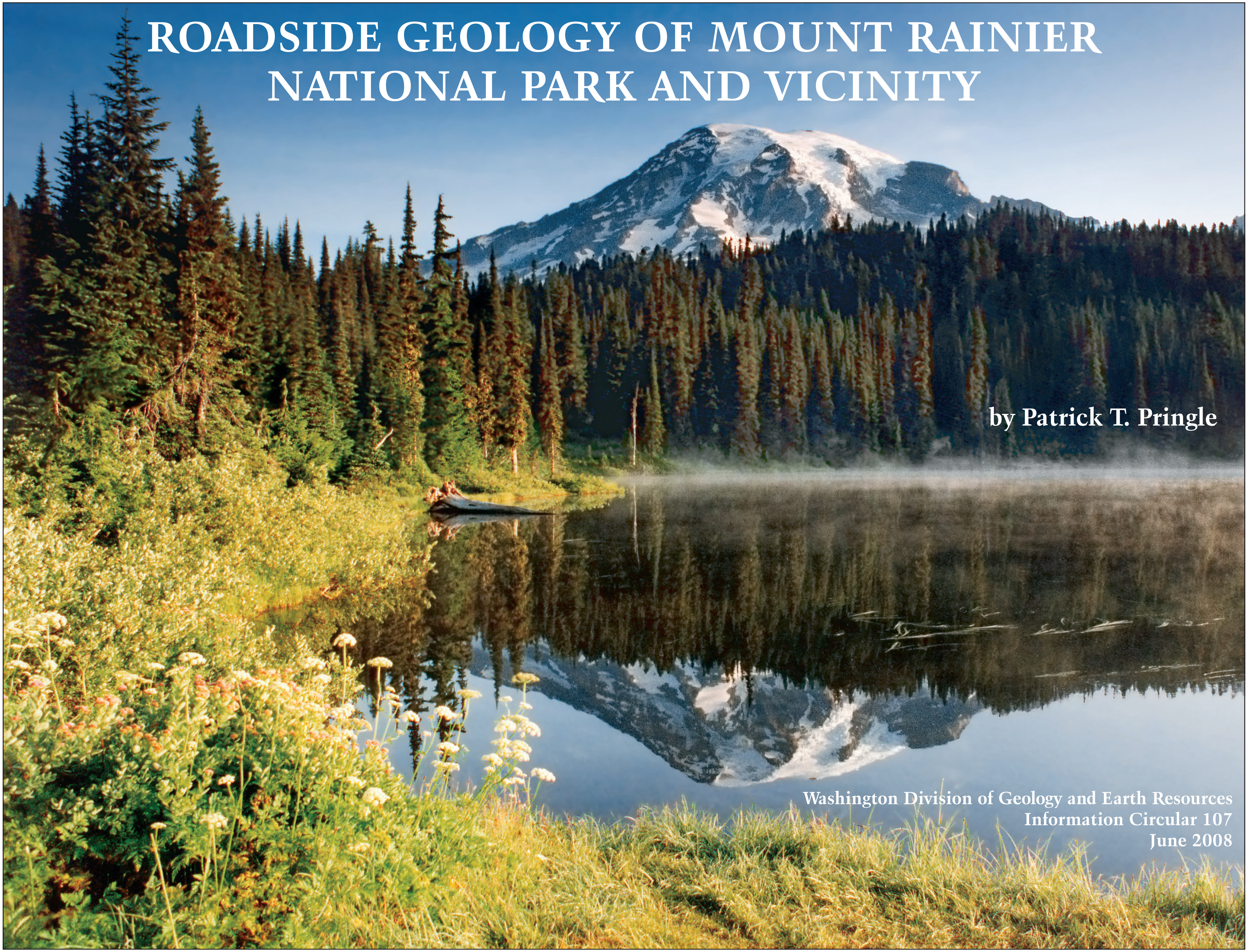
ROADSIDE GEOLOGY OF MOUNT RAINIER NATIONAL PARK AND VICINITY



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.

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

with

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Information Circular 107

June 2008

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Printed on recycled paper
Published in the United States of America

AMERICA'S BYWAYS®

This publication was funded in part by the
National Scenic Byways Program
of the Federal Highway Administration.
The grant was administered by the
Washington State Department of Transportation.

Washington State Department of Transportation

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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Suggested Citation: Pringle, Patrick T., 2008, Roadside geology of Mount Rainier National Park and vicinity: Washington Division of Geology and Earth Resources Information Circular 107, 191 p.

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.

CONTENTS

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

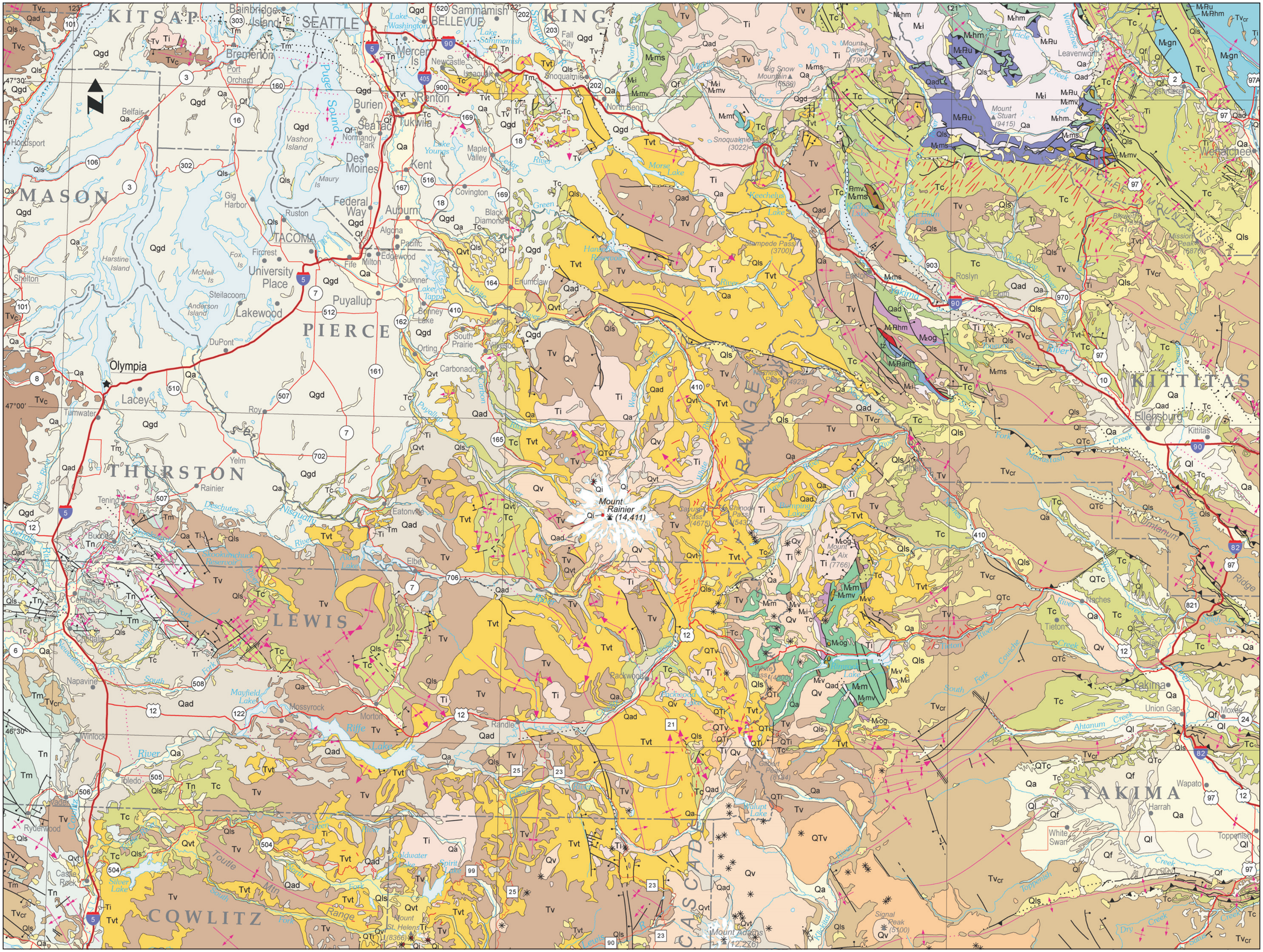
Welcome to Mount Rainier National Park and the beautiful Cascade Range of south-central Washington. The legs in this road guide circumnavigate the majestic Mount Rainier volcano (Fig. 1) and cut across the southern Cascade Range from the Puget Lowland on the west, to the Columbia Basin on the east, following 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
Sammamish
Bremerton
Bainbridge Island
Mercer Is
Renton
Burien
SeaTac
Tukwila
Des Moines
Kent
Federal Way
Auburn
TACOMA
University Place
Lakewood
Puyallup
Olympia
Lacey
Tumwater
Yelm
Rainier
Tenino
Eatonville
Elbe
Centralia
Chehalis
Napavine
Mossyrock
Morton
Randle
Packwood
Toledo
Winlock
Castle Rock
Ryderwood
Vader
Enumclaw
Buckley
Wilkeson
Carbonado
Orting
Sumner
Edgewood
Milton
Fife
Pacific
Algona
Covington
Maple Valley
Black Diamond
Issaquah
Newcastle
North Bend
Snoqualmie
Fall City
Leavenworth
Cashmere
Wenatchee
Roslyn
Cle Elum
Easton
Ellensburg
Kittitas
Naches
Tieton
Selah
Yakima
Union Gap
Moxee
Wapato
Harrah
White Swan
Toppenish
Shelton
Hoodsport
Belfair
Gig Harbor
Steilacoom
Roy
DuPont
Mount Rainier (14,411)
Mount Adams (12,276)
Mount St. Helens (8366)
Mount Stuart (9415)
Mount Daniel (7960)
Mount Aix (7766)
Snoqualmie Pass (3022)
Stampede Pass (3700)
Signal Peak (5100)
Puget Sound
Riffe Lake
Mayfield Lake
Silver Lake
Keechelus Lake
Cle Elum Lake
Rimrock Lake
Kachess Lake
Lake Washington
Lake Sammamish
Vashon Island
Maury Is
Anderson Island
McNeil Is
Fox Is
Harstine Island
47°30′
47°00′
46°30′

KEY TO GEOLOGIC UNITS

Unconsolidated Sediments

- Qa — Quaternary alluvium
- Qls — Quaternary mass-wasting deposits
- Ql — Quaternary loess
- Qf — Pleistocene outburst-flood deposits
- 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
- QTv — Quaternary–Tertiary volcanic rocks
- Tvcr — Tertiary volcanic rocks of the Columbia River Basalt Group
- Tv — Tertiary volcanic rocks
- Tvc — Tertiary volcanic rocks
- Mzv — Mesozoic volcanic rocks
- Qvt — Quaternary fragmental volcanic rocks
- Tvt — Tertiary fragmental volcanic rocks

Intrusive Rocks

- Qi — Quaternary intrusive rocks
- QTi — Quaternary–Tertiary intrusive rocks
- Ti — Tertiary intrusive rocks
- Mzi — Mesozoic intrusive rocks
- MzPzu — Mesozoic–Paleozoic ultramafic rocks

Metasedimentary and Metavolcanic Rocks

- Mzms — Mesozoic metasedimentary rocks
- Mzmt — Mesozoic metasedimentary and metavolcanic rocks
- Mzmv — Mesozoic metavolcanic rocks
- Pzmv — Paleozoic metavolcanic rocks

Metamorphic Rocks

- Mzhm — Mesozoic heterogeneous metamorphic rocks
- MzPzhm — Mesozoic–Paleozoic heterogeneous metamorphic rocks
- MzPzam — Mesozoic–Paleozoic amphibolite
- Mzgn — Mesozoic gneiss
- Mzog — Mesozoic orthogneiss

Other Geologic Units or Features

- Glaciers and ice fields
- tz — Tectonic zones; areas of intense cataclasis, including mylonitization
- Dike swarms; shown where dikes are too numerous to show individually at map scale; labeled as to geologic unit
- Eruptive centers; volcanic vents of Quaternary to Miocene age, generally the same age and composition as the surrounding volcanic rocks
- Dikes of Tertiary age

GEOLOGIC SYMBOLS

- Contact
- Anticline — Showing direction of plunge; dotted where concealed
- Syncline — Showing direction of plunge; dotted where concealed
- Overturned syncline — 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
- Right-lateral strike-slip fault — Arrows show relative movement; short-dashed where inferred, dotted where concealed; arrows omitted in crowded areas
- 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; short-dashed where inferred, dotted where concealed
- Normal right-lateral strike-slip fault — Arrows show relative horizontal movement, bar and ball on downthrown side; dotted where concealed

Roads and Boundaries

- 90 — Interstate Highway
- 12 — U.S. Highway
- 20 — Washington State Highway
- 23 — U.S. Forest Service Road
- PIERCE — County boundary and name

Communities

SEATTLE	More than 250,000 people	Tumwater	Fewer than 15,000 people or unincorporated
BELLEVUE	80,000 – 250,000 people	Yakima	County Seat
Puyallup	15,000 – 79,999 people	★ Olympia	State Capital

Scale

0 5 10 15 20 25 mi

0 10 20 30 40 km

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.

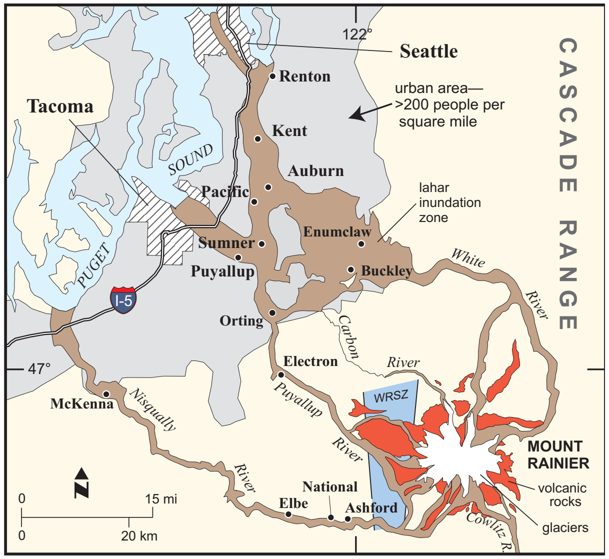


Figure 3. Areas inundated by lahars or laharic flooding (brown) from Mount Rainier in the past 6000 years. The Cowlitz River valley (lower right) was also flooded but is not shown. Hachured areas are city limits of Seattle and Tacoma; gray is the area of suburban development. Red areas are volcanic rocks 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)	mi	mile(s)
ft	foot, feet	MP	milepost
FR	Forest Road	m.y.	million years (time span)
hr	hour(s)	s	second(s)
I-	Interstate Highway	SR	State Route
in.	inch(es)	US	U.S. Highway
ka	kilo-annum or thousand years (age)	yd	yard(s)
km	kilometer(s)	yr B.P.	radiocarbon years before present (date); 'cal', calibrated with tree ring data
k.y.	thousand years (time span)		
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.

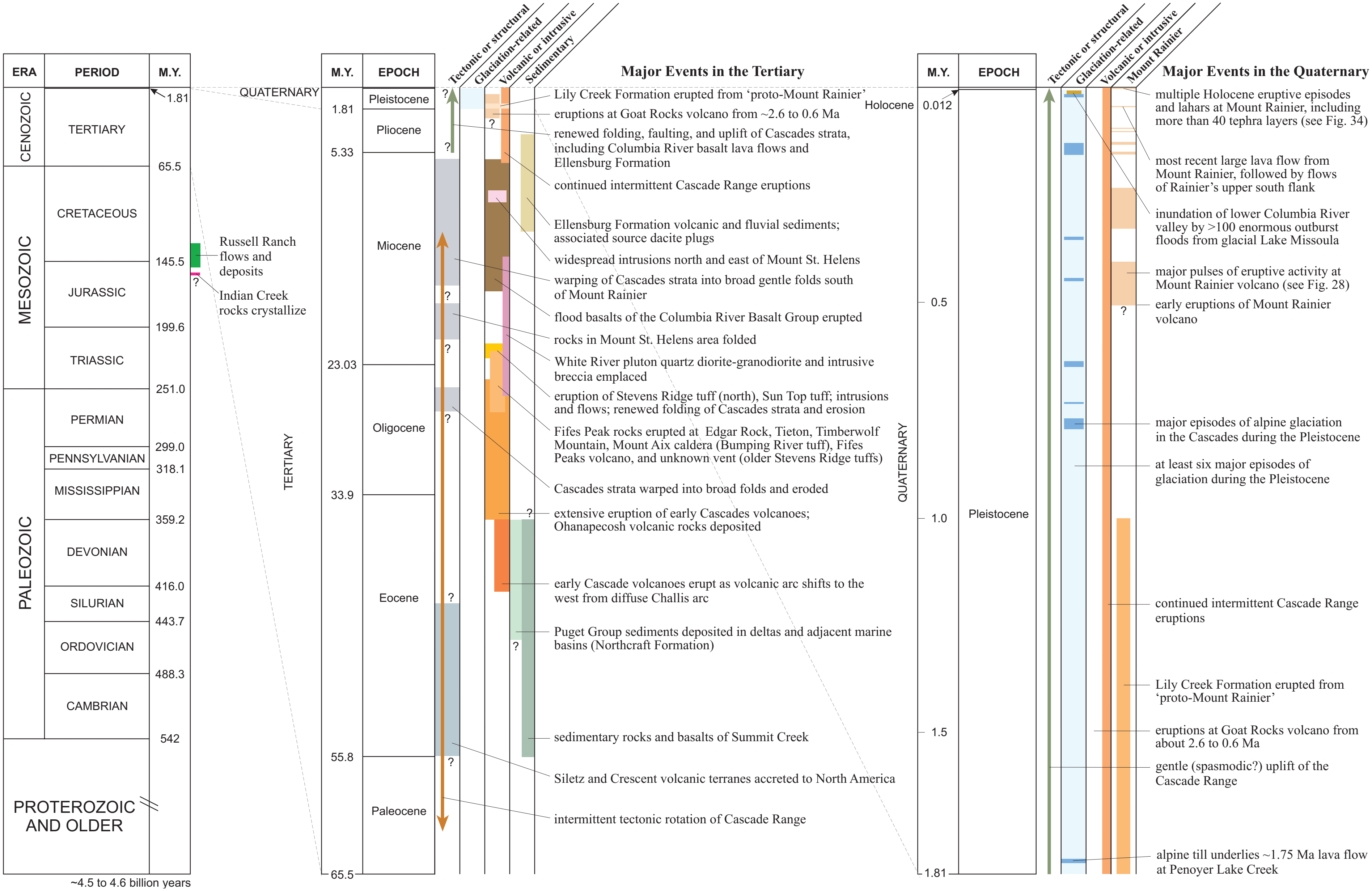


Figure 4. A simplified version of the geologic time scale showing major geologic events in the southwest Washington Cascades near Mount Rainier. The middle column is an expansion of the Tertiary, and the righthand column is an expansion of the Quaternary. The Holocene or Recent remains too small to show 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.

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

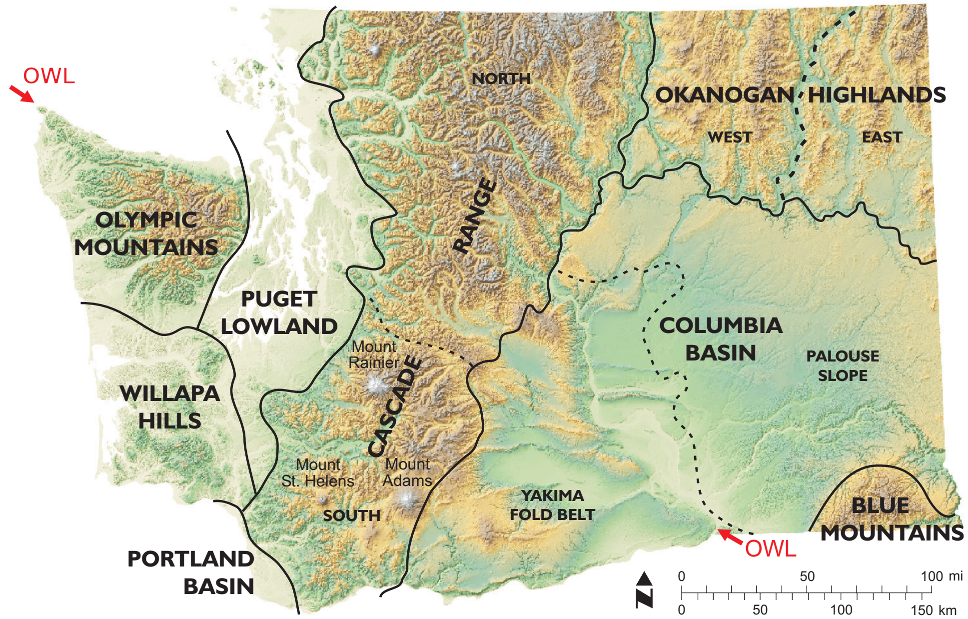


Figure 5. Relief map showing the physiographic provinces and subprovinces of Washington State. Red arrows show the general trend of the Olympic–Wallowa lineament or OWL.

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.

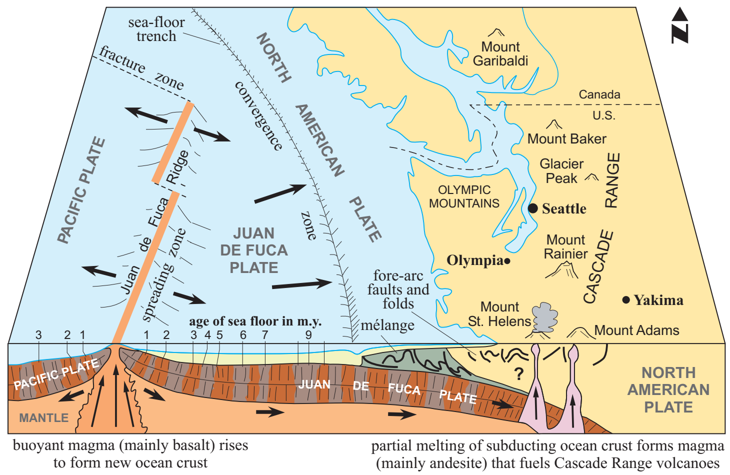


Figure 7. A diagrammatic cross section through the Juan de Fuca spreading ridge and the Cascadia subduction zone (the area from the trench east to where the Juan de Fuca plate sinks beneath the North American plate) showing the magnetic orientation of the sea floor recorded at the Juan de Fuca spreading 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).

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.

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-

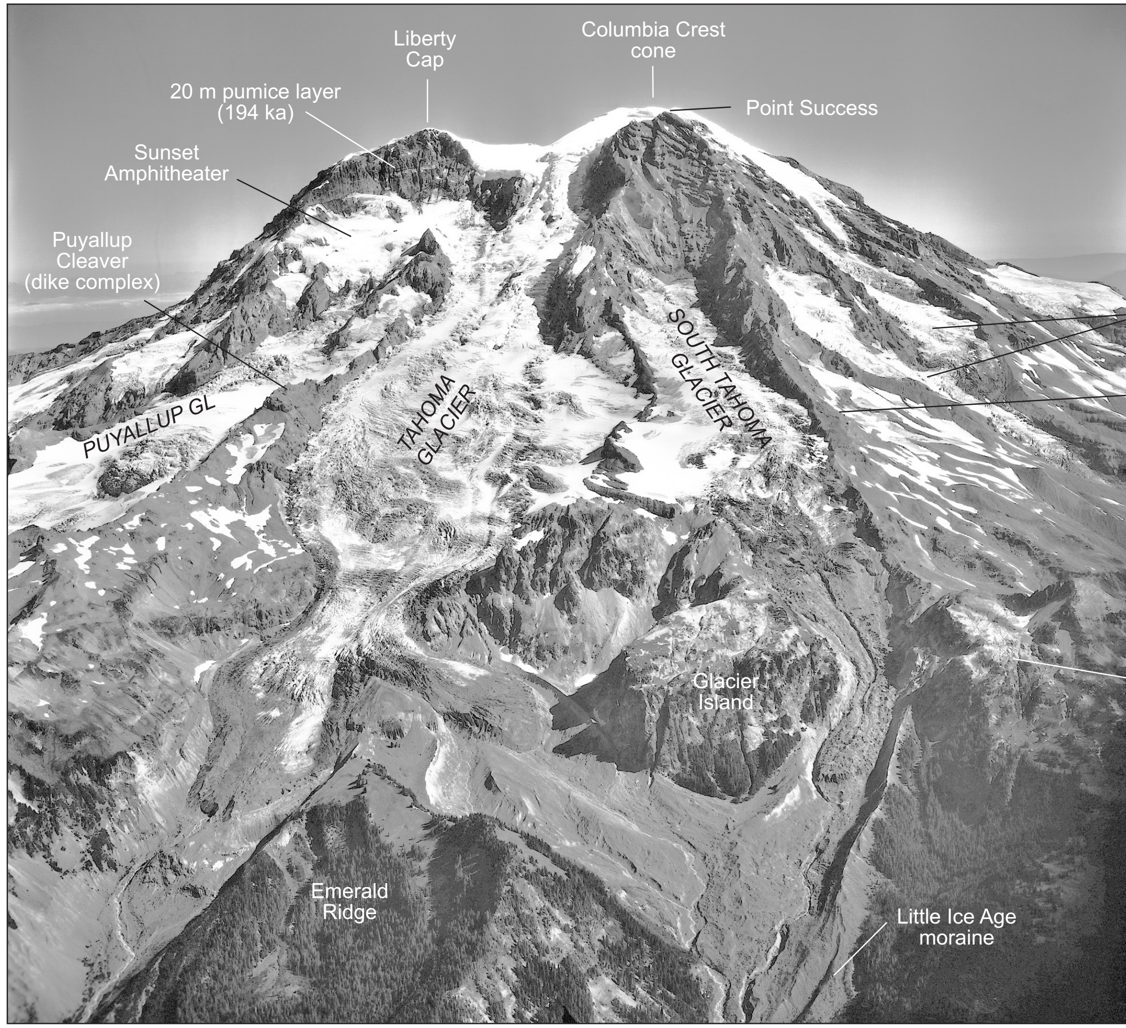


Figure 8. The impressive glacier-draped west flank of Mount Rainier. The Round Pass Mudflow (2,600 yr B.P.), a lahar about 1,000 yr B.P., and the Electron Mudflow (~A.D. 1502–1503) are major collapses that have eaten into this clay-rich upper portion of Mount Rainier. The Round Pass collapse breached 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.