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.

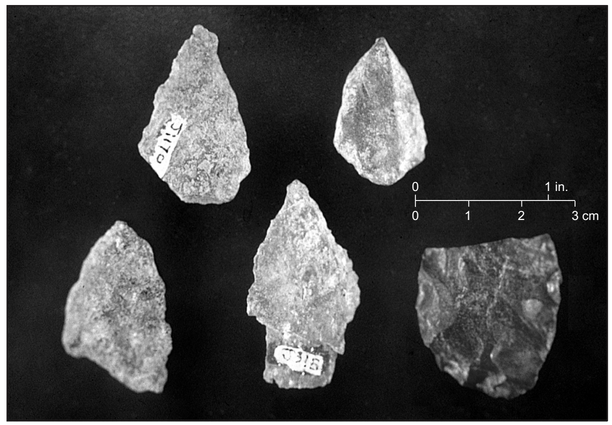


Figure 9. Several of the more than 200 artifacts found at the Jokumsen archaeological site near Enumclaw. These lithic artifacts include a broken scraping tool and several pieces that were possibly being made into arrowheads, but remained unfinished. According to Gerald Hedland, whose class excavated 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:

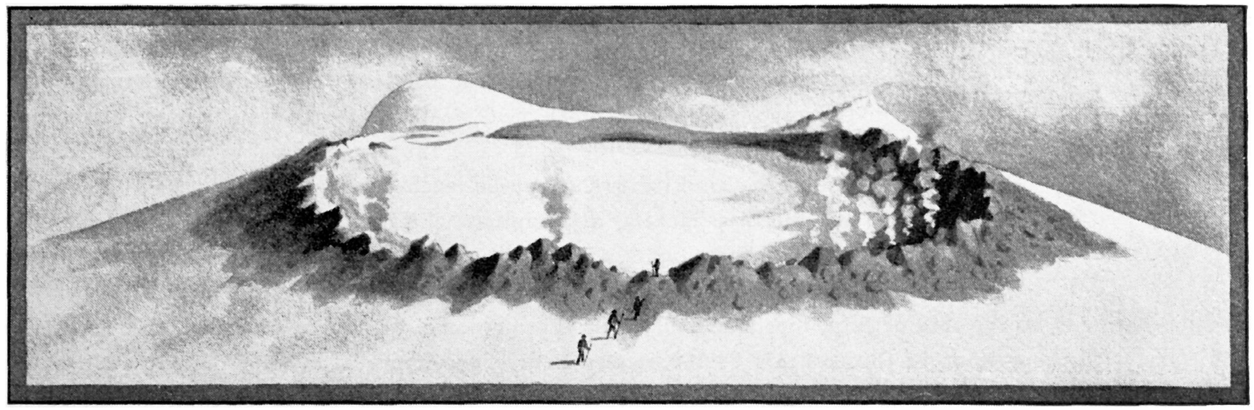


Figure 10. This illustration by C. C. Maring in Ingraham's "Pacific Forest Reserve and Mount Rainier" (1895) shows the active fumaroles of Mount Rainier's east crater in the late 1880s. View is to the northwest with Liberty Cap visible in the background above the crater rim on the right. Graphic reproduced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

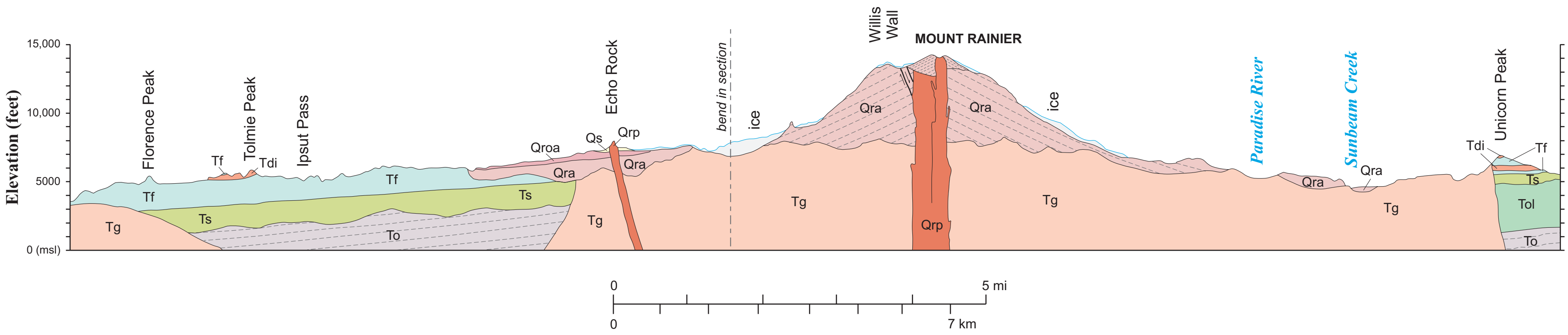
Geologists conducted early descriptive reconnaissance studies of the rocks and physiography of south-central Washington beginning in the mid-1800s. George Gibbs (1855) made an early reconnaissance of the area and described the rocks. Samuel Emmons (1871), representing Clarence King's 49th Parallel Corps, 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.

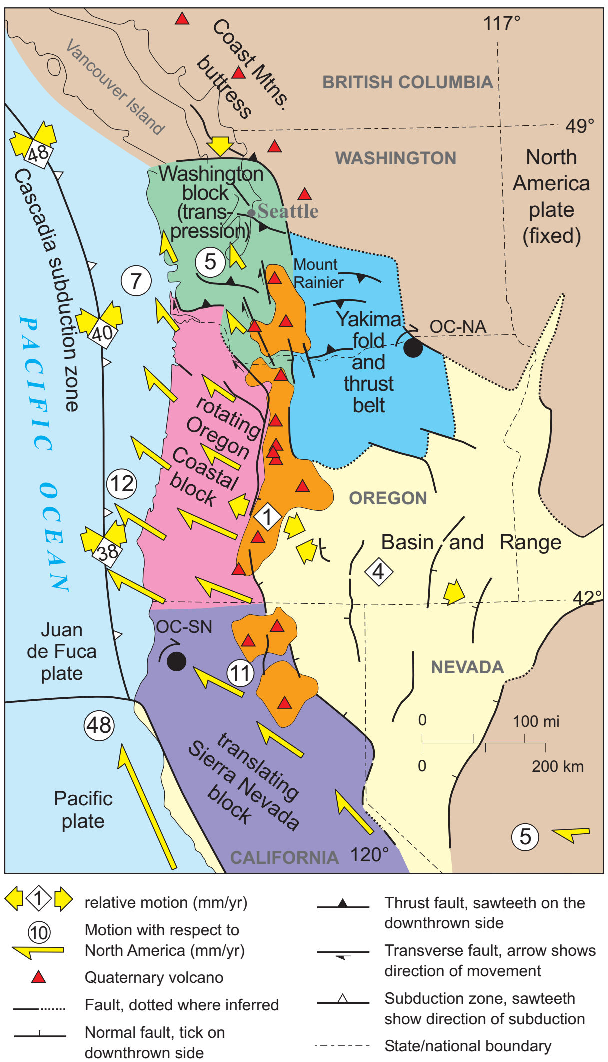
Jim Vallance has re-examined tephra deposits described by Mullineaux and has identified more than 30 so-called "lithic-rich tephras", nearly all of which he infers are juvenile. He has associated those layers with lahars and pyroclastic flow deposits in drainage basins that radiate away from the mountain. (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 Olympia 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.



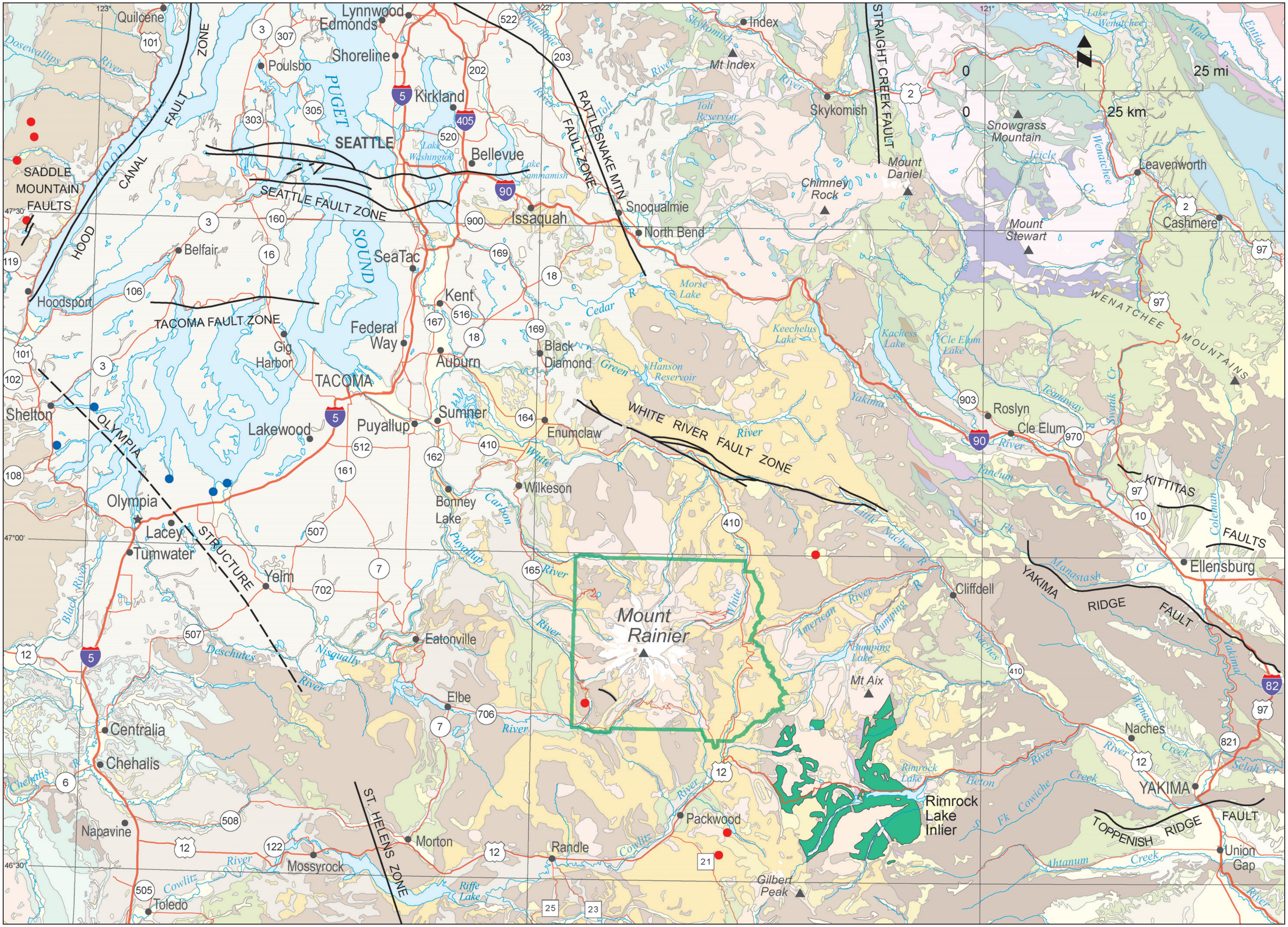
THE YAKIMA FOLD AND THRUST BELT

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?


HOOD CANAL FAULT ZONE
SADDLE MOUNTAIN FAULTS
SEATTLE FAULT ZONE
TACOMA FAULT ZONE
RATTLESNAKE MTN FAULT ZONE
STRAIGHT CREEK FAULT
WHITE RIVER FAULT ZONE
OLYMPIA STRUCTURE
ST. HELENS ZONE
WENATCHEE MOUNTAINS
KITTITAS FAULTS
YAKIMA RIDGE FAULT
TOPPENISH RIDGE FAULT
Mount Rainier
Rimrock Lake Inlier
PUGET SOUND
SEATTLE
TACOMA
YAKIMA
Quilcene
Lynnwood
Edmonds
Shoreline
Poulsbo
Kirkland
Bellevue
Issaquah
Snoqualmie
North Bend
Index
Mt Index
Skykomish
Mount Daniel
Chimney Rock
Snowgrass Mountain
Mount Stewart
Leavenworth
Cashmere
Belfair
SeaTac
Kent
Hoodsport
Federal Way
Gig Harbor
Auburn
Black Diamond
Shelton
Sumner
Puyallup
Lakewood
Enumclaw
Wilkeson
Bonney Lake
Olympia
Lacey
Tumwater
Yelm
Eatonville
Elbe
Centralia
Chehalis
Napavine
Morton
Mossyrock
Randle
Packwood
Toledo
Gilbert Peak
Mt Aix
Bumping Lake
Rimrock Lake
Cliffdell
Naches
Roslyn
Cle Elum
Ellensburg
Union Gap
Morse Lake
Keechelus Lake
Kachess Lake
Cle Elum Lake
Hanson Reservoir
Lake Washington
Lake Sammamish
Tolt Reservoir
Lake Wenatchee
Riffe Lake
0 25 mi
0 25 km
123°
122°
121°
47°30'
47°00'
46°30'

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.

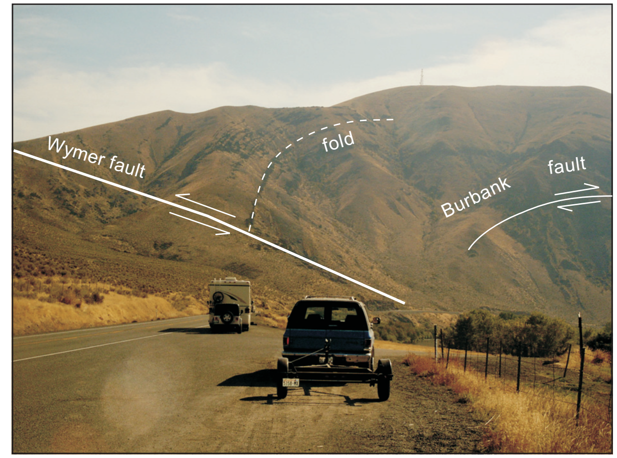


Figure 15. Folded (dashed line) Columbia River basalt flow units exposed in Umtanum Ridge where it is cut by the Yakima River canyon along SR 821 about 17 mi (27 km) north of Yakima. Thrust faults (solid lines) core the ridge here. Arrows show direction of movement. The younger Wymer fault may cut the 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).

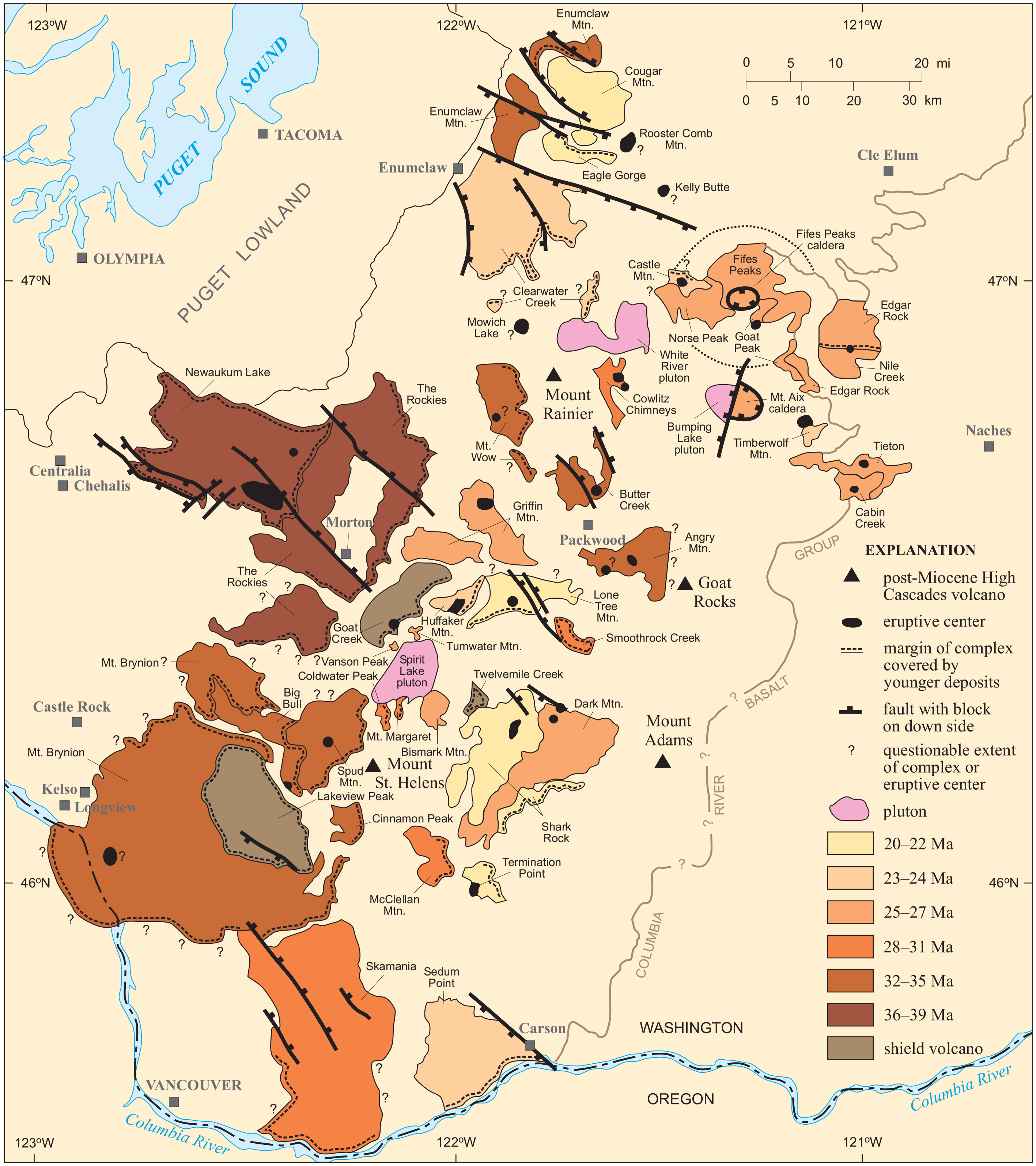


Figure 16. Lava-flow complexes in the southern Washington Cascade Range, modified from Hammond (1998). In his paper, Hammond grouped the complexes based on age and longitude in order to evaluate the structural deformation that has affected the Cascade Range. A lava-flow complex is the eroded remnant 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.

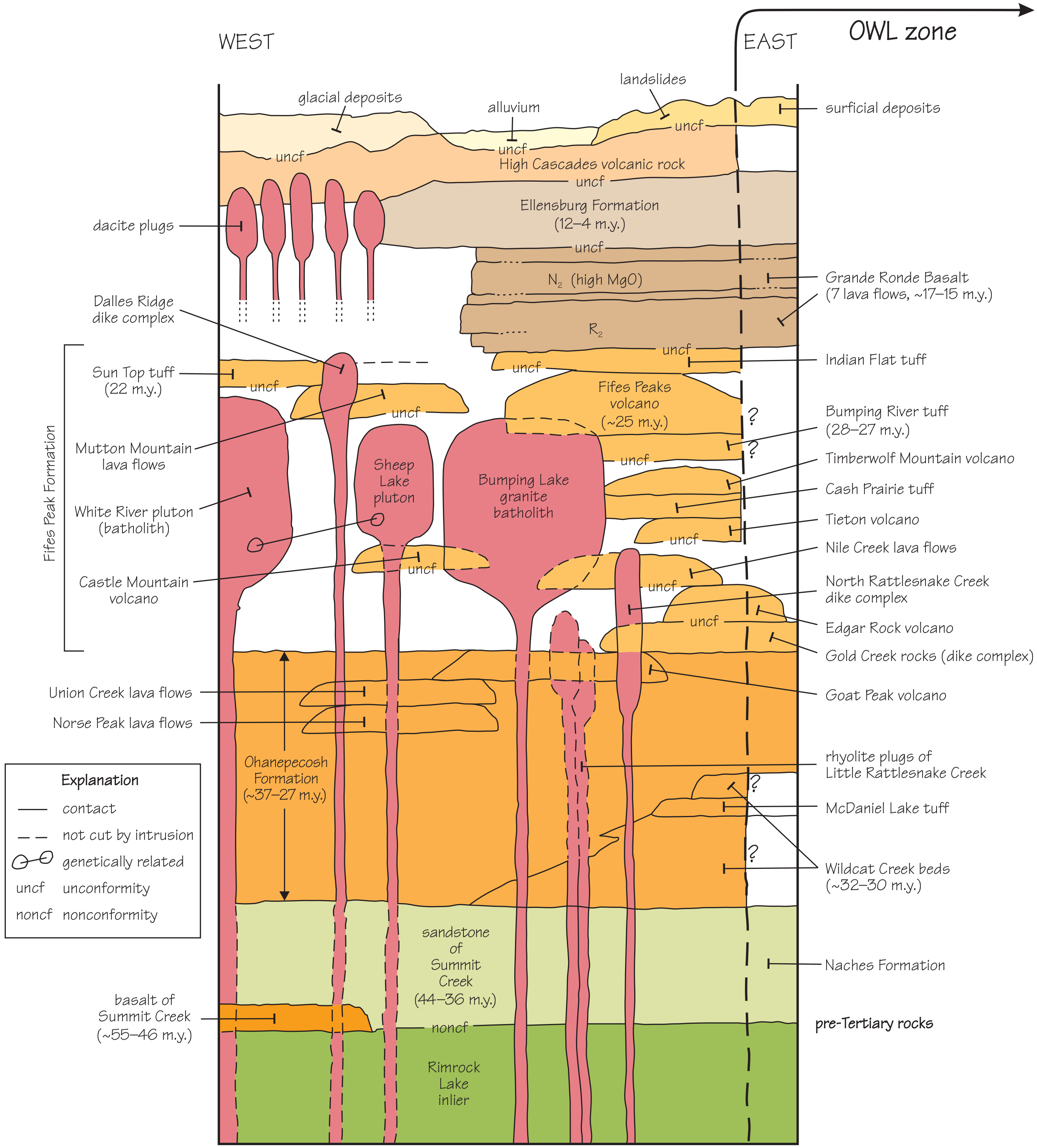


Figure 18. A schematic columnar section of principal rock units east of Mount Rainier National park. Units are shown in stratigraphic order—no scale in time, thickness, or size implied. OWL zone, rock units of the Olympic–Wallowa lineament. Modified from an unpublished section by Paul E. Hammond, 2008.

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

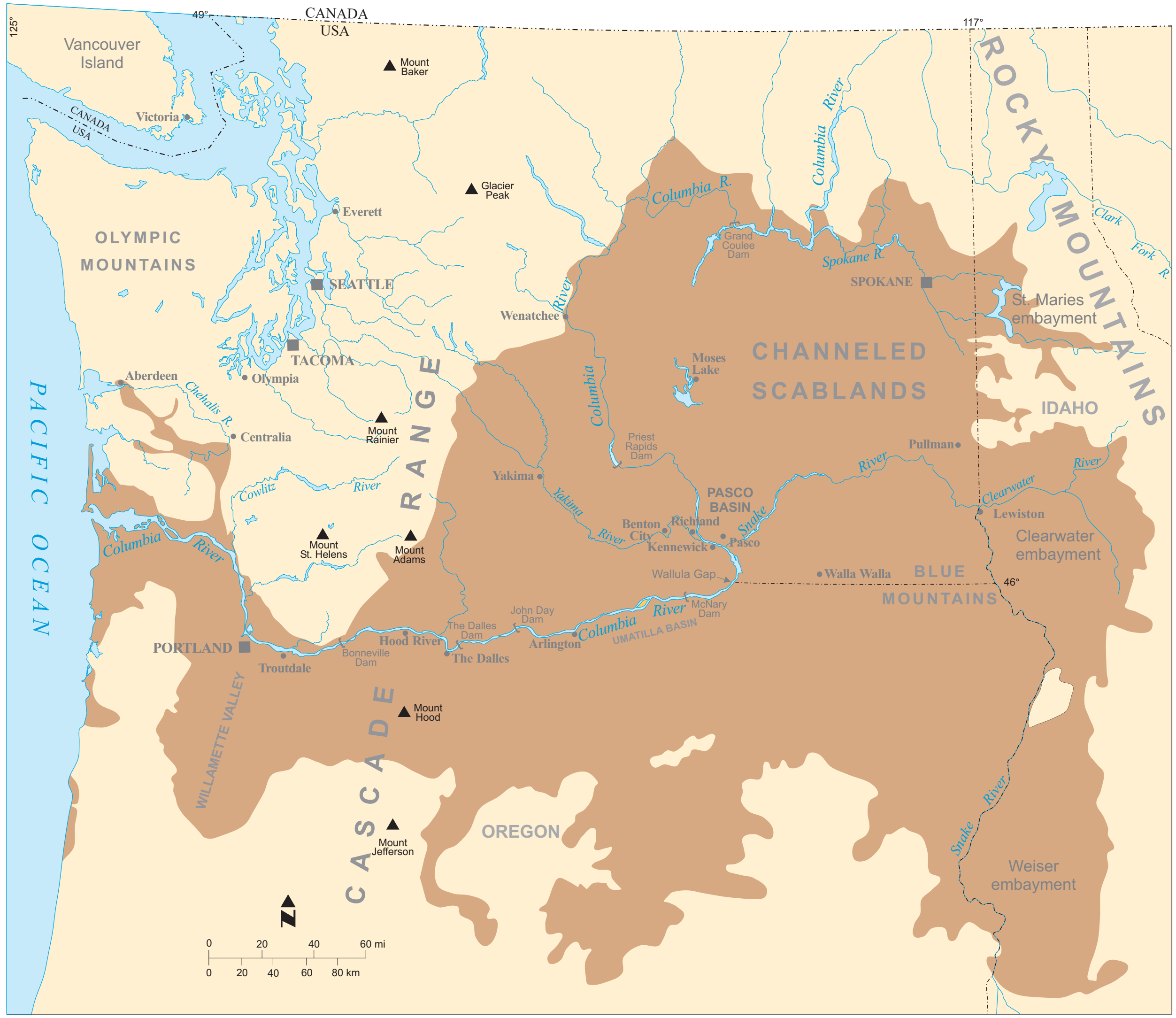


Figure 19. Diagrammatic sketch showing the combined extent of all Columbia River Basalt Group units (brown). Offshore extent is not shown. Modified from Reidel and others (1994).

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. ■

SYSTEM	SERIES	GROUP	SUB-GROUP	FORMATION	MEMBER	K-AR AGE (Ma)	MAGNETIC POLARITY	ASSOCIATED FLOWS AND SEDIMENTS
TERTIARY	MIOCENE – UPPER	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	SADDLE MOUNTAINS BASALT	LOWER MONUMENTAL MEMBER	6	N	
					erosional unconformity			unnamed interbed (discontinuous)
					ICE HARBOR MEMBER	8.5		
					basalt of Goose Island		N	
					basalt of Martindale		R	
					basalt of Basin City		N	
					erosional unconformity			Levey interbed
					BUFORD MEMBER		R	
	MIDDLE				ELEPHANT MOUNTAIN MEMBER	10.5	R,T	
					erosional unconformity			Rattlesnake Ridge interbed
					POMONA MEMBER	12	R	
					erosional unconformity			Selah interbed
					ESQUATZEL MEMBER		N	
					erosional unconformity			Cold Creek interbed
					WEISSENFELS RIDGE MEMBER			
					basalt of Slippery Creek		N	
					basalt of Tenmile Creek		N	
					basalt of Lewiston Orchards		N	
					basalt of Cloverland		N	
					ASOTIN MEMBER	13		
					basalt of Huntzinger		N	unnamed interbed (discontinuous)
					WILBUR CREEK MEMBER			
					basalt of Lapwai		N	
					basalt of Wahluke		N	
					local erosional unconformity			
					UMATILLA MEMBER	13.5		
					basalt of Sillusi		N	
					basalt of Umatilla		N	
					local erosional unconformity			Mabton interbed
				WANAPUM BASALT	PRIEST RAPIDS MEMBER	14.5		
					basalt of Lolo		R	
					basalt of Rosalia		R	
					local erosional unconformity			Quincy interbed (discontinuous)
					ROZA MEMBER		T,R	
					SHUMAKER CREEK MEMBER		N	Squaw Creek interbed (discontinuous)
					FRENCHMAN SPRINGS MEMBER			
					basalt of Lyons Ferry		N	
					basalt of Sentinel Gap		N	
					basalt of Sand Hollow	15.3	N	
					basalt of Silver Falls		N,E	
					basalt of Ginkgo		E	
					basalt of Palouse Falls		E	unnamed interbed (discontinuous)
					ECKLER MOUNTAIN MEMBER			
					basalt of Dodge		N	
					basalt of Robinette Mountain		N	
					local erosional unconformity			Vantage interbed
				GRANDE RONDE BASALT	Sentinel Bluffs Member	15.6	N_2	Museum flow, Rocky Coulee flow, McCoy Canyon flow, Cohasset flow
					member of Slack Canyon			
	LOWER				member of Fields Spring			
					member of Winter Water			
					member of Umtanum			
					member of Ortley			
					member of Armstrong Canyon			
					member of Meyer Ridge		R_2	
					member of Grouse Creek			Meeks Table flow (locally known)
					member of Wapshilla Ridge			
					member of Mount Horrible			
					member of China Creek		N_1	
					member of Downey Gulch			
					member of Center Creek		R_1	
					member of Rogersburg			
					Teepee Butte Member			
					member of Buckhorn Springs	16.5		
				IMNAHA BASALT		17.5		

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.

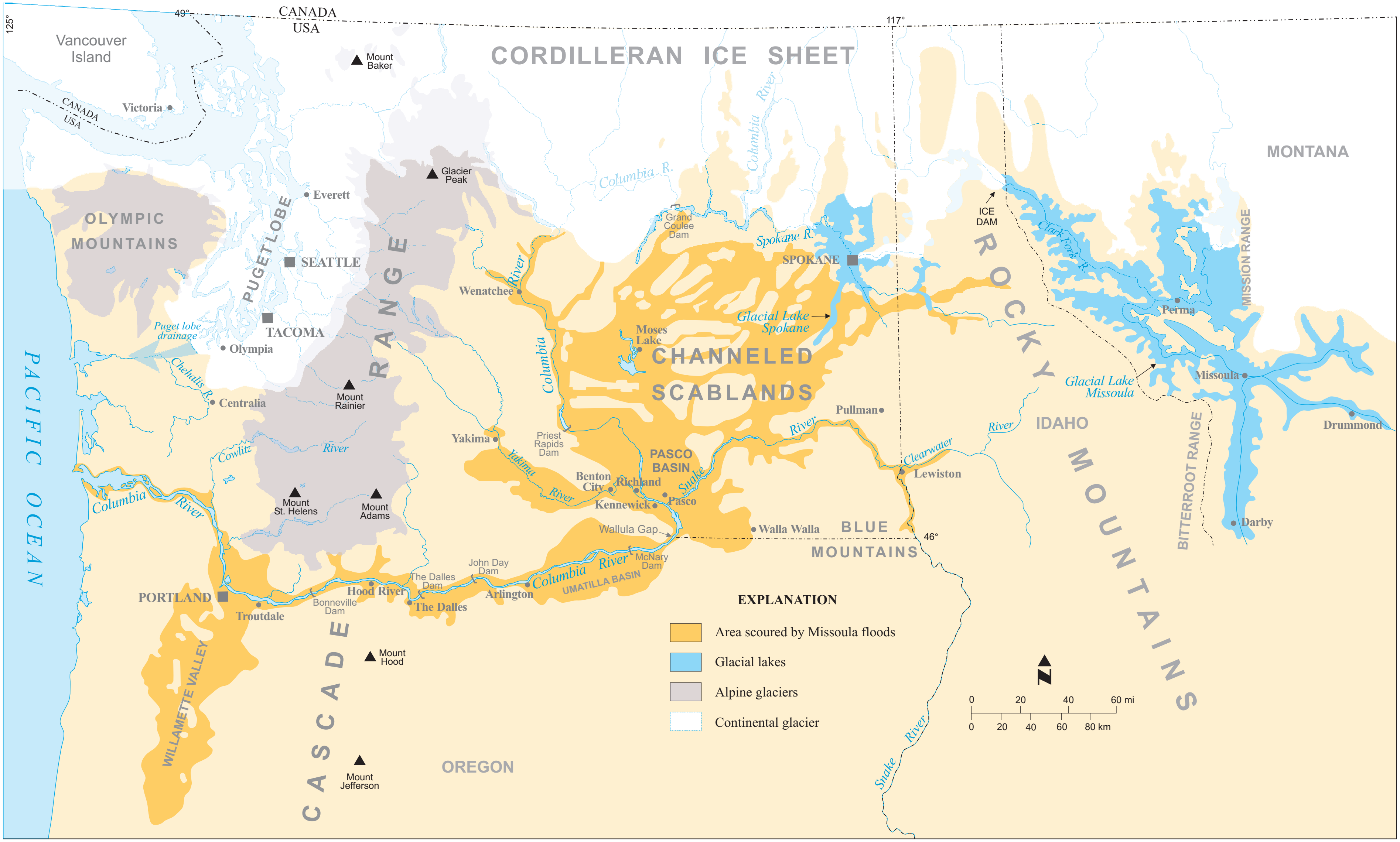


Figure 21. Diagrammatic sketch showing the approximate maximum extent of the Pleistocene continental and alpine glaciers in the Pacific Northwest. See Figure 6 for a more accurate depiction of the Chehalis River drainage during the Pleistocene. As in Figure 6, the modern Pacific coastline and drainage 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 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.

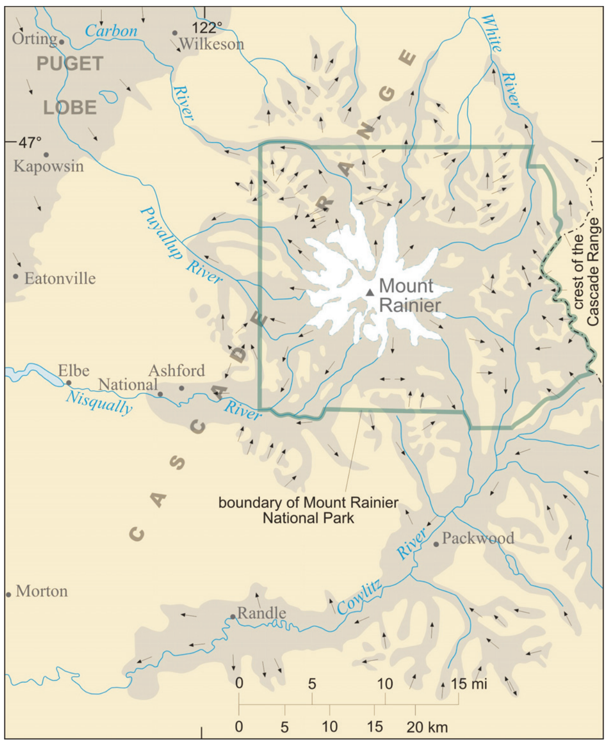


Figure 22. The extent of glaciers at Mount Rainier and in the adjacent mountains during the most recent major glaciation is shown by the gray shading. Also shown is the Puget lobe, the edge of which marks the boundary between the Puget Lowland and the Cascade Range. Arrows show the direction of glacier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

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),

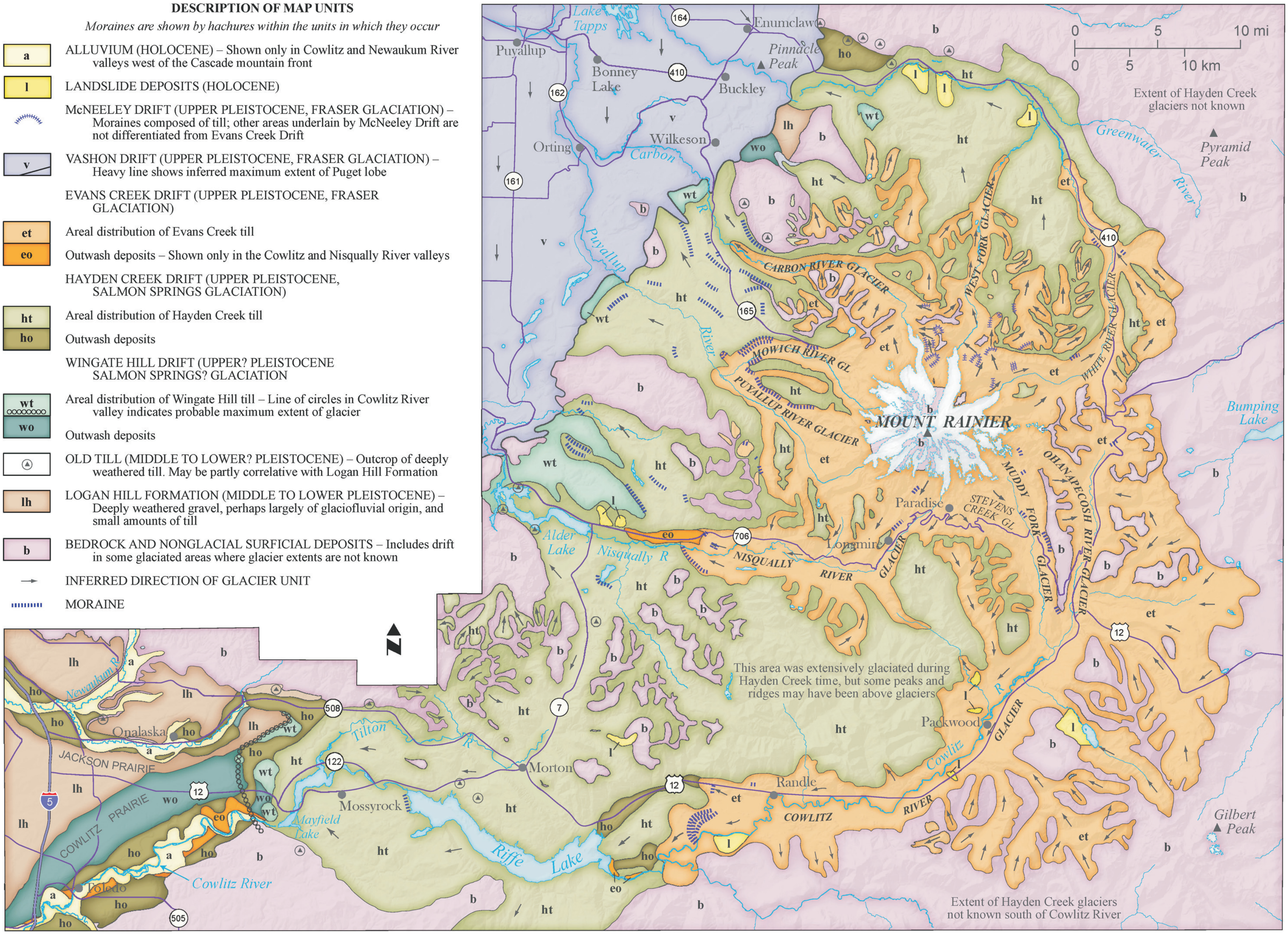


Figure 23. Distribution of surficial deposits and extents of Pleistocene glaciers in the vicinity of Mount Rainier. Modified from Crandell and Miller (1974) and Walsh and others (1987).

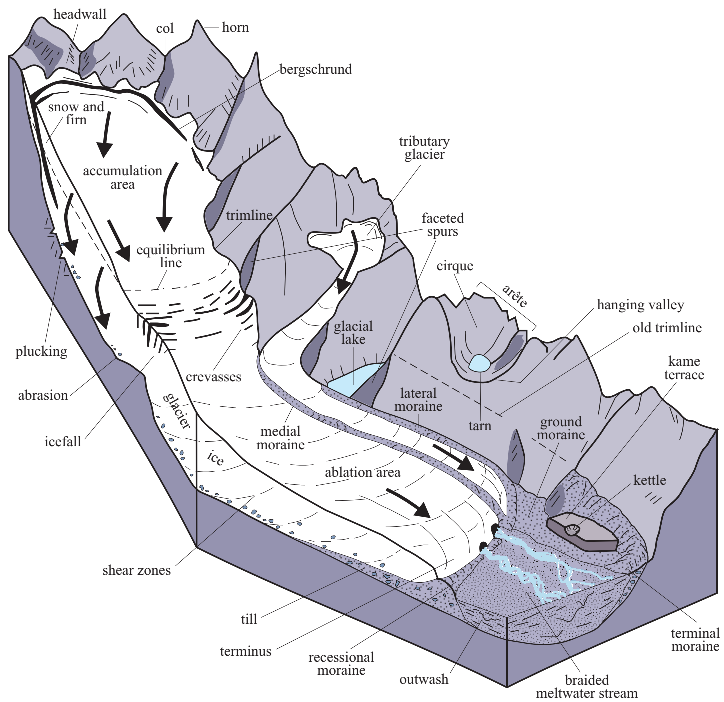


Figure 24. Oblique cross-sectional sketch showing structural and depositional features of an alpine (valley) glacier, including zones of snow and ice accumulation and ablation and alpine erosional features. Redrawn from Skinner and Porter (1992).

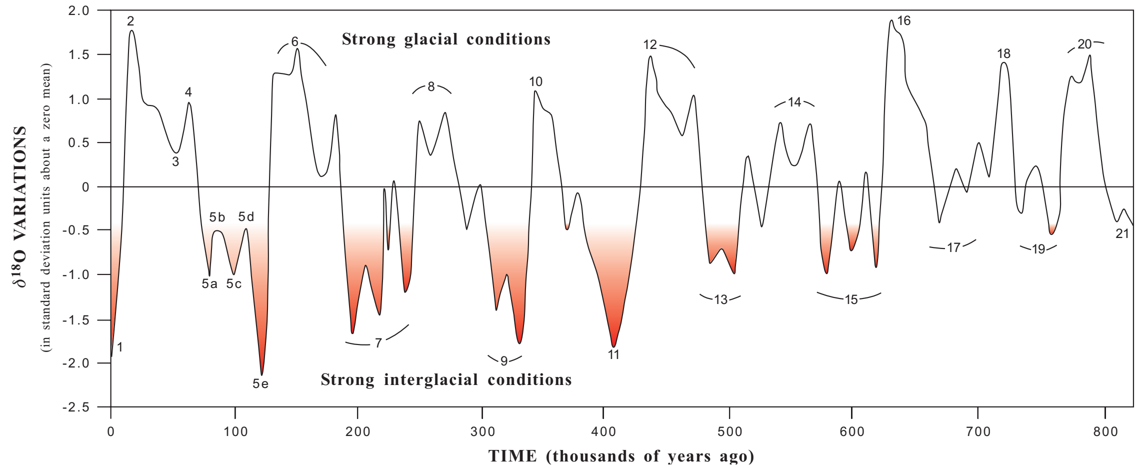


Figure 25. Marine oxygen-isotope stages for the past 800,000 years (from Morrison, 1991). The graph shows variations between $^{18}O/^{16}O$ over time. The numbers within the graph are stage numbers; the even-numbered peaks (at top) are glacial maxima, and the odd-numbered troughs (at bottom) are interglacial 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.

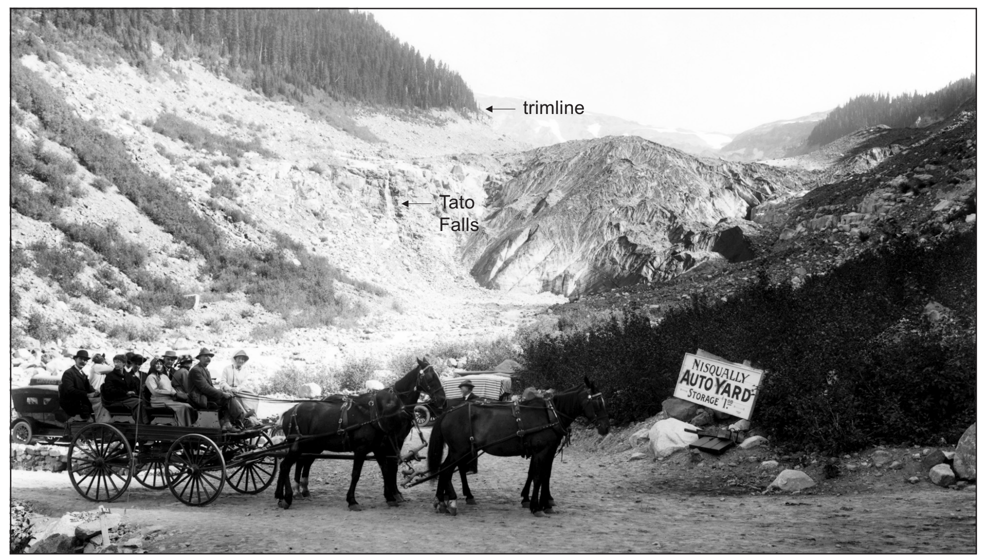


Figure 26. These tourists in 1914 got a closer look at the Nisqually Glacier's terminus than we do today. The terminus was just 300 ft (100 m) or so upstream of the Nisqually Bridge. The bridge was rebuilt about 245 ft (75 m) farther downstream after a 1955 washout. The old road no longer exists. In 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.

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 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

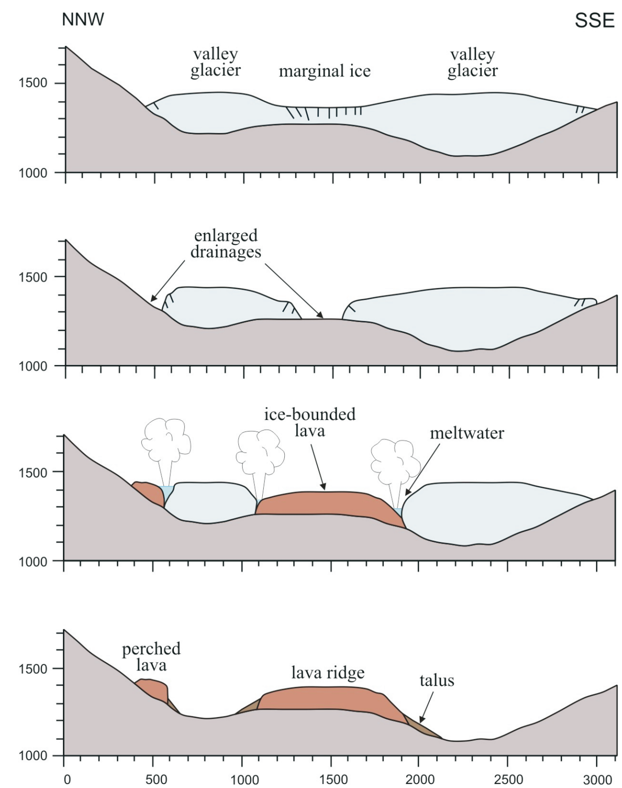


Figure 27. Sequential cross-sectional views (top to bottom) of proposed ice-marginal formation of ridge-forming and perched lava flows. The lava flows are confined by thick glacial ice. This allows the lava to pond. Later melting of the glaciers exposes the thick lava margins. Glassy lava fragments and 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 km^3 (34 mi^3) 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 km^3 (about 2 mi^3). 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 km^3 (0.1 mi^3), 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.

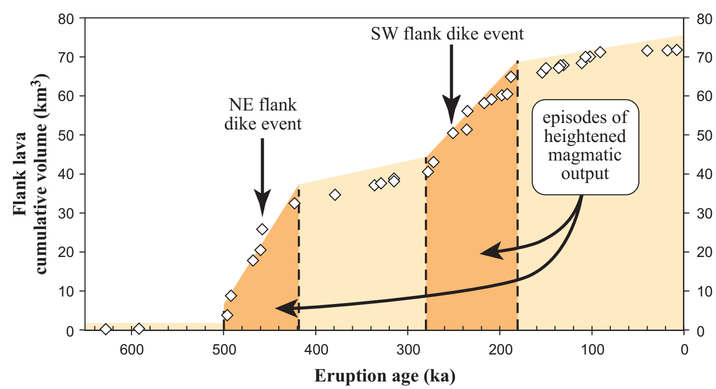


Figure 28. A cumulative growth curve for flank lavas of Mount Rainier based on geologic mapping and K-Ar and Ar-Ar dating by Sisson and Lanphere (1999). Each diamond symbol represents a mapped and dated lava flow or lava flow group. The large arrows show emplacement of large dike systems. Redrawn from 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 km^3 or 0.7–1 mi^3) 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 km^3 or ~2 mi^3), 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 km^3 or 0.24–1 mi^3 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

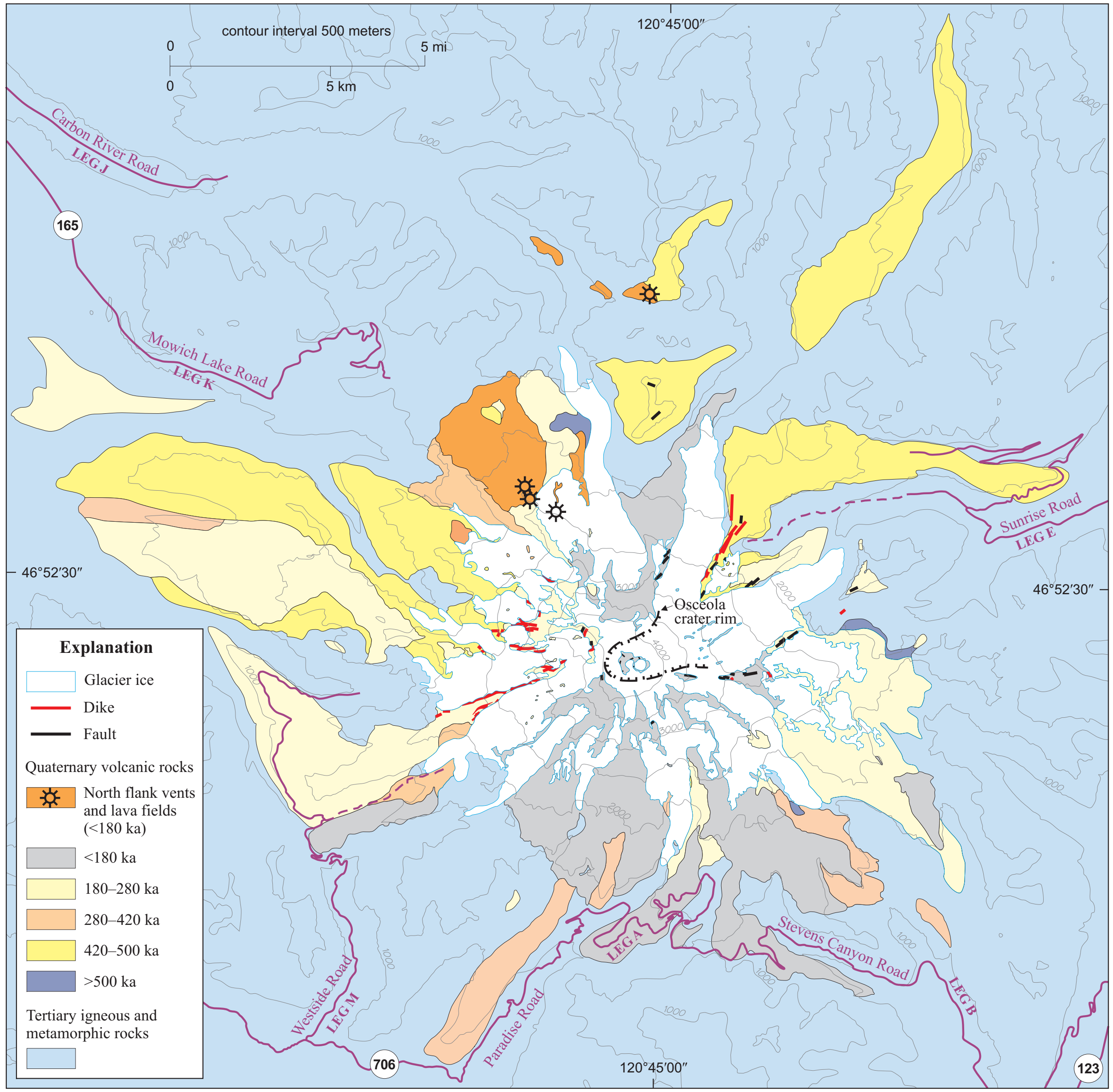


Figure 29. Simplified geologic map of major lava flows and eruptive products from Mount Rainier. Ages of flow units from Sisson and Lanphere (1999).

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

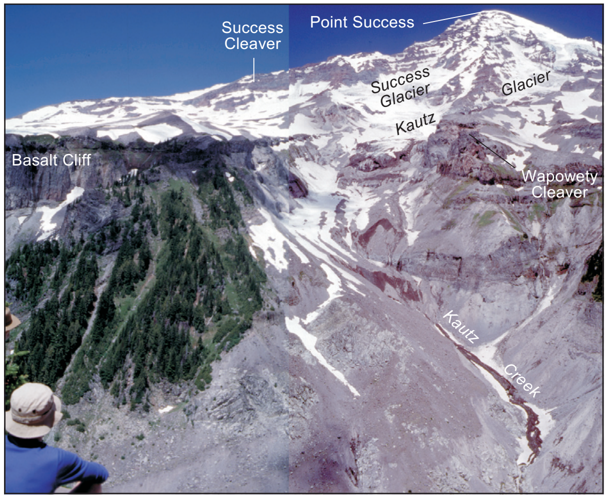


Figure 30. Kautz Glacier and canyon from Mildred Point (elev. 5935 ft; 1809 m). Basalt Cliff is a welded block-and-ash flow erupted about 100 ka (Sisson and Lanphere, 1999). The same welded deposit crops out in the cliff face at the upper right above Kautz Creek. View to the north-northwest; taken in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

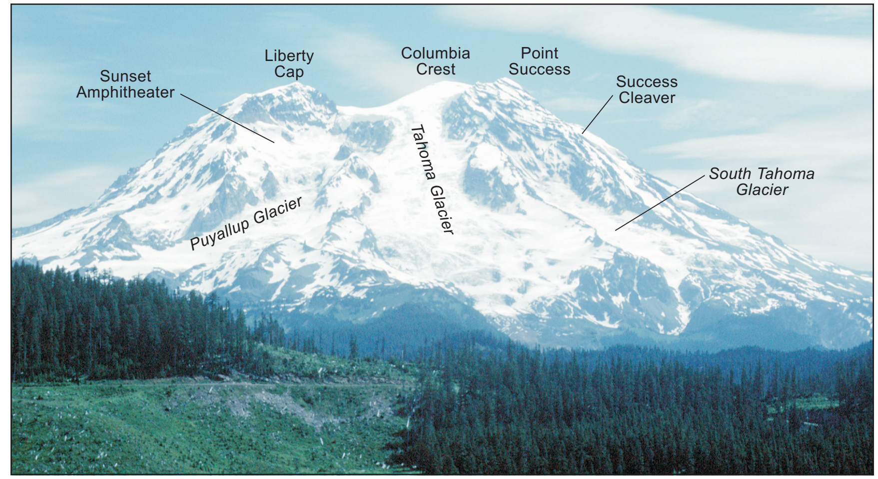


Figure 31. Mount Rainier's chiseled west face reveals interbedded layers of lava and fragmental debris, dikes, glaciers, and landforms that tell many stories of its past. The youthful Columbia Crest summit cone fills the gaping crater left after the 5,000 yr B.P. (5,600 cal yr B.P.) Osceola Mudflow carried 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.)

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 hummocks 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 km^3 (0.5–0.6 mi^3), transformed from an enormous debris avalanche into a lahar within a few kilometers of its source, and grew in volume to nearly 4 km^3 (1 mi^3) 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 km^2 (58 mi^2) of upland valleys and 210 km^2 (81 mi^2) of Puget Lowland. Dragovich and others (1994) used well logs to delineate an additional 190 km^2 (73 mi^2) of Osceola Mudflow deposits in the subsurface, 160 km^2 (62 mi^2) 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 km^2 (81 mi^2) of

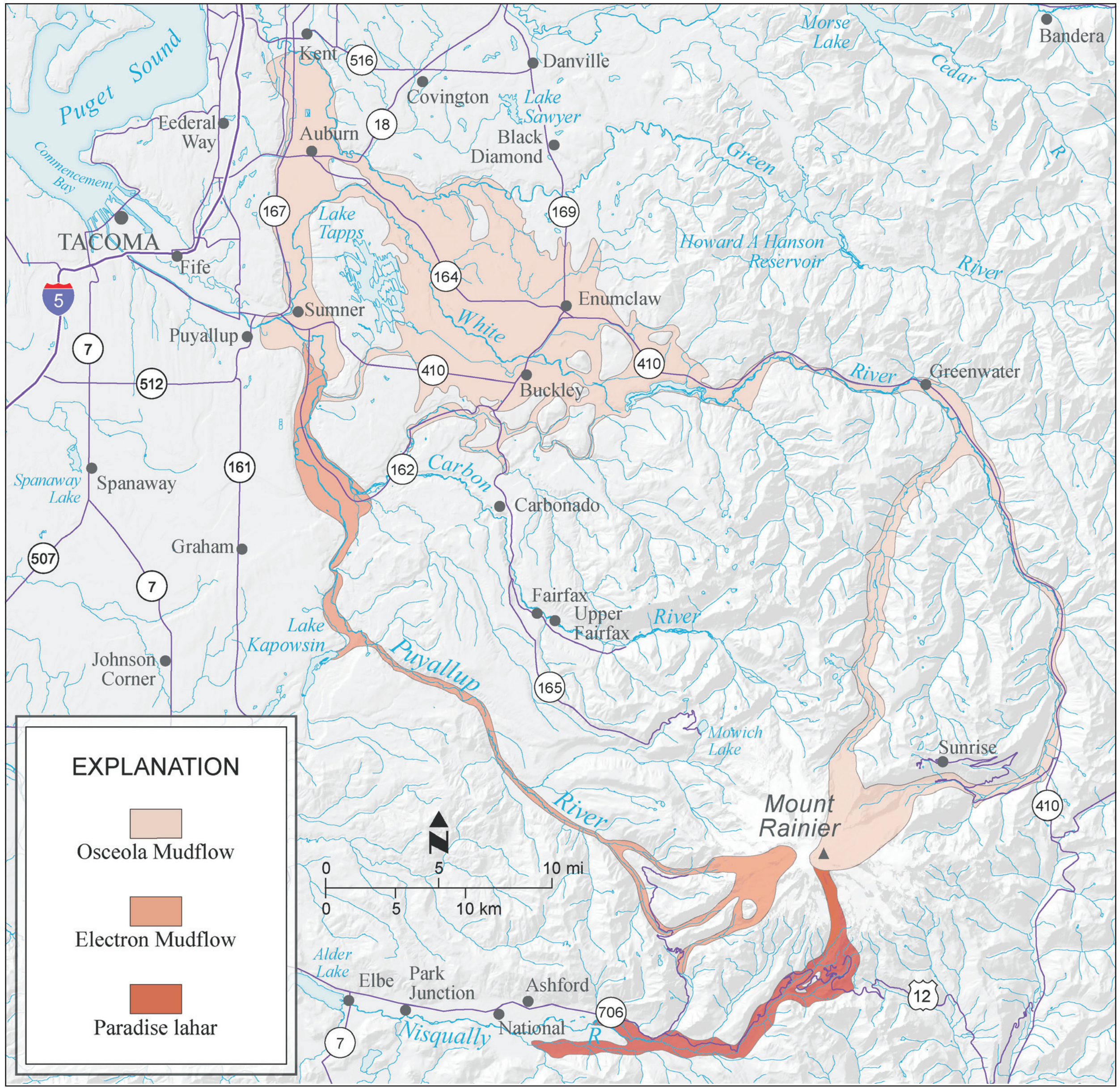


Figure 33. Inferred original extent of areas inundated by voluminous clay-rich lahars spawned by Mount Rainier during the past 6000 years, specifically the Osceola and Electron Mudflows and the Paradise lahar. More recent studies show that the Electron Mudflow likely reached the Nisqually River. Adapted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

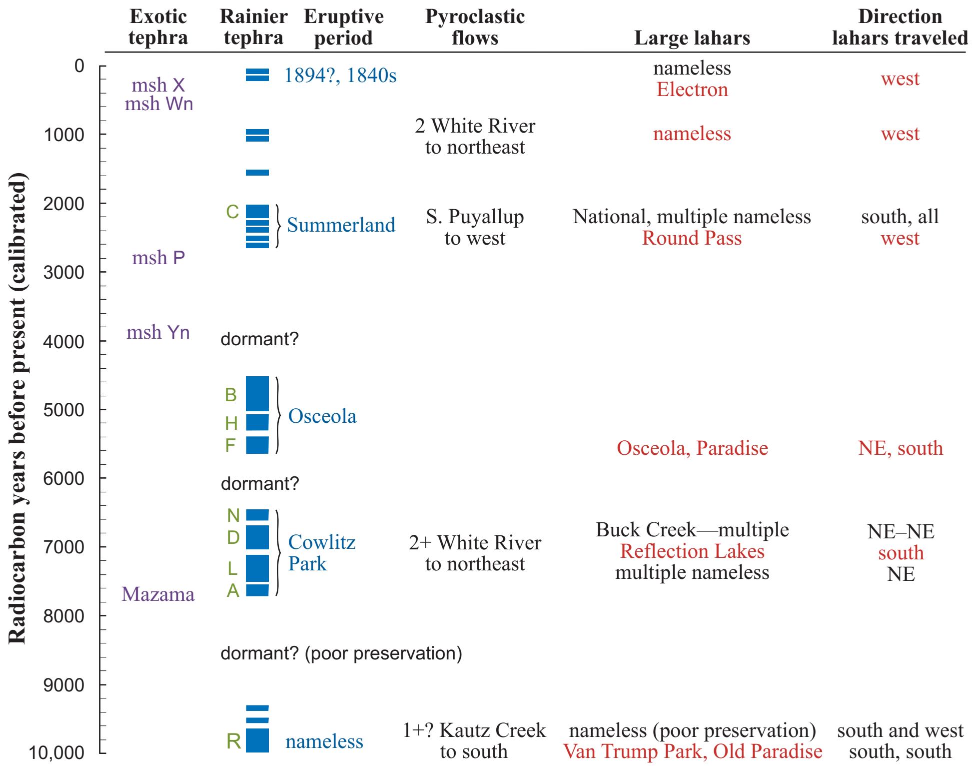


Figure 34. Eruptive periods and major lahars (>20 km or 12 mi long) at Mount Rainier during the Holocene. Blue bars show generalized eruptive periods, and green letters give tephra layer designations. Purple text indicates exotic tephra layers from Mount St. Helens (msh) and Mount Mazama (Crater Lake) 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

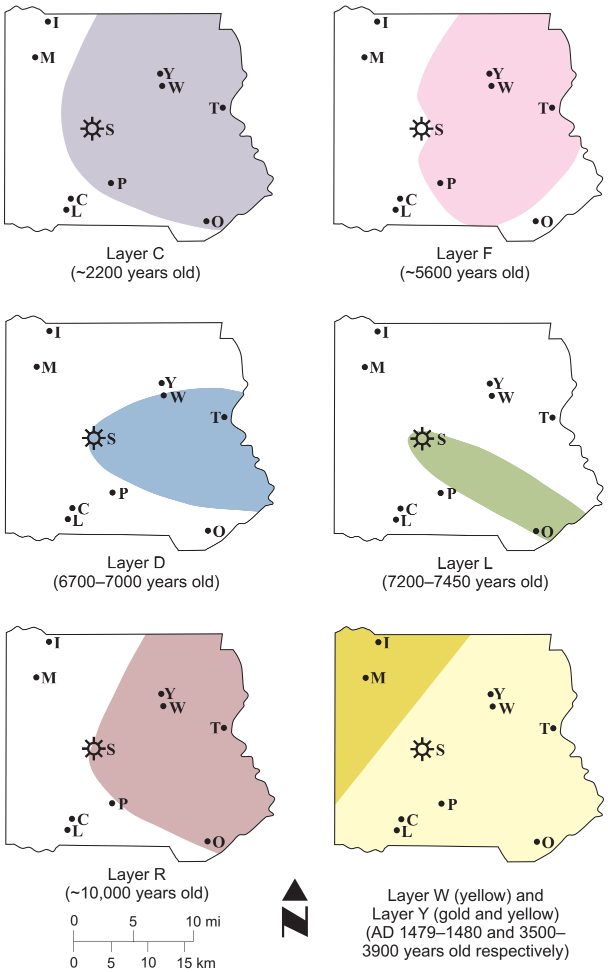


Figure 35. Generalized distribution of select pumiceous tephra layers within Mount Rainier National Park. Layers W and Y came from Mount St. Helens; the others originated at Mount Rainier. Letters represent the following localities: C, Cougar Rock campground; I, Ipsut Creek campground; L, Longmire; M, 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).

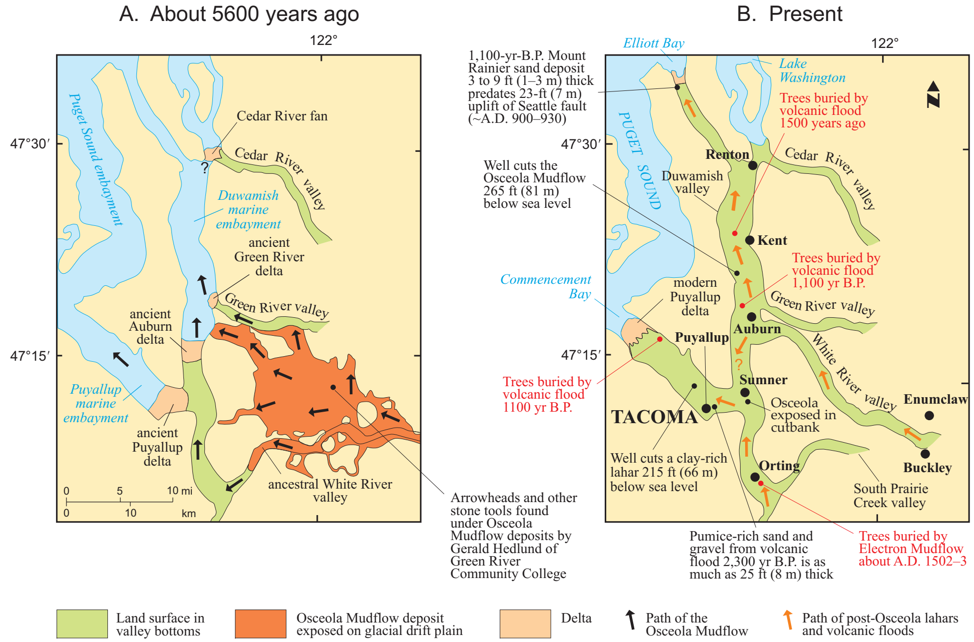


Figure 36. Approximate extent of the Osceola Mudflow, area of post-Osceola alluviation of the Puget Lowland near Seattle and Tacoma, and selected locations of forests buried by post-Osceola events (shown in red). Modified from Dragovich and others (1994) and Luzier (1969).

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 buried 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

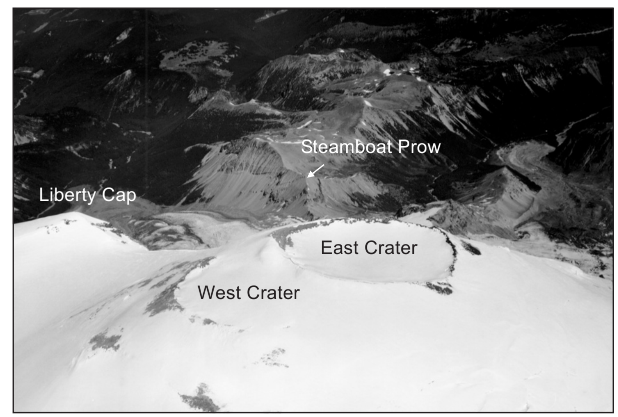


Figure 37. Aerial-oblique photo of Columbia Crest summit cone at Mount Rainier. Steamboat Prow is visible in the background. The bare ground along the rims of West and East Craters is kept snow free by geothermal heat. Some fumaroles in the East Crater are at the local boiling point (186°F; 86°C). View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

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

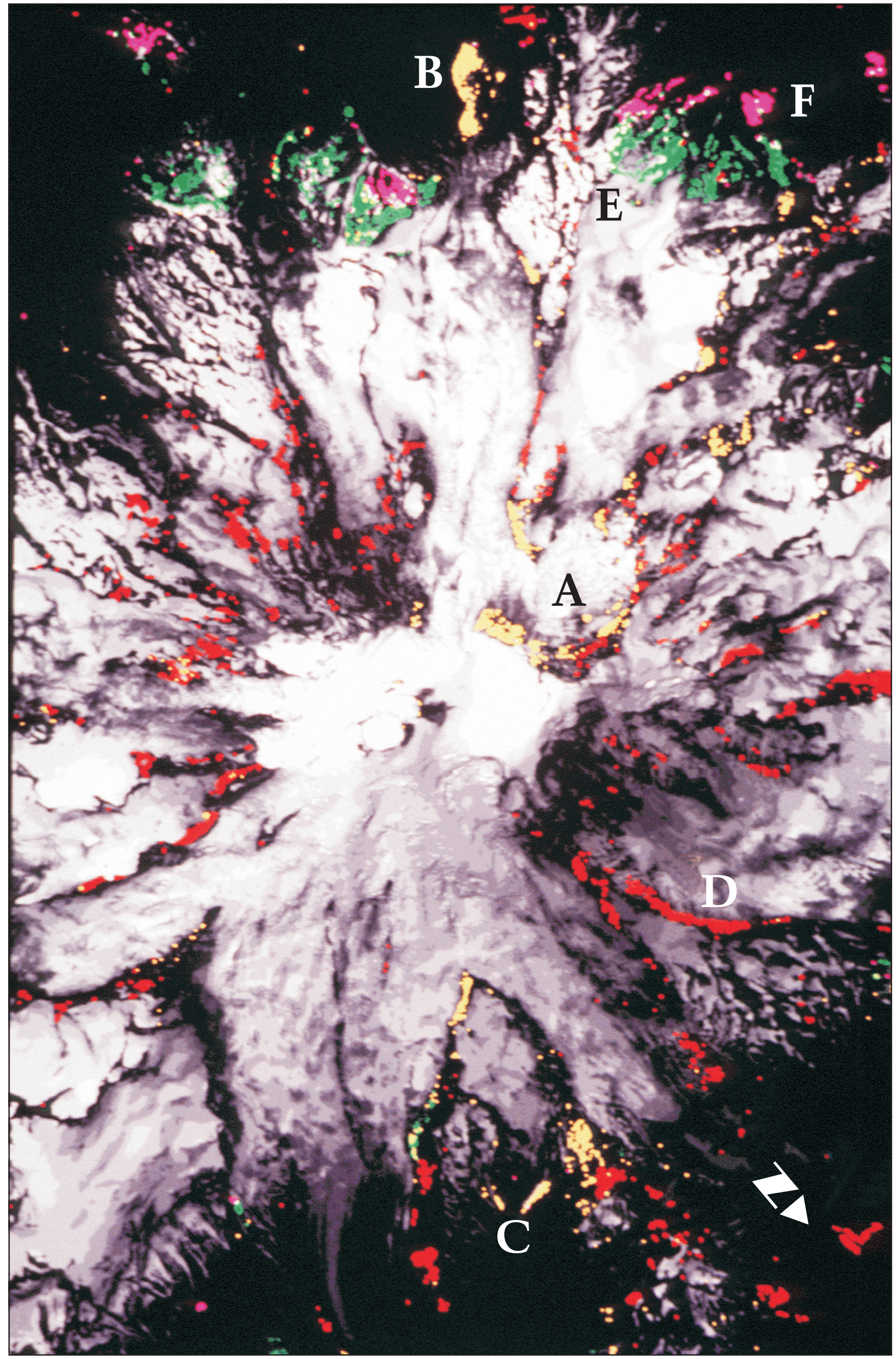


Figure 38. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) image of Mount Rainier. Note that north is toward the lower right. This image shows different types of altered rocks in various colors (Crowley and Zimbelman, 1997) and demonstrates where weak rocks are localized on Mount Rainier. Yellow 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.

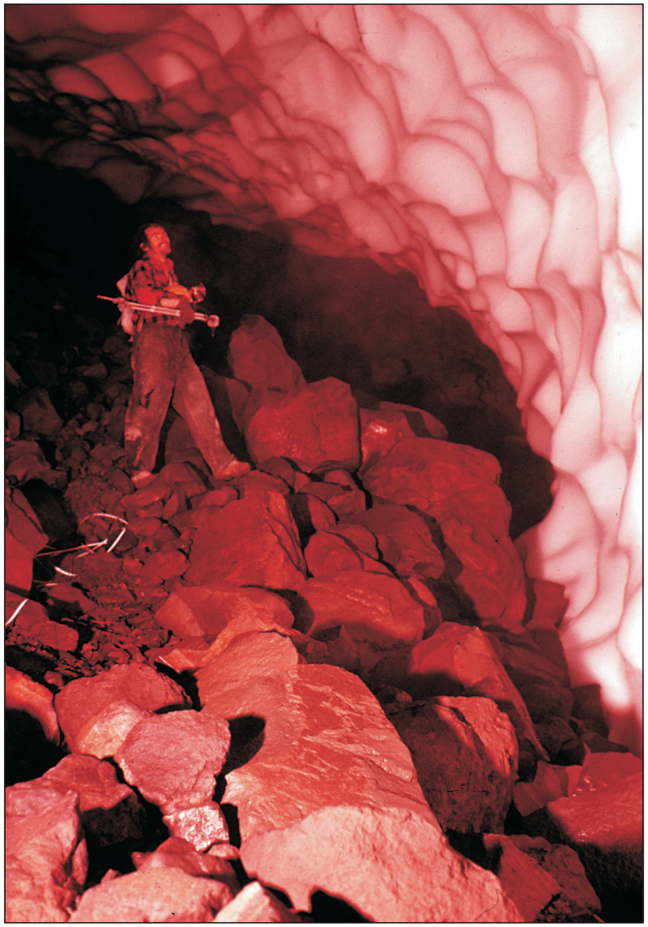
Hydrothermal activity has played an important role in the construction and destruction of Mount Rainier, as well as in localizing its zones of weakness. Hydrovolcanic activity (phreatic eruptions) produces fragmental deposits. Hydrothermal alteration forms secondary hydrothermal minerals from primary 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 magnetic 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 (Milller, 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.

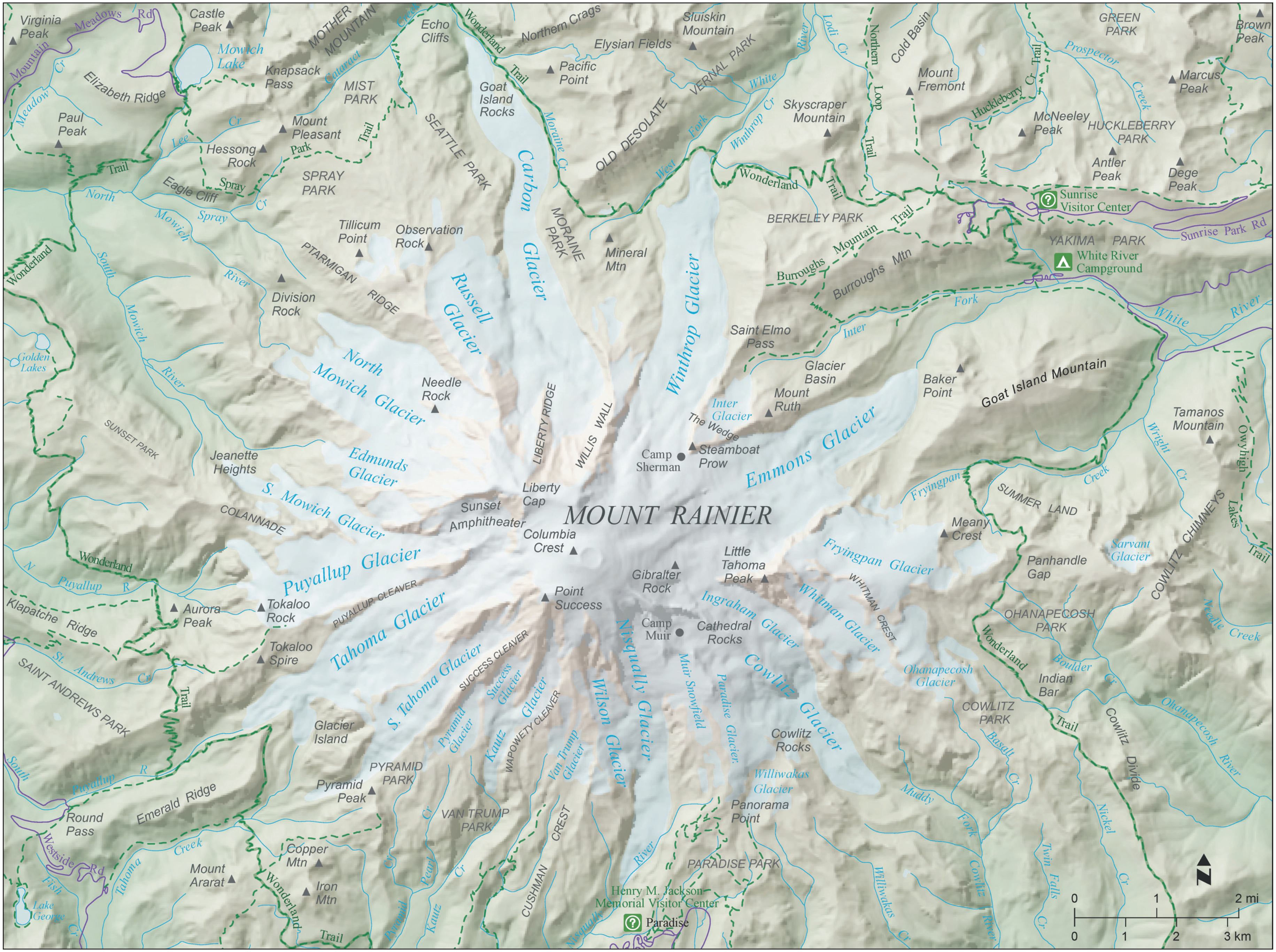


Figure 41. Mount Rainier's glaciers. Mount Rainier has the largest collection of glaciers of any single peak in the conterminous United States. The glaciers not only help carve the volcano's edifice, but also provide a source of water for lahars and groundwater for hydrothermal alteration.

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).

SEISMICITY—REGIONAL TECTONIC AND VOLCANO TECTONIC

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.

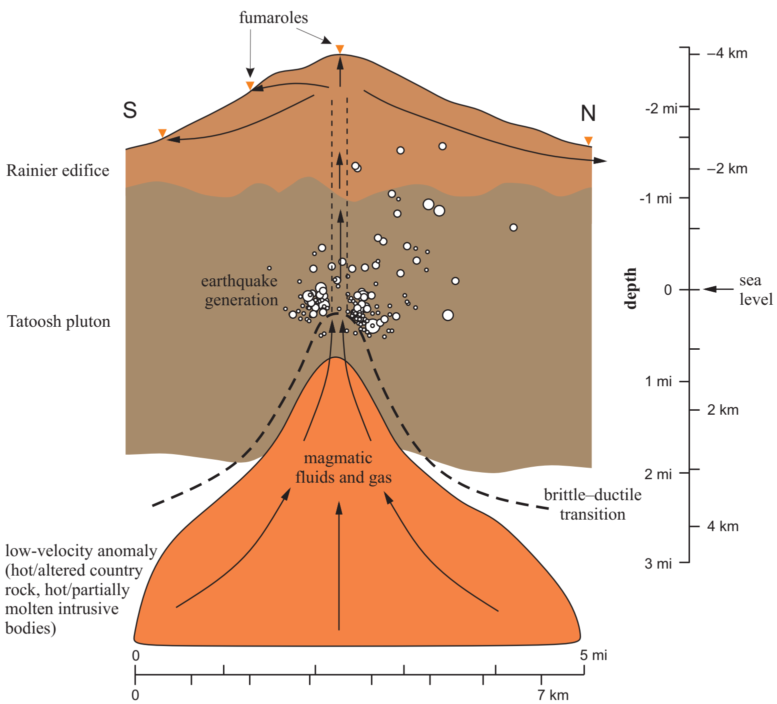


Figure 42. A conceptual model of the magmatic-hydrothermal system beneath Mount Rainier showing rising fluids. The model is derived from geochemical and seismic constraints. White dots show hypocenters (locations) of high-frequency volcanic earthquakes. Modified from Moran and others (2000).

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

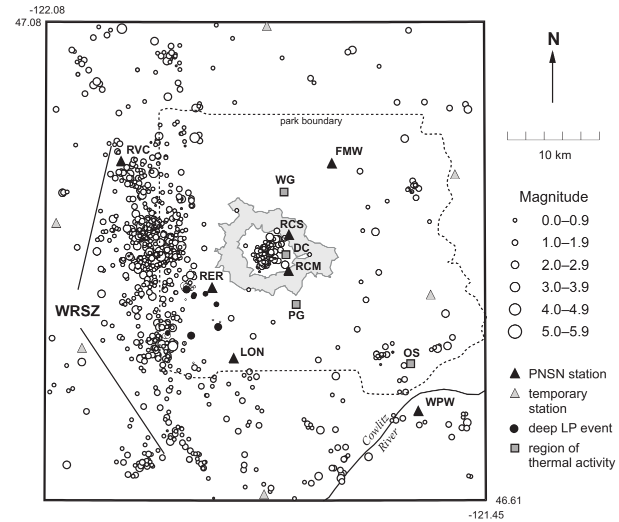


Figure 43. Seismicity in the area surrounding Mount Rainier for the period 1989 through 1997. Black triangles are permanent Pacific Northwest Seismic Network (PNSN) stations; gray triangles are temporary stations run 1995 to 1996. Hollow circles are earthquakes; solid black circles show locations of 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).

example, a regional tectonic earthquake triggered a deadly debris avalanche at Ontake volcano in Japan in 1984 (Nagaoka, 1987).

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).

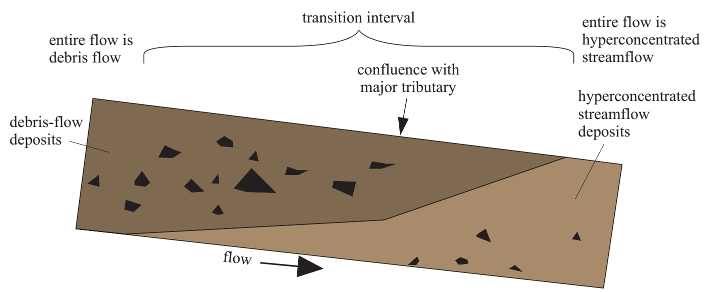


Figure 46. The transformation of a clay-poor lahar to a more dilute hyperconcentrated flow as it moves downstream away from the volcano. Observations of how lahars undergo changes in their concentration and flow properties along their courses as they move away from a volcano now help geologists to recognize 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 distinctive 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.

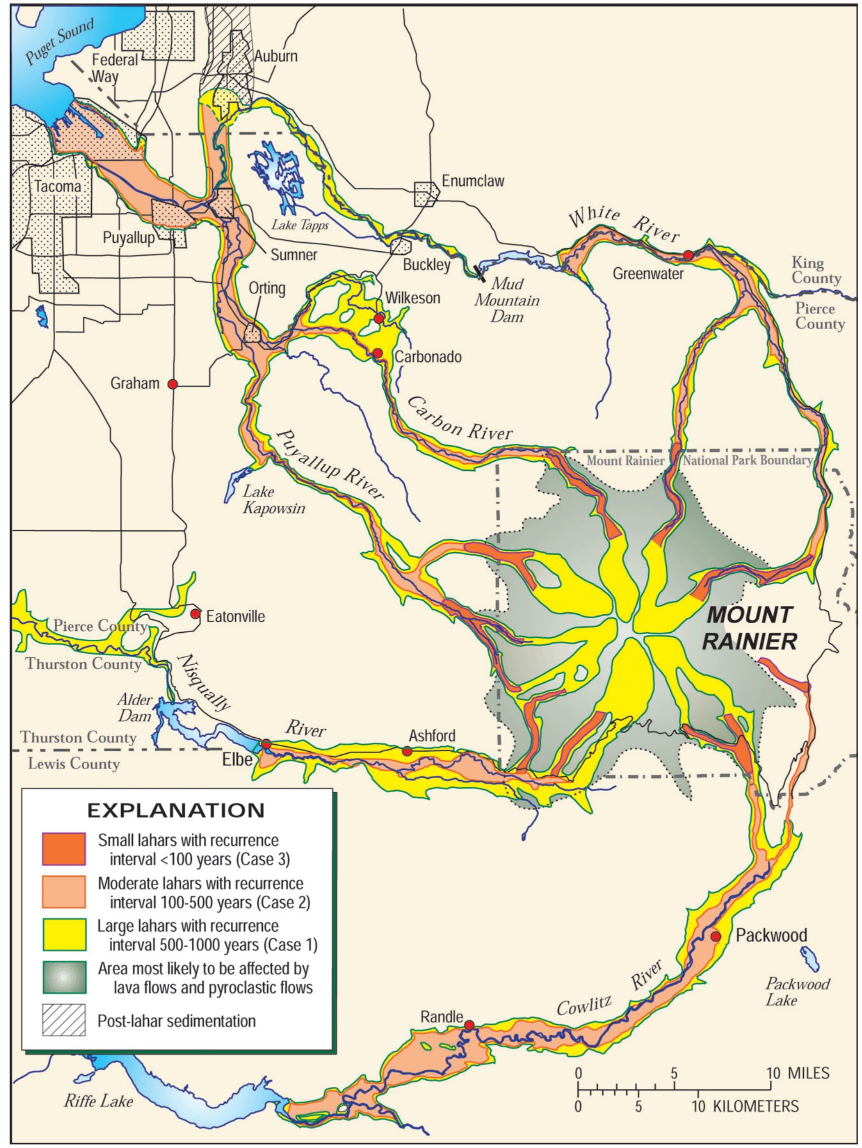


Figure 47. Hazard zones for lahars, lava flows, and pyroclastic flows from Mount Rainier (Hoblitt and others, 1998). The colored areas could be inundated if events similar in size to those of the past occurred today. Major lahars have occurred on average every 500 to 1000 years and smaller flows more 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.

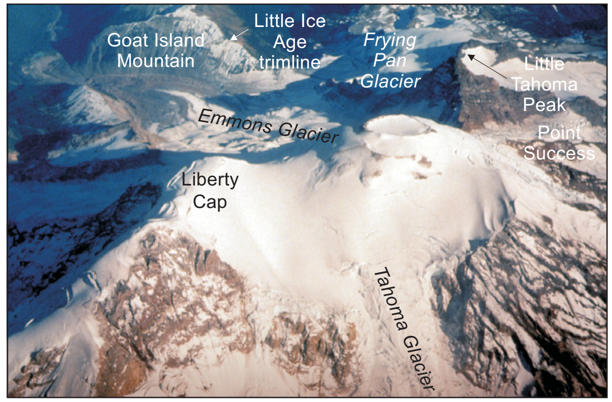


Figure 48. The twin summit craters of Mount Rainier. Columbia Crest cone (right) sits in and nearly fills the large crater created by the collapse that led to the 5,600-cal-yr-B.P. Osceola Mudflow. Little Tahoma Peak is visible in the upper right corner. Clockwise from left center to upper left: Winthrop 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.