bumping Lake Dam and to Bumping Lake Marina. The latter road extends about 1.4 mi (2.2 km) to the northwest and then for about 1.5 mi (2.4 km) along the west side of the lake. The paved road ends near here. Those who want to explore further can drive up to Deep Creek, although road conditions are not suitable for trailers.

There is an excellent vista from the top of the dam, a great location for a geological overview (Fig. O-5). At the dam, you are standing about 1 mi

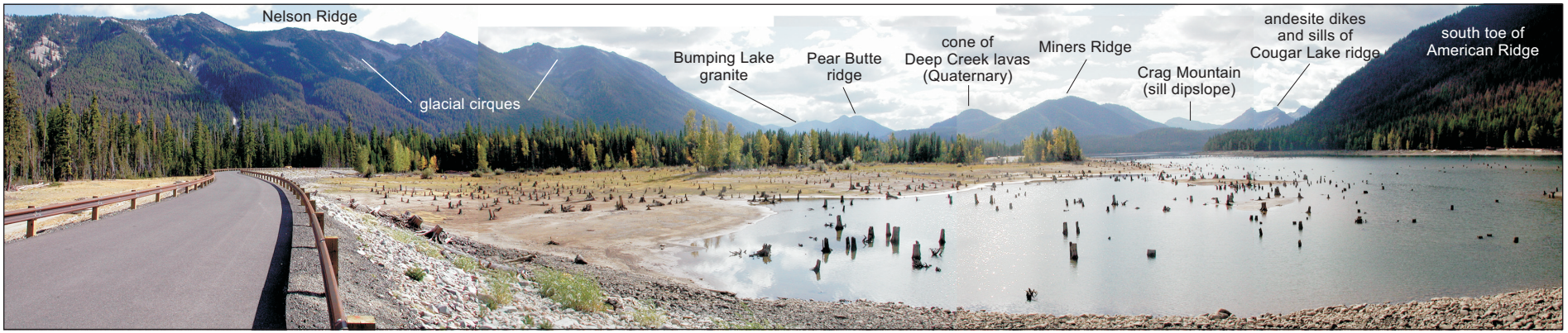


Figure O-5. Photo montage of the broad glacial valley of the Bumping River from Bumping Lake's north shore. This photo was taken in summer from the old earth-fill dam holding Bumping Lake. The stumps are remnants of trees killed by the filling of the reservoir. Excavations during maintenance revealed that the dam sits on pumiceous debris-flow deposits that contain charred logs (Newell Campbell, Yakima Valley Comm. College, oral commun., 1997, 2007); under the valley fill is the Bumping Lake granite (23.76 Ma). The view is toward the northern rim of the caldera of Mount Aix, about 1 mi (1.6 km) from this vantage point. Most of Nelson Ridge (left) is within the caldera. Miners Ridge is composed of granite of the Bumping Lake pluton. The sandstones of the Summit Creek rocks of Vance and others (1987) crop out at Crag Mountain and dip steeply to the west. The basal Summit Creek basalt, which sits underneath the sandstones, lies unconformably on the deformed rocks of the pre-Tertiary Rimrock Lake inlier. Pear Butte ridge (dacite, 6.29 Ma) is a local name. View is to the south-southwest.

(1.6 km) outside the north rim of the Mount Aix caldera (~25 Ma). Nelson Ridge, to the southeast, provides a cut through the caldera. A young dacite (4.7 Ma) is exposed to the north (left edge of Fig. O-5); roof pendants of older (Eocene) Puget Group sedimentary rocks are perched on the dacite. Most of the ridge to the south is capped by the Bumping River tuff, which is as much as 2600 ft (800 m) thick near here. Late Eocene to middle Oligocene Ohanapecosh Formation and coeval Wildcat Creek rocks crop out mid-slope, under the tuff, as a collapse breccia, whereas the lower, steeper parts of the ridge, are composed of the Bumping Lake granite (24.7 Ma), which fed the caldera. The northern part of Miners Ridge is entirely this granite.

The Bumping Lake Dam was constructed in 1910 and 1911 by the U.S. Bureau of Reclamation (USBR) in order to raise the water level and control the outflow of water for irrigation in the lower Naches River valley. The original (pre-reservoir) lake was dammed by a moraine of the last major (Evans Creek) alpine glaciation (Buehler, 1989). The current reservoir level is about 45 ft (14 m) higher than the original lake. Pumiceous debris-flow deposits and buried trees were exposed during excavations for the dam. The wood yielded radiocarbon ages of 340 and 500 yr B.P. The debris flow may have originated from Deep Creek (Newell Campbell, Yakima Valley Comm. College, oral commun., 1997). A USBR website (http://www.usbr.gov/dataweb/dams/wa00263.htm) notes that the pumiceous "lahar" deposit "mantles the glacial drift to a depth of up to 13 feet near the center of the valley floor and decrease to a thickness of approximately 4 feet at the ends of the dam".

11.2
18.0 Pavement ends near the turnoff for Bumping Lake Recreation Area and campgrounds. Turn right into the campgrounds. There is a good exposure of glacial drift of Evans Creek age in a road cut just before the pavement ends.

11.4
18.3 Nested Evans Creek age moraines are visible at nearby Bumping Lake campground, as well as glacial erratic boulders of various rock types.

This concludes the road log for this leg. The forest roads and trails that continue or that begin to the east, south, and west of Bumping Lake allow access to many worthwhile destinations including Mount Aix, Pear Butte, Tumac Mountain, Lily and Swamp Lakes, and Copper City, an old mining area.

Return north on this road to reach Yakima or Mount Rainier via SR 410. ■

PART III: USEFUL INFORMATION

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http://www.fs.fed.us/r6/mbs/recreation/

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http://www.nps.gov/archive/mora/home.htm

Mount Rainier National Park road status
http://www.nps.gov/mora/planyourvisit/road-status.htm

Mount Rainier Volcano Hazard Response Plan
Pierce County—http://www.co.pierce.wa.us/pc/Abtus/ourorg/dem/EMDiv/Mt%20Rainier%20VHRP.htm

Washington Emergency Management Division—http://www.emd.wa.gov/plans/documents/mtrainier_volcanic_hazards_response_plan.pdf

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Washington Emergency Management Division
http://www.emd.wa.gov/

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http://www.parks.wa.gov/reserve.asp
888-226-7688

WSDOT Mountain Pass Conditions
Washington State Department of Transportation
Phone: 1-800-695-7623; in Seattle 206-368-4499
http://www.wsdot.wa.gov/traffic/passes/text.asp

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GLOSSARY

Many definitions herein are taken, with permission, from the Glossary of Geology, published by the American Geological Institute (Neuendorf and others, 2005).

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

ablation till – poorly consolidated rock debris that was on or in a glacier and that later accumulated as the glacial ice was removed by ablation.

accretion – the process by which one terrane is attached to another having a different history. Typically, accretion occurs during tectonic collision.

accretionary lapilli – a mass of cemented ash 1 to 10 mm (0.04–0.4 in.) in size.

acoustic flow monitors – instruments that can detect sound vibrations in a specified frequency range. For detecting lahars or debris flows, acoustic flow monitors sensitive to the frequency range of about 50 to 80 Hz are used. A properly located array of such instruments can be programmed to detect significant ground vibrations and to automatically send a signal to a central location for interpretation and possible use in early warning alert systems for potential evacuation of downstream communities.

aggradation – the buildup of the Earth's surface by deposition, such as that performed by stream processes or volcanism.

aggraded – see *aggradation*.

alluvial fan – an outspread, gently sloping mass of alluvium deposited by a stream and/or debris flows.

alluvium – a general term for stream deposits.

alpine glaciation – the activity of a body of glacial ice whose source area is in a mountainous terrain in any latitude.

alpine glacier – a glacier in mountainous terrain. See *alpine glaciation*.

alteration – changes in the chemical and/or mineralogical composition of a rock, generally produced by weathering or hydrothermal activity. See *altered*; *hydrothermal alteration*.

altered – chemically or mineralogically changed, as via weathering or hydrothermal alteration.

amphibole – a group of dark, rock-forming ferromagnesian silicate minerals; for example, hornblende. Amphibolite is a rock consisting primarily of amphibole and plagioclase feldspar.

amygdule – a gas cavity in a lava that is filled with minerals (for example, opal, zeolites); *adj.*, amygdaloidal.

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

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

anticlinorium – a composite anticlinal structure of regional extent comprising multiple folds.

aragonite – a carbonate mineral ($CaCO_3$) that is denser and harder than calcite.

argillic – alteration in which certain minerals in a rock are converted to clay-group minerals

argillite – a compact sedimentary rock derived from mudstone or shale; *adj.*, argillaceous.

Ar/Ar, $^{40}Ar/^{39}Ar$ (Argon-40/Argon-39 age method) – a variation of K-Ar (potassium-argon) age estimation. One reason $^{40}Ar/^{39}Ar$ dating offers a significant advantage over conventional K-Ar dating is that potassium and argon are measured on the same sample by using isotopic ratios of argon; thus, very small samples and single crystals may be used. A good reference is http://www.diggles.com/bturrin/40Ar.html# aa2.

arkose – a feldspar-rich sandstone, typically derived from the rapid disintegration of granite or granitic rocks; *adj.* arkosic.

ash – see *volcanic ash*.

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

augite – a dark mineral of the pyroxene group that is common in igneous rocks.

axis – a line passing through a body or fold of rock around which it is symmetrically arranged.

back-arc basin – a basin floored by oceanic crust, formed by sea-floor spreading on the opposite side of a volcanic arc from an oceanic trench.

back thrust – a thrust fault that is oriented so that the direction of displacement is generally opposite that of the predominant direction of folding or faulting.

bar and swale – undulating topography on a flood plain, formed by the migrating channel of a river or creek; the bars are composed of coarse particles (sand, gravel, or cobbles), and the swales are depressions that contain fine sand, silts, and clays.

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

basaltic andesite – rocks that are intermediate in composition between andesite and basalt.

batholith – a mass of intrusive rock that has an area of at least 40 mi^2 (100 km^2).

bed – an individual layer or stratum, ranging from less than 0.5 in. (~1 cm) to more than several yards (meters) in thickness; the floor or bottom of a lake or stream; *adj.*, bedded.

bedding – stratification; the arrangement of layers in a sedimentary rock or deposit.

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

bergschrund – a large crevasse near the head of an alpine glacier.

biotite – black, brown, or dark green mica; a common mafic mineral.

bituminous coal – "soft coal"; coal that contains more than 14 percent volatile matter and has a caloric value of more than 11,500 BTU/lb. It is typically brown to black and burns with a smoky flame. The most abundant rank of coal.

block-and-ash flow – a pyroclastic flow containing blocks larger than 64 mm (2.6 in.); the slow cooling of these flows can cause the fragments to become welded.

bombs, breadcrust bombs – pyroclasts that are ejected while semi-molten and viscous and receive their shape during flight and/or impact. Shapes vary widely; many have a breadcrust-like texture (open cracks) on their outer surface caused by contraction during sudden cooling. (See Fig. A-11, p. 60.)

breadcrust – see *bombs*.

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 the collapse of an underlying magma chamber.

caliche – a light-colored, dominantly calcium carbonate or magnesium carbonate cement in soil layers that is precipitated from soil moisture in semi-arid regions, or the name given to a soil containing this material; hardpan.

carbonaceous – describes a rock unit or sediment rich in organic matter, coaly.

Cascade Range, Cascades – the north-trending volcanic arc near the western margin of North America.

Cascadia – the area of the Pacific Northwest whose physiography and geology has been directly influenced by the tectonic activity and history of the Cascadia subduction zone.

Cascadia subduction zone – the belt of subduction along the west coast of North America that extends from approximately the latitude of the middle of Vancouver Island, British Columbia, to Mendocino, California. (See Fig. 7, p. 9.)

Cenozoic – the geologic time encompassing the last 65 million years. (See Fig. 4, p. 5.)

chalcedony – a cryptocrystalline form of quartz, similar to chert, commonly found in vugs.

chert – a hard, dense rock consisting chiefly of microcrystalline quartz.

chlorite – a greenish clay mineral that is a common alteration product of ferromagnesian minerals.

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 mountain valley. (See Fig. 24, p. 29.)

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

clastic – made up of rock fragments.

clay-poor lahar – a lahar having less than 3 percent clay in the matrix; typically triggered when a pyroclastic flow or surge melts snow or ice or when a flood surge of any kind accumulates sediment on the flanks of a volcano.

clay-rich lahar – a lahar having greater than 3 percent clay in the matrix; typically triggered by transformation of a clay-rich landslide from collapse of a sector or flank of a volcano. See also *cohesive lahar*.

Clovis – a culture of early North Americans dating from roughly 13,500 to about 11,000 yr B.P.

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

coeval – originating or existing during the same time or period.

cohesive lahar – a volcanic debris flow or mudflow that contains more than 3 percent clay minerals in its matrix.

coke – the solid residue of coal after removal of the volatiles.

collapse breccia – fragmental deposits and blocks that have fallen into a collapse structure, such as a caldera or cave.

colluvium – a general term for loose soil and rock debris that accumulates near the base of a slope.

colonnade – in lava flows, a lower zone that has thicker columns that are better developed than those in the upper entablature. (See Fig. F-12, p. 110.)

column – see *columnar joints*.

columnar joints – fractures bounding polygonal columns that form in lava or a welded tuff deposit because of contraction that occurs as the unit cools. The columns typically form perpendicular to the cooling surface. (See Fig. F-12, p. 110.)

composite volcano – a steep-sided volcano consisting of alternating layers of lava and pyroclastic debris, as well as abundant dikes and sills; a stratovolcano.

conformable – describes layers that are formed or deposited in uninterrupted sequence, one on top of the other.

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

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

continental ice sheet – a thick glacial mass that is large enough to cover a significant part of a continent. (See Fig. 21, p. 27.)

country rock – the rock enclosing a mineral deposit or igneous intrusion.

creep – slow downhill movement of surficial materials (such as soil); also, the constantly increasing, slow deformation (strain) of rock that results from stress acting over a long time.

Cretaceous – the geological period from about 144 to 65 Ma. (See Fig. 4, p. 5.)

crevasse – a deep fissure in the surface of a glacier. (See Fig. 24, p. 29.)

cross beds – strata thicker than 0.4 in. (1 cm) that are inclined at an angle to the main strata. The nature of the cross beds can provide clues to the currents or winds that deposited them.

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

cuesta – an asymmetrical ridge with a long dip slope on one side and an abrupt cliff on the other.

cumulate – the rock material consisting of the crystals that settled to the bottom of a magma chamber.

cut-and-fill channel structures – typically bedded deposits, visible in cross-sectional view, left as fill in a stream channel that has been cut into older strata.

dacite – a fine-grained extrusive igneous rock typically having 62 to 69 percent silica; *adj.*, dacitic.

deep-seated – said of landslides whose failure plane is deep below the ground surface.

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

debris flow – a moving mass of debris, typically water-saturated. True debris flows commonly have sediment concentrations greater than 80 percent by weight (60 percent by volume).

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

dendrochronology – the scientific study of annual growth rings in trees for determining climatic or environmental information or the age of wood.

diamicton – a descriptive term for any poorly sorted deposit, such as a till, a debris flow, or a debris avalanche. Also diamict.

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

diorite – a coarse-grained intrusive rock having roughly the same chemical composition as andesite (54–62% silica); *adj.*, dioritic.

dip – the angle of inclination of a layer of rock measured from the horizontal.

dip slope – a hillside whose slope is similar to the dip of the rock strata.

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).

dish structure – a thin, typically concave upward lamina of mud that may form in a clay-poor lahar and lahar-derived deposits as they dewater immediately after deposition.

dome – see *volcanic dome*.

drift – a general term for any glacial deposit.

drumlin, drumlinoid – a low, elongate, rounded hill typically composed of compact glacial drift that is built and(or) shaped under flowing glacial ice and whose axis is parallel with the direction of ice movement. Drumlinoids are a less distinct form of drumlin.

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.

effective stress – intergranular pressure; the average normal force per unit area transmitted directly from particle to particle within a soil or rock mass.

effusion – the emission of moderately fluid lava onto the Earth's surface; the eruptive product thereof.

end moraine – see *terminal moraine*.

entablature – in lava flows, a zone that has thinner, less well developed columns; typically above the colonnade. (See Fig. F-12, p. 110.)

Eocene – the geologic epoch covering the time interval between about 54 and 34 Ma; it followed the Paleocene and preceded the Oligocene Epochs of the Tertiary Period. (See Fig. 4, p. 5.)

epiclastic – related to the fragmentation of rock by mechanical weathering or the accumulation or lithification of these fragments.

erratic – a large rock that has been transported far from its place of origin, typically by a glacier or cataclysmic flood event.

eruption column – the columnar eruption cloud from a volcano that results from the initial jet of volcanic material rising from the vent

extrusive – said of a rock that is erupted onto the Earth's surface.

facies – the characteristics (grain size, color, etc.) of a rock or sedimentary unit that distinguish it from another unit.

fan – a fan-shaped, gently sloping mass of debris or lava; see *alluvial fan*.

fault – a fracture along which one rock mass has slid past another.

fault breccia – angular rock fragments produced by fracturing and frictional slip along a fault.

feeder – the conduit through which lava passes from a magma chamber to some localized intrusion; for example, a feeder dike.

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

felsic – referring to igneous rocks that have abundant light-colored minerals or less than 50 percent ferromagnesian minerals.

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

fiamme – dark, glassy, flattened fragments in welded tuffs, possibly collapsed pumice; may reach several inches (centimeters) in length.

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

fission-track dating – a method for determining the age of a rock based on the number of tracks created by the emission of subatomic particles during radioactive decay.

flank collapse – a landslide in which part of a volcano's flank fails and slides and (or) flows downslope and outward from the volcano. Compare with sector collapse.

flaser bedding – incomplete or interrupted mud laminae found in coarse sediment and sedimentary rocks.

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

flow banding – stripes, lenses, or streaks in volcanic rocks of different colors, minerals, and(or) textures that originate during flow of a lava; such banding may indicated mixing of different magmas or zones of greater and lesser gas content.

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

flow units – a group of sheets or beds of lava or pyroclastic rocks that were formed a single eruption or outpouring.

fluidal glass – small globular glass particles included in pyroclastic deposits; represents juvenile eruptive products.

fluvial – of or related to rivers or river processes.

fold – a bend in a rock stratum or layer.

footwall – the mass of rock that is beneath, on the lower side of a dipping fault or sloping ore body or vein.

fore arc – the region between a subduction-related trench and a volcanic arc.

formation – a distinctive body of sedimentary rock that can be mapped or traced from one place to another.

forward looking infrared thermography (FLIR) – a technique that uses cameras (sensors) that can detect radiant energy in the infrared spectral range (heat energy).

Fraser Glaciation – a series of glacial advances that occurred in the Pacific Northwest between about 29 and 10 ka. This glaciation coincided with oxygen isotope stage 2.

fumarole – a volcanic vent that emits gases.

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

geode – a hollow or partly filled globular body in which the crystals (quartz, calcite, or zeolites) have grown toward the interior of the cavity.

geodesy – the science concerned with the precise shape, size, and physical aspects of the Earth.

geomagnetic – pertaining to the magnetic field of the Earth.

geomagnetic polarity – the orientation of the natural remanent magnetization of a rock. A rock having "normal" polarity has a natural remanent magnetization roughly parallel to the present ambient geomagnetic polarity, showing the magnetic negative pole to be near the geographic north pole at the time the rock was formed; a rock having "reversed" polarity has a natural remanent magnetization that shows the magnetic positive pole was near the present geographic north pole at the time the rock was formed. (See "Paleomagnetism" sidebar, p. 104.)

geomorphology – the science that treats the general configuration of the Earth's surface, its landforms, and their causes and history.

geophone – a seismic device that acts as a pickup and can detect ground vibrations within a certain range of frequencies.

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

glaciofluvial – pertaining to the meltwater streams that drain glaciers and the landforms and deposits left by these streams.

gneiss – a foliated or banded rock formed by regional metamorphism.

gouge – pulverized, commonly clayey, rock material found along faults and formed by the grinding action of rocks during faulting.

graded beds – layers of sediment that display a change in grain size, typically from coarser to finer upwards.

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

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

graywacke – an obsolete (but convenient!) term for a coarse-grained sandstone that contains poorly sorted, angular to subangular fragments of quartz and feldspar embedded in a clayey matrix and that contains common dark (ferromagnesian) minerals; graywackes are commonly interpreted to have been deposited by turbidity currents.

greenstone – a field term for any dark-green altered or metamorphosed mafic igneous rock that owes its color to the minerals chlorite, actinolite, or epidote.

groundmass – the matrix of a porphyritic igneous rock.

ground moraine – an extensive area of till having little or no relief. (See Fig. 24, p. 29.)

grus – an accumulation of angular crystals and rock grains formed in situ by the disintegration of crystalline rocks.

hackly – a result of jagged fracturing.

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

hanging wall – the mass of rock that lies above a dipping fault or sloping ore body or vein.

hanging valley – any tributary valley whose mouth is high above the floor of the main valley. (See Fig. 24, p. 29.)

headscarp – the steep wall from which a landslide has detached.

headwall – the steep slope at the head of a valley or cirque. (See Fig. 24, p. 29.)

heavy mineral – slang for ferromagnesian or mafic minerals that have a specific gravity greater than about 2.85.

historic – having importance in, or influence on history; the Washington Office of Archaeology and Historic Preservation has issued guidelines for designation of historic features or structures (see http://www.dahp.wa.gov/).

hogback – a ridge having a narrow summit and steeply dipping flanks. Hogbacks are typically formed by the sharp edges of steeply inclined bedded rocks that are resistant to erosion.

Holocene – the geologic epoch of the Quaternary Period that followed the Pleistocene Epoch and comprises the last 12,000 years.

hornblende – a dark mineral commonly found in igneous rocks.

hornfels – a fine-grained rock formed by recrystallization during contact metamorphism.

hyaloclastite – a deposit formed by the flow or intrusion of lava or magma into water, ice, or water-saturated sediments and its consequent shattering into small angular fragments.

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 chemical or physical alteration of rocks or minerals owing to contact with hydrothermal waters.

hydrous – a term referring to minerals containing water as part of their crystalline structure.

hyperconcentrated flow – a type of gravity-driven sediment-rich slurry that has sediment concentrations in the range of 40 to 80 percent solids by weight (20–60 percent by volume) and that commonly forms when a lahar or debris flow undergoes dilution.

hypersthene – a dark mineral of the orthopyroxene group that is common in igneous rocks.

ice-marginal – referring to features or environments adjacent to glacial ice, for example, ice-marginal lakes.

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

imbricated – overlapping; arranged like shingles or fish scales.

inclusion – a fragment of older rock within an igneous rock.

inholding – a plot of privately held land that is within the boundaries of land owned by the government.

inlier – an area or group of rocks that is surrounded by rocks of a younger age.

interferometric synthetic aperture radar (InSAR) – a technique for measuring small changes in deformation of the Earth's surface.

interbed – a bed, typically thin, of one type of rock material between, or alternating with, beds of another kind. In volcanic terrain, interbeds are commonly lake or stream deposits.

intermediate – said of an intrusive rock that is transitional between mafic and felsic.

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

invasive flow – a lava flow that sinks into sediments or material having a lower density.

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

jasper – a variety of chert, typically red.

joint – a fracture in a rock along which movement has not occurred. (See Fig. A-11, p. 60.)

jökulhlaup – an Icelandic term for glacial outburst flood.

Jurassic – the second period of the Mesozoic Era, spanning the time between about 200 and 145 Ma. (See Fig. 4, p. 5.)

juvenile material – volcanic rocks derived directly from magma that has reached the surface; see also *pyroclastic*.

K-Ar dating – see *potassium-argon dating*.

kame terrace – a terrace-like deposit of stratified sand and gravel formed between a melting glacier or stagnant ice lobe and a valley wall or moraine. (See Fig. 24, p. 29.)

kettle – a bowl-like depression formed by the melting of a detached mass of ice buried by sediment as a glacier recedes. (See Fig. 24, p. 29.)

kinematic wave – a wave that moves through a medium without regard to the mass of the medium or the applied force.

lacustrine – pertaining or related to lakes.

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

lahar runout – the muddy flood resulting from dilution of a lahar as it mixes with stream water. The deposits are typically sandy and have fewer large rocks than lahar deposits. Runouts have sediment concentrations of 40 to 80 percent solids by weight (hyperconcentrated).

lamina – the thinnest recognizable layer in a sediment or sedimentary rock, typically thinner than 1 mm; plural, laminae.

lapilli – volcanic particles in the range of 2 to 64 mm (0.07–2.52 in.).

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

latewood – the dark or higher density part of a tree's annual growth ring formed during the latter part of the growing season.

lava – magma that reaches the Earth's surface; also the rocks that result from its cooling.

levee – an area of deposits at the edges of a stream or lava flow that approximately records the maximum height of the flow.

lignite – a brownish-black coal that is intermediate between peat and subbituminous coal.

limb – the flank of a fold between two adjacent hinges.

lineament – a linear topographical feature of regional extent that is inferred to reflect crustal features or structures.

liquefaction – in a soil, the transformation from a solid to a liquid state as the result of increased pore pressure and reduced intragranular pressure.

lithic – of or related to rocks or their descriptive characteristics; lithologic.

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

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

lithologic – see *lithic*.

lithology – the description of rocks in outcrop or hand sample, or the physical characteristics of a rock.

lithosphere – the solid outer portion of the Earth.

Little Ice Age – a period of cold climate from about A.D. 1350 to A.D. 1850. During this time, alpine glaciers worldwide advanced, in places by as much as a mile (1–2 km) down their valleys.

loess – a blanket deposit of windblown silt, typically unstratified and homogeneous, considered to have originated as dust from glacial deposits.

long period – said of a cyclic interval of seismic activity that lasts longer than 6 seconds.

mafic – a term used to describe an igneous rock that contains mostly ferromagnesian minerals.

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

magmatism – the formation, movement, and solidification of magma.

magnetite – a common, dark, iron-rich oxide mineral.

magnetostratigraphic – said of a geologic unit that can be differentiated on the basis of its magnetic polarity or other geomagnetic property.

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

marine isotope stage – a time period representing an episode of glacial maximum or minimum defined on the basis of the ratio of ^{16}O and ^{18}O, two stable isotopes of oxygen. The ratio of these two isotopes in water is temperature dependent and is commonly measured in fossil shells or in layers of ice within a glacier. (See Fig. 25, p. 29.)

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

mass wasting – see *mass movement*.

matrix – the finer grained material that encloses either the coarser material in a sediment or sedimentary rock or the phenocrysts in a porphyritic igneous rock; in an igneous rock, the matrix is also called the groundmass.

matrix strength – the ability of a granular substance to support a weight, as when a debris flow carries large rocks.

matrix-supported – said of large rocks that are suspended in a finer grained matrix of a depositional unit.

megaclast – one of the larger fragments in a fragmental deposit or rock containing a variety of particle sizes.

megaripple – a ripple-like feature having a wavelength greater than 1 m (3.28 ft). Because they are commonly created or deposited during humongous flood events, such as the sudden emptying of a glacial lake, megaripples can consist in large part of pebbles, cobbles, and even boulders.

mélange – a mappable body of rock that includes exotic and native rocks and fragments of all sizes within a fragmented and commonly sheared matrix.

Mesozoic – the period of geologic time following the Paleozoic and preceding the Tertiary or Cenozoic. (See Fig. 4, p. 5.)

metagabbro – a metamorphosed gabbro.

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

metamorphism – mineralogical, chemical, and structural changes in a rock in response to physical and chemical conditions such as those caused by deep burial and (or) exposure to hot fluids.

mica – a group of silicate minerals that cleave into thin sheets; *adj*., micaceous, containing mica.

microdiorite – a fine-grained diorite.

mineral – a naturally formed solid inorganic substance having a fixed crystal structure and consistent chemical composition.

Miocene – the geologic epoch that covered the time span between about 23 and 5 Ma during the Tertiary Period.

monolithologic – consisting mostly of one rock type.

monzonite – a group of coarse-grained, intrusive rocks typically having a content of sodium- or potassium-rich feldspars higher than that of diorite.

moraine – a mound or ridge of unstratified drift, mostly till, that is directly deposited by ice; *adj*., morainal. (See Fig. 24, p. 29.)

mudline – the maximum level of inundation by a lahar or flood determined by the height of mud left on trees or rocks.

natural remanent magnetization – the permanent magnetization acquired by igneous rocks as they cool or by magnetic particles as they settle in sediments.

neoglacial – relating to readvances of mountain glaciers during the Little Ice Age and other late Holocene episodes of glaciation.

noncohesive lahar – see *clay-poor lahar*.

normal fault – a steeply dipping fault in which the hanging wall has moved downward relative to the footwall; typically a result of horizontal extension; compare with reverse fault.

North Cascades – the physiographic area of the Cascade Range that extends roughly from the Olympic Wallowa Lineament north to Mount Meager volcano in British Columbia, Canada. The North Cascades include a rugged, complex collage of accreted terranes that have been intruded by plutons and perforated by volcanoes of Quaternary age. (See Fig. 5, p. 7.)

obsidian – dark-colored volcanic glass, a result of very fast cooling of a gas-poor lava.

Oligocene – the geologic epoch that spanned the time between about 34 and 23 Ma during the Tertiary Period.

olivine – a greenish rock-forming mineral common to some mafic igneous rocks such as basalt and gabbro.

Olympic Mountains – the young and rugged range of coastal mountains north of the Chehalis River and south of the Strait of Juan de Fuca. (See Fig. 5, p. 7.)

orogeny – the tectonic process that results in the formation of mountains.

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

outcrop – an exposure of rock or a deposit; verb, to crop out.

outwash – stratified deposits produced by glacial meltwater.

overbank deposit – silt, clay, and (or) fine sand deposited from suspension on a flood plain. Overbank deposition begins when floodwaters can no longer be contained within the channel.

palagonite – a yellowish or orange mineral formed by the alteration of basaltic glass and typically found in the matrix surrounding basaltic fragments created as lava suddenly quenched and fractured in water.

paleo- – a prefix meaning old or ancient.

paleoclimatologists – scientists who study the record of ancient climate.

paleomagnetism – the natural remanent magnetism that was recorded by a geologic material at the time it formed; *adj.*, paleomagnetic.

Paleozoic – the geologic time period following the Precambrian and preceding the Mesozoic. (See Fig. 4, p. 5).

patent – a grant conferred by a government that allows sole rights to minerals on a piece of land for a set amount of time.

patterned ground – a group of more or less symmetrical landforms, such as circles, mounds, and stripes, that occur in surficial deposits affected by the actions of frost.

pegmatite – an exceptionally coarse grained igneous rock of granitic composition commonly found as dikes or veins at the margins of larger intrusive bodies.

permineralization – a process of fossilization wherein minerals are deposited in the original pore spaces of tissues or hard parts of a plant or animal.

petrographic – related to petrography, the branch of geology associated with the examination, description, and classification of different types of rocks.

petrology – the branch of geology relating to studying the origin, structure, and history of rocks; *adj.*, petrologic.

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

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

phreatomagmatic – an interaction of magma and water that produces an explosion of both steam and magmatic gases.

phyric – see *porphyritic*.

pillow lava – a name for any globular, pillow-shaped lava, typically formed under water.

plagioclase – a series of feldspar minerals that vary in sodium and calcium content.

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

plate tectonics – the theory that describes the Earth's lithosphere as divided into a number of individual quasi-rigid plates whose horizontal and vertical movements and interactions with other plates give rise to seismicity and volcanism.

platy jointing – rock fractures that form thin tabular sheets. In lavas, these typically form near a flow margin. (See Fig. F-12, p. 110.)

Pleistocene – the geologic period lasting from about 1.8 Ma to 12 ka and that includes the recent great Ice Ages. (See Fig. 4, p. 5.)

Pliocene – the geologic period preceding the Pleistocene and lasting from about 5.3 Ma to 1.8 Ma. (See Fig. 4, p. 5.)

plug – a vertical, pipe-like body of magmatic rock that is the conduit of a former volcanic vent.

pluton – a large intrusive rock mass formed deep in the crust.

point bar – an arcuate mass of sand and gravel that accumulates on the inside of a stream meander.

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

porphyry – an igneous intrusion of any rock type that contains phenocrysts.

porphyry copper deposit – a type of hydrothermal mineral deposit associated with plutons in which copper minerals are disseminated.

postglacial – referring to the time since the most recent major Ice Age.

potassium-argon dating – the radiometric age determination of a rock sample based on the ratio of argon-40 to potassium-40 and the decay rates of these isotopes; also referred to as K-Ar dating.

proglacial – immediately in front of or just beyond the limits of the glacier, especially its lower end.

progradation – the building water-ward of a beach, shoreline, or delta because of the delivery or accumulation of sediment.

propylitized (propylitic alteration) – low pressure and low temperature alteration of a fine-grained rock such as an andesite to secondary minerals such as chlorite.

Puget lobe – a large finger-like body of the continental ice sheet that flowed south into the Puget Lowland. (See Fig. 6, p. 8.)

Puget Lowland – the broad, glaciated lowland between the Olympic Mountains and the Cascade Range. (See Fig. 5, p. 7.)

pumice – solidified rock froth; a porous volcanic rock that floats; *adj.*, pumiceous, a term that describes a pyroclastic rock whose texture is finer than scoriaceous; also said of a pyroclastic deposit that consists largely of pumice.

pyrite – a common brass-colored iron-sulfide mineral, FeS_2.

pyroclastic – describing the clastic rock material ejected during a volcanic eruption; also pertaining to the texture of a rock thus formed. In the plural, the word is informally used as a noun, pyroclastics.

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.

pyroclastic flow – a mass of hot, dry, pyroclastic debris and gases that moves rapidly along the ground surface. It can be caused by an eruption or collapse of a volcanic 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 1.8 Ma to the present. It consists of the Pleistocene Epoch (ending ~12 ka) and the Holocene Epoch (12 ka–present). (See Fig. 4, p. 5.)

quenched – rapidly cooled.

radiocarbon dating – the calculation of the age of carbonaceous material by measuring the concentration of remaining ^{14}C.

radiocarbon years – years before A.D. 1950 (by convention) based on the ratio of the carbon-14 isotope to normal carbon, 12C. 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 11,000 years) has been devised; however, for simplicity, raw (uncalibrated) radiocarbon ages are mostly used in this guide. (See "Radiocarbon dates", p. 6.) Calibrated dates are expressed as 'cal yr B.P.'

radiolarian chert – sometimes described as "ribbon chert"; generally well-bedded microcrystalline rock containing fossil radiolaria (a type of protozoan) and well cemented by silica. This type of chert is thought to have formed in deep-marine environments.

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. See *Ar/Ar (argon-argon)* and *potassium-argon (K-Ar)dating*.

rank – the degree of metamorphism in coal; used to classify coal by grade from lignite (softest) to anthracite (hardest).

rain-on-snow event – a flood that is triggered when a moist warm front dumps a substantial amount of rain on snow-covered areas.

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

recession (glacial) – the melting backward or 'retreat' of the snout of a glacier from its farthest downvalley location when the supply of ice to the glacier is not sufficient to cause it to flow.

reentrant – from reentering or directed inward; for example, a transverse or tributary valley or recess that intersects another valley or escarpment.

refugium – an area that contains biological remnants of a previous environment, typically one that has persisted with little change during some severe natural disturbance. *Plural*, refugia.

resistivity – the amount of resistance to electrical charge flow.

reverse fault – a high-angle (>45°) fault in which the hanging wall has moved upward relative to the footwall; typically caused by horizontal compression.

rhyodacite – an obsolete term for a group of porphyritic extrusive igneous rocks that have a composition between dacite and rhyolite. Rhyodacite is roughly the extrusive equivalent of granodiorite.

rhyolite – a group of porphyritic extrusive igneous rock typically having more than 69 percent silica. It is the extrusive, finer grained equivalent of granite.

right lateral – a type of faulting or movement in which the side across the fault from the observer moves to the right.

Rimrock Lake inlier – an assemblage of pre-Cascade rock units, mostly of Mesozoic age, that are exposed east and south of Mount Rainier.

riprap – piles or layers of durable stone blocks used for engineering purposes such as breakwalls, for stabilizing landslides, or for armoring beaches and river banks; also the rock used for such purposes.

rock flour – silt- and clay-size rock particles produced by glacial pulverization.

roof pendant – a downward projection of older rock above and (or) into an intrusion.

rootless explosion crater – a small, shallow crater produced by a phreatic explosion.

runup – the advance of water, a slurry, or mass of debris up a slope or obstacle owing to its momentum.

sackung (or sackungen) – a type of deep-seated rock mass movement in which a ridge face creeps downslope. One feature of this motion is a sackung, a ridge-top trench or depression perpendicular to the direction of the slope movements. From the German word Sackung, sagging, subsidence).

sag pond – a small pond or body of water that occupies a closed depression on a landslide or along a fault and that formed because of fault or landslide movement.

sand volcano – an mound-like accumulation of sand produced by expulsion of liquefied sand to the surface.

saprolite – an ancient soil or weathered rock material that preserves some of the textures of the parent rock.

scarp slope – the slope on the opposite side of a hogback ridge from the dip slope.

schist – a strongly foliated metamorphic rock that can be readily broken into flakes and slabs because of the large percentage of parallel and subparallel crystals composing it; *adj*., schistose.

scoria – an igneous rock containing abundant cavities (vesicles) but that does not float, typically formed at the surface of a lava flow. (See Fig. F-12, p. 110.)

sector collapse – a volcanic landslide in which a major part of the volcano, typically its summit area, slides away. Compare with *flank collapse*.

secular variation – the drift of the Earth's geomagnetic field over the centuries. It can be used to date young rocks whose minerals record the location of the magnetic poles when the rocks are formed.

sedimentary rock – a layered rock that results from the consolidation of sediments.

sediment-gravity flow – a general term for movement of any sediment mixture downslope in response to gravity.

sediment yield – the amount of material eroded from the land surface within the drainage basin of a stream or river system and delivered to a stream system.

seismic activity – earth movements or vibrations caused by earthquakes, landslides, debris flows, or the activity of humans; also, seismicity, of or pertaining to seismic energy or seismic activity.

seismometer – a device that detects and records seismic activity.

sericite – a fine-grained potassium-rich mica that is an alteration product.

shale – a sedimentary rock whose component particles are predominantly silt size or smaller.

shear zone – a tabular zone of rock that has been crushed and brecciated, typically because of fault activity on both sides of the zone.

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

silicate – a mineral whose crystal structure contains silica (SiO_2).

silicic – an adjective referring to a silica-rich igneous rock or magma. Such rocks generally are at least 65 percent silica.

silicification – the introduction of, or replacement by silica, which results in formation of fine-grained quartz, chalcedony, or opal.

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

slickensides – grooves on, or a striated surface of a rock produced by abrasion along a fault.

slips – debris slides.

slosh line – see *trimline*, *mudline*.

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

snag – the trunk of a dead tree.

sorting – the degree of similarity of particle sizes (or other quality) of a sediment. Well-sorted material consists mostly of particles similar in size, whereas poorly sorted material consists of a wide variety of grain sizes.

spatter – an accumulation of very fluid pyroclastic debris, commonly basaltic, near a volcanic vent.

spheroidal weathering – chemical weathering that causes thin concentric shells/layers of decomposed rock to separate from a block of rock; caused by water penetrating the bounding joints.

spiracle – a vent or tube at the base of a lava flow formed as steam rose from underlying wet sediment or soil. (See Fig. F-12, p. 110.)

stage – in glaciology, a term for a major subdivision within a glacial epoch.

stock – a body of intrusive rock that has an area less than 40 mi^2 (100 km^2).

stone stripes – a type of patterned ground.

stratified – composed of layers of sediment.

stratigraphy – the study of geologic strata or layers, their succession, composition, fossils, and other characteristics, and what ancient environments they represent.

stratovolcano – see *composite volcano*.

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, fold, or other planar feature is oriented.

strike-slip fault – a fault along which displacement is parallel to the strike of the fault.

subaerial – formed on land.

subangular – said of rocks or particles that have been rounded somewhat but still retain part of their original shape.

subaqueous – formed under water.

subbituminous – a rank of coal intermediate between lignite (softest) and bituminous.

subduction – the process of one lithospheric plate descending under another.

subduction zone – a long narrow belt in which subduction takes place.

subfossil – biological remnants, such as dead trees, that are preserved but not permineralized.

surge – see *pyroclastic surge*.

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

syncline – a fold that is concave upward, like a trough, having stratigraphically younger rocks in its core.

tailings – the washed or milled ore regarded as too poor to be treated further.

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

tarn – a small mountain lake that occupies a cirque. (See Fig. 24, p. 29.)

tectonic – relating to the individual lithospheric plates, their movements and interactions with other plates. See *plate tectonics*.

tectonic suture – a boundary that separates two conjoined tectonic plates.

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

terminal moraine – the outermost end moraine of an ice sheet or glacier that marks the maximum extent of the ice. (See Fig. 24, p. 29.)

terminus – the lower margin or extremity of a glacier. (See Fig. 24, p. 29.)

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 65.5 Ma to 1.8 Ma. (See Fig. 4, p. 5.)

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

thunder egg – the popular term for a geode-like mass of chalcedony, agate, or opal that has weathered out of a vug in a welded tuff.

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

transform fault – a strike-slip fault that separates geologic plates or plate segments.

transgression – the spreading of the sea over land.

travertine – a finely crystalline or massive deposit of calcium carbonate, commonly crudely layered and (or) having fibrous structures, that is chemically precipitated from solution in surface and ground waters.

trench – an elongate depression on the sea floor roughly parallel to the continental margin and located between the margin and the subducting oceanic lithosphere.

trimline – the 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.

tufa – a spongy, porous variety of travertine that forms in deposits at springs, in stream beds, and locally in lakes.

tuff – a fine-grained rock composed mostly of volcanic ash; *adj*., tuffaceous.

turbidite – the deposit of a turbidity current.

turbidity current – a sediment-charged flow (density current) the moves swiftly down a subaqueous slope.

type locality – the geographic locality that best typifies and commonly gives its name to a geologic formation. The type section is the unique sequence of layers that defines a given geologic formation within the type area.

unconformable – said of rocks that do not succeed the underlying rocks in immediate order of age, implying a break in deposition or a period of erosion.

U-Pb dating – see *uranium-lead dating*.

uranium-lead dating – methods used to determine the age of rocks on the basis of the radioactive decay rate of uranium-238 to lead-206 or uranium-235 to lead-207, whose half lives are about 4.5 and 0.7 billion years respectively. This former technique is useful for very old rocks, such as those of Precambrian age.

valley glacier – a glacier that heads in one or more cirques and then flows into, and is confined by a valley; an alpine glacier. (See Fig. 24, p. 29.)

Vashon Drift – glacial deposits (including till and outwash) left by the Puget lobe of the continental ice sheet that moved through the Puget Lowland between 22 and 15 ka.

Vashon Glaciation – the most recent major episode of continental glaciation, during which a major lobe of ice, the Puget lobe, moved into and out of the Fraser–Puget Lowland between 22 and 15 ka (Vashon Glacier).

vent – the opening through which volcanic rocks are extruded or conduit through which these rocks pass during eruption.

verge – to slope, incline.

vesicle – a small cavity in a rock formed by the expansion of gas during formation of a volcanic rock. A spiracle is a large vesicle.

viscosity – resistance to internal flow.

volcanic arc – a curved belt of volcanoes and volcanic rocks lying above a subduction zone.

volcanic ash – fine pyroclastic particles (<2 mm or <0.08 in. in diameter).

volcanic dome – a steep-sided bulbous mass of lava, such as the Lava Dome at Mount St. Helens, 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.

volcaniclastic – a general term for all fragmental material produced by a volcano.

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

welded tuffs – fragmental volcanic (volcaniclastic) deposits that originate as flows of ash and pumice and that, because of their weight and heat, become welded together after they come to rest. Owing to this welding, they cool in a manner somewhat similar to a flow of lava, and thus many display crude columnar jointing.

wiggle-matching – finding the best fit of a series of radiocarbon ages for chronologically spaced samples with the calibration curve for radiocarbon. The samples submitted must have a known spacing in years. This technique can yield reduced errors.

Younger Dryas – the term for a period of cooling during late-glacial time that lasted from about 12,900 to about 11,500 calendar years ago.

zeolites – generic name for a large group of hydrous minerals that commonly form in vugs in volcanic rocks.

zircon – a common but minor mineral in igneous and metamorphic rocks; $ZrSiO_4$. ■

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DESCRIPTION OF MAP UNITS

The expanded unit descriptions shown here list the named units included in each map unit at the end of its description. The list covers those units that occur within the area of Figure 2. That figure depicts geologic units by age and lithology, and therefore some named units may be listed with more than one unit. Fewer units are shown in the map panels along each leg of the road guide than in Figure 2. Furthermore, because of the map scale, small outcrops of some units are too small to show on the leg maps. The road log refers to the units that are passed or the formation or informally named units that have a place in the geologic history of the study area. For more information, see the source map, GM 53 (Schuster, 2005), and the products from which it was prepared.

Note: Lithologies are not listed in order of abundance.

Unconsolidated Sedimentary Deposits

Qa **Quaternary alluvium** — Unconsolidated or semiconsolidated alluvium, alluvial fans, artificial fill, beach deposits, gravel, peat, regolith, talus, and terraced deposits. *Includes named unit:* Skokomish Gravel.

Qls **Quaternary mass-wasting deposits** — Primarily landslide deposits, but locally includes talus, colluvium, protalus ramparts, and rock glaciers.

Ql **Quaternary loess** — Eolian silt and fine sand. *Includes named unit:* Palouse Formation.

Qf **Pleistocene outburst flood deposits** — Silt, sand, gravel, and boulder deposits deposited by outburst floods from glacial Lake Missoula. *Includes named unit:* glacial Lake Missoula flood deposits and Touchet beds.

Qgd **Pleistocene continental glacial drift** — Till and outwash clay, silt, sand, gravel, cobbles, and boulders. *Includes named units:* Orting Drift, Salmon Springs Drift, Steilacomm Gravel, Stuck Drift, and Vashon Drift.

Qad **Pleistocene alpine glacial drift** — Till, outwash, and glaciolacustrine sediments. *Includes named units:* Burroughs Mountain Drift, Evans Creek Drift, pre-Evans Creek–post-Hayden Creek deposits, Garda Drift, Hayden Creek Drift, Kittitas Drift (undivided), Kittitas Drift (Indian John and Swauk Prairie subdrifts), Lakedale Drift (Bullfrog, Domerie, Hyak, and Ronald subdrifts), Logan Hill Formation, Lookout Mountain Ranch Drift, drift of McDonald Ridge, McNeely Drift, Wingate Hill Drift.

Sedimentary Rocks and Deposits

QTc **Quaternary–Tertiary continental sedimentary rocks and deposits** — Clay, conglomerate, gravel, sand, and silt. *Includes named units:* Alderton Formation, Kitsap Formation, Olympia-age nonglacial sediments, Puyallup Formation, and Whidbey Formation.

Tc **Tertiary continental sedimentary rocks** — Clay, silt, sand, and gravel deposits; claystone, coal, conglomerate, debris-flow breccia, fanglomerate, mudstone, sandstone, carbonaceous shale, siltstone, tephra interbeds, tuff, volcaniclastic breccias; commonly fossiliferous. *Includes named units:* Barlow Pass Volcanics, Carbonado Formation, beds of Chambers Creek, Chumstick Formation (undivided), Chumstick Formation (Nahahum Canyon Member), Eagle Creek Formation, Ellensburg Formation (undivided), Ellensburg Formation (Vantage Member),

sandstone of Lookout Creek, Manastash Formation, Mashel Formation, rocks of Mount Daniel, Naches Formation (undivided), Naches Formation (Guye Sedimentary Member), Puget Group (undivided), Puget Group (Renton and Tiger Mountain Formations), Roslyn Formation (lower, middle, and upper members), Spiketon Formation, sandstone of Summit Creek, Swauk Formation (undivided), Swauk Formation (arkosic rocks, conglomerate facies, fanglomerate, unidentified subdivision of), Thorp Gravel, Troutdale Formation, Wenatchee Formation, and Wilkes Formation.

Tn **Tertiary nearshore sedimentary rocks** — Claystone, conglomerate, lignite, sandstone, siltstone, tuff, volcaniclastic rocks; commonly fossiliferous. *Includes named units:* Cowlitz Formation, Skookumchuck Formation, and Toutle Formation.

Tm **Tertiary marine sedimentary rocks** — Breccia, claystone, conglomerate, mudstone, sandstone, semischist, shale, siltstone, slate, phyllite; locally tuffaceous; locally metamorphosed to zeolite facies; local pillow basalt; local chert pebbles. *Includes named units:* Astoria Formation, Blakeley Formation, sedimentary rocks of the Crescent Formation, Lincoln Creek Formation (undivided), sandstone member of the Lincoln Creek Formation, McIntosh Formation (undivided), sandstone member of the McIntosh Formation, and Raging River Formation.

Mzm **Mesozoic marine sedimentary rocks** — Argillite, chert, conglomerate, limestone, mudstone, pelite, shale, siltstone, and tuff. *Includes named unit:* clastic subunit of the Russell Ranch Formation.

Volcanic Rocks and Deposits

Qv **Quaternary volcanic rocks** — Andesite flows, basaltic andesite flows, basalt flows, dacite flows, and rhyodacite dikes, flow breccia, hypabyssal intrusives, cinder and scoria cones, tephra, bombs, tuff, scoria, breccia, pyroclastic flow deposits, and hyaloclastite. *Includes named units:* basalt of Badger Peak, basalt of Blue Lake, basalt of Canyon Creek, Clear Fork Dacite, andesite of Deep Creek, andesite of Deer Lake Mountain, basalt of East Canyon Creek, basalt of Glaciate Butte, basalt of Goat Butte, complex of Hellroaring and Big Muddy Creek, mafic rocks of Hogback Mountain, andesite of the Jess Lake complex, basalt of Kincaid Lake, basalt of Lakeview Mountain, basalt of Lava Creek, basaltic andesite of Little Mount Adams, basalt of The Loaf, andesite, olivine andesite, dacite, and rhyolite flows of Mount Adams, rocks and deposits of Mount St. Helens, andesite of Mount Rainier (undivided), andesite of Mt. Rainier (andesites of Observation and Echo Rocks), dacite of Olallie Lake, andesite of Old Snowy Mountain, basalt of Paradise Falls, andesite of Pear Lake, basaltic andesite of Potato Hill, basalt of Red Butte, basalt of Riley Creek, basalts of Rimrock Lake, andesite of Round Mountain, andesite of Russell Ridge, andesite of Signal Peak, dacite of Spiral Butte, basalt of Spring Creek, basalt of Spud Hill, andesite of Swampy Meadow, Tieton Andesite, basalt of Tumac Mountain, basalt of Two Lakes, and basalt of Walupt Lake.

QTv **Quaternary–Tertiary volcanic rocks** — Andesite flows and breccias, basalt and basaltic andesite flows, and dacite flows. *Includes named units:* andesite of Bee Flat, andesite of Goat Rocks, mafic rocks of Hogback Mountain, basalt of Lincoln Plateau, volcanic rocks of Simcoe Mountains, and dacite of Snyder Mountain.

Tv_{cr} **Tertiary volcanic rocks, Columbia River Basalt Group** — Fine-grained flood basalt flows and invasive flows and related volcanic products. *Consists of named units:* Grande Ronde Basalt (undivided), Grande Ronde Basalt (N_1, R_2, and N_2 magnetostratigraphic units undivided, and R_2 magnetostratigraphic unit [invasive flow of Hammond and invasive flow of Howard Creek]), Saddle Mountains Basalt (undivided), Saddle Mountains Basalt (Asotin, Elephant Mountain, Pomona, Umatilla, and Wilbur Creek Members), Wanapum Basalt (undivided), and Wanapum Basalt (Frenchman Springs, Priest Rapids, and Roza Members).

Tv **Tertiary volcanic rocks** — Andesite flows, basaltic andesite flows, basalt flows, breccia, volcanic conglomerate, dacite flows, diabase, obsidian, pyroclastic rocks, rhyolite flows, volcanic sandstone, tuff, welded tuff, dikes, sills, domes, plugs, and lahars; local hypabyssal intrusions, interbedded sedimentary rocks, coal. *Includes named units:* Barlow Pass Volcanics, olivine basalt of Bethel Ridge, andesite and dacite of Burch Mountain, basalt of the Chumstick Formation, volcanic rocks of Council Bluff, basalt of Dalles Ridge, rhyolite tuffs and flows of Devils Horns, basalt of Devils Washbasin, basalt of Discovery Creek, volcanic rocks of Eagle Gorge, Fifes Peak Formation (undivided), Fifes Peak Formation (andesite and basalt megabreccia), Fifes Peak Formation (tuff of Clear West Peak), basalt of Frost Mountain, Goble Volcanics, volcanic rocks of Grays River, Howson Andesite, olivine basalt of Milk Creek, volcanic rocks of Mount Daniel, volcanic rocks of Mount Persis, Naches Formation (undivided), Naches Formation (basalt and glomeroporphyritic basalt), Northcraft Formation, Ohanapecosh Formation, andesite of Peoh Point, Swauk Formation (Silver Pass Member), andesite of Smith Creek Butte, basalt of Summit Creek, Taneum Andesite, Teanaway Basalt, and basalt of Tieton Pass.

Tv_c **Tertiary volcanic rocks, Crescent Formation** — Dominantly submarine basalt flows and flow breccia, grades into flow-dominated, locally columnar-jointed, partially nonmarine rocks near the top. *Consists of named unit:* Crescent Formation.

Mzv **Mesozoic volcanic rocks** — Andesite flows, basalt flows, breccia, dacite flows, greenstone, metabasalt, rhyolite flows, tuff; minor argillite, chert, conglomerate, limestone, sandstone, and shale. *Includes named unit:* Russell Ranch Formation.

Qvt **Quaternary fragmental volcanic rocks and deposits (includes lahars)** — Ash, debris flows, lahars, pumice, pyroclastic deposits, tephra, and near-vent fragmental deposits; local rockfall breccia, caldera-collapse megablocks, cross-cutting andesite dikes, welded tuff, and irregular intrusions; minor lacustrine and fluvial deposits; rare dacite flows. *Includes named units:* Electron Mudflow; lahar of Greenwater; Lily Creek Formation; volcaniclastic rocks and debris flows of Mount Adams, rocks and deposits of Mount St. Helens, lahar of Muddy River; Osceola Mudflow; debris flow of Paradise; and mudflow of Round Pass.

Tvt **Tertiary fragmental volcanic rocks** — Ash-flow tuff, breccia, tuff breccia, mudflows, pyroclastic flows, welded and nonwelded tuff; local andesite, basalt, dacite, and rhyolite plugs and flows; local sandstone, shale, and siltstone; local volcanic conglomerate, sandstone, and siltstone; minor coal. *Includes named units:* tuff of Bumping River, tuff of Burnt Mountain, volcaniclastic rocks of Cooper Pass, Ellensburg Formation, Fifes Peak Formation (undivided), Fifes Peak Formation (tuff of Clear West Peak undivided), Fifes Peak Formation (tuff of Clear West Peak [Chenuis Ridge and Sun Top units]), Goble Volcanics, volcanic rocks of Mount Daniel, Naches Formation (Mount Catherine Rhyolite Member), Northcraft Formation, Ohanapecosh Formation (undivided), Ohanapecosh Formation (Lake Keechelus

tuff member), welded tuff of the Palisades, Puget Group (Tukwila Formation), tuff of Rattlesnake Creek, volcanic sandstone and conglomerate of Spencer Creek, welded tuff of Spencer Creek, Stevens Ridge Formation north of Mount Rainier, Stevens Ridge Formation south of Mount Rainier, and tuffaceous rocks of Wildcat Creek.

Intrusive Rocks

Qi **Quaternary intrusive rocks** — Intrusive andesite and dacite. *Consists of named units:* plugs and dikes of Mount Rainier, rocks and deposits of Mount St. Helens, and feeders for flows of Old Snowy Mountain.

QTi **Quaternary–Tertiary intrusive rocks** — Andesite, basaltic andesite, and dacite domes, plugs, and dikes. *Includes named unit:* dacite porphyry of Goat Mountain.

Ti **Tertiary intrusive rocks** — Acidic (felsic), intermediate, and basic (mafic) intrusive rocks; intrusive rocks (undivided), intrusive-volcanic complex, intrusive andesite, argillic alteration, intrusive basaltic andesite, intrusive breccia, intrusive dacite, diorite, gabbro, granite, granodiorite, pebble breccia, quartz diorite, quartz monzonite, intrusive rhyolite, tonalite plutons, stocks, plugs, domes, dikes, dike swarms, sills, flows, and intrusive breccia. *Includes named units:* intrusive diabase and basalt of Box Canyon, Bumping Lake pluton, associated stocks of Bumping Lake pluton, diabase of Camas Land, Carbon River stock, soda rhyolite of Clear West, Duncan Hill pluton, Fifes Peak Formation (rhyolite of Clear West Peak), Fuller Mountain plug, complex of Horse Lake Mountain, Index Batholith (Sunday Creek stock), sills of Jug Lake, quartz diorite of McCoy Creek, volcanic complex of Mount Aix, volcanic rocks of Mount Daniel, granodiorite and quartz diorite of Nisqually, complex of Skyscraper Mountain, Snoqualmie Batholith (undivided), Snoqualmie Batholith (granite of Mount Hinman), Spirit Lake pluton, Tatoosh pluton, rocks related to the Tatoosh pluton, and White River pluton.

Mzi **Mesozoic intrusive rocks** — Basic (mafic) intrusive rocks, diorite, gabbro, granodiorite, mixed metamorphic and igneous rocks, quartz diorite, and tonalite plutons, stocks, plugs, domes, dikes, pods, veins, and sills. *Includes named units:* rocks of the Eastern mélange belt, complex of Indian Creek, Ingalls tectonic complex, Lookout Mountain Formation of Stout (1964), Mount Stuart batholith, contact complex of the Mount Stuart batholith, eastern pluton of the Mount Stuart batholith, Harding Mountain tonalite of the Mount Stuart batholith, western pluton of the Mount Stuart batholith, Quartz Mountain stock of the Eastern mélange belt, and rocks of the Western mélange belt.

MzPzu **Mesozoic–Paleozoic ultramafic rocks** — Dunite, harzburgite, ophiolite, peridotite, pyroxenite, serpentinite, talc schist, and altered ultrabasic (ultramafic) rocks; local veins of chrysotile asbestos, layers of chromite, and intercalated greenstone and metatuff. *Includes named units:* Chelan Mountains terrane (Napeequa unit), Ingalls tectonic complex (undivided), Ingalls tectonic complex (serpentinite), Ingalls tectonic complex (silicate-carbonate rock), Tonga Formation, and rocks of the Western mélange belt.

Metasedimentary and Metavolcanic Rocks

Mzms **Mesozoic metasedimentary rocks** — Mesozoic argillite, marine metasedimentary rocks, cherty metasedimentary rocks, low-grade phyllite, and low-grade schist. *Includes named units:* Darrington Phyllite, rocks of the Eastern mélange belt, Easton Schist, Ingalls tectonic complex (undivided), Ingalls tectonic complex (Peshastin Formation), chert-tuff subunit of the Russell Ranch Formation, Shuksan Greenschist, Western mélange belt (undivided), and argillite, graywacke, and potassium-feldspar sandstone of the Western mélange belt.

Mzmt **Mesozoic metasedimentary and metavolcanic rocks** — Amphibolite, breccia, conglomerate, dikes, flows, gabbro, greenschist, greenstone, keratophyre, marble, meta-argillite, metabasalt, metachert, metaconglomerate, metadacite, metasandstone, metavolcanic rocks, phyllite, quartzite, feldspathic sandstone, volcanic sandstone, schist, serpentinite, sills, siltstone, tuffaceous rocks, and ultramafic rocks; local metadolomite, shale, and limestone; includes pillow basalt, argillite, and volcaniclastic rocks; minor chert-pebble conglomerate and metadiabase. *Consists of named unit:* rocks of the Eastern mélange belt.

Mzmv **Mesozoic metavolcanic rocks** — Andesite, meta-andesite, argillite, chert, dacite, metadacite, flow breccia, gabbro, greenstone, metabasalt, metadiabase, quartz porphyry dikes, volcanic-lithic and tuffaceous sandstone, tuff; local greenschist, meta-argillite, metaconglomerate, metalimestone, metaquartz-diorite, metasandstone, metasiltite, metawacke, pyroxenite, schist, serpentinite, siltstone, tuff breccia; rare amphibolite. *Consists of named units:* Ingalls tectonic complex (undivided), Ingalls tectonic complex (Hawkins Formation), Russell Ranch Formation, and rocks of the Western mélange belt.

Pzmv **Paleozoic metavolcanic rocks** — Pillow basalt, breccia, chert, lava flows, greenschist, greenstone, metabasalt, phyllite, tuff breccia, tuff, volcaniclastic rocks; local meta-argillite, metaconglomerate, metawacke, quartzite (metachert), phyllite; minor metalimestone. *Consists of named unit:* metavolcanic rocks of North Peak.

Metamorphic Rocks (Amphibolite Facies and Higher)

Mzhm **Mesozoic heterogeneous metamorphic rocks** — Heterogeneous metamorphic rocks, some chert-bearing, and high-grade schist. *Consists of named units:* Chiwaukum Schist (Nason terrane), Ingalls tectonic complex (undivided), Ingalls tectonic complex (Hawkins Formation), Lookout Mountain Formation of Stout (1964), tectonic complex of Stout (1964), and Tonga Formation.

MzPzhm **Mesozoic–Paleozoic heterogeneous metamorphic rocks** — Amphibolite, marble, and chert-bearing heterogeneous metamorphic rocks. *Consists of named units:* rocks of the Eastern mélange belt, Lookout Mountain Formation of Stout (1964), and Chelan Mountains terrane (hornblende-bearing Napeequa unit).

MzPzam **Mesozoic–Paleozoic amphibolite** — Amphibolite. *Consists of named units:* Ingalls tectonic complex, Lookout Mountain Formation of Stout (1964), and Swakane Biotite Gneiss.

Mzgn **Mesozoic gneiss** — Gneiss and banded gneiss. *Consists of named unit:* Swakane Biotite Gneiss

Mzog **Mesozoic orthogneiss** — Orthogneiss. *Consists of named units:* tonalite gneiss of Hicks Butte and complex of Indian Creek.

Tectonic Zones

tz **Tectonic zones** — Ultrabasic (ultramafic) rocks and low-grade schist in tectonically disrupted zones, age unknown.

LIST OF NAMED UNITS

Alderton Formation	QTc
Asotin Member of the Saddle Mountains Basalt	Tv_{cr}
Astoria Formation	Tm
Badger Peak, basalt of	Qv
Barlow Pass Volcanics	Tc, Tv
Bee Flat, andesite of	QTv
Bethel Ridge, olivine basalt of	Tv
Blakeley Formation	Tm
Blue Lake, basalt of	Qv
Box Canyon, intrusive diabase and basalt of	Ti
Bullfrog subdrift of the Lakedale Drift	Qad
Bumping Lake pluton	Ti
Bumping River, tuff of	Tvt
Burch Mountain, andesite and dacite of	Tv
Burnt Mountain, tuff of	Tvt
Burroughs Mountain Drift	Qad
Camas Land, diabase of	Ti
Canyon Creek, basalt of	Qv
Carbon River stock	Ti
Carbonado Formation	Tc
Chambers Creek, beds of	Tc
Chelan Mountians terrane, Napeequa unit of the	MzPzu
Chelan Mountians terrane, hornblende-bearing Napeequa unit of the	MzPzhm
Chenuis Ridge unit of the tuff of Clear West Peak of the Fifes Peak Formation	Tvt
Chiwaukum Schist of the Nason terrane	Mzhm
Chumstick Formation	Tc
Chumstick Formation, basalt of the	Tv
Chumstick Formation, redbed fanglomerate of the	Tc
Clear Fork Dacite	Qv
Clear West, soda rhyolite of	Ti
Clear West Peak, tuff of, of the Fifes Peak Formation	Tvt
Cooper Pass, volcaniclastic rocks of	Tvt
Columbia River Basalt Group	Tv_{cr}
Council Bluff, lava flows of	Tv
Cowlitz Formation	Tn
Crescent Formation	Tv_c
Dalles Ridge, basalt of	Tv
Darrington Phyllite	Mzms
Deep Creek, andesite of	Qv
Deer Lake Mountain, andesite of	Qv
Devils Horn, rhyolite of	Tv
Devils Horns, rhyolite tuffs and flows of	Tv
Devils Washbasin, basalt of	Tv
Discovery Creek basalt	Tv
Domerie subdrift of the Lakedale Drift	Qad
Duncan Hill pluton	Ti
Eagle Creek Formation	Tc
Eagle Gorge, volcanic rocks of	Tv
East Canyon Creek, basalt of	Qv
Eastern mélange belt, rocks of the	Mzi, Mzms, Mzmt, MzPzam
Easton Schist	Mzms
Electron Mudflow	Qvt
Elephant Mountain Member of the Saddle Mountains Basalt	Tv_{cr}
Ellensburg Formation	Tc, Tvt
Evans Creek Drift	Qad
Fidalgo Complex	MzPzu
Fifes Peak Formation	Ti, Tv
Fifes Peak Formation, andesite and basalt megabreccia of the	Tv
Fifes Peak Formation, Chenuis Ridge unit of the tuff of Clear West Peak of the	Tvt
Fifes Peak Formation, rhyolite of the tuff of Clear West Peak of the	Ti
Fifes Peak Formation, Sun Top unit of the tuff of Clear West Peak of the	Tvt
Fifes Peak Formation, tuff of Clear West Peak of the	Tv, Tvt
Frenchman Springs Member of the Wanapum Basalt	Tv_{cr}
Frost Mountain, basalt of	Tv
Fuller Mountain plug	Ti
Garda Drift	Qad
Glaciate Butte, basalt of	Qv
Goat Butte, basalt of	Qv
Goat Mountain, dacite porphyry of	QTi
Goat Rocks, andesite of	QTv
Goble Volcanics	Tv, Tvt
Grande Ronde Basalt of the Columbia River Basalt Group	Tv_{cr}
Grays River, volcanic rocks of	Tv
Greenwater, lahar of	Qvt
Guye Sedimentary Member of the Naches Formation	Tc
Hammond invasive flow of the R_2 magneto- stratigraphic unit of the Grande Ronde Basalt	Tv_{cr}
Harding Mountain, tonalite of, of the Mount Stuart batholith	Mzi
Hawkins Formation of the Ingalls Tectonic Complex	Mzhm, Mzmv
Hayden Creek Drift	Qad
Hellroaring and Big Muddy Creek complex	Qv
Hicks Butte, tonalite gneiss of	Mzog
Hogback Mountain, mafic rocks of	QTv, Qv
Horse Lake Mountain complex	Ti
Howard Creek invasive flow of the R2 magnetostratigraphic unit of the Grande Ronde Basalt	Tv_{cr}
Howson Andesite	Tv
Hyak subdrift of the Lakedale Drift	Qad
Index batholith, Sunday Creek stock of the	Ti
Indian Creek, complex of	Mzi, Mzog
Indian John subdrift of the Kittitas Drift	Qad
Ingalls Tectonic Complex	Mzhm, Mzi, Mzms Mzmv, MzPzam, MzPzu
Ingalls Tectonic Complex, Hawkins Formation of the	Mzhm, Mzmv
Ingalls Tectonic Complex, Peshastin Formation of the	Mzms
Ingalls Tectonic Complex, serpentinite of the	MzPzu
Ingalls Tectonic Complex, silicate-carbonate rocks of the	MzPzu
Jess Lake complex, andesite of the	Qv
Jug Lake, sills of	Ti
Kincaid Lake, basalt of	Qv
Kitsap Formation	QTc
Kittitas Drift	Qad
Kittitas Drift, Indian John subdrift of the	Qad
Kittitas Drift, Swauk Prairie subdrift of the	Qad

Lake Keechelus tuff member of the Ohanapecosh Formation Tvt
Lake Missoula, flood deposits of glacial Qf
Lakedale Drift Qa, Qad
Lakedale Drift, Bullfrog subdrift of the Qad
Lakedale Drift, Domerie subdrift of the Qad
Lakedale Drift, Hyak subdrift of the Qad
Lakedale Drift, Ronald subdrift of the Qad
Lava Creek, basalt of Qv
Lily Creek Formation, mudflows of the Qvt
Lincoln Creek Formation Tm
Lincoln Creek Formation, sandstone member of the Tm
Lincoln Plateau, basalt of QTv
Little Mount Adams, basaltic andesite of Qv
Loaf, basalt of The Qv
Logan Hill Formation Qad
Lookout Creek, sandstone of Tc
Lookout Mountain Formation Mzhm, Mzi MzPam, MzPhm
Lookout Mountain Ranch Drift Qad
Manastash Formation Tc
Mashel Formation Tc
McCoy Creek, quartz diorite of Ti
McDonald Ridge, drift of Qad
McIntosh Formation Tm
McIntosh Formation, sandstone member of the Tm
McNeely Drift Qad
Milk Creek, olivine basalt of Tv
Mount Adams, andesite and olivine andesite flows of Qv
Mount Adams, dacite flows of Qv
Mount Adams, Holocene andesite of Qv
Mount Adams, rhyolite of Qv
Mount Adams, volcaniclastic rocks and debris flows of Qvt
Mount Aix, volcanic complex of Ti
Mount Catherine Rhyolite Member of the Naches Formation Tvt
Mount Daniel, rocks of Tc, Ti, Tv
Mount Daniel, volcanic rocks of Ti, Tv, Tvt
Mount Persis, volcanic rocks of Tv
Mount Rainier, andesite of Qv
Mount Rainier, plugs and dikes of Qi
Mount St. Helens, rocks and deposits of Qi, Qv, Qvt
Mount Stuart batholith Mzi
Mount Stuart batholith, contact complex of Mzi
Mount Stuart batholith, eastern pluton of the Mzi
Mount Stuart batholith, tonalite of Harding Mountain of the Mzi
Mount Stuart batholith, western pluton of the Mzi
Muddy River lahar Qvt
N_1 magnetostratigraphic unit of the Grande Ronde Basalt Tv_{cr}
N_2 magnetostratigraphic unit of the Grande Ronde Basalt Tv_{cr}
Naches Formation Tc, Tv
Naches Formation, basalt of Tv
Naches Formation, glomeroporphyritic basalt of Tv
Naches Formation, Mount Catherine Rhyolite Member of the Tvt
Naches Formation, sandstone and volcanic rocks of Tc
Nahahum Canyon Member of the Chumstick Formation Tc
Napeequa unit of the Chelan Mountains terrane MzPu
Napeequa unit, hornblende-bearing, of the Chelan Mountains terrane MzPhm
Nisqually, granodiorite of Ti
Nisqually, quartz diorite of Ti
North Creek Volcanics Mzmt
Northcraft Formation Tv, Tvt
Observation and Echo Rocks andesites of the andesite of Mount Rainier Qv
Ohanapecosh Formation Tv, Tvt
Ohanapecosh Formation, Lake Keechelus tuff member of the Tvt
Olallie Lake, dacite of Qv
Old Snowy Mountain, andesite of Qv
Old Snowy Mountain, feeders for flows of Qi
Olympia-age nonglacial sediments QTc
Orting Drift Qgd
Osceola Mudflow Qvt
Palisades, welded tuff of The Tvt
Palouse Formation Ql
Paradise Falls, basalt of Qv
Paradise, debris flow (lahar) of Qvt
Pear Lake, andesite of Qv
Peoh Point, andesite of Ti
Peshastin Formation of the Ingalls Tectonic Complex Mzms
Peoh Point, andesite of Tv
Pomona Member of the Saddle Mountains Basalt Tv_{cr}
Potato Hill, basaltic andesite of Qv
pre-Evans Creek–post-Hayden Creek deposits Qad
Priest Rapids Member of the Wanapum Basalt Tv_{cr}
Puget Group Tc
Puyallup Formation Qa
Quartz Mountain stock of the Eastern mélange belt Mzi
R_2 magnetostratigraphic unit of the Grande Ronde Basalt Tv_{cr}
Randle laharic breccia-conglomerate Tvt
Raging River Formation Tm
Rattlesnake Creek, tuff of Tvt
Red Butte, basalt of Qv
Renton Formation of the Puget Group Tc
Riley Creek, basalt of Qv
Rimrock Lake, basalts of Qv
Ronald subdrift of the Lakedale Drift Qad
Roslyn Formation (lower, middle and upper members) Tc
Round Pass, mudflow of Qvt
Roza Member of the Wanapum Basalt Tv_{cr}
Russell Ranch Formation Mzmv, Mzv
Russell Ranch Formation, chert-tuff subunit of the Mzms
Russell Ranch Formation, clastic subunit of the Mzm
Russell Ridge, andesite of Qv
Saddle Mountains Basalt of the Columbia River Basalt Group Tv_{cr}
Saddle Mountains Basalt, Pomona Member of the Tv_{cr}
Salmon Springs Drift Qgd
Shuksan Greenschist Mzms
Signal Peak, andesite of Qv
Silver Pass Member of the Swauk Formation Tv
Simcoe Mountains, volcanic rocks of QTv, Tv
Skokomish Gravel Qa
Skookumchuck Formation Tn
Skyscraper Mountain, complex of Ti
Smith Creek Butte, andesite of Tv
Snoqualmie batholith Ti
Mount Hinman, granite of, of the Snoqualmie Batholith Ti

Snyder Mountain, dacite of QTv
Spencer Creek, volcanic sandstone and conglomerate of Tvt
Spencer Creek, volcanic sediments of Tvt
Spencer Creek, welded tuff of Tvt
Spiketon Formation Tc
Spiral Butte, dacite of Qv
Spirit Lake pluton Ti
Steilacoom Gravel Qgd
Spring Creek, basalt of Qv
Spud Hill, basalt of Qv
Steilacoom Gravel Qgd
Stevens Ridge Formation north of Mount Rainier Tvt
Stevens Ridge Formation south of Mount Rainier Tvt
Stuck Drift Qgd
Summit Creek, basalt of Tv
Summit Creek, sandstone of Tc
Sun Top unit of the tuff of Clear West Peak of the Fifes Peak Formation Tvt
Swakane Biotite Gneiss Mzgn, MzPam
Swauk Formation Tc
Swauk Formation, arkosic rocks of the Tc
Swauk Formation, conglomerate facies of the Tc
Swauk Formation, fanglomerate of the Tc
Swauk Formation, unidentified subdivision of the Tc
Taneum Andesite Tv
Tatoosh pluton Ti
Tatoosh pluton, rocks related to the Ti
Teanaway Basalt Tv
tectonic complex of Stout (1964) Mzhm
Thorp Gravel Tc
Tieton Andesite Qv
Tieton Pass, basalt of Tv
Tiger Mountain Formation of the Puget Group Tc
Tonga Formation Mzhm
Touchet beds Qf
Toutle Formation Tn
Toutle River lahars Qvt
transitional beds of Menard (1985) Qgd
Troutdale Formation QTc
Tukwila Formation of the Puget Group Tvt
Tumac Mountain, basalt of Qv
Two Lakes, basalt of Qv
Umatilla Member of the Saddle Mountains Basalt Tv_{cr}
Vantage Member of the Ellensburg Formation Tc
Vashon Drift Qgd
Walupt Lake, basalt of Qv
Wanapum Basalt of the Columbia River Basalt Group Tv_{cr}
Wenatchee Formation Tc
Western mélange belt, argillite and graywacke of the Mzms
Western mélange belt, potassium-feldspar sandstone of the Mzms
Western mélange belt, rocks of the Mzi, Mzms Mzmv, MzPu
White River pluton Ti
Wilbur Creek Member of the Saddle Mountains Basalt Tv_{cr}
Wildcat Creek, tuffaceous rocks of Qvt
Wilkes Formation Tc
Wingate Hill Drift Qad

EXPLANATION OF LEG MAPS

Below are the geologic units and symbols used in the leg maps in this guidebook. Note that the colors here may be muted or altered by the shaded relief base for the leg maps. More detailed descriptions of the map units are given in the "Description of Map Units" on page 185. These descriptions cover all of the units shown on Figure 2; the units on this page are only those units shown on the leg maps. Most map units contain or consist of one or more named units, and these are listed with the unit's description. The "List of Named Units" on page 188 links the formation or informal name to the map unit symbol, and thus to the unit description.

On all maps, geologic contacts are approximate because the source maps were prepared at a smaller scale than the maps in this book (WDGER, 2005). Also, a rock type mentioned in the text may not appear on a leg map because the polygon for its location is too small to be shown at leg map scale. To save space, some of the maps have been rotated away from true north. Keep your eye on the north arrows to determine map orientation.

KEY TO GEOLOGIC UNITS

Unconsolidated Sediments

- Qa — Quaternary alluvium
- Qls — Quaternary mass-wasting deposits
- Ql — Quaternary loess
- Qgd — Pleistocene continental glacial drift
- Qad — Pleistocene alpine glacial drift

Sedimentary Rocks and Deposits

- QTc — Quaternary–Tertiary continental sedimentary rocks and deposits
- Tc — Tertiary continental sedimentary rocks
- Tn — Tertiary nearshore sedimentary rocks
- Tm — Tertiary marine sedimentary rocks
- Mzm — Mesozoic marine sedimentary rocks

Volcanic Rocks and Deposits

- Qv — Quaternary volcanic rocks
- Tvcr — Tertiary volcanic rocks of the Columbia River Basalt Group
- Tv — Tertiary volcanic rocks
- Mzv — Mesozoic volcanic rocks
- Qvt — Quaternary fragmental volcanic rocks
- Tvt — Tertiary fragmental volcanic rocks

Intrusive Rocks

- Ti — Tertiary intrusive rocks
- Mzi — Mesozoic intrusive rocks

Metasedimentary and Metavolcanic Rocks

- Mzmv — Mesozoic metavolcanic rocks

Metamorphic Rocks

- Mzog — Mesozoic orthogneiss

Other Geologic Units

- Glaciers and ice fields

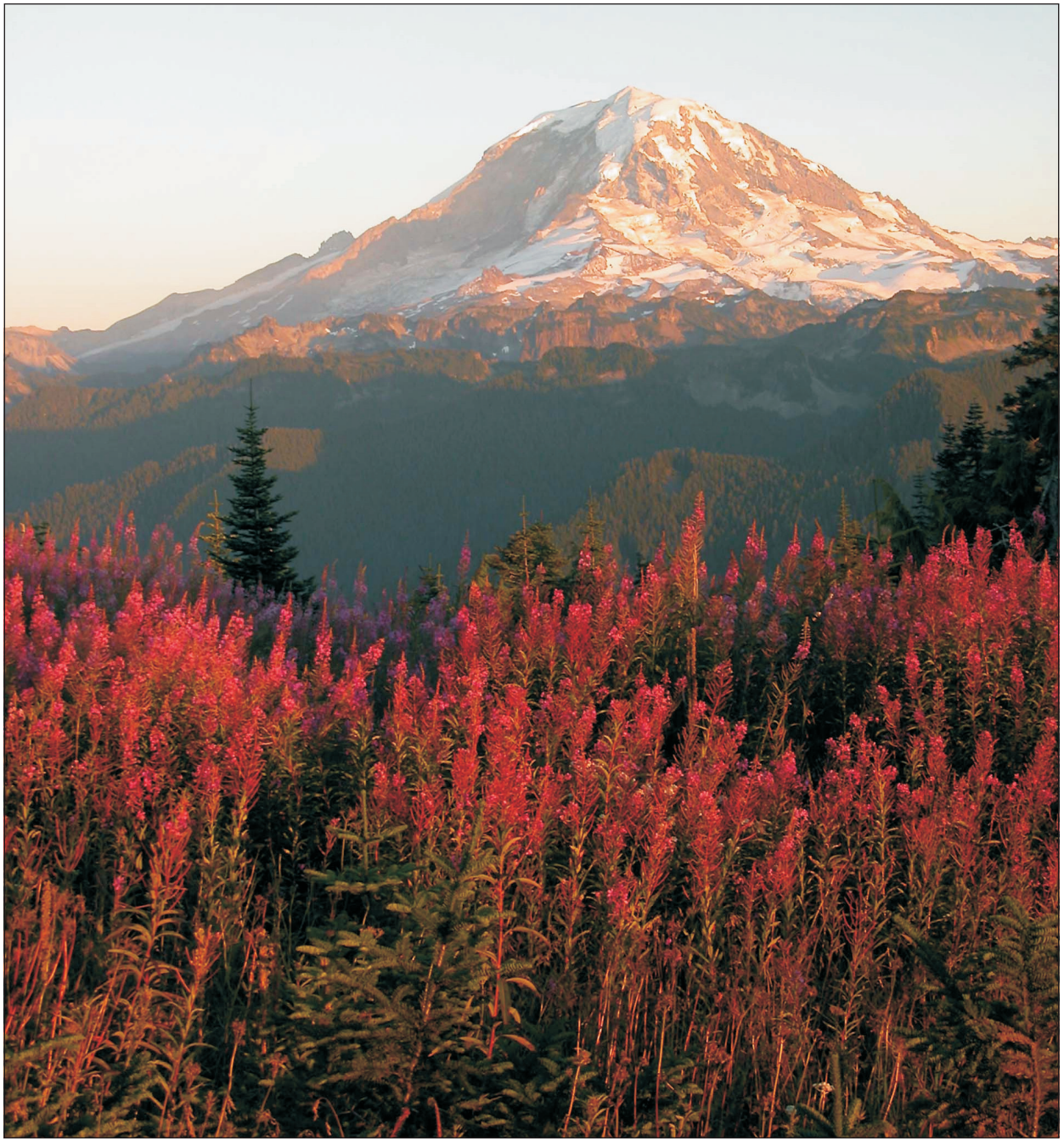
ROADS AND OTHER FEATURES

- 90 — Interstate Highway
- 12 — U.S. Highway
- 20 — Washington State Highway
- 23 — U.S. Forest Service Road
- National Park Boundary
- National Forest Boundary
- 6 — Leg route with milepost
- Trail
- National Park entrance or ranger station
- Visitor center
- Picnic area
- Camping
- State Park

GEOLOGIC SYMBOLS

- Contact — Dashed where scratch boundary
- Anticline — Showing direction of plunge; dotted where concealed
- Syncline — Showing direction of plunge; dotted where concealed
- Monocline — Dotted where concealed
- Fault — Long-dashed where approximately located, short-dashed where inferred, dotted where concealed
- Thrust fault — Sawteeth on upper plate; long-dashed where approximately located, short-dashed where inferred, dotted where concealed
- Left-lateral strike-slip fault — Arrows show relative movement; short-dashed where inferred, dotted where concealed; arrows omitted in crowded areas
- Dip-slip fault — Bar and ball on downthrown side; long-dashed where approximately located, short-dashed where inferred, dotted where concealed

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View of the northwest flank of Mount Rainier from an alpine meadow above the Carbon River Ranger Station about 8 mi from Mount Rainier. Photo by Elizabeth E. Thompson; taken in 2006.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
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