National Park Service
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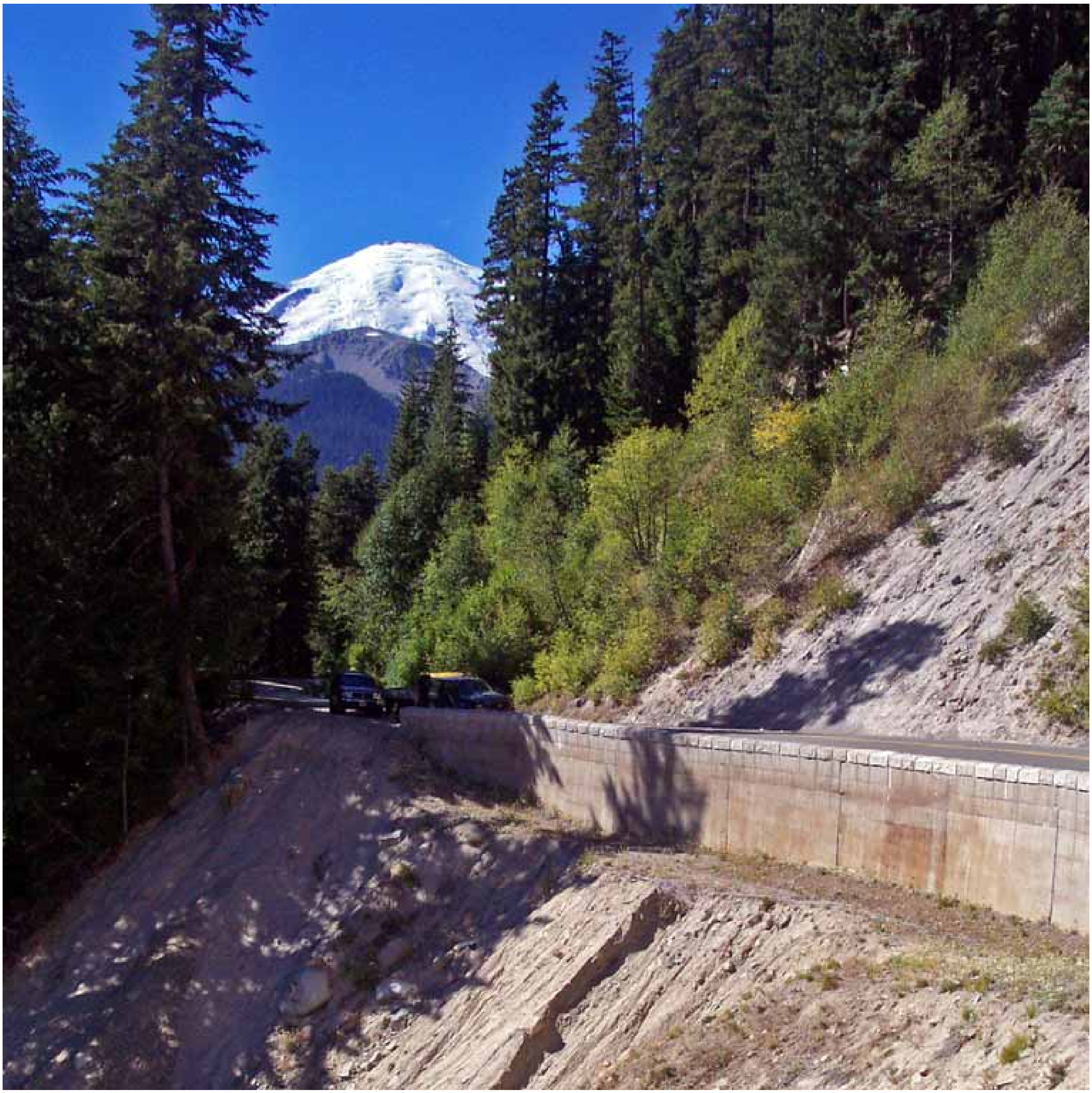
Natural Resource Program Center

Mount Rainier National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/007



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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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Executive Summary

This report accompanies the digital geologic map produced by Geologic Resource Evaluation staff for Mount Rainier National Park. It contains information relevant to resource management and scientific research.

Mount Rainier is the second highest peak in the conterminous United States at 14,410 feet (4393 meters). Over 35 square miles (91 sq km) of snow and ice encase Mount Rainier making it the largest single- peak glacial system in the United States. Glaciers radiate from the summit masking its explosive potential.

Like the other volcanic peaks in the Cascade Range, Mount Rainier is a stratovolcano that formed through successive eruptions of lava and pyroclastic flows. These types of volcanoes have the most violent types of eruptions as witnessed by the May 18, 1980, eruption of Mt. St. Helens. Large eruptions of Mt. Rainier took place as recently as 1,000 years ago. Today, steam from the volcano generates ice caves and fumeroles near the summit of the volcano.

In 2002 a scoping meeting for MORA was held to discuss geologic maps available for conversion to a digital format. The identification of park specific geologic issues was only addressed in a cursory manner. Nonetheless, some of major geologic management issues in the park include:

- Potential volcanic eruptions, producing tephra (ash), volcanic projectiles, pyroclastic flows and surges, lateral blasts, lava flows, and volcanic gases
- Edifice failure and debris avalanches
- Glacial outburst floods
- Lahars and debris flows
- Hydrothermal alteration zones
- Seismicity
- Snow avalanches, rock falls, ice falls, and landslides
- Cryptobiotic soils and soil erosion
- Glacial Monitoring

Due to the proximity of over 1.5 million people living within the shadow of Mount Rainier, it is considered the most dangerous volcano in the Cascade Range. A major eruption melting the ice and snow could send debris flows, pyroclastic flows, and lahars towards Puget Sound and the Seattle/Tacoma metropolitan area.

Volcanic hazard mapping has identified areas in the park that could be affected in the future by debris flows, lahars, pyroclastic flows and surges, lava flows, volcanic projectiles, tephra falls, and lateral blasts. Longmire Village and the Cougar Rock, Ohanapecosh, White River, Ipsut Creek, and Sunshine Point campgrounds are all vulnerable to these hazards. Monitoring of volcanic activity is on- going. There is a need for an emergency response plan to address these hazards.

The reaction between groundwater and rising gas and steam from the underlying magmatic system creates zones of hydrothermally altered rock. Fumeroles at the summit of the volcano are one result of this reaction. Another result is the largest volcanic ice- cave system in the world at the summit of Mount Rainier.

Earthquakes are also geologic hazards associated with Mount Rainier. Earthquakes precede a volcanic eruption although not every earthquake means an eruption is imminent. Other than Mt. St. Helens, Mount Rainier is the most seismically active volcano in the Cascades.

The destruction of cryptobiotic soils and general soil erosion by human impacts are important issues. A systematic soil survey is needed to identify and characterize soil types.

The glaciers of Mount Rainier are hydrologically significant and have both immediate and long- term impacts on the local and regional environment. Recent changes in glacial extent and volume make glacial monitoring an important issue for MORA.

Mount Rainier is known for interesting geologic features. Glacial features on Mount Rainier include horns, cirques and cirque lakes, glacial valleys, arêtes, and characteristic glacial topography defined by glacial moraines and glacial drift.

Volcanic processes have left many volcanic features, as well. Lava cones and flows, satellite volcano structures, rock walls, and summit features are present on Mount Rainier.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation program.

Purpose of the Geologic Resource Evaluation Program

Geologic resources serve as the foundation of park ecosystems and yield important information needed for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resources Division. The goal of the GRE Program is to provide each of the identified 274 "Natural Area" parks with a digital geologic map, a geologic evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and each is designed to be user friendly to non- geoscientists. In preparing products the GRE team works closely with park staff and partners (e.g., USGS, state geologic surveys, and academics).

GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss specific geologic issues affecting the park. Park staff are afforded the opportunity to meet with experts on the geology of their park during these meetings. Scoping meetings are usually held for individual parks although some meetings address an entire Vital Signs Monitoring Network.

For additional information regarding the Geologic Resources of Mount Rainier National Park, please contact the Geologic Resources Division, Denver, Colorado, or visit the National Park Service website at http://www2.nature.nps.gov/geology.

Regional Location

Towering 1.5 miles (2.4 km) above the surrounding mountains and about 3 miles (5 km) above the lowlands to the west, Mount Rainier is the second highest peak in the conterminous United States at 14,410 ft (4393 m). Mount Rainier also has the distinction of having the greatest single- peak glacial system in the United States. Over 35 square miles (91 sq km) of snow and ice cover this active volcano. Glaciers radiate from its summit so that its rocky, ice- mantled slopes above timberline contrast vividly with the green, verdant forests that include old growth trees. The snowfields, alpine tundra with vivid alpine flowers, and dense forests provide the park visitor with a variety of visitor experiences. In 1899, 235,625 acres were set aside as Mount Rainier National Park and today, 97% of this area is designated wilderness (Figure 1).

The Native Americans know the mountain as Tahoma or Takhoma or Ta- co- bet, names meaning "Snow Mountain" or the "Mountain that was God" or "Place where the Waters Begin". These names are more descriptive and perhaps capture the mountain's impact on the surrounding region better than the European moniker "Rainier", a name bestowed on the mountain by Captain Vancouver in 1792 in honor of his friend and superior officer, Rear Admiral Peter Rainier.

In terms of its potential impact on human populations, this "mountain of fire and ice" is the most dangerous volcano in the Cascade Range. In the shadow of Mount Rainier, live over 1.5 million people. The glaciers on Mount Rainier provide a steady flow of water for hydroelectric power in the region, regardless of the season. However, should an eruption occur, these 35 acres of ice and snow could melt and send debris flows towards Puget Sound and the Seattle/Tacoma metropolitan area.

General Geology

Compared to the total age of the earth, the rocks exposed within Mount Rainier National Park are relatively young. Earth formed about 4600 million years ago (4.6 billion years ago), but the rocks in the park formed within the last 60 million years, during the Tertiary and Quaternary Periods (Figure 2). By the time Mount Rainier formed, the dinosaurs were extinct and primitive ancestors of many of today's familiar mammals roamed the Earth. The trees and plants growing in Tertiary forests were clearly forerunners of today's forests.

Mount Rainier is a *stratovolcano*, a composite volcano created through successive eruptions of lava and pyroclastic flows. It is one of more than a dozen stratovolcanoes perched on older rocks of the Cascade Range (Figure 3). The impressive eruption of Mount St. Helens in 1980, demonstrated the explosive nature of these types of volcanoes.

The Cascade volcanoes are aligned in a north- south direction that roughly parallels the Pacific coastline for about 500 miles (800 km). The volcanic mountains of the Cascade Range are a small segment of the circum- Pacific volcanic belt, or "Ring of Fire," that encircles the Pacific Ocean. Volcanoes in the Ring of Fire mark converging lithospheric plate boundaries where dense, oceanic crust is subducted beneath the less dense, overriding continental crust or an island arc. The volcanoes in Washington and Oregon are the result of the collision between the oceanic Juan de Fucca plate, traveling northeast, and the continental North American plate, moving westward.

The prevailing rock type of the Cascade volcanoes is andesite, an igneous rock of intermediate composition between light- colored, silica- rich rocks (e.g., rhyolite) and dark, basaltic rocks that contain very little silica. Andesite is typically dark gray or greenish black in color and is composed of approximately equal amounts of light- colored minerals like plagioclase feldspars and dark minerals like hornblende, olivine, and pyroxenes.

The north- south trend of Cascade volcanoes is believed to be located above the zone of melting deep within the crust where rocks in the subducting plate begin to melt. Magma rises from this zone to erupt at the surface as lava.

Lithospheric plates moving past one another generate earthquakes. Few large- scale earthquakes have occurred in historic time along the Pacific Northwest coastal area, but severe earthquakes accompanied by tsunamis have occurred in prehistoric time. The Cascade subduction zone may be storing strain energy that, when released, could result in catastrophic earthquakes and tsunamis along the Washington and Oregon coasts.

The landscape of Mount Rainier is complex, but its origins are simple: fire and ice. The mountain first erupted about half a million years ago and as recently as in the 1840s. Two large eruptions took place, first about 2,300 years ago and another 1,000 years ago. About 90 percent of Mount Rainier's eruptions have been in the form of lava flows, which is unusual for a composite cone (Harris et al., 1995). In contrast, most of the other Cascade volcanoes, including Mount St. Helens, have had a more violent history with few lava flows and a high volume of pyroclastics. Much of the ash and pumice on Mount Rainier's slopes came from Mount St. Helens during explosive episodes like the 1980 eruption.

The mountain's great height and northerly location allowed glaciers to cut deeply into its volcanic deposits. Today, steam from the volcano creates ice caves near the summit of the volcano, and in the past, devastating debris flows and mudflows were triggered by lava and rock debris from Mount Rainier's eruptions. The consistency of these mudflows on Mount Rainier is like wet cement. The collapse of unstable parts of the volcano has led to additional debris flows. At one time, the summit rose perhaps 2,000 ft (600 m) higher than it does today. About 5,700 years ago, an eruption took off the top of the mountain and left a depression 1.25 miles (2.01 km) in diameter. The mountain is a history of lava flows, lahars, mudflows, pyroclastic explosions, and ash falls mixed with glacial debris, glacial outwash floods, and rockfalls.

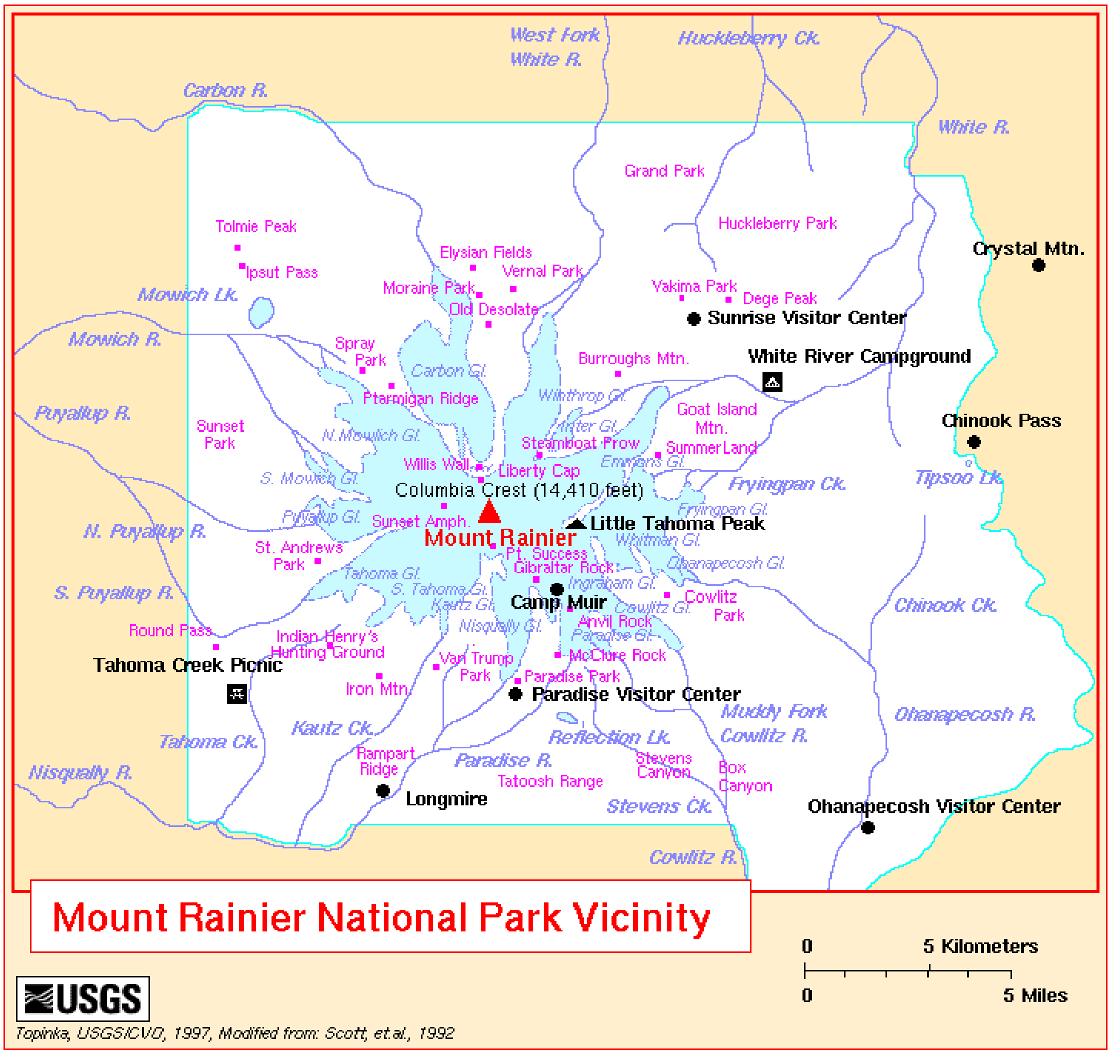

Figure 1: Location of glaciers, campgrounds, streams, and visitor centers at Mount Rainier National Park.

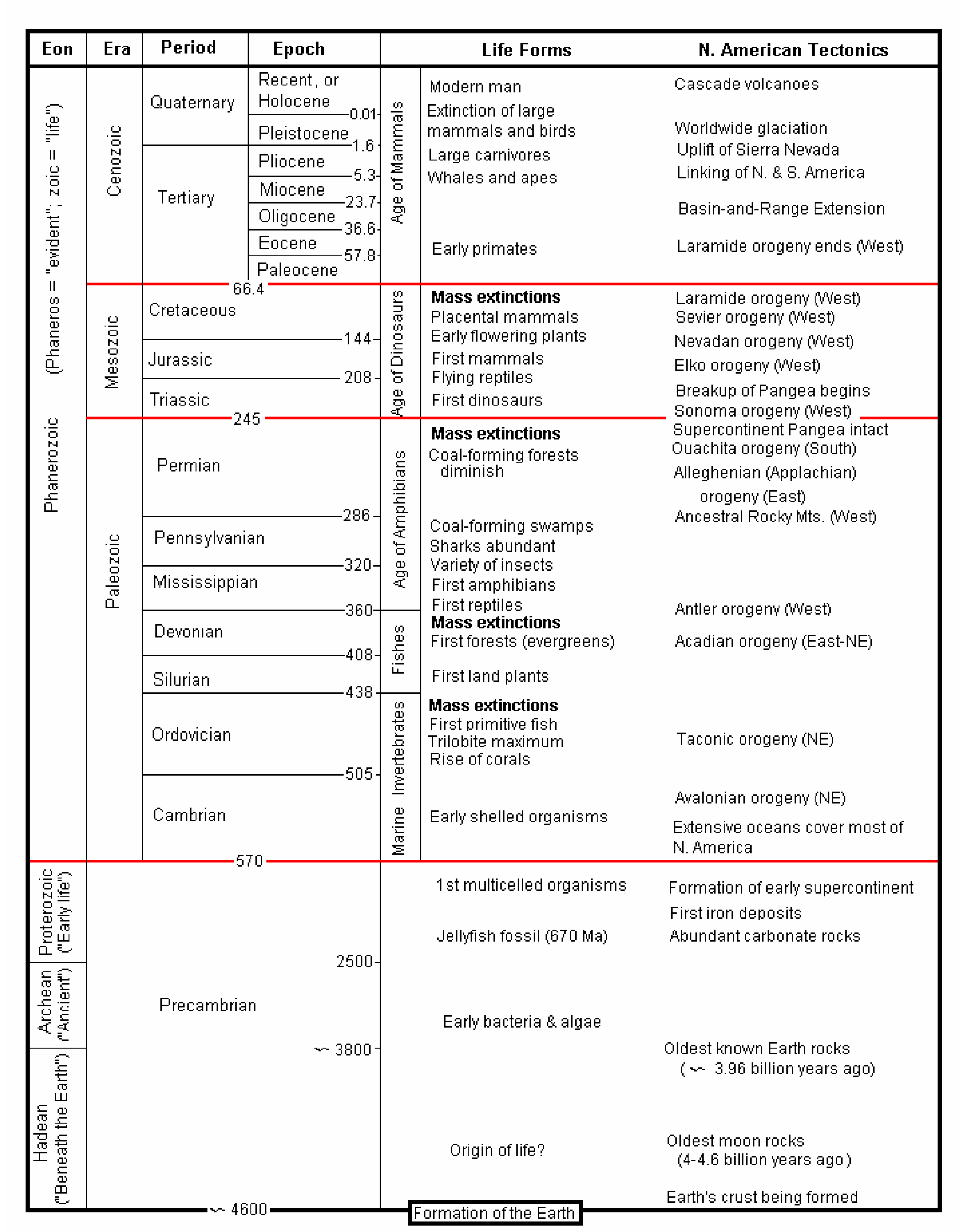

Figure 2: Geologic time scale. Red lines indicate major unconformities between eras. Absolute ages shown are in millions in years. Scale is from the U.S.G.S.

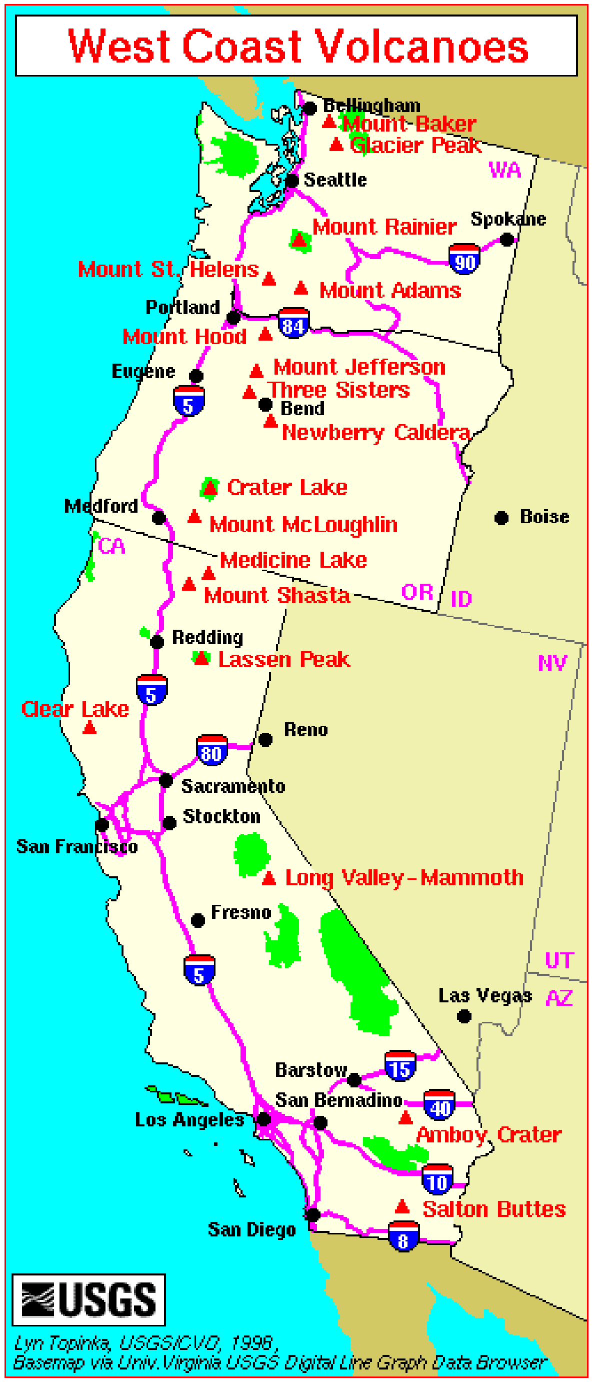

Figure 3: Volcanoes on the west coast of the conterminous United States. Green areas on the map represent units of the National Park Service.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Mount Rainier National Park on September 10- 12, 2002, to address the status of geologic mapping pertinent to the park. Resource management issues and needs were not discussed in depth. As a result, the following section only preliminarily discusses geologic resources management issues that may require attention from resource managers.

On clear days, about 2.5 million people of the greater Seattle- Tacoma metropolitan area can see Mount Rainier. About 150,000 live in areas swept by lahars and floods that emanated from the volcano during the last 6,000 years (Sisson et al., 2001). The large population at risk and the lack of information about Mount Rainier's edifice geology, pre- Holocene history, and hydromagmatic system prompted its inclusion as one of 16 volcanoes worldwide targeted for intense research as part of the United Nations' International Decade for Natural Disaster Reduction (IDNDR).

Decade Volcano designation led to new research and substantial progress in understanding hazards from Mount Rainier. In general, collapse hazards are greatest on the west flank and future edifice stability modeling promises to quantitatively assess collapse risks (Sisson et al., 2001). The likelihood of lahars formed by magma- ice interaction chiefly by pyroclastic flows is higher than was previously supposed. Such eruption- generated lahars threaten all valleys that radiate from the volcano. Mount Rainier has erupted more frequently than was previously known and the association between eruptions and lahars is stronger than previously thought. Although seismic and other eruption precursors serve to alert communities to increased risks, some sizeable lahars were shown to have no known eruptive triggers.

Results from geologic mapping, remote sensing, geotechnical, and geochemical studies show that geologic features controlling the most potentially destructive volcanic hazard types lie primarily in the east and west sectors of the volcano (Zimbelman et al., 2000B). The east and west sectors are more deeply dissected by glaciers, have hosted numerous historic debris avalanches and flows, and contain active fumaroles, large areas of hydrothermally altered rock, near- vertical fracture systems, and radial dikes. All of these geologic features offer the potential for large edifice- collapse events. In contrast, the north and south sectors of the volcano generally lack these features. Fewer collapse events have occurred in the north and south sectors. Risk mitigation efforts, therefore, will be most effective if they reflect this east- west distribution of the geologic controls on volcanic hazards.

Volcanic hazards from Mount Rainier include those that occur during eruptions such as tephra falls, pyroclastic flows and surges,, volcanic projectiles, and lava flows and those that occur during dormant periods such as debris avalanches, lahars, and floods. The National Research Council (1994) included the following volcanic hazards or volcanic related events as potential threats to persons or property:

- Volcanic eruptions – the eruption of ash flows and tephra (ash or pumice)
- Edifice failure – the gravitational collapse of a portion of the volcano
- Glacial outburst floods – the sudden release of meltwater from glaciers and snowpack or from glacier dammed lakes on the edifice
- Lahars or debris flows, and debris avalanches – gravitational movement of commonly water- saturated volcanic debris down the steep slopes of the volcano and into nearby valleys

Although boundaries have been applied to these hazard zones at Mount Rainier, too many uncertainties exist about the source, size and mobility of future events to locate these zones with absolute certainly (Hoblitt et al., 1998).

Seismicity

Earthquakes are precursors to volcanic eruptions although not every earthquake means an eruption is eminent. Mount Rainier is considered to be the second most seismically active volcano in the Cascades, second only to Mount St. Helens (Kiver and Harris, 1999). In a given month, an average of 1- 2 high- frequency *volcano-tectonic* (VT) earthquakes occurs directly beneath the summit (Moran and Malone, 2000). Seismicity is concentrated both at the edifice and to the west in a broad north- south belt known as the west Rainier seismic zone (WRSZ) (Sisson et al., 2001). The frequent seismicity raises concerns that earthquakes might be produced that would be powerful enough to trigger edifice collapse.

At Mount Rainier Moran and Malone (2000) showed that VT earthquakes occur from 0.6 mile to 1.2 miles (1 km to 2 km) below the inferred base of the volcanic edifice. Nearly all edifice- centered earthquakes originate beneath the base of the volcano atop a 6- mile- thick (10-km- thick) region of low seismic velocity. This low seismic velocity zone is interpreted to be nearly solidified small magma bodies and hydrothermally altered rocks. WRSZ earthquakes are most consistent with a network of relatively short faults that could produce an earthquake with a probable maximum magnitude of about 5.5 rather than the magnitude 7 earthquake anticipated if the zone were a single long fault. Conclusions from this research reduce, but do not eliminate, concerns for edifice collapse triggered by local or regional seismicity (Moran and Malone, 2000; Sisson et al., 2001).

Tephra (Volcanic Ash)

Explosive eruptions, like Mount St. Helens, produce vertical plumes of hot gases mixed with volcanic rock particles (tephra). If less dense than air, the mixture rises over the volcano's vent until it reaches an altitude at which it ceases to be buoyant. Fine tephra or volcanic ash in the plume will be carried downwind and will fall to produce a deposit that covers a broad area. Tephra thickness and particle size usually decrease with increasing distance from the volcano.

While large tephra fragments are capable of causing death and injury by impact and may be hot enough to start fires where they land, these hazards are usually restricted to within 6 miles (10 km) of the vent (Hoblitt et al., 1995, 1998). Most tephra- related injuries, fatalities, and social disruptions occur farther away from the vent, where tephra fragments may be less than one inch (a few centimeters) across. Clouds of ash block sunlight, greatly restrict visibility, and impede travel. Frequent lightning commonly accompanies such clouds. Inhaling volcanic ash may create or aggravate respiratory problems. Roofs may collapse with an accumulation of 4 inches (10 cm) or more of ash. Thin accumulations may ruin crops. Wet tephra can short out power lines. Fine tephra (ash) is abrasive and can damage mechanical devices. Tephra clouds are extremely hazardous to aircraft. Engines may stop and pilots' visibility may be reduced.

Even thin accumulations of tephra can profoundly disrupt social and economic activity over broad areas. For example 0.25 to 3 inches (6 to 80 mm) of volcanic ash caused significant disruptions in transportation, business activity, and community services in the Washington communities of Yakima, Ritzville, and Spokane when Mount St. Helens erupted in 1980.

Relative to other Cascade volcanoes, Mount Rainier is a moderate tephra producer. The average time interval between eruptions is about 900 years (Hoblitt et al., 1998). At present, maps for tephra fallout hazard are not detailed enough to distinguish among park developed areas because Mount Rainier is within tephra fallout zones from several other Cascade Range volcanoes. In the past, however, tephra fallout from Mount Rainier eruptions has been largely confined to the east half of the park due to prevailing westerly winds (Crandell, 1967).

While Mount St. Helens produced voluminous pumice-fall deposits, Mount Rainier has erupted only modest amounts of pumice in the Holocene. The rock record suggests that voluminous pumice eruptions as at Mt. St. Helens are less likely. (Sisson et al., 2001). However, voluminous pumice- fall deposits are known from the Pleistocene record of Mt. Rainier. The conspicuous 60-foot- thick (20- m- thick) white band in Sunset Amphitheater headwall that can be seen from the southern Puget Sound lowlands is one of these Pleistocene pumice deposits.

Volcanic Projectiles

Volcanic projectiles are particles thrown from the vent on ballistic arcs, like artillery shells. The range of these projectiles rarely exceeds 3 miles (5 km) from the vent (Hoblitt et al., 1998). Most projectiles are less than 3 feet (1 m) across. The primary hazard from volcanic projectiles is from direct impact. Because they may be quite hot when they land, the projectiles also may start fires if they land near combustible materials.

Pyroclastic Flows and Pyroclastic Surges

Pyroclastic flows are denser- than- air mixtures of hot rock fragments and gases whose down slope movement is controlled by topography. Pyroclastic flows are composed of particles and gas, but if the mixture is gas-rich, it is called a pyroclastic surge. A pyroclastic surge is only weakly controlled by topography. The two often occur simultaneously.

Both pyroclastic flows and pyroclastic surges are extremely hazardous. Their speeds typically exceed 20 miles/hour (10 m/s) and sometimes exceed 200 miles/hour (100 m/s), making escape from their paths difficult or impossible (Hoblitt et al., 1998; NPS, 2001). Temperatures in pyroclastic flows are usually greater than 570° Fahrenheit (300° Celsius). Because of their high densities, high velocities, and high temperatures, pyroclastic flows can destroy all structures and kill all living things in their paths. Although they have lower densities and temperatures, pyroclastic surges may also be quite destructive and lethal. Animals may be killed by direct impact by rocks, severe burns, or suffocation.

Deposits of pyroclastic flows and surges exist at Mount Rainier, but not in abundance (Figure 4). Pyroclastic flow deposits about 2,500 years old are exposed in the South Puyallup River valley, about 7.5 miles (12 km) southwest of the volcano's summit. A thin surge deposit about 1,000 years old was discovered in White River valley about 7 miles (11 km) northeast of the summit (Hoblitt et al., 1998). Pyroclastic flows that travel across glaciers, however, do not weld and so do not leave long- lasting deposits. The dearth of pyroclastic flows, therefore, may be the result of pyroclastic flows and surges passing over snow and ice and being converted to debris flows (Hoblitt et al., 1998; Sisson et al., 2001). Hot rock fragments melt snow and ice, mix with the meltwater, and form lahars. Because Mount Rainier supports glaciers on all its sides, pyroclastic flows and the lahars they produce threaten all the valleys that originate on the volcano.

The types of pyroclastic flows at Mount Rainier are termed "block- and- ash" pyroclastic flows that are generally the result of lava dome collapse. Since Mount Rainier has only one lava dome exposed, the pyroclastic flows probably derived from other processes such as vent clearing explosions, voluminous hydromagmatic eruptions, or the sudden failure of thick, viscous lavas flowing over steep headwalls (Sisson et al., 2001).

Lava Flows

Andesite lava flows compose much of Mount Rainier. Because of the chemical composition of andesite, lavas composed of andesite tend to be viscous and rather slow moving. On gentle slopes, andesite lava flows more slowly than a person can walk. Lava flows will, however, destroy everything in their paths either by fire, impact, or burial. While the hazard to people from lava flows is low, a more serious hazard results when lava comes in contact with snow and ice. Flowing lava on the ice- covered slopes of Mount Rainier may break up, avalanche, and form much larger lahars (Sisson et al., 2001).

Unlike Mount St. Helens, Mount Rainier does not have significant lava domes. Two eruptive episodes in the past, one from 500,000- 420,000 years ago and one from 280,000- 180,000 years ago, produced lava flows that extended up to 14 miles (22 km) radially from the present summit location with individual volumes of up to 9 km^3 (cubic kilometers), but such voluminous and far-reaching lava flows are unlikely today (Sisson et al., 2001). Lava flows erupting outside of the two periods mentioned above have generally traveled no farther than 6 miles (10 km) from the summit and have volumes less than 0.5 km^3.

Throughout the history of the volcano, pyroclastic flows accompanied lava eruptions and probably are a greater hazard to life and property than are lava flows. Lava flows will probably extend no farther than the present terminus of the glaciers.

Volcanic Gases

Magma contains dissolved gasses that are released during and between eruptions. Andesitic volcanoes contain gases composed primarily of water vapor. Secondary gases are carbon dioxide and sulfur compounds. Minor amounts of carbon monoxide, chlorine, fluorine, boron compounds, ammonia, and several other compounds may be present, as well (Hoblitt et al., 1998).

Volcanic gases are distributed by wind. They may be concentrated near a vent and then diffuse rapidly downwind. Injuries to eyes and lungs from acids, ammonia, and other compounds and suffocation by denser- than- air gases, such as carbon dioxide, are possible. Metals can be severely corroded by volcanic gases.

Information about volcanic gases at Mount Rainier comes from studies of the volcano's hydrothermal system. In 1982, gas samples collected from fumaroles at Mount Rainier's summit recorded air enriched with carbon dioxide but no sulfurous gases. Presently, volcanic gases are only a hazard to climbers who enter the summit ice caves. When the volcano erupts, however, the gas- emission rate will increase as will the potential hazard from volcanic gases.

Mineral springs and meadows just northwest of the Longmire developed area in the park are potential hazards due to lethal volcanic gases. Carbon dioxide, carbon monoxide, and other potentially dangerous emissions are known to have killed animals at the site. However, the gases pose little risk to trail hikers passing through the area (NPS, 2001).

Debris Avalanches, Debris Flows, and Lahars

In 1980, at Mount St. Helens, rising magma created a bulge that broke away from the rest of the volcano and generated a rapidly moving landslide. Landslides caused by the failure of unstable slopes are called debris avalanches. A volcano's slopes can also fail even if magma isn't involved. Slopes may become unstable by melting of snow during periods of unusually high temperatures or unusually heavy rain in summer or early autumn, by glacial erosion, or as the strength of the rock is reduced by hydrothermal alteration. Hydrothermal alteration causes the rock to become weaker by chemically altering it to clay and other minerals. Eventually, the affected part of the volcano collapses under its own weight, generating a debris avalanche.

Non- magmatic debris avalanches are especially dangerous because they can happen without warning. Debris avalanches may be triggered by earthquakes, steam explosions, and intense rainstorms affecting weakened slopes in the park.

Debris avalanches can travel tens of kilometers at speeds of tens to hundreds of kilometers per hour. Like pyroclastic flows, escape from a debris avalanche is difficult to impossible. Topography controls a debris avalanche, which will destroy everything in its path and leave a deposit that is usually a few meters to hundreds of meters thick (Hoblitt et al., 1998). Large debris avalanches may block the mouths of tributary valleys and cause lakes to form. When impounded water spills over the dam formed by the debris avalanche, it can quickly cut a channel and cause the lake to drain catastrophically.

Debris avalanches commonly contain enough water, snow, or ice to transform them into debris flows or lahars. Lahars are slurries of water and sediment (60 percent or more by volume) that resemble flowing cement. Lahars are sometimes called mudflows and can travel at speeds reaching a few tens of kilometers per hour along gently sloping distal valleys to more than 100 kilometers (60 miles) per hour on steep slopes near the volcano (Crandell, 1969A; Fiske et al., 1963, 1988; Scott et al., 1995; Hoblitt et al., 1998; Kiver and Harris, 1999). Water in reservoirs may be displaced by lahars and could cause floods farther downstream.

At least 60 lahars of various sized have flowed down valleys on Mount Rainier during the past 10,000 years (Figure 4). All of these lahars can be grouped into two general categories: cohesive and non- cohesive lahars. Cohesive lahars contain relatively large amounts of clay derived from chemically altered rocks. They form when debris avalanches originate from hydrothermally altered parts of the volcano. Non- cohesive lahars contain relatively little clay and are triggered whenever water mixes with loose rock debris. This can be caused by the mixing of pyroclastic flows or pyroclastic surges with snow or ice; relatively small debris avalanches; unusually heavy rain; or an abrupt release of glacier- stored water.

The largest lahar at MORA in the last 10,000 years was a cohesive lahar known as the Osceola Mudflow. The Osceola Mudflow occurred about 5,600 years ago and was at least 10 times larger than any other known lahar from Mount Rainier. Perhaps triggered as magma forced its way into the volcano, the mudflow was the product of a large debris avalanche composed mostly of hydrothermally- altered material. Extending at least as far as the Seattle suburb of Kent and to Commencement Bay (now the site of the Port of Tacoma), the Osceola Mudflow left deposits that cover an area of about 212 square miles (550 sq km) in the Puget Sound lowland (Hoblitt et al., 1998). The mudflow deposited more than 4.9 billion cubic yards (3.7 billion cu meters) of material (NPS, 2001). Remnants of the mudflow on the sides of the White River and West Fork valleys show that both valleys were temporarily filled with streams of mud more than 500 feet (150 m) thick (Crandell, 1969B).

Today, a similar event would produce a mudflow in the reservoir behind Mud Mountain Dam where it would acquire more water and thus increase its mobility. The reservoir dam would be destroyed and the mudflow would easily inundate the towns of Enumclaw, Buckley, Kent, Auburn, Sumner, and Puyallup, a combined population of 125,000 people in 1999. If an emergency warning sounded at the time the mudflow began, most people would have less than 2 hours to evacuate their homes.

The Electron Mudflow originated from a slope failure on the west flank of Mount Rainier about 600 years ago and is unique in that it has not been correlated with a volcanic eruption. The mudflow reached the Puget Sound lowland along the Puyallup River. When the mudflow reached the community of Electron, it was more than 98 feet (30 m) deep. At Orting, mudflow deposits are as much as 20 feet (6 m) thick and contain remnants of an old- growth forest (Hoblitt et al., 1998).

Large non- cohesive lahars are associated with volcanism. Valleys of both forks of the White River were filled to depths of 60 to 90 feet (20 to 30 m) about 1,200 years ago by a non- cohesive lahar, which flowed 60 miles (100 km) to Auburn. About 2,200 years ago, another lahar, named the National Lahar, inundated the Nisqually River valley to depths of 30 to 120 feet (10 to 40 m) and flowed all the way to Puget Sound. These non- cohesive lahars form as hot rock fragments flow over glacier ice and snow. The vast quantities of meltwater then mix with rock debris to form lahars. In the past 6,000 years, periods of volcanism have produced more than a dozen non- cohesive lahars.

Geologic circumstances conducive to debris avalanches and lahars include:

- Substantial volumes of hydrothermally altered rock
- Substantial topographic relief
- Great volumes of ice
- Potential for renewed volcanism

All of these circumstances are present at Mount Rainier, making lahars a larger threat to communities down valley from Mount Rainier than any other volcanic phenomenon.

Lahars at Mount Rainier can be classed in to three groups according to their genesis: 1) flank collapse of hydrothermally altered, water- saturated rock; 2) eruption- related release of water and loose debris; and 3) hydrologic release of water and debris (Scott and Vallance, 1995; Scott et al., 1995; Vallance et al., 2003). Vallance and others (2003) distinguish lahars in the third category as debris flows. Debris flows are less voluminous than the other lahars, but occur frequently at Mount Rainier, often with little or no warning.

In the past, glacial outburst floods, torrential rains, and stream capture have caused small- to moderate- size debris flows. Commonly, debris flows occur in drainages that have large glaciers in them. However, a drainage diversion may trigger a debris flow in an unglaciated drainage basin such as the diversion of Kautz Glacier meltwater into Van Trump basin on the south side of Rainier which occurred in August, 2001 (Vallance et al., 2003).

At Mount Rainier, many of the developed sites are located in valley bottoms on historic debris flow and lahar deposits. Seventeen of twenty- three developed sites in the park are within mapped debris flow hazard zones (Hoblitt et al., 1995, 1998; NPS, 2001). These hazard zones identify where debris flows could occur and at what frequency (recurrence interval) and magnitude they might occur (Figure 5). For the purpose of hazard assessment, four classes of lahars have been designated: Case M, Case I, Case II, and Case III lahars (Hoblitt et al., 1998).

Case M flows (not shown on Figure 5) are extreme flows such as the Osceola mudflow. Lahars of this magnitude are too infrequent to estimate an annual probability (Hoblitt et al., 1998).

Case I flows originate from debris avalanches of weak, chemically altered rock. Case I debris flows have a recurrence interval of 500 to 1,000 years, an annual probability of 0.1 to 0.2 percent. The Electron Mudflow is an example of a Case I debris flow. The Electron

Mudflow, however, inundated floodplains that were covered by a mature old- growth forest. Today, an Electron- size mudflow would spread farther and faster across floodplains that are now deforested and thus hydraulically smoother. Consequently, hazard zone maps reflect this modern scenario that might inundate 40 percent more area than the original Electron Mudflow (Hoblitt et al., 1998). A Case I lahar could destroy all or parts of Orting, Sumner, Puyallup, Fife, the Port of Tacoma, and possibly Auburn.

Case II flows are relatively large non- cohesive flows containing coarser materials and lower clay contents than Case I flows. They occur on an estimated recurrence interval of 100 to 500 years, analogous to the 100- year flood commonly considered in engineering practice. As with Case I flows, both eruptive and non- eruptive origins are possible for Case II flows. For example, in 1947, a Case II flow occurred at Kautz Creek due to heavy rain and the release of water stored within a glacier. The National Lahar, which occurred in the Nisqually River valley less than 2,000 years ago, is considered a characteristic Case II flow. The Case II inundation zone of Hoblitt and others (1998) reflects the recent discovery of lahar- related deposits from Mount Rainier that apparently filled the lower Duwamish River valley from wall to wall as far as Elliott Bay in Puget Sound.

Case III flows may be moderately large debris avalanches or small, non- cohesive debris flows that typically extend to the base of the volcano near the park boundary. The recurrence interval for Case III flows is 1 to 100 years. This class includes small debris avalanches as well as lahars. Most commonly, Case III flows are lahars triggered by a sudden, unpredictable release of water stored by glaciers. For the purposes of hazard assessment, the lahar that occurred about 500 years ago in the Tahoma Creek valley is considered a characteristic Case III flow (Hoblitt et al., 1998).

The revised hazard maps of Hoblitt and others (1998) also reflect the potential failure of Alder Lake on the Nisqually River. Since Alder Dam exists for power generation, the lake is never empty. Should a Case I flow enter the reservoir, the dam might fail or a significant volume of water in storage could be displaced, causing catastrophic downstream flooding. The inundation zone would, therefore, be similar to that determined for a sudden failure of the dam (Hoblitt et al., 1998).

Facilities at the Paradise area of the park are located on the south flank of Mount Rainier about 5,260 feet (1,604 m) above sea level and less than 6.5 miles (10 km) from the summit crater. Because Paradise is located on a bench above the floors of the Paradise and Nisqually Valleys, it is not in a debris flow inundation area. Its location near the summit, however, makes it one of the most vulnerable sites for volcanic hazards associated with eruptions.

Sunrise is also located on a ridge top, well above the debris flow hazard zones on the Whiter River valley floor. However, like Paradise, Sunrise is near the summit and may be impacted by a volcanic eruption (NPS, 2001).

Research has shown that eruptions can trigger lahars either directly by hot rock avalanches and pyroclastic flows, or indirectly when volcanic unrest dislodges unstable edifice flanks (Sisson et al., 2001). Spontaneous, unheralded collapses of Mount Rainier's flanks appear less common than was previously supposed. Pre- eruptive seismicity, enhanced gas emissions, or edifice deformation may precede and warn of future large lahars. The alteration- rich Electron Mudflow of about 560 years ago, however, is an exception to this rule as no evidence of an associated eruption has yet been found.

Lateral Blasts

All of the parks' developed areas are within a 22- mile (35- km) diameter lateral blast zone (Crandell and Hoblitt, 1986; Hoblitt et al., 1995). Lateral blasts occur when the side of a shallow magma body or hydrothermal system is suddenly depressurized. The explosion produces a pyroclastic surge that can travel tens of miles (tens of kilometers) from the volcano. In 1980, a body of magma accumulated within Mount St. Helens over a period of 52 days and caused the north flank to bulge outward. The bulging enlarged and the northern sector broke away from the rest of the volcano, producing a great debris avalanche, and the depressurized magma body exploded, producing a lateral blast (Hoblitt et al., 1998). A lateral blast also was associated with the debris avalanche that produced the Osceola Mudflow.

Lateral blasts caused by magma moving into a volcano can be predicted with adequate monitoring. Lateral blasts may occur, however, without the movement of magma if a non- magmatic debris avalanche uncovers an active hydrothermal system, which then explodes. Three factors, all of which are present at Mount Rainier, include:

- Substantial volumes of weak hydrothermally altered rock
- Substantial topographic relief
- An active hydrothermal system

Hydrothermal Alteration Zones

The Osceola Mudflow, the signature event in the Holocene history of Mount Rainier, was remarkable in its volume, abundance of hydrothermal clay, and its nearly immediate transformation to a mobile lahar (Sisson et al., 2001). Several other far- reaching Holocene lahars from Mount Rainier also contain clays and other hydrothermal minerals, raising the concern that the volcano's edifice is composed of widespread weak altered rocks. However, detailed geologic mapping, remote sensing, and geochronology showed that intense and pervasive alteration of edifice rocks is confined to a relatively narrow east- northeast to west- southwest trending belt that passes through the summit (Sisson et al., 2001). In contrast to the narrow belt of hydrothermally altered rock, the dominant unaltered portions of the edifice have been stable, as is shown by widespread preservation of rocks as old as 200,000 years above 13,780 feet (4,200 m) elevation on the volcano's northwest face.

High- resolution aeromagnetic and electrical resistivity surveys and three- dimensional slope stability models further assessed the distribution of altered, structurally weak rocks and the consequences if they collapse at Mount Rainier. Research showed that large volumes of highly altered rock are restricted to Mount Rainier's upper west flank and to smaller bodies in the subsurface that partially ring the Osceola collapse crater. Only very small amounts of extremely altered rock underlie the volcano's summit and upper northeast slope (Sisson et al., 2001). Mount Rainer's upper west flank has the greatest likelihood of gravitational failure and the lahars produced from this potential collapse pose the greatest risk to the Puyallup River valley that heads on the volcano's altered west flank.

Recent geologic mapping has identified valleys in the park that might host a large debris flow or small debris avalanche (Sisson, 1995; Zimbelman, 1995; Crowley and Zimbelman, 1997). Mapping included zones of rock weakened by fractures, faults, and the alteration of minerals to weak clay minerals by hot gases (hydrothermal alteration). Areas containing fractures caused by down slope movement of hydrothermally altered rocks include Little Tahoma Peak, the east side of the volcano, and the west side of Sunset Amphitheater (Figure 5).

Glacial Outburst Floods

Glacial outburst floods are a type of flood that is caused by a massive, sudden release of water from a glacier. These may occur on sunny or rainy days in the summer or fall (Walder and Driedger, 1993). Outburst floods pose a serious hazard to life and property. Peak discharge of an outburst flood may be greater than the 100- year flood commonly considered in engineering practices. Since 1926, bridges, roads, and National Park visitor facilities have been destroyed or damaged on about ten occasions by outburst floods. Rarely, however, are the effects of outburst floods noticeable outside the park boundaries (Hoblitt et al., 1998).

Outburst floods have occurred from the Kautz, Nisqually, South Tahoma and Winthrop glaciers. Many of these outburst floods became lahars as they incorporated large quantities of sediment in their flows. Sediment is available since the glaciers on Mount Rainier have retreated substantially since the mid- 19th century (Hoblitt et al., 1998). Upon glacial retreat, stagnant masses of sediment- rich glacial ice become stranded in valleys downstream from present- day glaciers. Floods easily erode these stagnant ice masses. Over a period of decades, as the stagnant ice melts, stream channels should become more stable and less affected by outburst floods. Nisqually Glacier produced outburst floods in the 1950s and 1960s, but the glacier has not produced a flood since 1990.

Glacial outburst floods are not related to volcanic activity at Mount Rainier (Hoblitt et al., 1998). Rather, studies show that outburst floods are correlated with periods of unusually high temperatures or unusually heavy rain in summer or early autumn.

Flooding

Rivers that drain Mount Rainier are on the steep- slopes of the volcano. They carry vast amounts of water, sand, gravel, and boulders. Streams in the park generally have a braided channel pattern and highly unstable and eroding banks because of the large volume of sediment and debris carried by the rivers. Stream channel instability in valleys throughout the park is caused by deposition of glacial sediments by floods and debris flows. Because channels are not stable, the 100 and 500- year floodplains associated with Mount Rainier rivers are not static and continue to change over time.

Floods can occur in MORA year- round and can be triggered by a number of events, including glacial outbursts, precipitation, melting of snow and ice, and volcanic activity. Debris flows and precipitation- induced flooding are two end members on a continuum of hydrologic and geologic events.

On average, precipitation- induced flooding occurs twice a year on rivers at MORA. The largest and most frequent precipitation- induced floods occur during late fall and early winter, when heavy rainfall melts snow at higher elevations. High peak flows in these floods have damaged both the Carbon River Road and Westside Road. Rapid melting of snow produces spring floods in April and May. Spring floods have smaller peak flows but longer duration than do the fall and winter floods (NPS, 2001).

Melting glacial ice (meltwater) produces floods primarily during the summer and fall, primarily in late July and August. Daily cycles of high afternoon discharge rates on glacial meltwater streams also pose a safety hazard for hikers.

Extreme floods trigger debris flows (or lahars) composed of water, ice, sediment, and other debris. Debris flows can begin as outburst floods from glaciers and then transform into sediment- laden debris flows as they flow down slope. They occur less frequently than other types of floods, but are far more destructive than water- dominated floods.

Floodplain assessments conducted at the 13 developed sites with overnight housing and sensitive facilities at MORA showed that 9 of the 13 sites were outside their regulatory floodplains (100- or 500- year floodplain). The Carbon River entrance and the Ipsut Creek campground appear to be within the regulatory floodplain. The Longmire complex and Sunshine Point, although outside the regulatory floodplain, are prone to outburst flooding (NPS, 2001).

Although a flood in 1959 inundated the Longmire compound, a 1994 hydraulic model showed that 100-year and 500- year floods would be contained within the Nisqually River channel and would not flood the Longmire compound. Flood velocities, however, would cause severe erosion along unvegetated channel banks, such as along the levee constructed to protect Longmire.

The model further indicated that flood flows from a 500- year outburst flood would overflow the channel and flood the Longmire compound. Results from the model indicated that the 1959 flood was probably a small debris flow that may have started as an outburst flood from the Nisqually Glacier rather than a precipitation- induced event. Sediment deposited in the Nisqually River where the river exits a canyon near Longmire may have caused floodwater to be diverted into the compound (NPS, 2001). Longmire is in a Case III debris flow inundation zone (Figure 4).

Like Longmire, Sunshine Point campground was affected by prior flooding along the Nisqually River as a result of outburst flood activity from the Nisqually Glacier. However, outburst flooding from the glacier has decreased over the past few decades so that the probability that the campground would flood from such an event is small. Continued sediment deposition in the Nisqually River could cause higher flood elevations and require continued maintenance within the regulatory floodplain to avoid erosion of the campground's protective levees.

Ipsut Creek campground is in a high flood hazard area adjacent to the floodplain of the Carbon River. The channels within this large braided channel network shift constantly. Depths of flow for the 50- year and 100- year floods in the main channel of the Carbon River are shallow, only 3.5 feet (1 m), but velocities are rapid, estimated to be 8 feet per second (146 m/ min).

Parts of Ipsut Creek campground, former walk- in sites, and the entrance road occupy very low parts of the floodplain. Most of the campground is located on a low terrace rising 5 to 6 feet (1.8 m) above the current channel. The walk- in sites were permanently closed in 1997 after it was shown that these sites were isolated by swift water in a side channel during even small flood events. Discharges of 1,000 cubic feet per second or greater generate a high flood hazard for this area.

Results from a hydraulic model indicated that most of the Ipsut Creek campground is outside the 100- year floodplain. However, the model's boundaries for the 100- year floodplain may need to be adjusted due to the unstable nature of braided channels and the location of parts of the campground at lower elevations than the active river channel.

Continued deposition in the modern channel and upstream channel alignment may cause the Carbon River to shift to the south. If the channel does shift, it would isolate and claim all or parts of the campground and cause considerable damage to roads, trails, and other facilities (NPS, 2001).

Hydraulic models indicate that all the facilities at the Carbon River entrance are outside the 100- year regulatory floodplain. Historic flooding may have been caused by a shift in the channel of June Creek, a tributary to the Carbon River, to the west of the entrance area. Flooding that does occur at the entrance is shallow, less than 2 feet (0.6 m) of standing water, with very low velocities.

Other evidence, however, indicates that the Carbon River entrance facilities are within the floodplain. Floodplain soils, a levee, and an apparent absence of volcanic tephra point to larger floods that might have occasionally inundated this site in the recent past. Although the hydraulic model suggests otherwise, the entrance facilities have been placed within the regulatory floodplain because of the erosion of soils and the potential for floods to inundate the site (NPS, 2001).

Bank erosion over the next few decades also could threaten Carbon River entrance facilities. Channel changes have resulted in the migration of the Carbon River from its north bank to its south bank over the past few years. Because of this change, the road, which lies below the river in some places, has been flooded with smaller flood discharges.

Geologic Hazards During Dormant Periods

Snow avalanches, rockfalls, and landslides are geologic hazards that occur throughout MORA during dormant periods (termed "non- volcanic geologic hazards" in Figure 5). In 1963, the largest rockslide ever recorded in the park occurred on the east flank of Mount Rainier. A series of avalanches from the steep side of Little Tahoma Peak carried 4 billion cubic feet (113 cu m) of rock onto the Emmons glacier and to within 0.6 miles (1 km) of the White River campground (Crandell, 1969B).

Unstable bedrock on the slopes of Mount Wow have sent several mass movements into the Tahoma Creek valley and this area still remains a geologic hazard (Scott et al., 1995). Westside road crosses a small talus field and rockfall hazard east of Lake Allen and a larger talus field, rockfall and snow avalanche area between Dry Creek and the former picnic area. Visitors who park at the current end of the road (Dry Creek) are exposed to potential rockfall hazards.

The location of the White River campground poses major safety hazards to both overnight and daytime visitors (NPS, 2001). The site is in a Case III inundation zone for debris flows and in the pyroclastic flow zone (Figure 5). The campground rests on a terrace only 35 feet (11.5 m) above the White River. The terrace was formed by a debris flow deposit estimated to be 500-

2,000 years old (Crandell, 1971). A large mass of fractured, hydrothermally altered rock is perched just above the campground on Little Tahoma Peak. These weakened rocks were the source of a 1963 debris avalanche that stopped about 3,000 feet (0.6 mile or 600 meters) short of the campground after it had already traveled 4.3 miles (7 km).

The proximity of Cougar Rock campground to the volcano and the site's location on a low- elevation debris flow terrace within the Case III inundation zone makes overnight use at the campground highly hazardous. Several debris flows formed the terrace, including the National and Paradise lahars that inundated the site in the last 5,000 years.

Cliffs on a ridge descending from Rampart Ridge pose a potential rockfall hazard at the southwest end of the campground. A potential landslide 1.5 miles (2.5 km) upstream on the west side of the Nisqually River at an elevation of 5,600 feet (1,700 m) could threaten Cougar Rock Campground. The Nisqually Glacier undercut this slope, which is now covered with unstable glacial sediments.

Rockfall also is a potential non- volcanic geologic hazard at the Stevens Canyon entrance and in the Stevens Canyon area.

Park facilities at Ohanapecosh are located in a Case II inundation zone on a series of river terraces and bedrock benches along the Ohanapecosh River. Potential failure of the weak rocks of the Ohanapecosh Formation on the east valley wall threatens visitors and employees at the site. The presence of hot springs indicates the continued hydrothermal alteration and weakening of the host rock.

While the ridge top location of Mowich Lake is well above the valley floor where debris flows could occur, debris flows may block roads in the Carbon River valley and affect evacuation efforts.

Glacial Monitoring

The glaciers on Mount Rainier are important sources of streamflow for several rivers, including some that provide water for hydroelectric power and irrigation. They also pose geologic hazards in the form of glacial outburst floods. Glaciers are sensitive indicators of climate changes and affect the distribution of aquatic and terrestrial habitat through their advance and retreat. Because Mount Rainier glaciers are a significant component of the regional hydrologic system and have both immediate and long- term impacts on the local and regional environment, glacial monitoring becomes an important issue for MORA.

Measuring and monitoring glacial response to climate is commonly accomplished by measuring the terminus position and surface elevation of a glacier. Nisqually Glacier has the lengthiest surface- elevation record of any in North America. Begun in 1931, the record shows the glacier's responses to small but significant climatic variations.

In 2004, data from maps and aerial photographs were compiled into a geographic information system (GIS) database (Nylen, 2004). The spatial and temporal variations of Mount Rainier glaciers from 1913 to 1994 show that:

- the glaciers on Mt. Rainier have decreased in area, volume, and length;
- the retreat of the glaciers from 1913- 1994 was not continuous;
- the temporal changes in area, volume and terminus position of the glaciers are driven by climate variations;
- spatial differences affected the response of the glaciers to climate variation.

Between 1913- 1994, the total area and volume of Mount Rainier glaciers shrank by 21 percent and 25 percent, respectively. The average retreat of the 11 largest glaciers was 3,737 feet (1,139 m), an average of 46 feet per year (14 meters/year). South Tahoma Glacier had the largest retreat of 8,334 feet (2,540 m) (Nylen, 2004).

The 11 monitored glaciers in Nylen's study advanced an average of 1,280 feet (390 m) between the mid- 1950s and the mid- 1980s. High snowfalls during the 1960s and 1970s led to the advance of the Carbon, Cowlitz, Emmons, and Nisqually Glaciers during the 1970s and early 1980s (Driedger, 1992; Nylen, 2004). Except for Emmons and Cowlitz glaciers, the glaciers retreated after the mid- 1980s. Debris cover on Emmons and Cowlitz glaciers may have slowed melting.

Some glaciers have retreated more than two miles (3.2 km) up their valleys since reaching their maximum post- Pleistocene extent during the Little Ice Age (between the 14th century and 1850 A.D.) (Driedger, 1986). At the time of the Little Ice Age, the Nisqually Glacier advanced to a position 650- 800 feet (183- 244 m) down valley from the site of the Glacier Bridge. Tahoma and South Tahoma Glaciers merged at the base of Glacier Island, and the terminus of Emmons Glacier reached within 1.2 miles (1.9 km) of the White River Campground.

Between 1954 and 1994, winter snowfall at the Paradise Station decreased by 5.1 cm/year. A corresponding retreat in the terminus position of Mount Rainier glaciers correlates with this drop in precipitation (Nylen, 2004).

At Mount Rainier, southern glaciers decreased in area, volume, and length more than the northern glaciers. The southern glaciers are smaller than the northern glaciers, and size appears to be the controlling factor on area decrease. Smaller glaciers have small elevation ranges and are, therefore, more sensitive to climate changes than larger glaciers.

Cloud cover increased by 45 percent between 1963 and 1983 and decreased by 69 percent between 1983 and 1992. Glacial advance and retreat can be correlated with these time periods. Nylen also showed that aspect and cloud cover are directly related. Fewer clouds mean relatively more energy available to melt the southern glaciers.

Nylen's research demonstrated that monitoring only one glacier is not adequate when trying to determine regional variations in glacial response to climate change. At MORA, a long- term monitoring protocol is being developed that will identify a number of index glaciers to represent the larger population of MORA glaciers (Paul Kennard, MORA Regional Geomorphologist, personal communication). Measurable objectives of this protocol include:

- determining summer, winter and net mass balance at index glaciers;
- determining glacial contribution to summer runoff for two MORA watersheds;
- assessing surface features changes related to glacial hazards at MORA;
- determining glacier volume and area for index glaciers at 10 year intervals, and for all glaciers every 20 years
- tracking annual surface elevation changes across 3 fixed lateral transects at Nisqually Glacier, in order to track trends in kinematic waves;
- determining relationships among surface elevation data, mass balance data, and glacier dynamics and movement.

Implementation of these protocols will help track the response of glaciers to variations in both temperature and precipitation and thus record regional and global climate change over longer time periods than most other climate measures.

Soils

Cryptobiotic soil crusts are the foundation of high-elevation ecosystems. Cryptobiotic soil crusts bind soil particles together, thus increasing soil stability, and have been shown to increase rainfall infiltration, to reduce sediment production and runoff, and to facilitate the establishment of vascular plants by enhancing nutrient and water availability for these plants.

No systematic soil mapping project has been conducted for Mount Rainier National Park (NPS, 2001). Solid rock and talus slopes with virtually no topsoil occupy the higher elevations of Mount Rainier while lower elevations are composed of glacial till. Valley bottoms contain layers of mixed rocks and benches of silt deposited by streams and glaciers. Subalpine meadows have very shallow, loose, friable soils that are easily eroded by foot and horse traffic.

A classification system developed for forest soils and based on the geological origin, relief, and drainage features of the park identified the following four most common soil groups in the forested areas of Mount Rainier(Hobson, 1976).

- Tephra soils: pyroclastic deposits
- Colluvial soils: unstable soils
- Alluvial soils: formed from river deposition, glacial outburst floods, and ephemeral streams carrying snowmelt discharge
- Mudflow soils: result of lahars

Tephra soils are identified by individual ash layers and are the result of volcanic eruptions of Mount Rainier, Mount St. Helens, and to a lesser extent, Mount Mazama (the volcano that erupted about 7,000 years ago to form Crater Lake). Although thin, these soils support the subalpine and alpine meadows in the park.

Colluvial soils are rapidly drained and consist of coarse, unconsolidated, mixed parent materials. These soils are found on slopes at all elevations. They are especially prevalent on steep slopes and south- facing areas of the park.

Alluvial soils are often found in major river valleys, along streams, on wet benches, and on alluvial slopes and fans.

Mudflow soils are surface or subsurface parent materials within the rooting zone. Mudflow soils may contain tephra W, a volcanic ash layer from a Mount St. Helens eruption, as well as alluvial or colluvial surface deposits.

The destruction of cryptobiotic soil crusts by visitor use is a geologic issue at MORA (NPS, 2001). The most severe damage is in subalpine and alpine meadows. In these areas, the "damage ranges from trampled vegetation in campsites or informal (social) trails to severely eroded social or designated trails, some over 3 feet deep" (NPS, 2001, p. 139).

In Paradise Meadows, approximately 89 percent of the human impacts were in the form of social trails. Of 1,126 social trails studied in 1987, high elevation trails were found to be more susceptible to erosion than middle and low elevation trails while slope was the variable accounting for the most variance in trail depth (Fritzke, 1992). In the same study, five plant communities were evaluated, and the heath shrub community was found to be the most susceptible to damage when a social trail was established.

The remaining impacts were large bare areas used as rest stops and viewpoints. Many of these impacts were over 20 years old. The *Paradise Meadow Plan* (Rochefort, 1989) identified 913 human- caused bare ground impacts, with 28.5 miles (46 km) of social trail compared to 13.5 miles (22 km) of maintained trails.

Studies of human impacts have been done since the late 1960s above Paradise in the Muir corridor. Unauthorized campsites and social trails have been documented in these studies. Most of the campsites were found in rocky areas.

Intensive human use also has led to severely eroded areas and bare ground in Spray Park, Mowich Lake, Reflection Lake, and Tipsoo Lake.

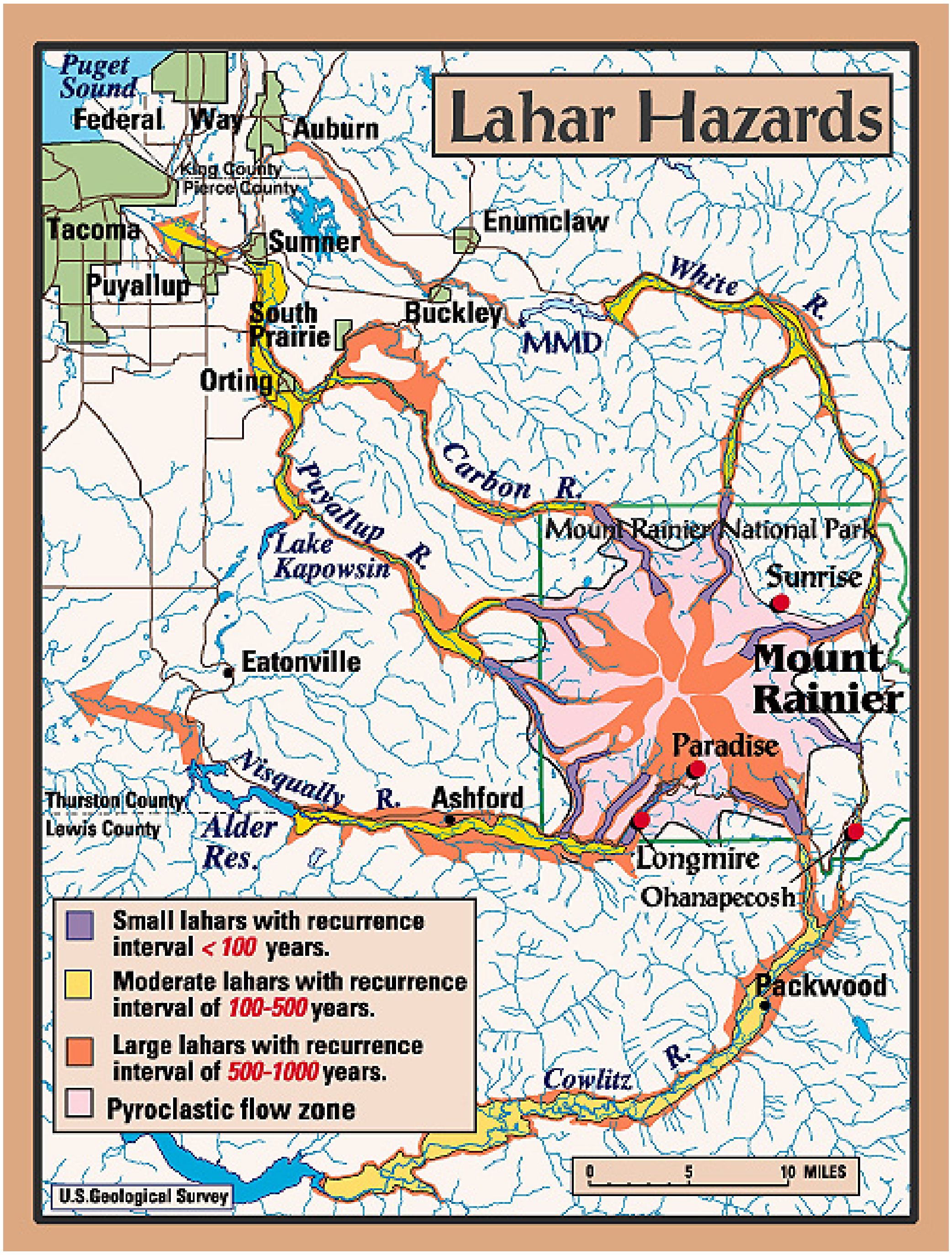

Figure 4: Hazard zones for lahars and pyroclastic flows from Mount Rainier (Hoblitt et al., 1998). The map shows areas that could be inundated if events similar in size to those of the past occurred today. Puyallup Valley is the valley most susceptible to lahars caused by flank collapse. MMD: Mud Mountain Dam.

Sites at Mount Rainier within volcanic and non-volcanic hazard zones

Park Site	Case I Debris Flow Zone	Case II Debris Flow Zone	Case III Debris Flow Zone	Hydro-thermally altered rock	Non-volcanic geologic hazard	Pyroclastic Flow Zone
Tahoma Woods	X			X		
Nisqually entrance		X		X	X	X
Sunshine Pt. Campground		X		X	X	X
Kautz Creek			X		X	X
Westside Rd	X	X	X		X	X
Longmire			X		X	X
Cougar Rk campground			X		X	X
Paradise						X
Camp Muir	X					X
Narada Falls picnic area	X				X	X
Box Canyon picnic area			X	X		X
Ohanapecosh		X			X	X
Stevens Canyon entrance		X			X	
White River entrance		X		X		X
White River campground			X	X		X
Camp Schuman	X				X	X
Sunrise					X	X
Mowich Lake						X
Carbon River entrance		X			X	X
Falls Creek picnic area		X			X	X
Ipsut Creek campground			X		X	X

Figure 5: Reproduced from the Mount Rainier National Park General Management Plan, page 156 (2001).

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Mount Rainier National Park.

At present, the Cascade Province contains four national parks and one volcanic monument: Mount Rainier National Park (WA), North Cascades National Park (WA), Crater Lake National Park (OR), Lassen Volcanic National Park (CA) and Mount St. Helens Volcanic Monument (WA), managed by the U.S. Forest Service. These parks, as well as other Cascade Mountain areas, contain world- class examples of volcanic and glacial features. The geologic features and processes in MORA are divided into the following sections:

- Glacial Features and Glacier Processes
- Volcanic Features
- Thermal Features and Ice Caves

Glacial Features and Glacier Processes

Glaciers are highly effective erosional agents, shaping mountains into picturesque landforms with such distinctive erosional features as *horns* (peaks), *cirques* (deep, bowl- shaped, steep- walled recesses in a mountain), *glacial valleys* (U- shaped valleys), and *arêtes* (rugged crests or ridges between two mountains). Tipsoo Lake, Crescent Lake, and Mowich Lake are examples of cirque lakes at MORA. Some tributary streams end as waterfalls at the mouth of *hanging valleys* like Christine Falls and Comet Falls. Carved by glaciers, hanging valleys are erosional features in which the floor of the valley is notably higher than the level of the valley to which it leads. Most of the glacial landforms on Mount Rainier are the result of Pleistocene glaciers that formed 25,000 to 10,000 years ago and continue to erode the mountain today.

Depositional features are formed from material eroded from the mountain that is transported down valley and deposited as rock debris termed *drift*. Glacial *till* is unconsolidated, poorly sorted drift that forms end and lateral *moraines,* undulating mounds composed of boulders, cobbles, pebbles, sand, silt, and clay clasts. Many of the deposits left by mudflows, debris flows, and avalanches also are associated with the glaciers on Mount Rainier.

The valley glaciers that create the backcountry of Mount Rainier radiate like spokes on a wheel from the summit of the volcano (Figure 1). About 35,000 years ago, the Cowlitz Glacier on the southeast side of the mountain extended 65 miles (105 km) from the mountain and about 8 miles (13 km) west of the present town of Randle (Kiver and Harris, 1999). The end of the Pleistocene Ice Age came about 10,000 years ago, about the same time as the eruptive event that formed the main cone of Mount Rainier.

The extreme height and massive character of the volcano allows it to intercept moisture- laden westerly winds from the Pacific and to receive abundant snowfall that helps maintain glacial cover. For example, during the winter of 1971- 1972, slightly more than 102 feet (31 m) of snow fell on the mountain, setting a world's record at an official weather station (Kiver and Harris, 1999). Since the mid- 1800s, however, the glaciers have lost as much as 35 percent of their surface area. This trend is synchronous with glacier retreat recorded elsewhere around the world and reflects global warming trends from natural perturbations and human influences. From 1900 to 1960, the Nisqually Glacier retreated about 1 mile (1.6 km) upstream from the old highway bridge (Kiver and Harris, 1999). Paradise Ice Caves, once a major attraction for visitors, collapsed in the fall of 1991 due to the effects of global warming.

The glaciers of Mount Rainier form the largest glacier system in the conterminous United States. Some of the glaciers originate from the summit of the volcano while others extend down the mountain flanks from cirques located in the high- precipitation zone at middle elevations. Linear rock ridges or arêtes, locally known as *cleavers*, separate the glaciers. The Willis Wall is the 3,600- foot- high (1,100 m) vertical headwall that marks the Carbon Glacier cirque. Over a mile wide, the Carbon Glacier cirque is the largest in the Cascade Mountains (Kiver and Harris, 1999).

Over one cubic mile of snow and ice is estimated to perpetually cover Mount Rainier. Only a relatively thin veil separates this ice from the "Mountain of Fire". If this ice were to melt during an eruption, huge floods and mudflows would easily reach the densely populated areas in the Puget Lowland.

The following points of interest are associated with Mount Rainier glaciers or glacial processes. Emmons, Ingraham (Cowlitz- Ingraham), Nisqually, Tahoma, and Winthrop glaciers are the predominant glaciers originating on the summit of Mount Rainier.

Emmons Glacier: Named for geologist, Samuel F. Emmons, the Emmons Glacier is the largest glacier in the contiguous United States. Located on the east slope of Mount Rainier, the Emmons Glacier covers 4.3 square miles (11.1 sq km). A landslide in 1963 covered the lower glacier with rock debris, which insulates the ice from melting. As a result if irregular melting, a vast hummocky topography has formed over the area.

Cowlitz- Ingraham Glacier: The Cowlitz- Ingraham Glacier is currently thinning and retreating although it made a notable advance in the mid- 1970s and continued to slowly advance until the mid- 1980s.

Nisqually Glacier: One of the most accessible glaciers on Mount Rainier, Nisqually glacier can be viewed from Nisqually and Glacier Vistas. Nisqually Glacier holds the record for the fastest measured downhill movement for a Mount Rainier glacier: 29 inches per day (74 cm/d). The glacier thinned by 53 feet (16 m) in the region immediately west of Glacier Vista between 1985 and 1991, but the retreat may be slowing.

Winthrop Glacier: With an area of 3.5 square miles (9.1 sq km), the Winthrop Glacier is the second largest glacier on Mount Rainier. The glacier extends from the summit to the 4,700- feet level (1,433 m) of the West Fork White River Valley. Winthrop Glacier was named for Theodore Winthrop who visited the mountain in 1853, described his experiences in his book *Canoe and Saddle*, and died on the field of battle during the Civil War.

Carbon Glacier: Measurements of the Carbon Glacier, the largest in the park, recorded a thickness of over 700 feet (215 m). Although the third largest glacier by area on Mount Rainier, Carbon Glacier has the greatest thickness and volume (0.2 cubic miles) of any glacier in the contiguous United States. It is 5.7 miles long (9.2 km), which makes it also the longest glacier on Mount Rainier. Beginning just below the imposing 4,000- foot- high (1,219 m) Willis Wall, the glacier's terminus is surrounded by mature forest and shrubbery at an altitude of 3,500 feet (1,067 m).

Kautz Glacier: Kautz Glacier, named in honor of Lieutenant (later General) A.V. Kautz, is one of the primary glaciers on the mountain. In 1857, Kautz made the first attempt to scale the peak by climbing along the edge of the glacier that bears his name. He failed to reach the summit by only a few feet. Kautz Creek originates in the Kautz Glacier and flows into the Nisqually River.

Paradise Glacier: The Paradise Glacier area was one of the main attractions for visitors in the early part of the twentieth century. Because of this attraction, the Paradise Inn was built and opened for business in 1917.

Russell Glacier and Wilson Glacier: These two glaciers are tributary glaciers of major glaciers in the park. Russell Glacier is named after Professor Israel C. Russell, the first scientist to describe the glaciers of the park, and is one of the largest inter- glaciers of the park. It is a tributary to the Carbon Glacier on the north side of Mount Rainier.

Wilson Glacier is a tributary to the Nisqually Glacier on the mountain's south side. It was named for A.D. Wilson. In 1870, Wilson and Professor S.F. Emmons made the second successful ascent of Mount Rainier.

Stevens Glacier, Van Trump Glacier, and Sluiskin Falls: The Stevens Glacier and the Van Trump Glacier are on the southern slope of the mountain. In 1870, Philemon Beecher Van Trump and General Hazard Stevens made the first successful ascent to the summit of Mount Rainier. The Yakima Indian brave, Sluiskin, guided the two men. They named the falls at the head of the Paradise River after their guide.

Sunset Amphitheatre: Chiseled and dredged by rockslides, glacial erosion, and frost action, Sunset Amphitheatre is a cirque- like gouge near the summit of the mountain. Puyallup Glacier originates in Sunset Amphitheatre. A cliff collapse that formed this cirque may have triggered the Electron Mudflow about 500 years ago. This mudflow inundated at least 14 square miles (36 sq km) of Puget Sound Lowland and formed the valley surface around Orting, Washington.

Volcanic Features

The eruption of Mount Rainier also left some distinctive volcanic features. Summit features, rock walls, and satellite volcanoes rim the mountain.

Columbia Crest, Liberty Cap, Point Success: These three distinct summits are high points at the top of Mount Rainier. At 14,410 feet (4,392 m), Columbia Crest is the highest and lies in the rim of a small recent lava cone. The cone is indented by two craters. The larger of the two is about one- quarter mile (0.4 km) in diameter, and both craters are nearly filled with snow and ice. Volcanic heat and steam have melted a system of tunnels and caves in the ice. Liberty Cap and Point Success are remnants of the sides of an old, high cone.

Echo Rock and Observation Rock: Echo Rock and Observation Rock are dissected satellite volcanoes. Olivine andesite erupted from these satellite volcanoes on the northwestern flank of Mount Rainier.

Little Tahoma and McClure Rock: Northwest American Indians named the mountain Takhoma, Tahoma, Ta-co- bet and other names that mean "big mountain", or "snowy peak", or "place where the waters begin". Little Tahoma is a prominent rock outcrop on the east side of Mount Rainier.

McClure Rock is a prominent point on the southern shoulder of the mountain. The point was named for Professor McClure, University of Oregon, who fell and died while doing scientific research on the mountain.

Ptarmigan Ridge and Wapowety Cleaver: The rugged surface surrounding Mount Rainier is evidence of thick intra- canyon flows. At least 1,200 feet (366 m) thick, Ptarmigan Ridge is an example of a thick flow that was once confined in a canyon. Since deposition, the canyon walls have eroded away, leaving the flow as a resistant ridge in the surrounding landscape.

Wapowety Cleaver is another ridge of rock located between the Kautz and the Wilson Glaciers. Kautz climbed the ridge in 1857 and the ridge was named after Kautz's Indian guide.

The Palisades: Located at the northwestern corner of White River Park, The Palisades form a great cliff of columnar- jointed black rock that rises abruptly from the headwaters of Lost Creek. The cliff is composed of a rhyodacite welded tuff that is as much as 800 feet (244 m) thick.

Willis Wall: Willis Wall forms the rear wall of the cirque of the Carbon Glacier. Named in honor of California geologist, Bailey Willis, the wall is an almost sheer wall of lava some 3,600 feet (1.097 m) high. Willis explored the north side of the mountain and blazed the first trail to the Carbon Glacier in 1881. He was also influential in securing the passage of the bill that created Mount Rainier National Park.

Thermal Features and Ice Caves

In 1870, active fumaroles were recognized at the summit of Mount Rainier during the first authenticated climb to the top of the volcano (Crandell, 1971). These summit fumaroles, ice caves associated with the fumeroles, and Ohanapecosh Springs are hydrothermal features listed in the Geothermal Steam Act (Barr, 2001). In response to the Geothermal Steam Act, Amendments of 1988, an evaluation of "significant thermal features" in MORA was conducted by the Bureau of Land Management (Korosec, 1989). Thermal features of the park fall into six separate groups:

- Summit thermal area
- Upper- flank thermal areas
- Winthrop Springs
- Paradise Springs
- Longmire Mineral Springs
- Ohanapecosh Hot Springs

Fumeroles at the summit of Mount Rainier are small vents that release steam in an area where the ground temperature is 174° to 185° F (65° to 71° C). The summit thermal area, upper- flank thermal areas, and the Winthrop and Paradise Springs on the lower flanks are thought to be part of a single geothermal system within the edifice of the volcano (Korosec, 1989). Hot acid sulfate- chloride water flows from the upper part of the cone outward toward areas of leakage on the lower flanks (Frank, 2000).

Thermal groundwater flowing from the cone appears to be neutralized by reaction with andesite and cooled by dilution with cold groundwater prior to being discharged into surface waters. Elevated sulfate and chloride were found in two sets of thermal springs near Paradise and Winthrop Glaciers. Cold neutral water with elevated sulfate and chloride discharges was found issuing from Winthrop Glacier (Frank, 2000).

The vented steam at the summit continues to melt ice to form ice caves. The creation of ice caves by the steam vents in an active glacier area represents an unusual geologic feature. The two craters atop the summit of Mount Rainier contain the world's largest volcanic ice-cave system (Zimbelman et al., 2000A). In 1997, two active fumeroles were sampled for stable isotopic, gas, and geochemical studies. Data indicate that the hydrothermal system in the edifice of Mount Rainier consists of shallow, meteoric water reservoirs that receive gas and steam from an underlying magmatic system.

In the eastern crater, 2,300 feet (700 m) of caves were mapped in 1997- 1998 (Le Guem et al., 2000). Researchers found the main fumaroles located at the eastern entrance. Very few fumeroles were observed deep within the cave. No sulfur was detected in the gases and CO_2 concentration in the cave atmosphere was close to 300 ppm and around 1 percent in the fumaroles.

155 meters (508 feet) of caves were mapped in the western crater. H_2S concentrations in the cave atmosphere were 2 to 5 ppm, giving it a rotten egg odor, and 0.3 percent CO_2 (Le Guem et al., 2000). Isotope data indicate that meteoric groundwater has diluted the H_2S concentrations, but samples taken from incrustations around a dormant vent record a past history of magmatic components episodically venting at the surface (Zimbelman et al., 2000A).

Ice caves also are usually visible at the base of Paradise, Carbon, and other glaciers. However, these caves formed as a result of glacial meltwater rather than hydrothermal processes.

Longmire Mineral Springs are part of a separate geothermal system. The heat source is probably related to the volcano's magmatic system at depth and may be fault and/or fracture controlled. This system is of limited extent and has a volume of perhaps three cubic kilometers covering about three square kilometers.

Ohanapecosh Hot Springs consists of 25 springs, ranging from small seeps to small springs. The springs are located near the base of Mount Rainier in the southeast part of the park and like the Longmire Mineral Springs are part of a separate geothermal system, also of limited extent. The springs are indicators of subsurface thermal processes. Temperatures have been reported as high as 122° F (50° C). Flows have been measured between 110-250 liters per minute.

Yellow- orange to white travertine deposits of unknown thickness underlie parts of a meadow at Longmire and a small area near Ohanapecosh campground (Crandell, 1969B). Travertine is a calcium carbonate mineral and has formed by warm spring water present at both localities.

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Mount Rainier National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

The rocks exposed at MORA fall into three main groups:

- Bedded rocks of Eocene, Oligocene, and Miocene age
- Granitic intrusive rocks of Miocene and Pliocene age
- Lava flows and related Quaternary- age rocks of Mount Rainier volcano

The bedded rocks include the Puget Group (exposed west of the park), Ohanapecosh Formation, Stevens Ridge Formation, and the Fifes Peak Formation. A brief description of the three main groups of rocks is given in the following Map Unit Properties Table.

The table is a stratigraphic column and itemized list of features for each rock unit. The table includes properties specific to each unit such as: geologic map symbol, formation name, rock description, resistance to erosion, suitability for development, hazard potential, mineral resources, and global significance.

Resistance to erosion is a subjective category. In general, igneous rocks such as andesite and basalt are more resistant to erosion relative to sedimentary rock types and soil. In the wet climate of the Pacific Northwest, however, chemical weathering of less stable minerals in igneous rocks such as olivine, augite, and plagioclase feldspar, might contribute to enhanced erosion rates.

In addition, glacial weathering processes may accelerate erosion. Glacial plucking of formations immediately adjacent to the glacial ice may destabilize the formations and lead to over steepening and ultimately, rockfall.

Map Unit Properties Table

Period	Epoch	Map Unit (symbol)	Rock/Unit Description	Resistance to Erosion	Hazard Potential	Suitability for Development	Mineral Resources	Global Significance
Quaternary	Holocene	Surficial Deposits (Qs)	Alluvium, mudflows, lahars, & glacial deposits; variable thickness	Low	May be incorporated into glacial outburst flows & debris flows	Bentonitic soils; volcanic ash & clay-rich zones; floodplains	Copper in Eagle Peak area; kaolinite in lahars & hydrothermal alteration zones	Osceola Mudflow, one of largest volcanic mudflows in world
		Landslides (Qls)	Unconsolidated, poorly sorted deposits; variable thickness	Low	Inactive slides may be reactivated; some actively moving: Backbone Ridge; Nisqually River valley	Poor: disturbing the toe of an inactive landslide may lead to reactivation	Unknown	None
	Pleistocene	Mount Rainier plugs and dikes (Qrp)	Central plug of opalized andesite in Sunset Amphitheater; satellite plugs of olivine andesite at Observation Rock & Echo Rock; radial dikes	Variable	Limited aerial extent; rockfalls	Poor: limited aerial extent	Opal in Sunset Amphitheater	None
		Andesite of Mt. Rainier volcano (Qra; Qroa)	Qra: chiefly hypersthene- augite andesite & minor olivine andesite in thick intracanyon lava flows & associated mudflows near base of volcano: thinner flows & interlayered breccia on upper slopes; up to 2000 ft (610 m) thick Qroa: olivine andesite flows from Echo Rock & Observation Rock vents	Variable; glacial plucking forms “cleavers.”	May be incorporated into debris flows, avalanches & rockfalls	Forms “cleavers” and ridges with unstable rock units	Unknown	None
		Regional Unconformity						
Tertiary	Pliocene	Tatoosh granodiorite and quartz monzonite (Tg)	Subordinate amounts of quartz diorite, contact breccia, & fine- grained border rocks; central pluton & associated stocks	High	Rockfalls	Forms steep slopes and narrow ridges (i.e., Sunrise Ridge); underlies White River valley	Quartz crystals in void spaces	None
		Andesite of Bee Flat (Tha)	Intracanyon lava flow of hypersthene- hornblende	High	Rockfalls	Limited aerial extent	Quartz crystals in void spaces	None
	Miocene	Tatoosh diorite, quartz diorite, granodiorite, and quartz monzonite porphyries (Tdi)	Subordinate amount of microgranite, porphyritic granophyre, and felsite; swarms of sills, dikes, & irregular small intrusive bodies clustered mainly near borders of the Tatoosh pluton and associated stocks; poor exposures in valleys of Panther, Laughingwater, and Chenuis Creeks.	High	Limited aerial extent; rockfall potential; underlies West Fork White River valley	Limited aerial extent	Quartz crystals in void spaces	None
		Welded tuff of The Palisades (Tw)	Pyroclastic rocks that grade downward into The Palisades plug; 800+ feet (240+ m) thick.	High	Rockfalls?	Limited aerial extent (The Palisades)	Quartz crystals in void spaces	None
		Regional Unconformity						
		Pre- Tatoosh diabase & basalt (Td)	Chiefly in dikes and sill swarms; the Box Canyon sill complex along Cowlitz River.	Limited aerial extent	Limited aerial extent	Limited aerial extent	Unknown	None
		Stevens Ridge Fm. (Ts) Fifes Peak Fm. (Tf)	Ts: Rhyodacitic ash flows; subordinate amounts of volcanic breccia, sandstone, and siltstone of epiclastic & pyroclastic origin; 450- 3000 feet (137- 914 m) thick. Tf: Basalt, basaltic andesite, & andesite flows; minor rhyolite flows, ash flows, & tuff breccia, volcanic sandstone, & volcanic siltstone of epiclastic & pyroclastic origin; 24,000+ feet (730+ m) thick.	Low : Tf mostly removed from park by erosion.	Rockfall	Ts: Limited aerial extent; ash flows form ridges and steep slopes	Ts is the bedrock exposed at Copper (Crystal) and Iron Mountains	Ts: type locality is from Stevens Ridge
	Oligocene	Regional Unconformity						
		Ohanapecosh Fm. (To, Tol, Tor)	To: volcanic breccia, sandstone, & siltstone of epiclastic & pyroclastic origin, Tol: local thick accumulations of basaltic andesite flows & coarse mudflows, Tor: rhyolite Total formation thickness: 10,000+ feet (3,000 m)	Variable: To exhibits vertical fractures on cliffs	Variable; potential for rockfalls	One of primary formations in park	Zeolites	Type locality in southeast corner of park
	Eocene	Regional Unconformity						
		Pre- Tatoosh basaltic andesite & rhyolite (Tar)	Plugs of massive & brecciated basaltic andesite which supplied lava & fragmental material to the Ohanapecosh Formation. South Cowlitz Chimney is a flow- banded rhyolite plug	Very limited aerial extent	Rockfalls?	Poor: forms plugs of very limited aerial extent in southeast quadrant of park	Unknown	None
		Puget Group	Sandstone, claystone, coal exposed west of Mount Rainier National Park; thickness 10,000+ feet (3,000+ m).	Less resistant than igneous rocks	Not in MORA	Not in MORA	Not in MORA	Not in MORA
	Paleocene	Regional Unconformity						
Cretaceous/ Jurassic		Russell Ranch Fm? (KJvb)	Basalt flows of fault- bounded greenstone unit consisting of pillow lavas and minor shale interbeds; not exposed in MORA.	Not in MORA	Not in MORA	Not in MORA	Not in MORA	Not in MORA

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Mount Rainier National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

The volcanoes in the north- south trending Cascade Province evolved through a history of complex plate tectonic processes and glaciation. Different tectonic models have been proposed for the development of the Cascades, but all models include subduction, addition of exotic terranes, and oblique plate movements as important components in creating today's Cascade Range (Kiver and Harris, 1999). In general, the North American plate edge was located farther east during the Mesozoic in Nevada, western Idaho, and eastern Washington. Subduction processes added larger masses of continental materials, island- like masses called *microcontinents*, *microplates*, or *exotic terranes* to the western margin of North American. Addition of these microplates shifted the plate edge westward.

The first Cascade volcanoes erupted about 42 million years ago (Ma), forming the older Western Cascades. At the time, the range was oriented northwesterly but would later rotate clockwise to achieve today's north- south orientation. Continued subduction formed rows of volcanic vents that become younger to the east. As a result of clockwise rotation, extensive fissures opened up to the east and voluminous eruptions of the Columbia River Basalt occurred about 17 Ma.

Subduction and accompanying volcanism continued for some 25 million years in the older Cascade Range. As magma rose, rocks were heated and began to expand. Large lithospheric blocks dropped downward along north- south oriented faults creating linear depressions, or *grabens* (fault- bounded basins). The faults opened pathways that enabled large volumes of magma to rise. The grabens filled and overflowed with overlapping shield and cinder cones to form a volcanic plateau called the Eastern, or High, Cascades.

The present generation of volcanoes is believed to be no more than 400,000- 600,000 years old. Mount St. Helens was formed only 40,000 years ago. Coincident with the growth of these recent volcanoes was the Pleistocene Ice Age, which began about 1.6 Ma. Glaciers formed on each volcanic cone when it reached sufficient height. At the peak of glaciation, a continuous icecap buried the upper Cascades from Canada to northern California, broken only in the Columbia Gorge area where elevations approached sea level (Kiver and Harris, 1999). Alpine glaciers on Mount Rainier flowed as far as 65 miles (105 km) from the mountain. Most of the glacial sculpturing seen today occurred during the Wisconsin glacial stage, which reached its maximum only 15,000- 20,000 years ago.

For Mount Rainier National Park, the terrestrial history begins in the Tertiary Period of the Cenozoic Era in the Eocene Epoch, 36.6- 52 Ma.

Tertiary Period: Eocene Epoch

Western Washington looked far different in the Eocene than it does today. Mount Rainier and the Cascade Mountain Range did not exist. Rather, deltas, swamps, and inlets formed a broad lowland bordering the Pacific Ocean. Rivers drained into this lowland from the east. The sand, clay, and peat that accumulated were compacted into the 10,000- foot (3,000 m) sequence of sandstone, shale, and coal of the Puget Group, exposed west of the park (Harris et al., 1995; Kiver and Harris, 1999).

On the western margin of North America, a complex tectonic framework created a complex sedimentary assemblage. In Oregon, Eocene deep- sea sedimentary fans developed west of an accreted and subsiding seamount chain in a new fore- arc basin (the Tyee fore- arc basin in Figure 6). The basin developed in the Coast Range, west of the older Mesozoic fore- arc basin of central Oregon (Miller et al., 1992). In the Klamath Mountains, Hornbrook Basin area, and northern part of the Great Valley fore- arc basin (California), regional uplift during the Paleocene to early Eocene caused non- marine Eocene strata to unconformably overlie Cretaceous marine rocks. Sedimentation continued in the Great Valley fore- arc basin.

Middle and upper Eocene submarine sedimentary fans and continental- slope deposits that graded eastward into shallow- marine, deltaic, and fluvial equivalents buried newly accreted, subsiding terranes in the Pacific Northwest from about 55- 43 Ma (Christiansen and Yeats, 1992). Pull- apart basins created by oblique subduction on the northwest flank of the North Cascades were filled with thick nonmarine arkosic sandstones and conglomerates. From the North Cascades to central Idaho, extensional faulting juxtaposed upper- crustal sections against mid- crustal, metamorphic rocks in relatively continuous *metamorphic core complexes*. These metamorphic core complexes formed domes between which graben- like basins formed and filled with thick sediments and contemporaneous volcanics.

In latest Eocene (about 43 Ma), the coastal region rotated clockwise at a rate of one degree per million years. Lakes and alluvial basins occupied the area east of the continental divide while the *Cascade Arc*, an arcuate trend of offshore volcanoes, extended from British Columbia southward into southern Oregon. South of the arc, most of California was either eroding upland or coastal plain that bordered a continental shelf and slope to the west.

Tertiary Period: Oligocene Epoch

Ohanapecosh Formation: Beginning in the Oligocene about 35 Ma and continuing until 28 Ma, plate movement along the western subduction zone increased, the descent of the oceanic plate became less steep, and the rigorous movement generated abundant magma. Large lakes or embayments of the sea inundated the lowland, and clusters of volcanoes erupted under the sea and on land. Breccia from volcanic explosions and material from lava flows, mudflows, and ash falls, all of which accumulated in shallow water, comprise the Ohanapecosh Formation (Harris et al., 1995; Kiver and Harris, 1999).

The most explosive volcanoes were underwater where percolating water triggered steam- blasted eruptions. Andesites, rhyolites, and volcanic breccia are well exposed in the eastern part of the park where, locally, layer upon layer of volcanic debris may reach over 10,000 feet (3,000 m) thick (Kiver and Harris, 1999). These layers are exposed in highway road cuts on the east side of Backbone Ridge, and remnants of volcanic centers are well exposed in the steep cliffs below the Sarvent Glaciers, just east of Mount Rainier. Volcanic vents, now plugged with masses of solidified lava, are visible at the South Cowlitz Chimney, Double Peak, and Barrier Peak.

After the volcanic activity subsided, the Ohanapecosh Formation was compressed into broad folds. Zeolites (a group of hydrous aluminosilicate minerals common as replacement minerals in volcanic rocks) and other minerals replaced most of the original minerals, and these new minerals firmly cemented the fragmental debris into hard rocks. They also imparted the dark gray and green colors typical of Ohanapecosh deposits. Uplift of the entire area followed. In the warm, wet climate, streams and rivers carved deep valleys into this hilly terrain. Valleys as deep as 1,500 feet (457 m) were eroded into the underlying Ohanapecosh Formation.

Stevens Ridge Formation: During the Oligocene and Miocene (Figure 2), thin layers of pumice and ash were deposited over the hilly terrain. These layers are the initial deposits of the Stevens Ridge Formation (Figure 7). The first thin ash falls had little affect on the many trees growing on the hills, but that was about to change. The most catastrophic event ever to befall the area blasted a series of searing hot ash flows over the area and smothered the former landscape. The ash flows consisted of mixtures of volcanic dust, bits of pumice, and other hot volcanic fragments buoyed up and greatly mobilized by hot volcanic gases that expanded and lubricated the flows so that flow velocities may have reached 60 or 80 miles per hour (97- 129 km/hr). Flowing into the valleys carved in the underlying Ohanapecosh Formation, the first ash flows choked streams, disturbed the soil, and killed trees that stood in their path. Subsequent ash flows eventually filled the valleys with deposits hundreds of feet thick and completely covered the pre- existing hills. When the hot volcanic ash was deposited, the heat fused the small bits of volcanic glass and pumice together into a rock known as *welded tuff*.

Only remnants of the Stevens Ridge ash flows survive in the park. Highway road cuts near the top of Backbone Ridge contain pieces of wood, bits of soil, and other debris chaotically mixed into the lower part of the basal Stevens Ridge ash flow. This ash flow can be traced northwestward to the lower slopes of Stevens Ridge where it is visible along the Stevens Canyon highway. Other ash flows are well exposed in the cliffs on the southern slope of Stevens Ridge.

Tertiary Period: Miocene Epoch

Fifes Peak Formation: The Fifes Peak Formation is primarily composed of andesite and basalt lava that erupted directly on top of the Stevens Ridge Formation (Figure 7, Appendix A). Rather than erupting bits of ash and pumice, the volcanoes responsible for the Fifes Peak Formation produced streams of lava that built low, overlapping volcanic cones. Up to 2,400 feet (730 m) of interfingering lava flows covered the area although erosion has removed all but a small remnant of this lava field from the park. The largest remnant of the Fifes Peak Formation underlies much of the rugged area near Mowich Lake, northwest of Mount Rainier.

Although the volcanoes have been dissected and mostly removed by erosion, feeder dikes to the volcanoes still remain. The dikes can be traced for about a mile along the surface and vary from 6 inches (15 cm) to 20 feet (6 m) thick. Swarms of dikes that cut the Stevens Ridge and Ohanapecosh Formations may be found on Backbone Ridge and on Stevens Peak, Mount Wow, and in the headwaters of the North Fork of the Puyallup River.

Lava also was forcefully injected between underground layers of Ohanapecosh and Stevens Ridge strata, which, when cooled, formed tabular bodies known as *sills*. These sills can be found in the low country along the Muddy Fork of the Cowlitz River and near Longmire. The Box Canyon of the Cowlitz slices into one of these thick Fifes Peak Formation sills.

Following the eruptions of Fifes Peak lava, the area was once again compressed and folded. The folds that formed after deposition of the Ohanapecosh Formation became tighter. Faults broke the strata of the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations as the rocks shifted to relieve the compressive stresses. For example, near vertical movement caused 910 meters (3,000 feet) of displacement between the base of the Stevens Ridge Formation and the Stevens Ridge Formation strata in Stevens Canyon. Continued plate collisions on the western margin caused this folding and faulting and set the stage for the second major episode in the geologic history of MORA – the emplacement of the Tatoosh pluton.

Granitic Intrusive Rocks of Miocene and Pliocene Age

By 20 Ma (early Miocene), only remnants of the Farallon plate remained (Figure 8). Most of western Washington and Oregon had emerged above sea level by late Miocene time. Upper Miocene and lower Pliocene nonmarine sediments accumulated locally in basins in the Puget Lowland, in the Willamette Valley, and along the Columbia River.

Tatoosh Pluton and Associated Intrusives: About 9 Ma (late Miocene), the rate of collision between lithospheric plates slowed and the angle of descent of the subducting plate steepened, like it is today (Figure 9). In the Miocene and Pliocene, a great upward surge of molten rock stopped short of the surface and intruded the rocks of the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations, solidifying as intrusive igneous bodies, called plutons (Figures 7, 10) (Fiske et al., 1963, 1988). Dikes and sills riddle the bedded formations. Some of these intrusive bodies are large enough to be mapped; some are not. Some of the magma erupted onto the surface although all but the welded tuff at The Palisades has been eroded from the park.

Igneous activity such as eruption of the lava flow at Bee Flat occurred sporadically throughout the rest of the Pliocene time. But uplift and erosion were the dominant processes at the time, and these processes developed the unconformity that separates the Pliocene from the Pleistocene (Map Unit Properties Table). Over time, the thin roof of older rocks was partly eroded away to expose the top of a large and complex granitic pluton. Some of the best exposures are found in the rugged cirques and peaks of the Tatoosh Range, from which the pluton is named (Appendix A). The granodiorite of the Tatoosh pluton is also exposed in the Carbon and White River valleys and part of the upper Nisqually River valley. Mapping reveals that the Tatoosh pluton completely underlies Mount Rainier and forms a platform upon which the volcano grew (Figure 10) (Fiske et al., 1988).

Quaternary Period: Pleistocene Epoch

The eruptive centers that would create North Cascades National Park, Mount Rainier National Park, Crater Lake National Park, and Lassen Volcanic National Park erupted from 7 to 2 Ma (Figure 11).

At the time of the great Pleistocene Ice Age, the Tatoosh Mountains were undergoing glaciation in a very cold climate. A series of relatively fluid andesitic lava flows early in the Pleistocene flowed onto the rugged terrain carved into the mountain (Figure 7; Appendix A). Intra-canyon lava flows filled ancient canyons to depths of 2.000 feet (610 m) and traveled up to 15 miles (24 km) from the young volcano (Fiske et al., 1988). Evidence of mudflow and glacial deposits interlayered with the lava flows indicates that glaciation was ongoing throughout this time.

These intra- canyon flows now form ridges or flat benches far above today's canyons. Originally, the flows filled the canyons, but the lava was more resistant to erosion than the surrounding strata. The vigorous erosion by rivers and glaciers preferentially cut the weaker rocks, excavating far below the floors of the old filled canyons.

Good exposures of old intra- canyon flows can be seen at Burroughs Mountain and the flat surface of Yakima Park where a stream of lava flowed about 7 miles (11 km) down the canyon of the ancestral White River. The end of this flow is exposed in the highway road cuts below Sunrise Ridge. The present- day canyon cut by the White River lies to the south side of the intra- canyon flow. The thick lava flow that underlies Rampart Ridge, just west of Longmire, is another example of a ridge that was once a canyon. Originally, the flow poured into the upper canyon of the Nisqually River. The ridges of old intra-canyon flows stand in stark contrast to the younger flows that now lie at the bottom of a few present- day canyons.

The projecting fingers of intra- canyon lava lie in the shadows of the main cone of Mount Rainier. The cone is built from hundreds of thin lava flows, breccia deposits, and debris and mudflows. The cone began to be built from short streams of lava interspersed with ejections of breccia and ash. About 75,000 years ago, the volcano reached its greatest height of perhaps 15,500 to 16,000 feet (4,700 to 4,900 m) (Harris et al., 1995). Dikes radiated from the center of the volcano, like spokes in a wheel, and a plug of solidified magma filled the central vent.

Quaternary Period: Holocene (Recent) Epoch

Figure 12 summarizes the lahars, mudflows, debris flows, avalanches, and recent eruptions of Mount Rainier over the past 70,000 years that are listed on the USGS website, http://vulcan.wr.usgs.gov/Volcanoes/Rainier/framework.html. The recent eruptions have ejected minor amounts of pumice and ash high into the air to be deposited in the park. Figure 13 breaks out the recent eruptions from the list of events in Figure 12. Although eleven eruptions from Mount Rainier, two eruptions from Mount St. Helens, and one eruption from Mount Mazama have deposited pumice in the Mount Rainier area, the total thickness of these deposits ranges from less than an inch to a few feet, and this unconsolidated material has been completely eroded away from many areas.

About 5,000 years ago, the weak clay zones, steep slopes, high elevation, and abundant water and ice combined with a volcanic eruption to produce the Osceola Mudflow, one of Earth's largest known mudflows. The upper 3,000 feet (910 m) of Mount Rainier collapsed as distinct blocks of rocks quickly disintegrated into a giant debris avalanche, and mixing with abundant water and clay particles, transformed into a wall of mud cascading down the White River drainage. Thinning away from the mountain, the Osceola Mudflow deposited 100 feet (30 m) of mud near the present site of Enumclaw, 35 miles (56 km) downstream (Figure 4). Traveling at about 40 miles per hour (64 km/hr), the mudflow buried the site of an Indian village and eventually poured into Puget

Sound, 75 miles (120 km) from the mountain (Kiver and Harris, 1999).

Mount Rainier was built from material erupting from a central vent. A plug of solidified lava now fills this vent and is exposed in the precipitous east wall of Sunset Amphitheater (Appendix A). Two small plugs on the northwestern flank of Mount Rainier denote satellite volcanoes and three thick radial dikes extending outward from the summit area mark locations where lava erupted and flowed onto the lower slopes of the volcano. Two prominent dikes can be seen at Puyallup Cleaver and St. Elmo Pass where they stand as resistant ribs above the rocks they intrude.

Although Mount Rainier is the second highest peak in the conterminous United States, the mountain's peak was once considerably higher than it's 14,410 feet (4,390 m) today. The truncated lava flows in the upper part of the mountain slant upward to a former summit that was at least 100 feet (30 m) higher than the present summit (Fiske et al., 1988). Three hypotheses have been proposed as reasons for the summit's removal. Some geologists believe the pinnacle of Mount Rainier was removed by a violent explosive eruption, but fragments from this eruption have not been found. Others believe that avalanches and glacial erosion rapidly ate away the upper part of the mountain. Still others see the former summit collapsing into the central vent when the column of lava temporarily subsided.

The largest rockfalls on Mount Rainier in historic time occurred in December 1963, when a series of rockfalls, hundreds of feet across, fell from the steep north face of Little Tahoma Peak onto Emmons Glacier (Crandell, 1969A, B; Kiver and Harris, 1999). When the rock hit the glacier, it shattered into dust and countless fragments and then avalanched down the steep ice surface at a tremendous speed. At the end of the glacier, the rock debris traveled toward the valley floor over a layer of compressed air that reduced the friction and permitted the avalanche to move almost 2 miles (3 km) beyond the end of the glacier. This avalanche passed over a small wooden gage house about 5 feet (1.5 m) high without damaging it and then slammed into the north base of Goat Island Mountain. The force of the avalanche scraped away trees and bushes in the path of the flow. A later avalanche stopped just short of the gage house, but unfortunately, when the trapped wind was expelled from beneath the rock debris, the gage house was destroyed. At least seven rockfalls and avalanches from Little Tahoma Peak occurred in a matter of minutes or hours and some came to rest only a short distance up- valley from the White River Campground.

Today, fumaroles and occasional steam explosions on the flanks of Mount Rainier indicate continued heat flow, and seismic tremors suggest that future volcanic eruptions are possible.

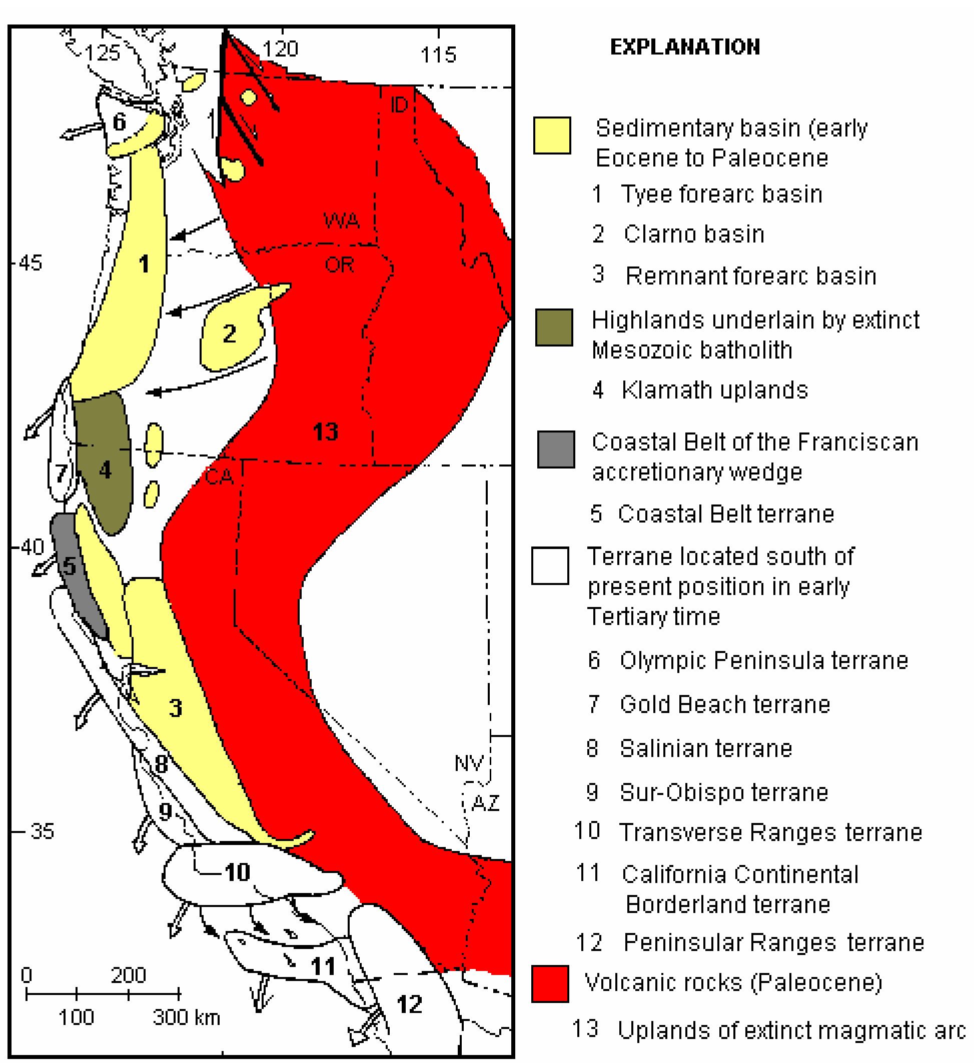

Figure 6: Paleogeographic map of the western margin of North America during the Paleocene and early Eocene time. Modified from Miller and others, 1992.

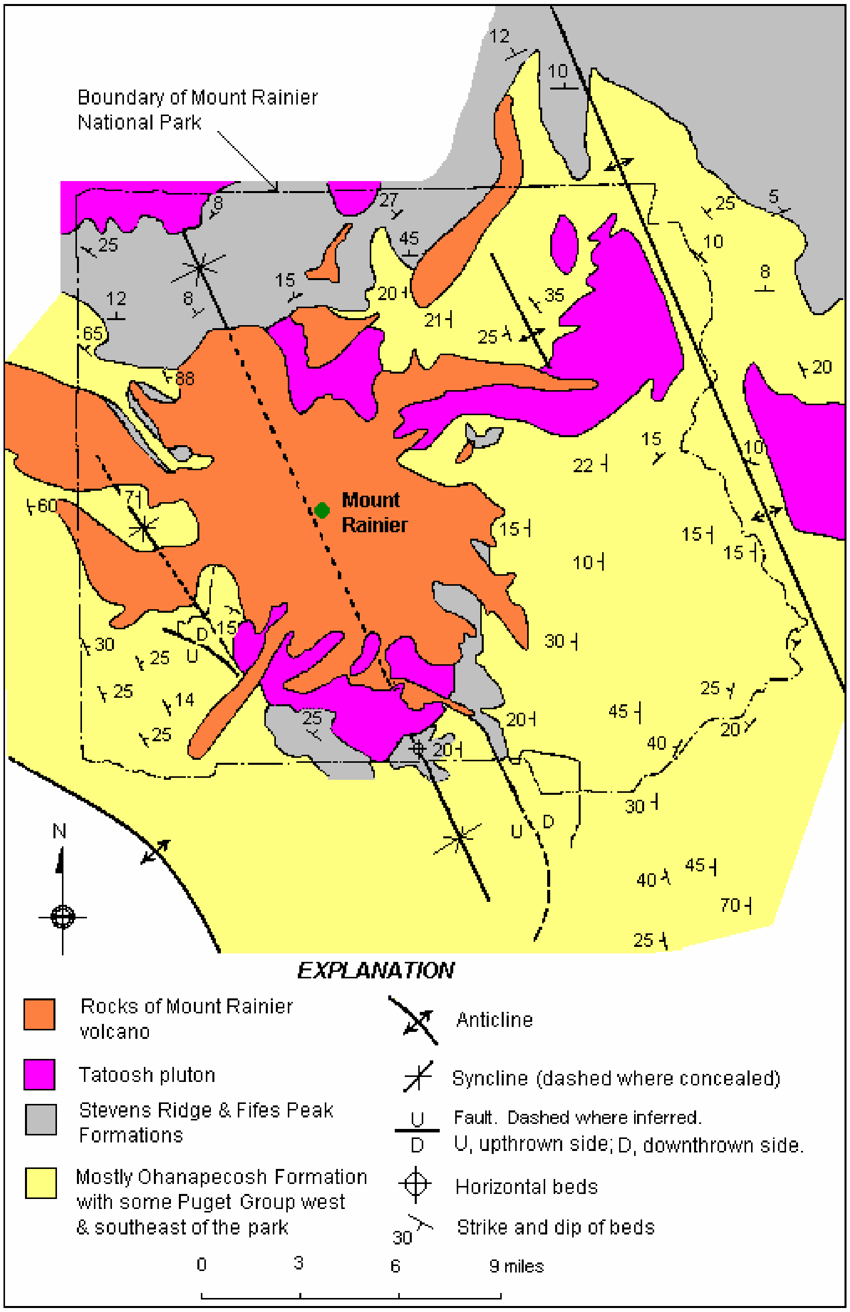

Figure 7: Simplified geologic map of Mount Rainier National Park showing rock units and the location of the synclines, anticlines, faults, and dip of beds.

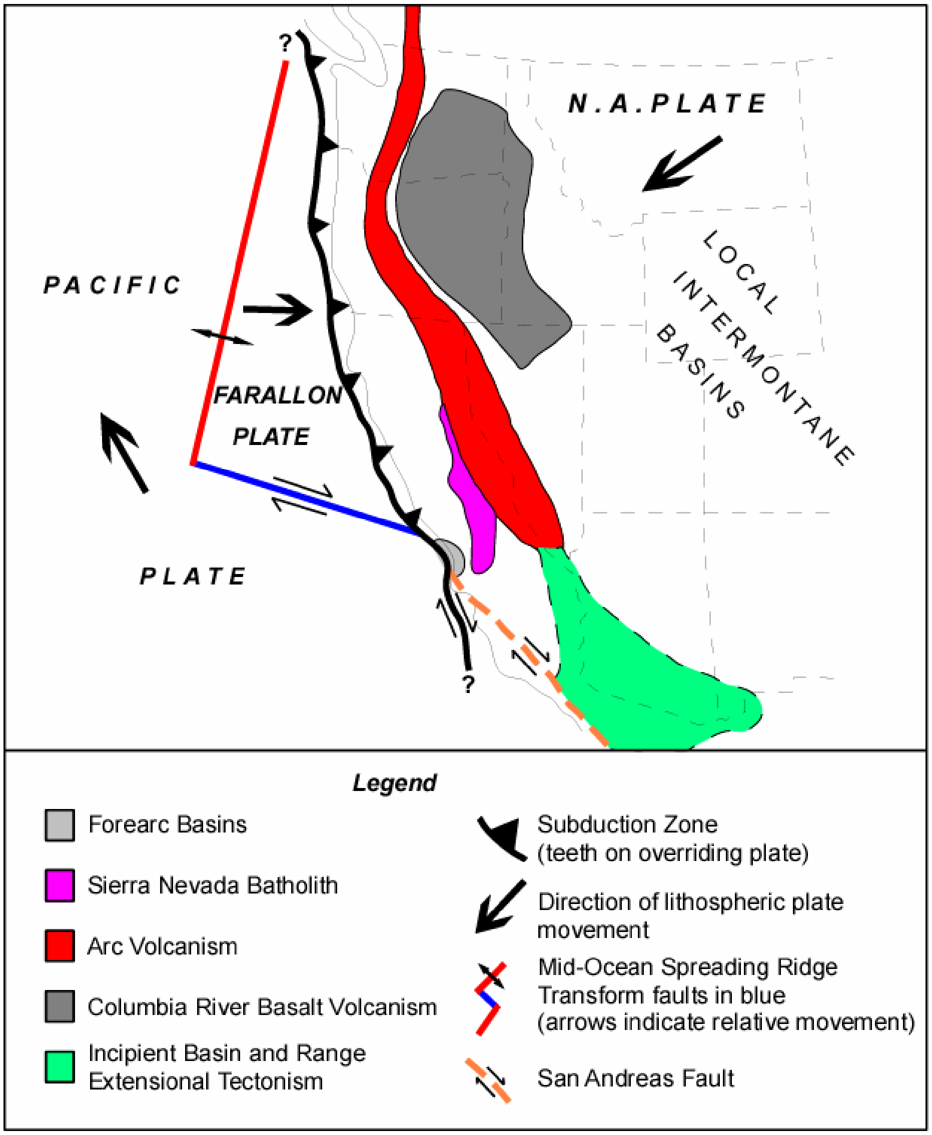

Figure 8: Paleotectonic map of western United States approximately 15 Ma in the Miocene Epoch. Initiation of basin and range faulting and the San Andres fault system takes place about this time. Modified from Dickinson, 1976.

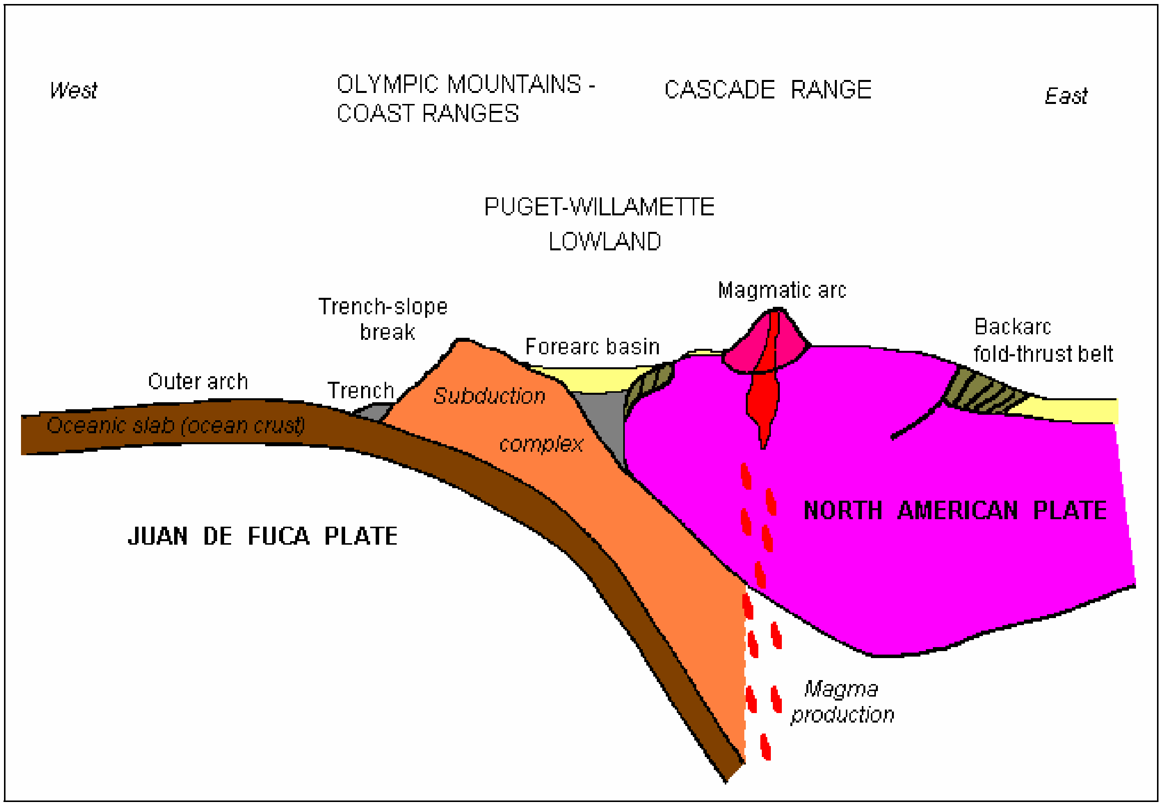

Figure 9: Plate tectonic cross-section sketch illustrating the general tectonic setting for the present northwestern margin of the United States. Modified from Dickinson (1976).

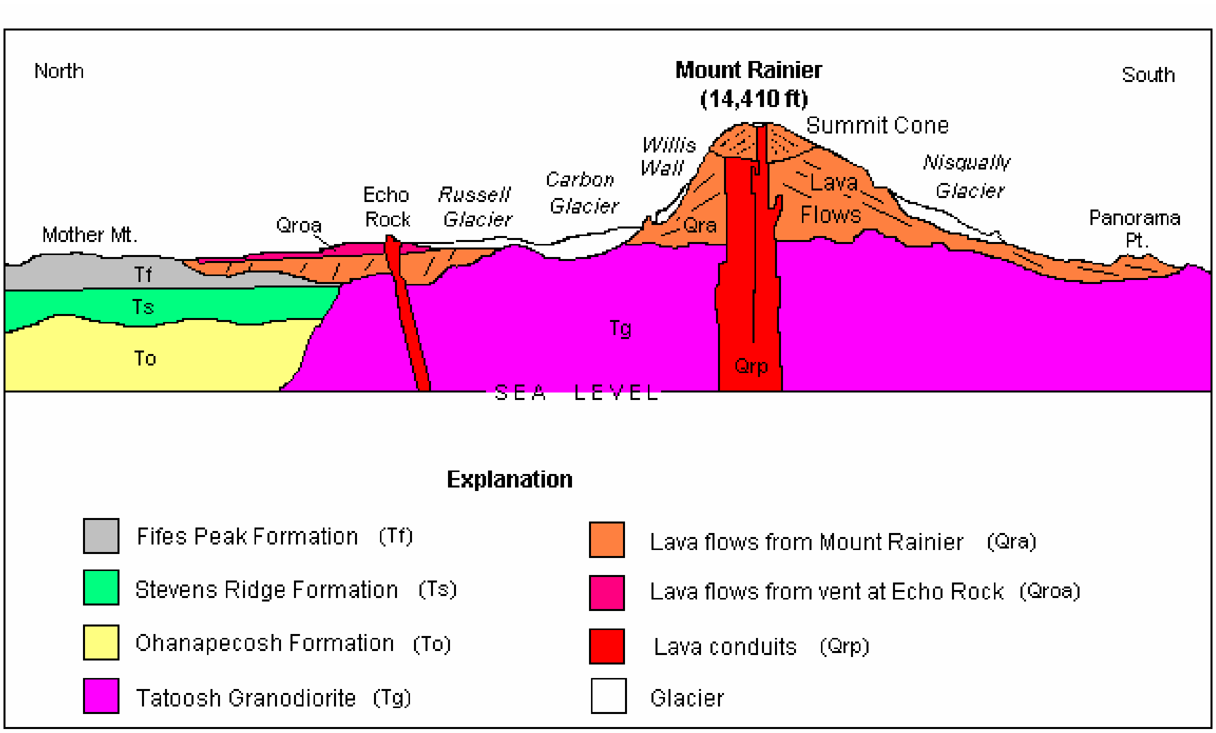

Figure 10: Generalized north-south geologic cross-section through Mount Rainier National Park showing the central vent, glaciers, Tatoosh pluton, and adjacent bedded strata. Modified from Crandell (1969A) and Fiske and others (1988).

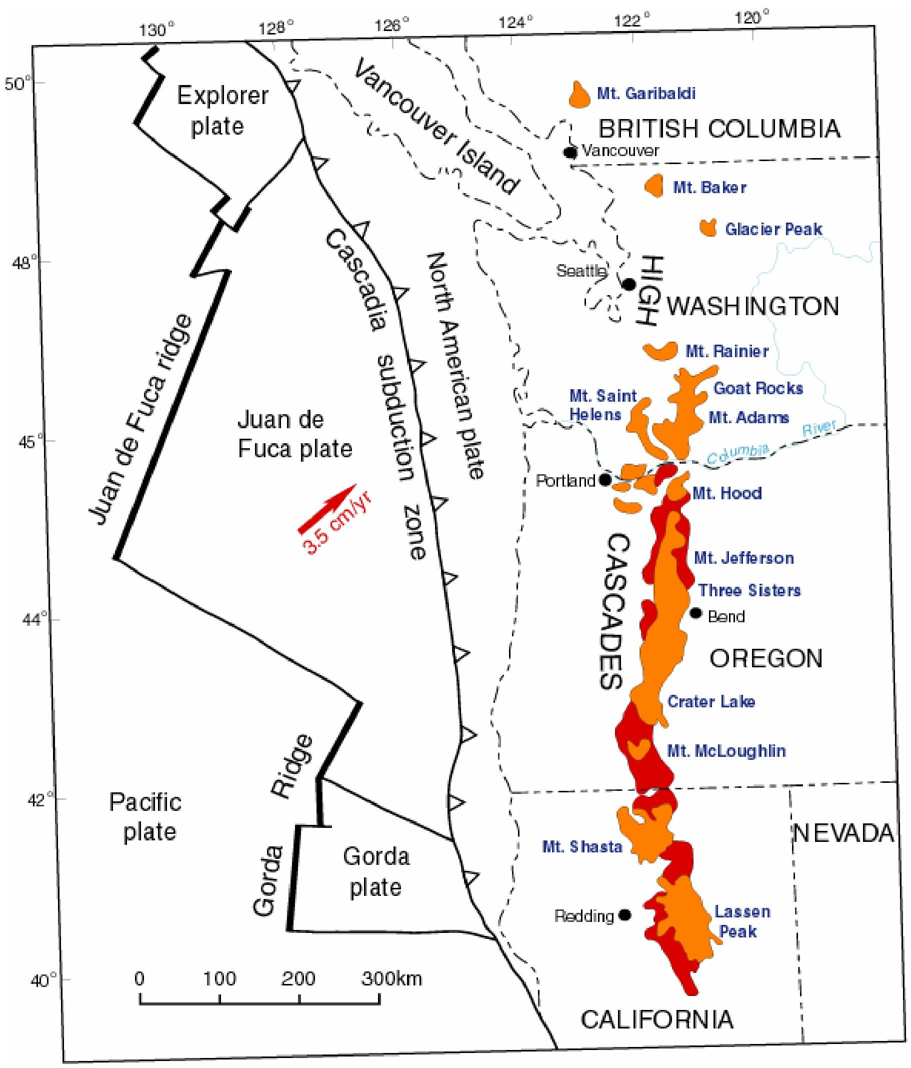

Figure 11: Map of late Miocene and younger magmatic systems in the Cascade Mountains. Light coloring indicates volcanic rocks of 7 to 2 Ma age; dark coloring indicates volcanic rocks of 2 to 0 Ma age. The arrow indicates relative convergence between the Juan de Fuca and North American Plates. Modified from Christiansen and others, 1992.

Recent events associated with Mount Rainier

Event	Age/Date	Description and Comments
Glacial outburst floods	Late 1960s	Geothermal (?) melting of South Tahoma Glacier
Little Tahoma Peak avalanche	1963	Extended as far as 4.3 miles down valley; impacted Inter Fork and White River valleys; lahar from main avalanche was <2- 4% clay; extent to White River Campground
Kautz Creek Mudflow	Oct. 2- 3, 1947	Rain induced lahars; extent to Nisqually River
Tahoma Glacier avalanche	1910- 1930	Small debris flow; Puyallup River drainage; extent below glacier terminus
Pumice layer G	1820- 1860	
Pumice layer X	1820- 1860	Scattered pumice lapilli
West Fork White River debris flow	1570- 1695	Lahar extended at least 18 mi beyond Winthrop Glacier
White River debris flow	1550	Large gravel- rich debris flow & flood gravel aggraded present channel; non- volcanic in origin; extent to Mud Mountain Reservoir
Tahoma Lahar	Post- pumice layer W	Tahoma Creek & Nisqually River drainages; 3- 4% clay; extent to Elbe
Pumice layer W (from Mt. St. Helens)	1480- 1520	Pumice ash; white; fine to med sand size; thickens from 0.25 inches on west side to 3 inches near SE corner
Electron Mudflow	1400- 1420	Subrounded to subangular pebbles, cobbles, and boulders in plastic matrix of clayey sand; 200+ million cubic yards at average thickness of 15 ft; extended about 30 miles down South Puyallup River Valley; underlies about 14 sq mi of the Puyallup River Valley in the Puget Sound lowland
1,000- year- old lahar	900- 970	Extended at least 14 miles beyond Tahoma Glacier (South Puyallup River Valley); 5- 12% clay
National Lahar	Post- pumice layer C, pre- W	Runout phase inundated all valley bottoms above Alder Reservoir to at least 9 ft depth; extent to Puget Sound
Columbia Crest Summit Cone	33 A.D.; Post- pumice layer C, pre- W	Pyroclastic surge; lava flows forming summit cone
Pumice layer C	2,200 years- before- present (BP)	Pumice lapilli & scattered blocks; widely distributed over most of park east of the volcano; 1 to several inches thick; most widespread & voluminous of Mt. Rainier tephras
Block- and- Ash flow	2,350 BP	Extended about 3 miles beyond Tahoma Glacier (South Puyallup River Valley)
Lahar	2,533- 2,833 BP	Extended at least 3 miles beyond Tahoma Glacier (South Puyallup River Valley)
Round Pass Mudflow	2,170- 2,790 BP	Extended at least 7 miles beyond South Tahoma Glacier and 15 miles beyond Tahoma Glacier (Tahoma Creek & Puyallup River drainages); 4- 5% clay
Pumice layer P (from Mt. St. Helens)	2,500- 3,000 BP	
Pumice layer Y (from Mt. St. Helens)	3.400 BP	Pumice ash; light yellow- brown; med to very coarse sand size; thickens from 1 inch near east edge of park to 12 inches near SW corner
Pre- Y lahar at Round Pass	>3,400 BP	About 3% clay; Puyallup River drainage & Tahoma Creek; unknown extent
Pumice layer B	4,000- 4,500 BP	Pumice ash & scattered lapilli, scoria, lithic fragments
Pumice layer H	4,033- 5,000 BP	Scattered pumice lapilli, lithic fragments
Osceola Mudflow	4,500- 5,000 BP	Probable total volume of a little more than half a cubic mile; largest mudflow of postglacial age at Mt. Rainier; covers an area of over 100 sq miles; extends down the White River to the Puget Sound lowland; deposits range in thickness from a few feet to over 200 feet; 2- 15% clay
Greenwater Lahar	4,500- 5,000 BP	Extended at least 28 miles down valley from volcano (Inter Fork and White River valleys); <3% clay; probably part of Osceola; extent to Puget Sound lowland

Recent events associated with Mount Rainier (cont.)

Event	Age/Date	Description and Comments
LOSS OF SUMMIT	5,733 BP	The present summit of Mt. Rainier is at the top of a young lava cone constructed within a large depression about 1.25 miles across; high points on the rim of this depression are Point Success, Gibraltar Rock, and along the ridge between Liberty Cap and Russell Cliff; these high points record the removal of the volcano's summit above an altitude of 14,000 feet; material removed from the summit may have formed very large rockslides and avalanches that led to the Osceola Mudflow
Pumice layer F	5,700- 5,800 BP	Montmorillonite- rich lithic ash; lithic fragments, pumice, crystals, clay; similar clay contents and age of Osceola Mudflow; supposition is that Layer F records phreatic activity preceding or accompanying generation of the avalanche and resulting debris flow
White River flows	5,700- 6,600 BP	Bomb- bearing flows in White River Valley
Pumice layer S	5,200 BP	Sand- to block- sized lithic rubble; angular rock fragments as large as 1.5 feet across;
Pumice layer N	5,500- 6,500 BP	Lithic fragments, ash
Pumice layer D	5,500- 6,500 BP	Pumice lapilli, scoria, lithic fragments; basaltic andesite
Pumice layer L	5,500- 6,500 BP	Pumice lapilli; silicic andesite
Pumice layer A	5,500- 6,500 BP	Pumice ash and scattered lapilli, lithic fragments
Paradise Lahar	5,833- 6,633 BP	Unsorted deposit of angular to subrounded rock fragments in a plastic matrix consisting of a mixture of sand, silt, and clay; extended at least 18 miles down Nisqually River valley; younger than pyroclastic layer O and predates pyroclastic Layer D; 1- 6% clay; Paradise River and Nisqually River drainages
Pumice layer O (from Mt. Mazama)	6,633- 6,900 BP	Pumice ash; blankets entire park and adjoining area to depth of 1- 2 inches; distinctive yellow- orange color
Pumice layer R	>8,750 BP	Pumice, lithic fragments
Main Cone of Mount Rainier	About 10,000 BP	Flows and breccia eventually built a cone standing 6,900 to 7,900 feet (2,100 to 2,400 m) above its surrounding topography before the end of the latest glaciation
Ash layer	30,000- 70,000 BP	A thick pumice layer northeast, east, and southeast of the volcano may have been erupted from Mount Rainier;

Figure 12: Summarized from USGS website. Blue signifies floods; orange signifies avalanches; yellow signifies debris flows, lahars, or mudflows; gray signifies pumice deposits; white represents a constructive phase of the volcanic cone; and red represents a destructive phase of the summit cone.

Layer	Age (years BP)	Dominant Materials	Source	Thickness in inches West/East	Volume in millions of cubic ft (m^3)
X	+/- 150	Pumice	Mt. Rainier	0 / 1	35 (1)
W	485	Pumice	Mt. St. Helens	0- 1 / 1- 3	?
C	2200	Pumice, scoria, lithic fragments	Mt. Rainier	0 / 1- 8	10,000 (300)
Y	3250- 4000	Pumice	Mt. St. Helens	5- 20 / 1- 5	?
B	>4000	Scoria, lithic fragments	Mt. Rainier	?	180 (5)
H	>5000	Pumice, lithic fragments	Mt. Rainier	?	35 (1)
F	5000	Lithic fragments, pumice, clay	Mt. Rainier	?	880 (25)
S	5200	Lithic fragments	Mt. Rainier	?	700 (20)
N	5500	Lithic fragments, pumice	Mt. Rainier	?	70 (2)
D	6000	Scoria, lithic fragments	Mt. Rainier	0 / 0- 6	2,600 (75)
L	6400	Pumice	Mt. Rainier	0 / 0- 8	1,800 (50)
A	6500	Pumice, lithic fragments	Mt. Rainier	?	180 (5)
O	6600	Pumice	Mt. Mazama	1- 3 / 1- 3	?
R	>8750	Pumice, lithic fragments	Mt. Rainier	0 / 0- 5	880 (25)

Figure 13: Holocene tephras in Mount Rainier National Park. Data from USGS website and Crandell (1969B). Age is in radiocarbon years before present (BP) except for Layer X, which was dated using tree rings.

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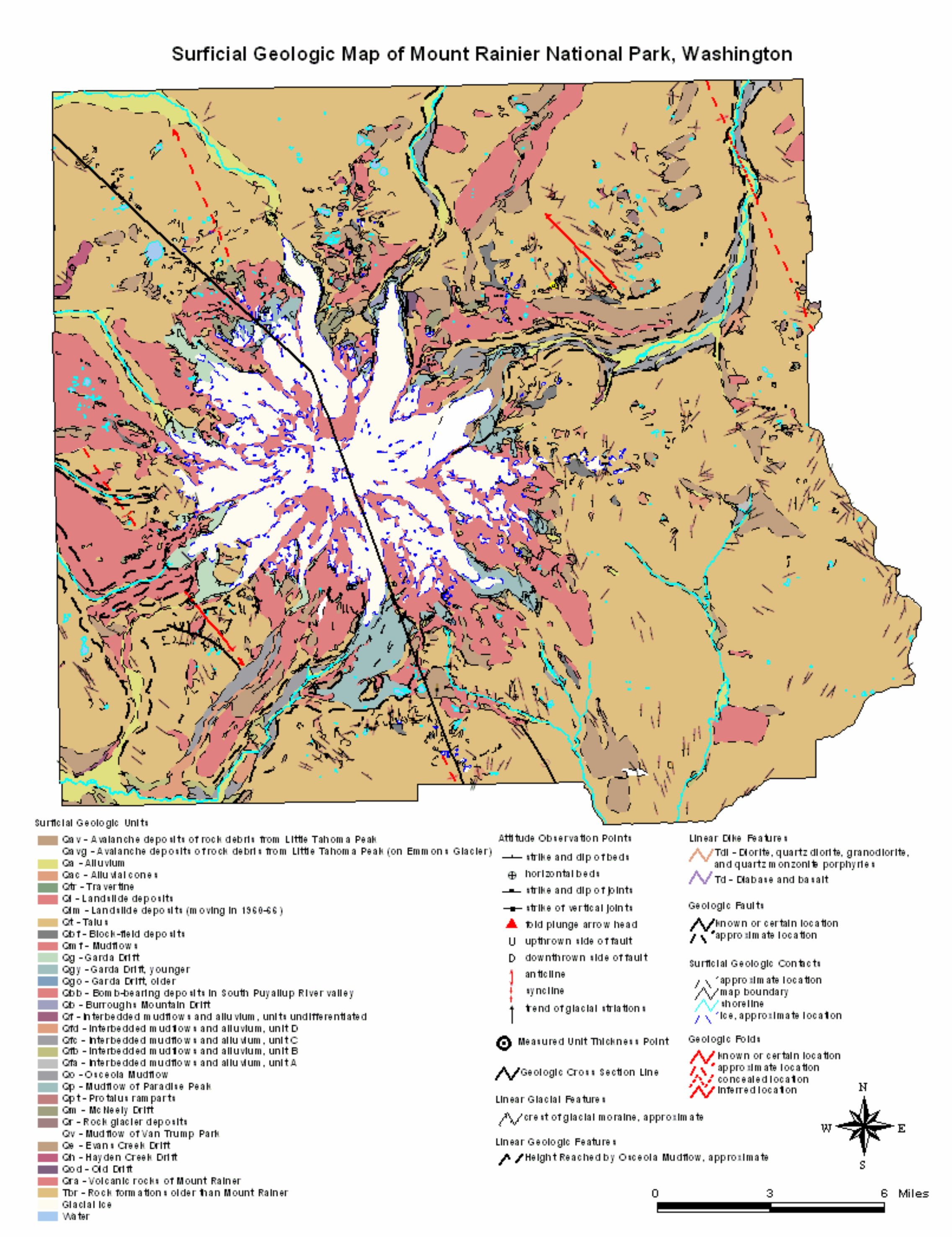
Appendix A: Geologic Map Graphic

This image provides a preview or "snapshot" of the geologic map for Mount Rainier National Park. For a detailed digital geologic map, see included CD.



The original map digitized by NPS staff to create the above surficial map was: Crandell, D.R., 1969, Surficial geology of Mount Rainier National Park, Washington, USGS, Bulletin 1288, 1:48,000 scale. In addition a bedrock geologic map: Fiske, R.S., Hopson, C.A., and Waters, A.C., 1964, Geologic map and section of Mount Rainier National Park, Washington, USGS, I-432, 1:62,500 scale, was digitized as part of the GRE program. For detailed digital geologic data and cross sections, see included CD.

Mount Rainier National Park
Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/007
NPS D-535, September 2005

National Park Service
Director • Fran P. Mainella

Natural Resource Stewardship and Science
Associate Director • Michael A. Soukup

Natural Resource Program Center
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Geologic Resources Division
Chief • David B. Shaver
Planning Evaluation and Permits Branch Chief • Carol McCoy

Credits
Author • Dr. John Graham
Editing • Lisa Norby and Sid Covington
Digital Map Production • Victor DeWolfe, Stephanie O'Meara, Josiah Engblom, and Melissa Copfer
Map Layout Design • Melanie Ransmeier

National Park Service
U.S. Department of the Interior

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, CO 80225

http://www.nature.nps.gov/geology/inventory/
(303) 969-2090