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Geomorphology of Mount Rainier

Landform Mapping at Mount Rainier National Park, Washington

Natural Resource Report NPS/MORA/NRR—2016/1234

ON THE COVER
View looking up the West Fork White River at the debris covered terminus of the Winthrop Glacier, with the north face of Mount Rainer looming in the background.
Photograph by: Stephen Dorsch, National Park Service

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Jon Riedel and Stephen Dorsch

National Park Service
North Cascades National Park Service Complex
7280 Ranger Station Road
Marblemount, Washington 98267

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Executive Summary

The Geomorphology of Mount Rainier National Park (MORA) was completed as one of the 12 basic inventories desired for each park in the 1998 Natural Resources Challenge Inventory Program. It is closely linked to ongoing mapping of soils by the Natural Resource Conservation Service and to the multi-scaled USFS National Hierarchical Framework for Ecological Units (Cleland et al. 1997) to provide opportunities for ecosystem management with adjacent national forest lands.

In the broadest sense, the geology of MORA is a testament to the awesome power of tectonic forces near a subduction zone that created the largest stratovolcano in the lower 48 states. At a small scale (Subsection) Mount Rainier volcano is surrounded by mountains dominated by older volcanic rocks, setting it apart from Glacier Peak and Mount Baker to the north. The geomorphology of the park is also strongly shaped by surficial Earth processes that are controlled largely by climate, such as glaciation, mass wasting, and river erosion and deposition that are controlled largely by climate. These processes created the shape of the landscape adjacent to the volcanic cone that dominates the skyline for hundreds of miles and accounts for about 8% of the park.

Erosion by glaciers created the dominant landforms of the park, the cirque and valley wall. Slightly more than half of MORA is mapped as valley wall, while the heads of all major valleys are mapped as glacial cirques and account for 7% of the park. Glacial moraines are common landforms and are scattered at various elevations. The youngest of these moraines tower above the termini of modern glaciers and attest to the sensitivity of the glaciers to climate change. Only 100 years ago, glaciers filled the valleys above the moraines to cover about 30% more of the park than they do today.

Mass-wasting processes are important on the steep slopes of the volcanic cone and valleys walls. The largest landslides in the recent history of the park created the Osceola and Sunset amphitheaters on the volcanic cone, and triggered massive lahars that reached all the way to Puget Sound as little as 600 years ago. We also mapped 116 large landslides (debris avalanches) along valley walls; many of these are very old features, while many others remain active today. Rock falls and topples are also common from cliffs and rock summits across MORA. Most of the material being eroded from valley walls ends up at the bottom of these steep slopes to form debris aprons. This landform is the second most prevalent in the park, covering about 12% of the total area, and has a significant amount of volcanic ash from more than 30 eruptions of Mount Rainier and other Cascade volcanoes.

Five major watersheds radiate from the volcanic cone, and each has a somewhat unique geologic history. Because they head on the heavily glaciated active volcano, Cowlitz, Carbon, Nisqually, Puyallup and White rivers have broad glacial valleys with wide, terraced floodplains and braided rivers. They all have carried large lahars from the volcanic cone to surrounding lowlands. In contrast, the Ohanapecosh valley is the largest in the park that does not head on the volcano and, as a result, has a different geomorphology than the others. This is evidence by a higher proportion of valley walls (71% of basin) and a narrow floodplain that accounts for less than 1% of the watershed.

Most of the valleys have broad, U-shapes created by glaciers, but steep, rock-walled river canyons also occur throughout the park and include popular visitor destinations such as Box Canyon on the

Muddy Fork of the Cowlitz River. In some cases the canyons are found down-valley from the reach of glaciers, while in other settings they are carved into the flat floors of glacial valleys.

Several unusual landforms were identified in this inventory. A sackung was identified along the west side of Iron Mountain in the Kautz Creek watershed. Sackungs are typically identified as depressions running near the crest of a ridge and are deep-seated slope failures driven by gravitational forces acting on valley-walls over-steepened by glacial erosion. Parklands are gently sloping former lava flows that are favored destinations for visitors because of their accessibility and beautiful open subalpine meadows. This inventory identified 55 individual parklands that cover about 29 km^2 of MORA. Another noteworthy landform at MORA is patterned ground, which consists of stone lines or rock polygons created by frost action on fine-grained deposits at elevations high above treeline. We identified nine sites in the park with these features; all are found along high ridges where winter temperatures are extremely cold and high winds remove insulating snow cover.

The data contained in this report has several important management implications for MORA. Landforms provide critical information on three of five soil forming factors (parent material, time, and relief) and are also closely linked to vegetation. Combining landform, soils and vegetation data will allow park staff to unlock many key ecological relationships, identify habitat for key species of plants and animals, and guide ecological reference site selection and restoration. This report also presents important information for management of geologic hazards, including volcanic (lahars) and non-volcanic (rock falls, debris cones, debris avalanches). Many of the mapped landforms provide information on past climate change in the park; these include features which range from less than 100 years old to glacial moraines as old as the last ice age (13,000 years ago). Data included in this report will also assist with cultural resource management because landform age is known to correspond to the density of archeological sites. Finally, this report contains many stories about the natural history of the park that interpreters can share with the public. These stories include, but are not limited to, the history of the volcano and the unique natural history of each major valley, the sensitivity of the park to climate change, prehistoric human use of MORA, and the inter-relationships between geology, climate, geomorphic processes, soils, vegetation, and habitat.

Acknowledgments

This project was funded as part of the Natural Resources Challenge Inventory Program by the NPS Geological Resources Division. It would not have been possible without the support of NPS Soil Scientist Pete Biggam and a concerted, sustained effort by a team of geologists over a period of eight years. This team included NOCA staff Nicole Bowerman, Sharon Brady, Rob Burrows, Michael Larrabee, Jeanna Wenger and other numerous interns and volunteers. We also greatly appreciate the support provided by MORA staff Paul Kennard, Rebecca Lofgren, and Barbara Samora. Carl Davis and staff from Wenatchee National Forest conducted the Landtype Association scale mapping and, along with Jerry Sherrid from Mount Baker Snoqualmie National Forest, assisted with Subsection scale mapping. Finally, we thank MORA Geologist Scott Beason and NPS Geologist Marsha Davis for their careful review of this manuscript.

1. Introduction and Background

1.1 Purpose and Scope

The primary purpose of this report is to describe the background information, methods and results of a surficial geology inventory within Mount Rainier National Park (MORA). This is one of twelve basic inventories called for in the National Park Service (NPS) National Resource Challenge. A secondary goal is to provide an overview of the park's geology, climate and hydrology as they affect geomorphic processes.

Background information presented in this report focuses on key processes that created the landforms within MORA. These include glaciation, mass-wasting, volcanism and the fluvial processes. Several factors that influence these processes include bedrock geology and structure, glacial history, climate, hydrologic setting, and vegetation. A brief discussion on landform age follows the background information to give geomorphic processes a temporal context. A detailed description of methods is provided before discussing the results and interpretations of the landform inventory.

The results and discussion section of this report gives detailed analysis for the individual watersheds mapped at MORA. Discussion of each watershed includes the unique characteristics of the individual valleys and specific examples of landform genesis. Detailed information is gathered for each mass movement in order to reveal both historic and on-going mass wasting occurring in each watershed.

1.2 Applications of Landform Mapping Data

Understanding surficial processes and materials is critical for resource managers in mountainous terrain. Surficial processes such as landslides, floods, and glaciation directly impact the human use and management of rugged landscapes. The sediments produced by these processes influence soil and vegetation patterns and provide information on geologic hazards, prehistoric landscape use, habitat, and ecological disturbance. Knowledge of the function of surficial processes and distribution of materials assists the NPS in selection of ecological reference sites, identification of rare or threatened habitat, management of risk from geologic hazards (Riedel and Probala 2005) and cultural resources (Mierendorf et al. 1988).

Landform mapping is specifically being utilized as an input for the creation of a soils distribution map for MORA. Traditional methodologies, relative inaccessibility, and estimated high costs have not allowed for extensive soil surveys in the rugged wilderness parks of the North Coast and Cascades Network. Parent material, time (stability/age), and relief are three of five soil-forming factors linked to distinct landforms. Therefore, knowledge of landforms are a critical component to mapping soils in remote, rugged landscapes. Linking soils to landforms is a cooperative effort among North Cascades National Park (NOCA), the Natural Resources Conservation Service (NRCS) state mapping program, the United States Forest Service (USFS), Washington State University, and the NPS Soils Program.

1.3 Project History

In 1988, staff at NOCA began using an eight landform mapping scheme to assess distribution of archeology sites. This program continued to develop in the early 1990's when a suite of 15 landforms were mapped to support a general management plan for Lake Chelan National Recreation Area. In 1995, the program expanded to meet the needs of NOCA as a prototype park for long-term ecological monitoring (LTEM) programs. This included the development of a 23 landform scheme to support classification and assessment of aquatic habitat. There are now 38 distinct units in a regional landform scheme, of which 34 are found in MORA. Landform units are created by discrete geologic processes, many of which are still active and relatively easy to identify. The landform scheme has now been applied to several watersheds in five of the seven NPS units of the North Coast and Cascade Network (NCCN), including MORA, NOCA, and Olympic National Park (OLYM), Ebey's Landing National Historic Reserve, and San Juan Island National Historic Park.

The development of this program was assisted by the Natural Resource Challenge to obtain 12 basic inventories for all NPS areas, including surficial geology and soils. In 2001, NOCA landform mapping was linked with the United States Forest Service (USFS) multi-scaled "National Hierarchical Framework for Ecological Units" (Cleland et al. 1997) for public lands in the North Cascades. The approach uses a nested system in which each scale (eight total) fit inside one another. Together the USFS and NPS have mapped at three of these scales; 1-Subsection (1:250,000), 2-Landtype Association (LTA) (1:62,500), and 3-Landform scales (1:24,000). The first product was a seamless coverage in the North Cascade region at the Subsection scale. These units focus on climate, bedrock geology, and topography at a regional scale. The LTA scale is mapped by watershed and units are based on topography and process. LTAs were mapped from 1:62,500 air photos by staff from the Wenatchee National Forest in 2004.

Landform mapping at MORA began in 2001 in the Nisqually River watershed. Subsequent field visits continued each summer season to new watersheds working counterclockwise around the mountain; field work concluded in the Puyallup River watershed in 2009. This report gives detailed results for all watersheds at MORA, including a discussion of the unique geomorphology and history of the major river valleys at MORA, as well as a summary of landslide inventory data.

2. Study Area

2.1 Geographic Setting

Mount Rainier is the highest stratovolcano in the Cascade Range at 4,392 m and is one of the highest peaks in the conterminous United States. It dominates the landscape of a large part of western Washington State and is known as ‘The Mountain’ to residents of the Puget Sound. MORA surrounds the volcano and encompasses 954 km^2 on the west side of the Cascade Range. MORA is located about 100 km southeast of the Seattle metropolitan area (Figure 1). The park is approximately 97% designated Wilderness, 3% National Historic Landmark District and receives approximately 2 million visitors per year.

Mount Rainer stands 4 km above the Puget lowlands to the west and 2.5 km higher than the adjacent Cascade Mountains. It is an active volcano that last erupted about 150 years ago (Scott et al. 1995). Approximately 58% of the park is forested, 23% is subalpine parkland, and the remaining 19% is above tree line. Half of the area above treeline is vegetated and the other half consists of permanent snowfields, ice and rock. Over 91 km^2 of snow and ice encase Mount Rainier making it the largest single-peak glacial system in the United States (Driedger and Kennard 1986).

These glaciers drain into five major rivers and their tributaries: the Puyallup and Carbon Rivers in the northwest, the Nisqually River in the southwest, the Cowlitz River in the southeast and the White River in the northeast (Figure 1). All of these rivers, except for the Cowlitz, traverse the Cascade Range and Puget lowland before draining into Puget Sound. The Cowlitz River flows more than 140 km southward and enters the Columbia River. Each major river occupies a deep valley with floors that are 300 to 900 m below the adjacent watershed divides. Valley floor gradients are steep and increase markedly at the base of the volcanic edifice near Longmire, White River Campground and other locations. The mountain’s summit towers 2,750 to 3,350 m above valley floors only 5 to 10 km away. In addition to glaciers, other water resources in the park include 470 mapped rivers and streams, 382 mapped lakes and ponds, more than 10 km^2 of wetland, numerous waterfalls, and mineral springs (NPS 2001).

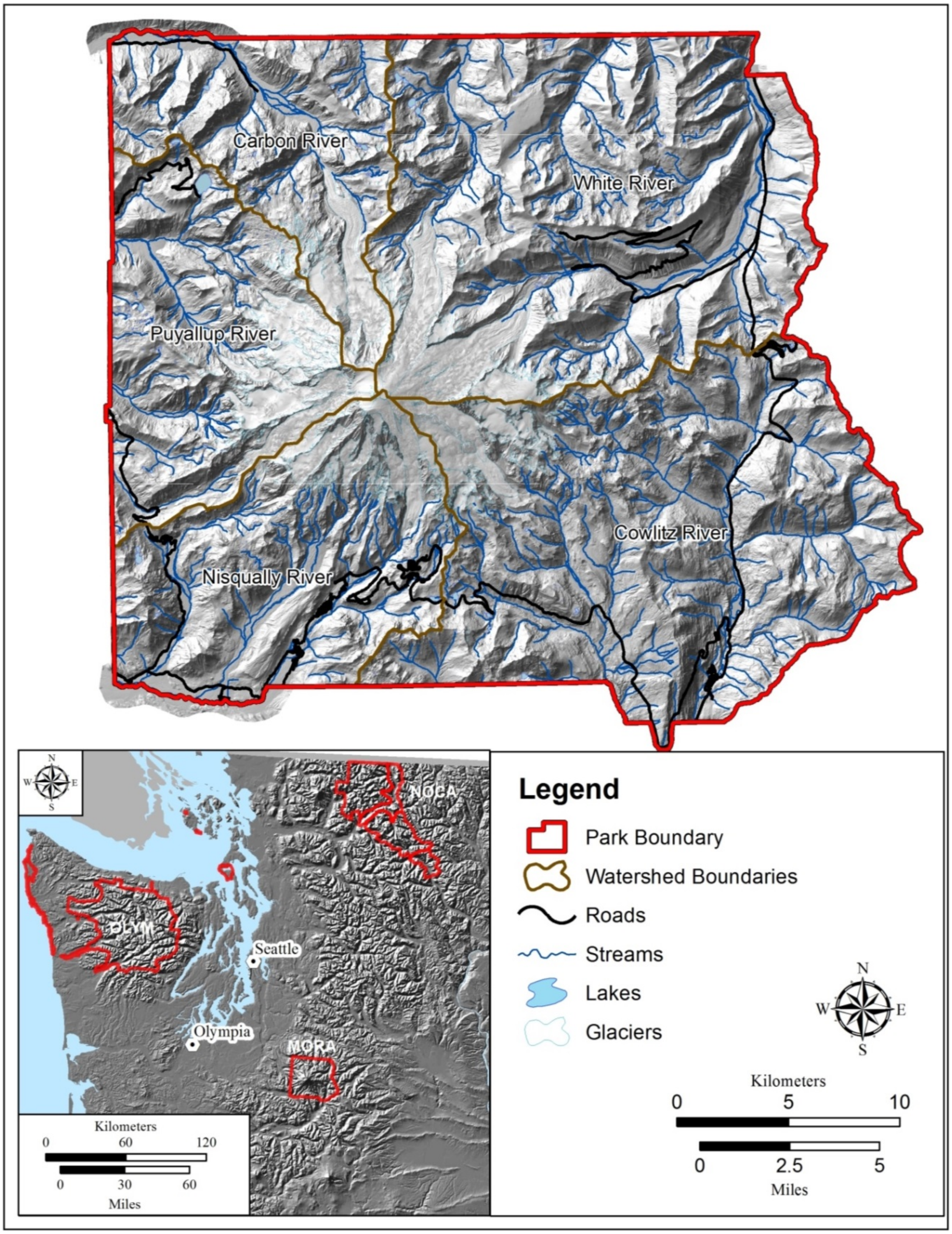

Figure 1. Map showing the location of Mount Rainier National Park (MORA) and the major watersheds discussed in the text. Insert map shows the location of MORA within Washington State, as well as North Cascades National Park (NOCA) and Olympic National Park (OLYM).

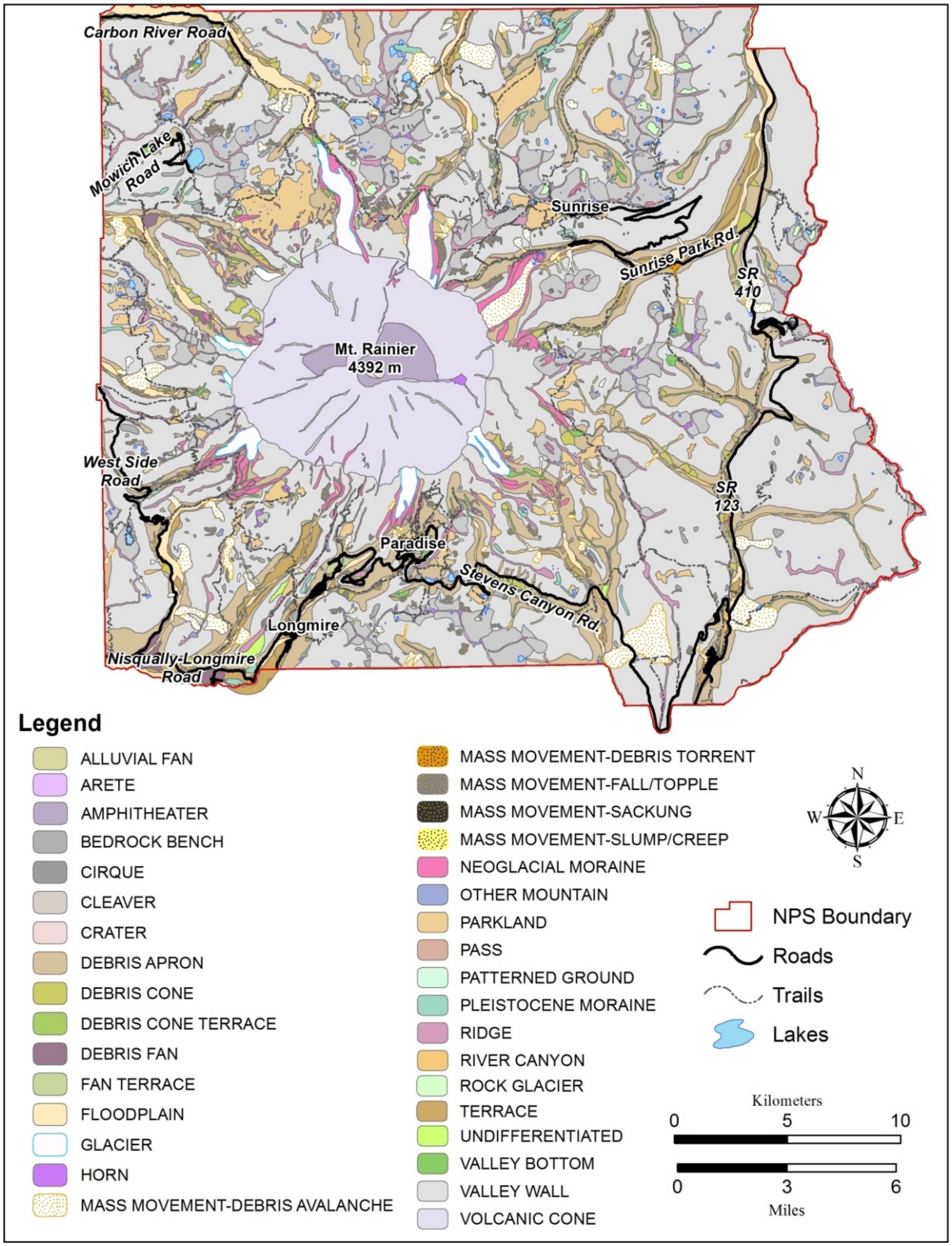

Figure 2. Landform map of Mount Rainier National Park with the locations of major localities and roads that are referred to in the text.

2.2 Geologic Setting

Mount Rainier is the largest peak in the Cascade Mountains, which stretch from Mount Lassen in northern California to Mount Garibaldi in southern British Columbia. The general character of the Cascades, from geochemical signatures to physiographic appearance, varies from north to south with the boundary roughly running northwest-southeast along the Olympic-Wallowa Lineament (OWL). The OWL is a large physiographic feature first described by Raisz (1945).

The bedrock geology of MORA has been mapped at the 1:62,500 scale by Fiske et al. (1963 and 1988) and spans approximately 56 million years of Earth history. The base of the modern volcano overlies Tertiary (Eocene – Miocene) sedimentary and volcanic rocks that were folded and intruded by the Miocence Tatoosh plutonic complex (Fiske et al. 1963). Development of the Mount Rainier volcanic cone likely began in the early or middle Pleistocene and is largely composed of intermediate magmatic material sourced from oblique subduction of the Juan de Fuca plate beneath North America (Crandell 1963, Crandell and Miller 1974). The following is a brief overview of the geologic history of Mount Rainier summarized from Pringle (2008).

1. 55.8 – 43 Ma: Sediments deposited in marine basins and river deltas to the west of MORA.
2. 43 – 37 Ma: The earliest Cascade volcanoes begin to erupt, mainly mafic lavas, and form on a coastal plane.
3. 37 – 27 Ma: Sea level transgresses and pushes the coastline to the east. Also, another early Cascade volcanic arc begins to emerge further to the east. Silica content of lava increases, which raises the viscosity and explosiveness of the volcanoes.
4. 27 – 22 Ma: Volcanic activity increases.
5. 22 – 5 Ma: Volcanism activity slows or is otherwise not preserved in the rock record due to increased erosion from uplift during this time. The Tatoosh pluton is emplaced (~25 – 6 Ma). Columbia River Flood Basalts flow to the east of MORA (17.5 – 6 Ma). Dikes and sills intrude areas north and east of Mount Rainier.
6. 5 Ma – into Holocene: Volcanic activity increases again. Approximately 2 – 1 Ma ancestral Mount Rainier begins to form, but is subsequently eroded drastically. The modern Mount Rainier begins to form ~ 500 ka – present day. Glaciation marks the late Holocene with the Hayden Creek glaciation (~170 – 130 ka), the Evans Creek glaciation (~22 – 15 ka), and the Neoglacial advances that were most extensive during the Little Ice Age.

2.2.1 Geologic Units

A detailed description of the geology is found in Fiske et al. (1963 and 1988) and is summarized below. A generalized geologic cross-section (Pringle 2008) provides a regional perspective of the distribution of geologic units at MORA (Figure 3).

The oldest rocks belong to the Eocene Puget Group of sedimentary rocks. The sediments were deposited in a coastal plain and formed sandstone, siltstone, mudstone, claystone, and coal over a broad area west of Mount Rainier (Kiver and Harris 1999). The start of the Oligocene was marked by an increase of volcanic activity evidenced by the deposition of the approximately

3,000 m thick Ohanapecosh Formation (35 – 28 Ma). The Ohanapecosh has clusters of subaerial and subaqueous volcanic deposits of breccias, lava flows, mudflows, and ash falls interpreted to be from shallow water depositional environments. The volcanic material is largely felsic to intermediate in silica content, but also has had replacement minerals such as zeolites that have altered the original mineralogy and colors to dark grey and green. The area was uplifted and folded during the Oligocene and large valleys were carved into this formation. In the upper Oligocene and lower Miocene, ash falls and lava flows of the Stevens Ridge Formation were deposited with enough heat to fuse into welded tuff in some locations.

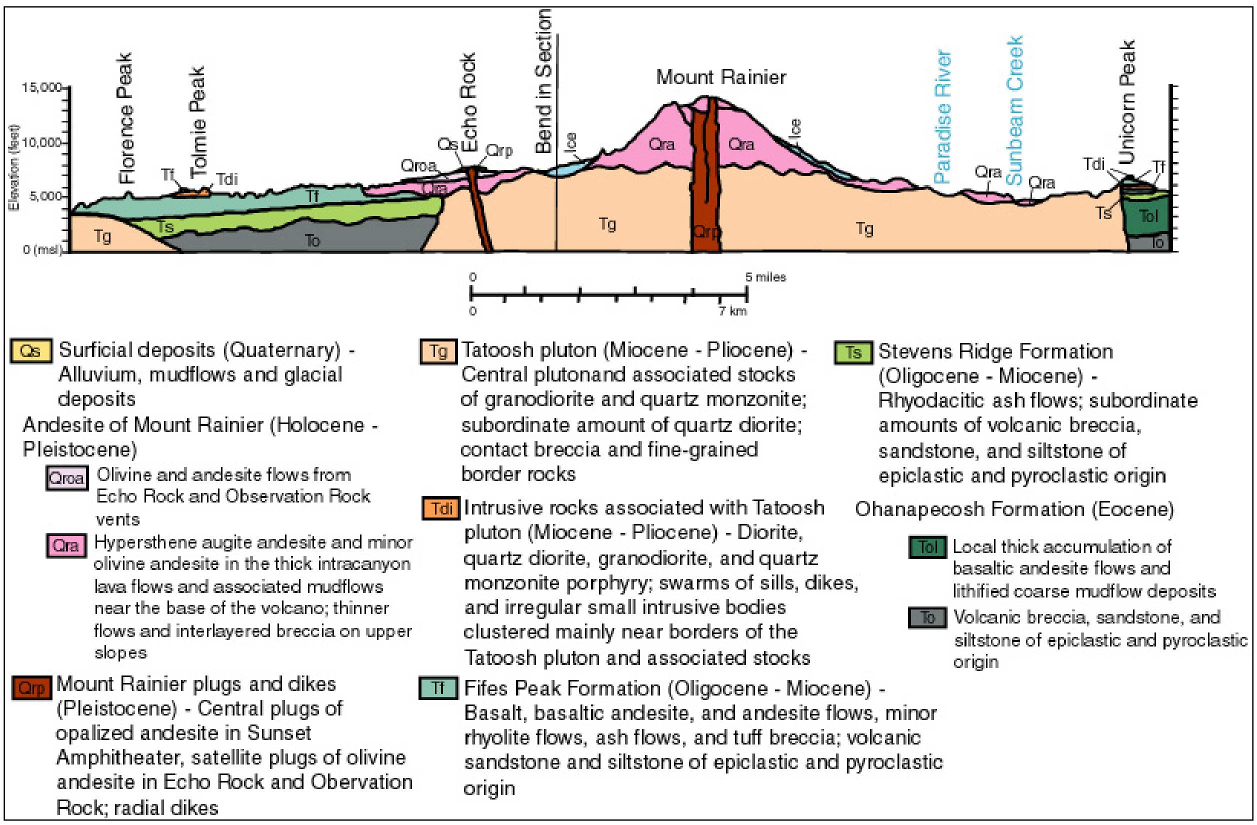

Figure 3. Geologic cross section of Mount Rainer showing the bedrock units of Mount Rainer National Park and surrounding areas that are described in the text (Modified from Pringle 2008).

Also deposited in the lower Miocene and overlying the Stevens Ridge Formation is the volcanic Fifes Peak Formation, which includes andesitic and basaltic lava flows. Much of the flow deposits have been eroded, but feeder dikes and sills that were injected between strata of the Ohanapecosh and Stevens Ridge Formations are still observable. A period of compressional deformation folded and faulted the area enough to displace the basal strata of the Stevens Ridge Formation. The Tatoosh pluton and associated dikes and sills were emplaced at the end of the Oligocene and during much of the Miocene, approximately 25 – 6 Ma. The Tatoosh rocks are largely granodiorites, which intruded the older Ohanapecosh and Stevens Ridge Formations. Much of the Tatoosh rocks have been eroded from the surface and are best observed in the Carbon, White River and upper Nisqually drainages. Fiske et al. (1988) suggest that Mount Rainier is underlain by the Tatoosh pluton.

Ancestral Mount Rainier began to form in the upper Miocene and into the Pleistocene, 7 – 2 Ma, however most of the known eruptive history is from the upper Pleistocene to the present. During the Pleistocene, glaciers eroded large valleys into the landscape, which then filled with andesitic lava flows that now stand as some of the modern day ridges of Mount Rainier, such as Rampart Ridge (Fiske et al. 1988). New research suggests that some of these lavas flowed between valley glaciers on ridge tops (Sisson and Lanphere 1999).

Glaciation, volcanic eruptions, and lahars/debris flows mark the most recent geologic history of Mount Rainier. The modern day Mount Rainier volcanic cone has been built up by overlapping layers of lava flows and tephra debris and may have reached its greatest height of approximately 4,700 – 4,900 m in the upper Pleistocene, approximately 75 ka (Harris et al. 1995). Holocene eruptive activity at Mount Rainier produced 11 pumiceous tephra layers ranging in estimated volumes from 0.001 to 0.3 km^3 (Crandell and Mullineaux 1967, Crandell 1969a, Mullineaux 1974); as many as 30 lithic-rich, vesicle poor tephra layers have also been identified (Vallance and Donoghue 2000). The cumulative amount of tephra erupted in the past 10 ka totals more than 0.5 km^3 (Pringle 2008). In addition to these Mount Rainier tephra layers, ash from Mount Mazama (Crater Lake) and Mount St. Helens is widespread within MORA (Mullineaux 1974). A number of pyroclastic flows have also been documented in MORA and can be further researched in Fiske et al. (1963 and 1988).

Many lahar and debris flow deposits have been documented as well. The largest of the debris flow documented off Mount Rainier is the Osceola Mudflow, which occurred 5.6 ka. The Osceola Mudflow transported an estimated 3 km^3 of debris at least 110 km down the White River watershed and deposited the material over areas that are now heavily populated in the Puget Lowland. Often these debris and lahar deposits are interbedded with glacial deposits. Lahars and their associated deposits at MORA are discussed in greater detail later on in the Postglacial History section of this report.

2.2.2 Tectonics and Structure

Southwestern Washington geologic structure is a complex assemblage of accreted terranes, volcanic arcs, and underplated magmatic rocks. The older accreted terranes are well exposed in the North Cascades, but are underlying Tertiary volcanics to the south with the Rimrock inlier being the southernmost exposure southeast of Mount Rainier. In the Eocene, the basement terrane rocks were cut by large dextral strike-slip faults, such as the north-south trending Straight Creek Fault, that created pull-apart basins that were subsequently filled by Puget Group sediments. The volcanic rocks and volcanoes of the Cascade magmatic arc represent the last 40 Ma of subduction of the Juan de Fuca and predecessor plates.

Most structure in southwestern Washington is due to oblique subduction of the Juan de Fuca plate underneath the North American plate. The oblique subduction rotates regional crustal blocks, which put Mount Rainier in a zone of largely north-south compression (Wells et al. 1998). This north south compression is manifested in the active northwest-southeast trending Yakima fold and thrust belt to the east of Mount Rainier and the east-west trending Seattle and Tacoma fault zones to the west of Mount Rainier.

Many earthquakes have been observed in a north-south trend in an area approximately 15 km west of Mount Rainier known as the western Rainier seismic zone (WRSZ). The WRSZ also correlates spatially with the Carbon River-Skate Mountain and Morton anticlines, which were created by folding and uplift of Oligocene and younger sedimentary rocks (Fiske et al. 1963). Directly underneath Mount Rainier there are frequent shallow earthquakes that are likely related to local stress field changes rather than regional stress changes.

The Cascade arc can be divided into five different regions based on the distribution of volcanic vents produced in the last 5 million years (Guffanti and Weaver 1988). Mount Rainier is located in the northern part of an area marked with relatively low production and dominated by basaltic lava. However, Mount Rainier is andesitic and dacitic in composition, along with Mount St. Helens, Goat Rocks Volcano, Mount Adams, and Mount Hood. The north and south Cascades are also marked by physiographic differences and the boundary between the two coincides with the location of the OWL, which also truncates the Straight Creek Fault and may or may not denote a larger northwest-southeast trending structural feature in the region.

2.3 Glacial History

Mount Rainier National Park’s long and complex glacial legacy continues to be shaped by the massive modern glaciers that grace about 11% of the park. The 4392m height and broad shape of Mount Rainier nourish a total of 26 large glaciers (Figure 4) with a combined volume of 4.4 cubic kilometers (Driedger and Kennard 1986). As impressive as the modern glaciers are, they are relatively small when compared to the large tongues of ice that filled the park’s five major valleys for most of the past several million years.

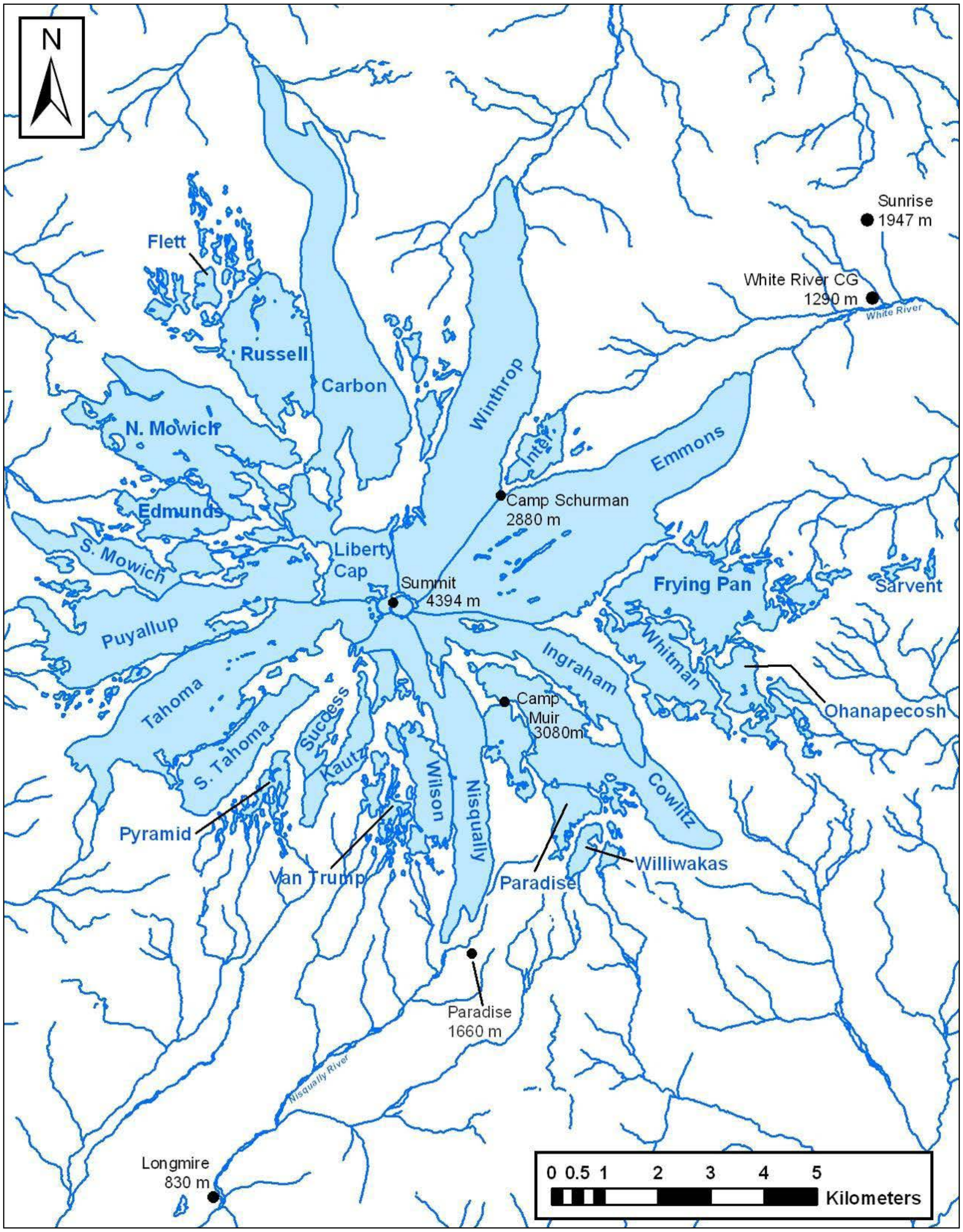

Figure 4. The 26 major glaciers on Mount Rainier (Riedel et al. 2010).

Glacial and volcanic processes have shaped the park landscape for the past several million years (Pringle 2008). Glaciers at Mount Rainier undoubtedly preceded development of the modern volcanic cone, which began about 500 ka (Sisson et al. 2001). Since that time, glaciers have continued to shape, and be shaped by, the mountain. The volcano was likely built upon a volcanic and glacial landscape similar to the one surrounding the mountain today. It is now recognized that parts of many of the more recent inter-canyon lava flows were placed between glaciers (Sisson and Lanphere 1999). Lava flows, mud flows, pyroclastic flows and collapses of portions of the volcanic edifice have also eroded or buried glacial deposits from early glaciations in the five main valleys in the park.

2.3.1 Pleistocene

Based on studies of polar ice cores and sea floor sediment cores, it is likely that there have been a dozen or more ice ages in the past 2.5 million years. Climate for most of this time was significantly colder than today. Prolonged periods of extensive glaciation known as ice ages led to development of small ice caps centered on Mount Rainier that covered up to 800 km^2 (Crandell and Miller 1974). The ice caps fed 100 km long streams of ice that radiated from Mount Rainier west to Puget Lowland. Ice thickness on the steep sides of the mountain likely never exceeded 30-40 m, but in parks and in major valleys, ice accumulated from tributaries reached several hundred meters in depth. At some point, the ice cap was thick enough to spill south across the Tatoosh Range via several passes into Butler Creek (Crandell and Miller 1974).

Along the way, these several hundred meter thick glaciers cut long, straight, U-shaped troughs, leaving tributaries as hanging valleys. At the heads of large valleys and on the flanks of the mountain, glaciers cut deep basins called cirques with floors as low as 1,200 m. These circular-shaped basins hold many of the park's largest and deepest lakes (e.g. Mowich, Tipsoo, Louise) (Crandell and Miller 1974). In alpine areas, glacial and freeze-thaw processes have removed hundreds of meters of rock, and exposed the deeply buried Tatoosh granodiorite and other rocks. The effect of ice erosion is likely so severe that it may limit the height of the non-volcanic peaks in the Cascade Range (Mitchell and Montgomery 2006).

While these erosional landforms were formed by repeated glaciation, deposits from several ice age glacial advances from Mount Rainier have been identified and roughly dated to specific events in the past 700,000 years (Crandell and Miller 1974). Each major advance built a large terminal moraine with thick sand and gravel outwash that extends tens of kilometers downstream.

For the most part, moraines from near and within the park can be correlated with those in the surrounding Cascades, including the Yakima and Wenatchee valleys to the northeast (Porter 1971, Porter and Swanson 2008) and the Skagit valley to the north (Riedel 2009), as well as the western Olympic Mountains (Thackray 2001). However, due to a glacier's ability to erode or bury older glacial deposits in their path, the record in any one valley is usually incomplete. Furthermore, within MORA, older glacial deposits are restricted to near the tops of ridges, where they were not covered by smaller later glaciations and volcanic deposits.

In general, the earlier Pleistocene advances were more extensive than recent ones, and terminal positions for all of the ice age advances are well outside the park. Glacial deposits about 600 ka are contained in the Lily Creek Formation, and have been described on the west flank of Burroughs Mountain, Ohanapecosh Park, and in other locations. They are buried by more recent volcanic deposits, including lava flows, volcanic rubble and lahars (Crandell and Miller 1974).

The Wingate Hill glaciation reached 6 km west of Mossyrock in the Cowlitz valley, and to Alder Lake in the Nisqually valley about 500 ka. Soils formed in the glacial deposits are deeply weathered, with stones having rinds as thick as 7 mm (Crandell and Miller 1974). A large outwash plain from this event is composed of sand and gravel and forms the Cowlitz Prairie north of Toledo.

Another glaciation that occurred between 170-130 ka is called the Hayden Creek advance, although the exact timing of this event is poorly understood. This advance reached as far as the Wingate Hill advance in the major valleys and left a prominent terminal moraine just northeast of Ohop, Washington. Glacial till from this advance was observed on the top of Iron and Copper mountains in the southwest part of the park, while glacial striations have been observed at the summit of Mount Ararat at 1,800 m, meaning that the ice cap was 900 m thick (Crandell and Miller 1974). Hayden Creek till can be observed in road cuts along the highway to Yakima Park.

Widespread evidence of a third advance, named the Evans Creek for a moraine near that stream in the Carbon valley, occurred in the most recent ice age, known as the Fraser Glaciation. Glacial deposits of this age are generally weathered to depths of 1.2 m, and stones appear fresh with small, or absent, weathering rinds. This advance was less extensive than previous ones, but still reached well outside of MORA.

Most of what is known about the influence of large glaciers comes from deposits of the most recent extensive ice age (the Fraser Glaciation). At two points in the last ice age, about 70 and 30 ka, alpine glaciers made major advances. It seems likely, however, that glacial margins fluctuated by several kilometers during these general periods of ice build-up, as well as during periods of general ice recession.

By about 30 ka, alpine glaciers throughout the region had reached positions as much as 60 km from their valley heads (Porter 1971, Crandell and Miller 1974, Thackray 2001, Porter and Swanson 2008, Riedel et al. 2010). The Cowlitz valley glacier was the largest heading on Mount Rainier during the last ice age, extending 67 km from the present Cowlitz Glacier terminus. These long valley glacier systems remained in extended positions for most of the succeeding 15,000 years before they began to recede about 15 ka. During the next 2,000 years, alpine glaciers at Mount Rainier probably continued to be extensive, but generally receded while fluctuating at thousand-year time-scales.

Toward the end of the last ice age, a continental glacier grew out of south-central British Columbia and advanced to its maximum position about 17.5 ka (Porter and Swanson 1998). At this time, the Cordilleran Ice Sheet was 500 km long, more than 2.5 km thick (Riedel et al. 2010), and blocked and altered the courses of the Nisqually, Puyallup, Carbon, and White rivers. Large deposits of sand and gravel across the mouths of these valleys east of Eatonville, Kapowsin, Enumclaw and Wilkeson mark the former edge of the ice sheet (Crandell 1969b, Waitt and Thorson 1983).

Following rapid retreat of the ice sheet after 17 ka, an abrupt return to colder global climate occurred about 13 ka. It was likely caused by the sudden drainage of massive Glacial Lake Agassiz into the North Atlantic Ocean (Broecker et al. 1988). This cold and dry climate triggered the McNeely advance of glaciers at Mount Rainier. At this time, glaciers generally reached 5-10 km beyond modern margins (Crandell and Miller 1974, Heine 1997). This advance was driven by a several hundred meter drop in snowline that lasted for many centuries. Based on the existence of multiple moraines at most sites, there were several different glacial advances in a 1,500 year period (Riedel 2007). One example is Mystic Lake, which was formed by a lateral moraine constructed by Carbon Glacier that overtopped the divide and spilled into West Fork White River (Crandell and Miller 1974).

2.3.2 Holocene – Neoglacial

Alpine glaciers at MORA generally retreated between approximately 11.5 and 8.5 ka. This period of warm and dry climate likely left glacial extents slightly smaller than observed today, and may have caused the demise of some of the small, low-elevation glaciers on the flanks of Mount Rainier, such as the Sarvant glaciers, small ice patches on Sluiskin Mountain, Flett Glacier, and small glaciers in the Tatoosh Range. Regional re-advance of glaciers after 7 ka is known as the Neoglacial Period, which is defined as a period of 'renewed growth of glaciers following a period of maximum (post ice age) shrinkage…' (Matthes 1914). In an early summary of data for North America, Porter and Denton (1967) suggested there were three periods of glacial resurgence in Neoglacial time, including one around 4.6 ka another between 2.6 ka and 2.3 ka, and another in the past 800 years.

The Neoglacial Period in the Pacific Northwest is characterized by the long-term advance of glaciers to positions within a few kilometers of McNeely moraine limits, which were deposited 13 ka. Based on a regional compilation of data at other Cascade volcanoes, it seems clear that these advances were getting larger and larger for at least 7,000 years. This led to a glacial record at MORA dominated by glacial moraines constructed in the last few thousand years.

At Mount Rainier, Crandell and Miller (1974) named the Neoglacial Period the Winthrop Glaciation, which occurred about 3.5 ka and likely obliterated evidence of earlier Neoglacial advances. The Winthrop Glaciation included the distinct Burroughs Mountain and Garda advances. Moraines from the earlier Burroughs Mountain advance are not widespread in the park, but Garda moraines enclose nearly every cirque and glacier.

The Burroughs Mountain advance generally coincides with the timing of major advances of alpine glaciers throughout western North America (Samolczyk et al. 2010). This advance climaxed about 2.6 ka in many areas in the US. In White River valley, Winthrop Glacier advanced to build a moraine 2.5 km northwest of the summit of Burroughs Mountain (Crandell and Miller 1974).

An examination of the record of dated moraines in western North America reveals that there were as many as 7 or 8 advances of alpine glaciers. Furthermore, glacial advances during this period were getting ever larger over the past 7,000 years, with the most extensive post ice age advance at Mount Rainier occurring during the Little Ice Age (Samolczyk et al. 2010). Crandell and Miller (1974) named this the Garda Advance, a time when the major glaciers on the mountain advanced about 2-3 km below modern termini. The Little Ice Age ended in the late 19th century, although the past century of overall retreat was punctuated by brief still stands or minor advances of the major glaciers between 1950 and late 1970s.

Glaciers on Mount Rainier were undoubtedly affected by the numerous volcanic events of the past 8,000 years, including eruptions and edifice collapses. During eruptions, lava and hot pyroclastic flows would have resulted in massive melting of glacial ice that would have triggered mud flows in major valleys. The Cowlitz (~7 ka), Osceola (~5 ka) and the Summerland (~2.2 ka) eruptive periods produced tephra (volcanic ash) and other volcanic deposits that likely caused significant temporary destruction of glaciers in the Neoglacial period. Smaller eruptions produced ash that would have covered glaciers and slowed surface melting.

Glacial erosion during the ice age also likely contributed to the collapse of large sectors of the volcanic edifice, which produced the Osceola mudflow about 6 ka and the Electron mudflow about 500 years ago. These landslides incorporated glacial ice from the mountain and covered glacial deposits in the White, Nisqually and Puyallup valley bottoms all the way to Puget Lowland. In their wake, these events also left a smaller mountain with less room for glaciers.

2.3.3 Recent Glacial History – Past Century

In the past century there has been a net loss of approximately 30% of the glacial area at MORA (Nylen 2002). The present size and length of the larger glaciers gives them an approximately 10-year lag time with climate; in other words, it takes more than a decade for a significant increase in accumulation to be reflected in an advance of the terminus (Hodge 1972).

Seasonal mass balance monitoring on Emmons and Nisqually glaciers began in 2003. Since then, cumulative mass balance is -9 m w.e. (water equivalence) for Nisqually and -7 m w.e. for Emmons (Riedel et al. 2010). Water year 2010 was the first since 2003 with a positive net mass balance for both glaciers. While about 4 km^3 (Driedger and Kennard 1986) of glacial ice remains on the mountain, these recent measurements suggest that glacial volume may be changing faster than glacial area. As a result, the glaciers may appear to the casual observer to have changed very little in the past decades. This form of glacial retreat is known as down-wasting, in comparison to a gradual change in climate where glaciers retreat mainly by back-wasting, or recession of the terminus.

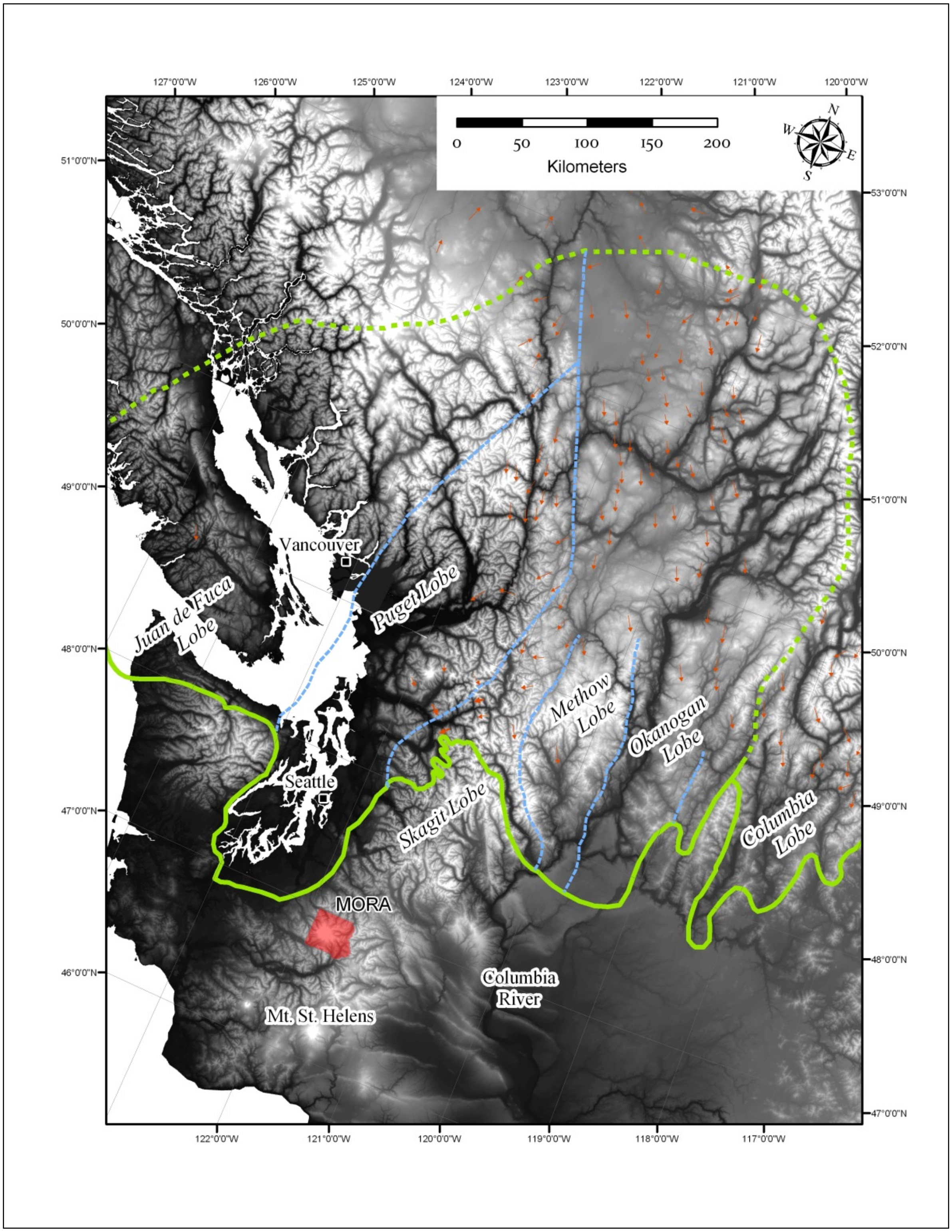

Figure 5. Map of the known extent of the Cordilleran Ice Sheet during the Fraser Glaciation relative to Mount Rainier National Park (MORA). Note the various lobes of the ice sheet mapped, extending down into the United States.

2.4 Postglacial history

2.4.1 Lahars

Lahars, or volcanic debris flows and their deposits, have occurred frequently over the past several thousand years at MORA (Scott et al. 1995 and 2001). Lahars can flow rapidly along valleys for significant distances and are considered one of the primary geologic hazards associated with Mount Rainier due to the increasing population centers along its lowland drainages. Lahars also create extensive surficial deposits and landforms, and directly influence soil formation and vegetation. More than sixty Holocene lahars have been identified at MORA. Many of these lahars are related to eruptive periods, but many are not.

Lahars at MORA can be divided into two distinct types, cohesive and non-cohesive. Cohesive lahars are the largest lahars that occur at Mount Rainier. They are relatively clay rich in composition (more than 3 to 5 percent clay, or ‘muddy’). Clay rich lahars commonly begin as volcanic landslides, the largest of which are referred to as sector collapse. These events shape the summit of a volcano and have removed rock volumes of 1 km^3 or more at MORA. Smaller slides, known as flank collapses, do not involve the volcano’s summit (Scott et al. 2001). These lahars can have very large volumes; i.e. the Electron, Osceola, Round Pass and Paradise lahars.

Non-cohesive lahars (less than 3 to 5 percent clay or ‘granular’) typically begin as a flood surge that incorporates sediment as it travels. There can be numerous triggers for these non-cohesive lahars, such as a glacial outburst floods down the steep volcanic cone, meteorological events (heavy rainstorms, rain-on-snow events), failure of a landslide-dammed lake, or interaction of a pyroclastic density current (flow) with snow and ice (Pringle 2008).

Previous mapping efforts by Crandell (1969a) and Scott et al. (1995) were used to delineate the surficial extent of lahar deposits within MORA. These deposits typically occur flanking the floodplains of rivers at MORA and have subsequently been incised and left behind as terraces. They are also interbedded with glacial deposits in lateral moraines. This landform mapping scheme identifies lahar deposits as terraces based upon their known origins established by previous work.

2.5 Climate

Climate on Mount Rainier is primarily dependent on proximity to the Pacific Ocean, latitude within westerly winds and topography (Hayes et al. 2002). Weather and climate information has been gathered at the Paradise Ranger Station since 1948. At 1,677 m, this site represents climate close to the terminus of the Nisqually Glacier, with a mean annual temperature of 2.8° C and a mean annual precipitation of 2.9 m. Most of the precipitation, 2.6 m water equivalent, occurs as snowfall during the winter season, October through May. The average June through September temperature is 9.5° C.

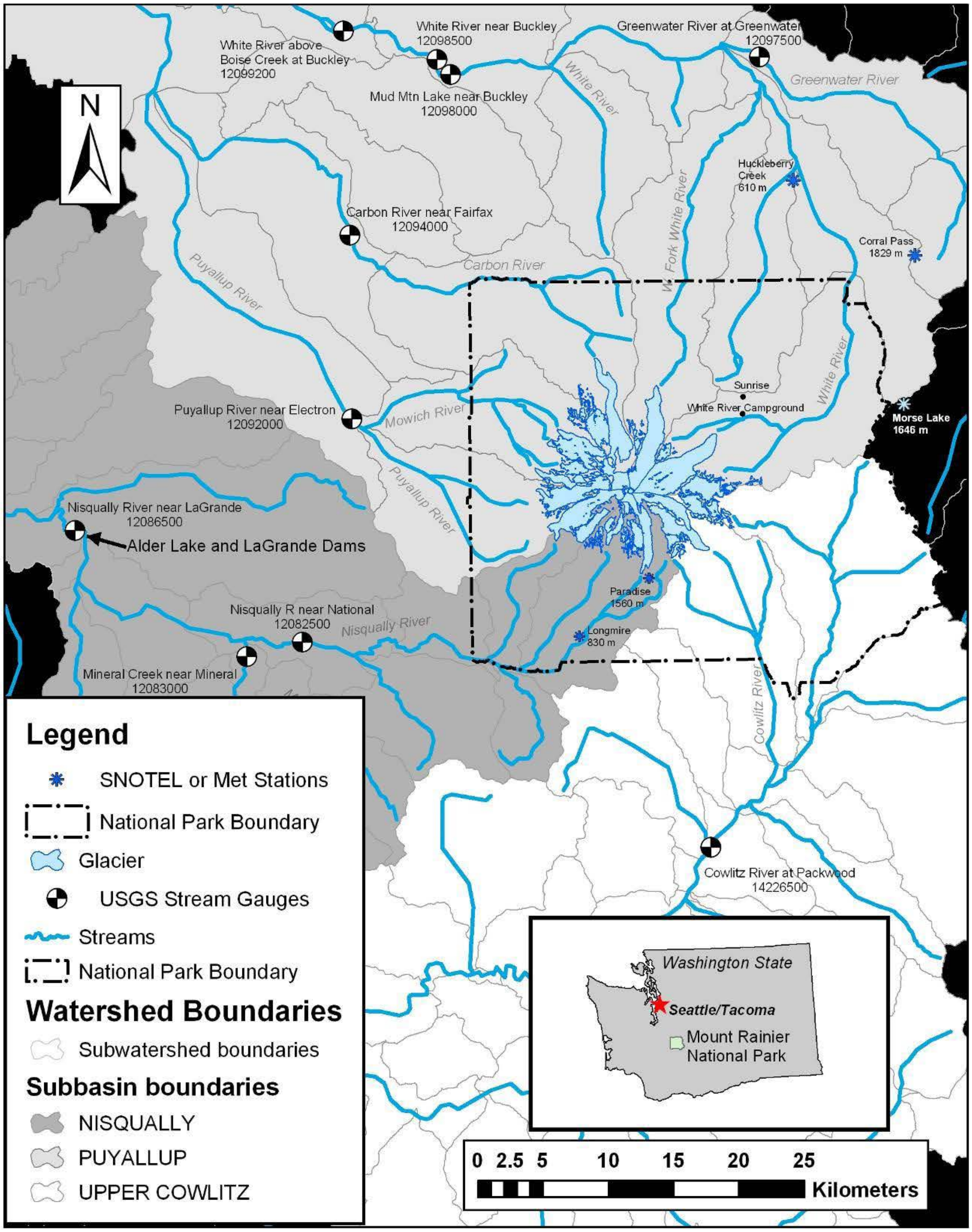

Figure 6. Map of Mount Rainier region with major watersheds, streams, USGS stream gauges, and weather stations discussed in text (Riedel et al. 2010).

Rainfall and temperature data were collected from both Natural Resource Conservation Service (NRCS) snowpack telemetry sites (SNOTEL) and Cooperative Network station sites (Table 1). Overall, yearly temperature average highs tend to occur in August, with an average high temperature of 16.6° C at Paradise and 22.4° C at the lower elevation Huckleberry Creek station. Winter low temperatures tend to occur in December through February, with Paradise averaging -6.3° C and Huckleberry Creek averaging -2.5° C. November, December, and January are routinely the wettest months, with averages varying between 17.3 cm and 47.7 cm. Generally, over 75% of yearly precipitation occurs in the winter months of November through March. Conversely, the summer months of June through August tend to be the driest, averaging only 6% of yearly total.

Table 1. Summary of data from SNOTEL and COOP sites located closest to Mount Rainier National Park (NRCS 2010, NWS COOP 2010). Data are provisional and subject to revision.

Station Name	Huckleberry Creek (SNOTEL)	Longmire Ranger Station (COOP)	Mowich (SNOTEL)	Morse Lake (SNOTEL)	Paradise Ranger Station (COOP)	Corral Pass (SNOTEL)
Watershed	White	Nisqually	Carbon	White	Nisqually	White
Elevation (m)	682	836	958	1639	1682	1758
Beginning year of data collection	1997	1978	1998	1978	1948	1979
End year of data collection	Present	2006	Present	Present	2005	Present
Mean annual temperature (°C)	7.0	7.1	7.7	2..3	3.1	2.4
Avg. high temperature (°C - Month)	22.8 - Aug.	23.6 - Aug.	14.9 - Jul.	11.3 - Aug.	16.6 - Aug.	10.8 - Jul./Aug.
Avg. low temperature (°C - Month)	-2.5 - Feb.	-2.9 - Dec.	2.7 - Feb.	-4.5 - Dec.	-6.3 - Jan.	-3.6 - Jan.
Mean annual precipitation (cm)	104.1	201.4	133.5	200.8	296.2	151.9
Avg. high precipitation (cm - Month)	17.3 - Jan.	32.6 - Nov.	19.0 - Jan.	36.2 - Dec.	47.7 - Dec.	23.6 - Dec.
Avg. low precipitation (cm - Month)	1.6 - Aug.	4.1 - Aug.	2.2 - Aug.	2.3 - Aug.	4.7 - Jul.	2.5 - Aug.

2.6 Vegetation

The park's vegetation is diverse, reflecting the varied climatic and environmental conditions encountered across the park's 4,870 m elevation range. Approximately 973 vascular plant species and more than 250 nonvascular plant species have been identified in the park (Rochefort 2010). The vegetation of Mount Rainier can be categorized into three broad vegetation zones: forest, subalpine and alpine. Vegetation cover and composition at MORA is influenced by temperature, moisture regime and length of time since disturbance (Franklin et al. 1988).

The subalpine zone encompasses about 23% of the park and extends from forestline (closed canopy forests) to treeline (highest elevation of upright trees). Forest and treeline vary with aspect, but in general the zone is found between 1600 and 1900m**.** This zone is a mosaic of tree islands and herbaceous communities. Tree species prominent in the subalpine zone include Mountain Hemlock (*Tsuga mertensiana*), Subalpine Fir (*Abies lasiocarpa*), Alaska Yellow Cedar (*Callitropsis* *nootkatensis*), Silver Fir (*Abies amabilis*), Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*). Interspersed among the tree islands are the park's iconic herbaceous meadow communities. Prior investigations into the subalpine meadows of Mount Rainier have classified these communities into five broad categories: the dwarf shrubs of the *Phyllodoce-Cassiope-Vaccinium* group, the lush herbaceous perennials of the *Valerian sitchensis-Carex spectabilis* group, the dwarf sedges of the *Carex nigricans* group, the "Rawmark" group of early colonizing herbaceous species, and the bunchgrass *Festuca viridula* group (Franklin and Dyrness 1988, Henderson et al. 1992, Biek 2000).

At elevations below the subalpine, landscape is characterized by nearly continuous coniferous forest. This zone occupies approximately 58% of the park and can be described in three broad zones: Mountain Hemlock (*Tsuga mertensiana),* Silver fir (*Abies amalblis*), and Western hemlock (*Tsuga heterophylla*). Temperature is the primary determinant of changes in forest composition with elevation, but the duration and depth of winter snowpack is also a strong force in determining species composition in the high-elevation Mountain hemlock zone and the mid-elevation Silver fir zones (Franklin et al 1988). The major tree species within the park are: Silver fir, Grand fir (*Abies grandis*), Noble fir (*Abies procera*), Alaska yellow cedar, Engelmann spruce, whitebark pine, Lodgepole pine (*Pinus contorta*), western white pine (*Pinus monticola*), Douglas fir (*Pseudostuga menziesii*), western hemlock, and western red cedar (*Thuja plicata*). Rare tree species in the park include Ponderosa pine (*Pinus ponderosa*) on the east side of the park and Sitka spruce *(Picea sitchensis*) in low elevations of the Carbon River watershed.

3. Landform Mapping at MORA

3.1 National Hierarchical Framework for Ecological Units

MORA landform mapping is linked with the USFS multi-scaled "National Hierarchical Framework for Ecological Units" (Cleland et al. 1997) for public lands in western Washington (Table 2). Together the USFS and NPS have mapped at the Subsection (1:250,000), Landtype Association (1:62,500), and Landform (1:24,000) scales. Ecological land units describe the physical and biological processes that occur across the landscape and are used for ecosystem classification and mapping purposes (Davis 2004).

Table 2. Map scale and polygon size in the National Hierarchical Framework for Ecological Units (Cleland et al. 1997).

Ecological unit	Map scale range	General polygon size
Domain	1:30,000,000 or smaller	1,000,000s of square km
Division	1:30,000,000 to 1:7,500,000	100,000 of square km
Province	1:15,000,000 to 1:5,000,000	10,000s of square km
Section	1:7,500,000 to 1:3,500,000	1,000s of square km
Subsection	1:3,500,000 to 1:250,000	10s to low 1,000s of square km
Landtype association	1:250,000 to 1:60,000	1,000s to 10,000s of ha
Landtype	1:60,000 to 1:24,000	100s to 1,000s of ha
Landtype phase (Landform)	1:24,000 or larger	<100 ha

3.1.1 Subsection (1:250,000)

The first product was a seamless coverage in the North Cascade region at the Subsection scale; mapping units are defined on the basis of climate, bedrock geology and topography at a regional scale. Features of the landscape such as regional hydrologic divides, contacts between major bedrock terranes and glaciated topography are boundaries of Subsection mapping units. In the North Cascades, the Subsection map (Figure 7) identifies 17 mapping units including: Major Valley Bottoms, Crystalline Glaciated Cascade Mountains, Volcanic Cones and Flows, Sedimentary Cascade Hills, etc. These units were developed by Wenatchee National Forest (Davis 2004 and 2006) and applied to the west slope of the Cascades by staff from Wenatchee National Forest and NOCA (Riedel and Probala 2005). MORA is part of the Volcanic Cones and Flows, Volcanic Cascade Mountains and Major West Side Valleys subsections (Figure 7).

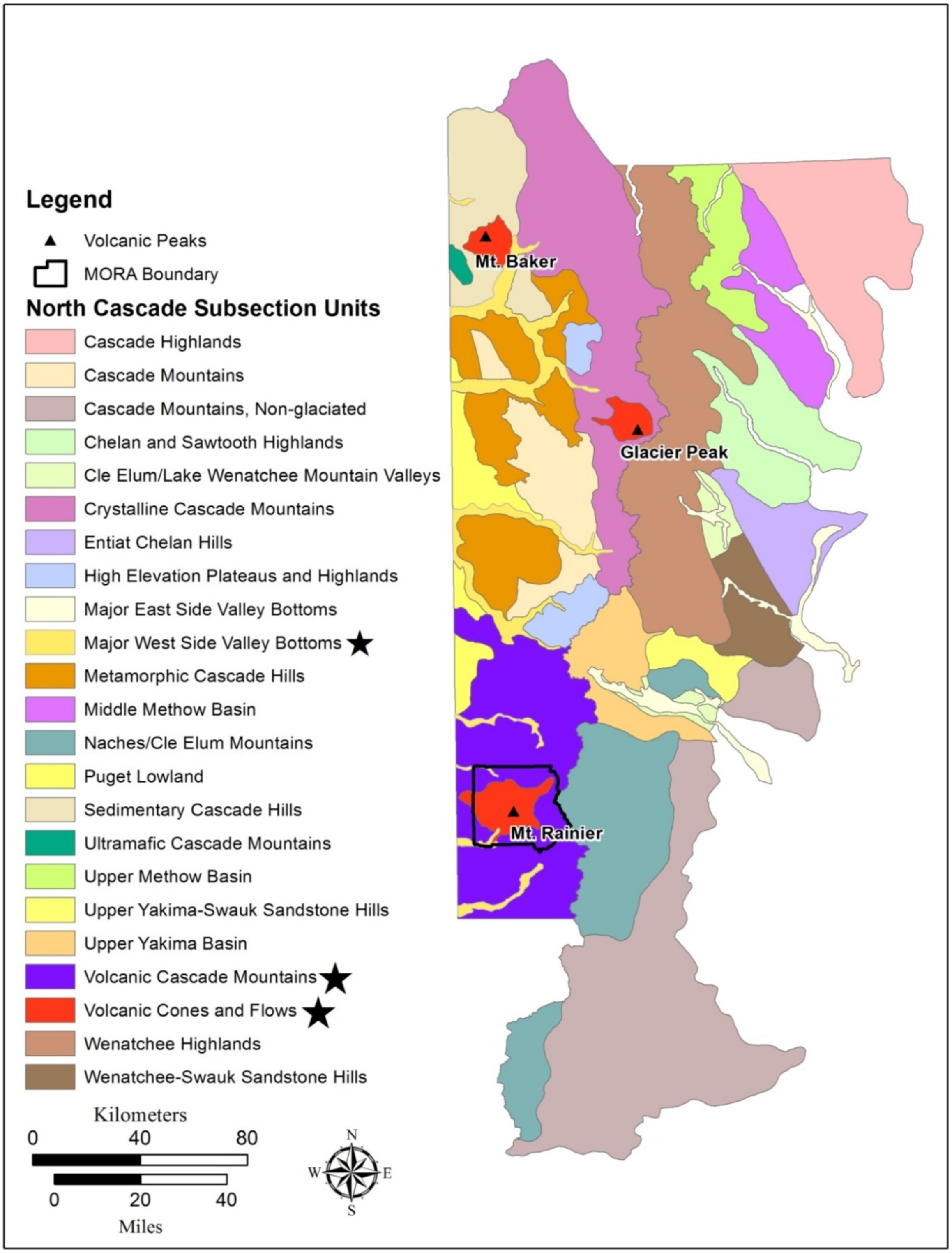

Figure 7. Subsection map (1:250,000) of the North Cascade region showing the location of Mount Rainier National Park within the Volcanic Cascade Mountains, Volcanic Cones and Major West Side Valley Bottoms Subsections.

3.1.2 Landtype Association (1:62,500)

Landscape scale ecological units or Landtype Associations (LTAs) are the smallest scale within the hierarchical framework that meets most NPS challenges and management needs. At this mapping scale, geomorphic process and topography become more important than climate and bedrock geology. The first step in mapping LTAs is to identify large-scale erosional features of mountains and valleys such as valley bottom, cirque basin, glaciated valley, and river-cut valley (Davis 2004). Final map units incorporate data on vegetation and bedrock type. For example, at Mount Rainier, a valley would be broken into three units that coincide with major elevation-controlled changes in vegetation and topographic breaks. Mapping is conducted by interpretation of 1:62,500 scale stereo aerial photography and topographic maps. The LTA units used at MORA are based on a mapping scheme developed by the USFS (Davis 2004) at Mount Adams. Dominant LTA units at MORA include Headland Catchment Basins, Scoured Glacial Troughwall, Scoured Glaciated Slopes, Glacial Cirque Basins, Glacial Troughwalls, Meltwater Coulees, Glaciated Trough Valley Bottoms, Valley Bottom Outwash and Landslides Undifferentiated (Figure 8).

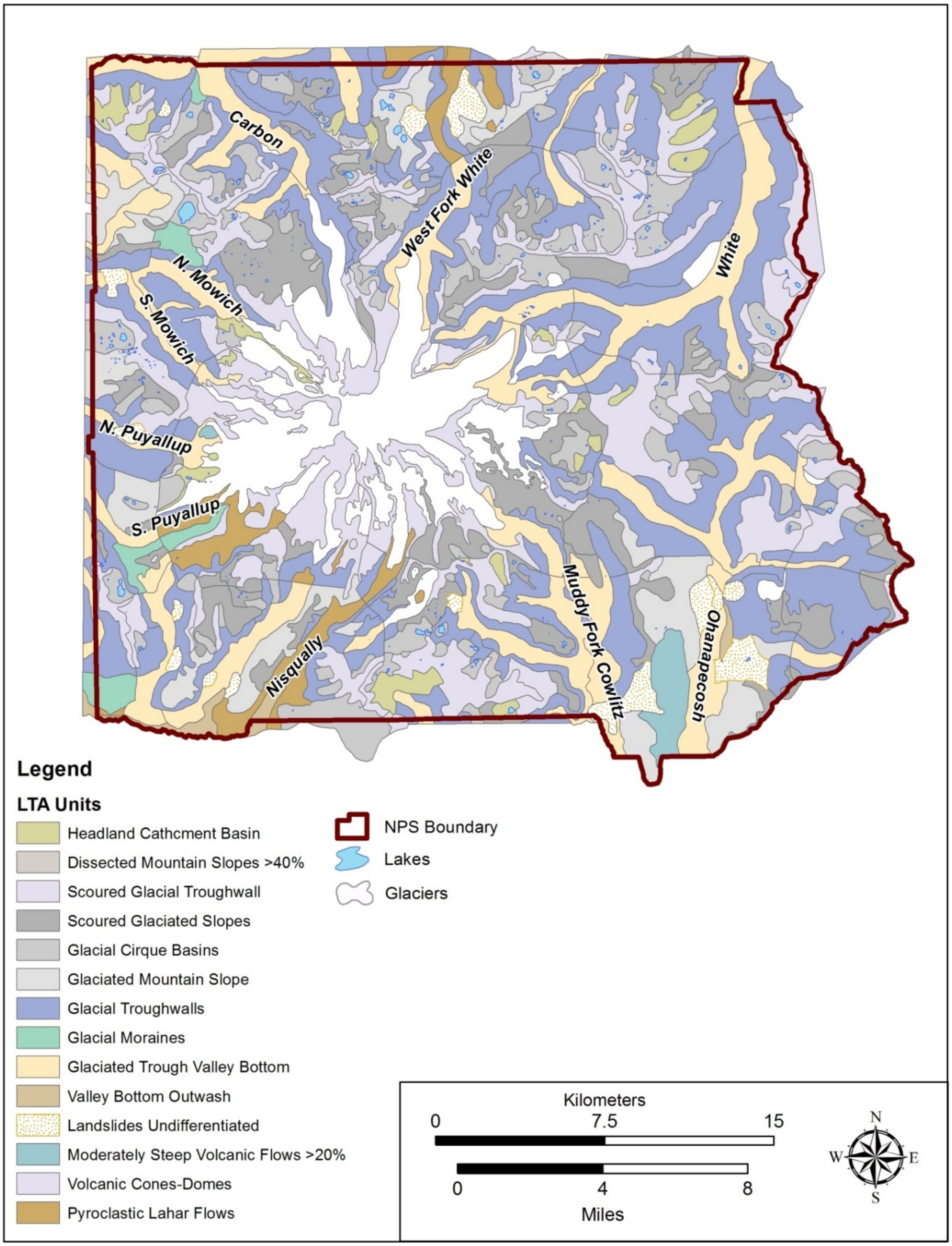

Figure 8. LTA map (1:62,500) of Mount Rainier National Park (Davis 2006).

3.1.3 Landtype Phase (Landform) (1:24,000)

Landforms are the smallest functional units of the landscape that are created by discreet geologic processes, many of which are currently active. These subdivisions of Landtypes, or landforms, are based on topographic criteria, hydrologic characteristics, associations of soil taxa, and plant communities. They are readily identified on topographic maps and aerial photographs, but require field-verification when beneath closed canopy forests. A suite of 34 different landforms were mapped at MORA (Table 3). A detailed description of each landform, which includes information on location, associated landforms, process, material, mapping guidelines and potential natural vegetation is presented in Appendix A.

Table 3. Landform (1:24,000) legend for Mount Rainier National Park.

Landform	Unit	Description
High elevation landforms (primarily erosional in genesis)	A	Arête
	AT	Amphitheater
	C	Cirque
	O	Other mountain
	H	Horn
	R	Ridge
	P	Pass
	CL	Cleaver
	VC	Volcanic cone
	CR	Crater
Valley slope landforms (primarily erosional in genesis)	VW	Valley wall
	RC	River canyon
	BB	Bedrock bench
Transitional landforms between valley slope (erosion) and valley floor (deposition)	MM-F	Rock Fall and Topple
	MM-A	Debris avalanche
	MM-S	Slump and Creep
	MM-DT	Debris torrent
	MM-SK	Sackung
	DA	Debris apron
	DC	Debris cone
	DCT	Debris cone terrace
Valley bottom landforms (primarily depositional in genesis)	DF	Debris fan
	AF	Alluvial fan
	FT	Fan terrace
	FP	Floodplain
	VB	Valley bottom
	T	Terrace
Other landforms	PK	Parkland
	PG	Patterned ground
	NM	Neoglacial moraine
	PM	Pleistocene moraine
	G	Glacier (below vc)
	RG	Rock glacier
	U	Undifferentiated

3.2 Landform Age

Landforms can either be depositional in nature, such as moraines and alluvial fans, or they can be erosional such as bedrock benches and horns. Many depositional features, such as moraines and terraces, were formed during the last ice age. Other depositional features, such as debris cones and landslides, continue to be produced. Landform age can vary greatly within a watershed depending on the surficial process that created it. Approximate ages can be assigned to depositional landforms based on available radiocarbon dates, associated process of formation, volcanic tephra, soil development and vegetation type and age. The approximate surface ages of landforms at MORA (Table 4) were taken from previous studies by the USGS and other private researchers including Crandell (1971), Scott et al. (1995 and 2001) and Pringle (2008).

Table 4. Approximate surface ages at Mount Rainer National Park.

Landform	Age (Calendar yrs BP)
Debris cones, floodplains, alluvial fans	<500
Most Neoglacial moraines	100 - 3,000
Valley walls	100 - 12,000
Lahar terraces	500 - 10,000
Osceola Mudflow	4,500 - 5,000
Paradise Lahar	4,500 - 5,000
Round Pass Mudflow	2,170 - 2,710
Electron Mudflow	530 - 550
High outwash terraces and fan terraces	10,000 - 12,000
Pleistocene moraines	12,000 - 25,000
Bedrock benches, horns, arêtes	12,000 – 25,000
Mass movements (landslides)	0 - 25,000
Volcanic Cone and Crater	1 - 500,000

3.2.1 Landforms and Soils

Mount Rainier provides a challenging environment to compile a traditional soil survey. Previous studies in the North Cascades and the surrounding vicinity link pedogenic processes to soil-landscape relationships and provide insight to the links between landforms and soils (Rodgers 2000, Briggs 2004, Briggs et al. 2006). Soil distribution is closely linked to the geomorphic processes at play over the last 15,000 years. NRCS soil scientists incorporate landform maps as an indicator of soil stability and parent material (Rodgers 2000, Briggs 2004, Frazier et al. 2009).

As a result of the glaciers from Mount Rainer scouring much of the park over the last ice age, bedrock as a parent material seldom influences soil formation. Upon retreat of the ice sheet, glacial drift was deposited unevenly across the landscape. This glacial drift, along with subsequent tephra deposits, provides the primary parent materials for soil formation. Soil classification within MORA is largely determined by the presence or absence of tephra. In large part, it is the preservation, mixing and removal of tephra that provides one indication of landform stability, age and soil type. The table below (Table 5) is a summary of major tephra layers found at MORA (Scott et al. 1995). Of these tephra layers, Mazama O and St. Helens Y are present over the entire park (Mullineaux 1974). The dominant soil order found within MORA will, thus, likely include mostly Andisols, with smaller areas of Inceptisols, Entisols, Spodosols and Histosols based on information from the surrounding soil survey (USDA 1992). Lahar deposits in the Nisqually, Puyallup, and White River valleys may also influence soil classification in these locations.

Table 5. Summary of the major tephras present at Mount Rainier National Park.

Tephra	Vent of Origin	Approximate Age	Texture/Comments
R	Rainier	>8750	Pumice and lithic lapilli and ash
O	Mazama	6800	Pumice ash
A	Rainier	5500 to 6500	Pumice ash and scattered lapilli
L	Rainier	5500 to 6500	Pumice lapilli
D	Rainier	5500 to 6500	Pumice lapilli
N	Rainier	5500 to 6500	Lithic ash
S	Rainier	5200	Sand to block sized lithic rubble
F	Rainier	5700	Monmorillonite-rich lithic ash
H	Rainier	4700	Scattered pumice lapilli
B	Rainier	4500	Pumice ash and scattered lapilli
Y	St. Helens	3400	Pumice ash, medium to very coarse sand in size
C	Rainier	2200	Pumice lapilli and scattered blocks
W	St. Helens	450	White pumice ash, fine to medium sand in size
X	Rainier	110 to 150	Scattered pumice lapilli

4. Methods

4.1 Preliminary Methods

At the beginning of the mapping process, MORA was divided into watersheds that were mapped separately. This project recognizes a watershed as a major drainage system on a fourth order or larger stream. Each watershed is further broken down into smaller units referred to in the text as sub-watersheds. These landform maps represent a compilation of several quadrangles over a number of years of fieldwork. The combination of mapping techniques used to conduct this inventory include the use of color stereo-pair air photos at the 1:12,000 scale, USFS LTA line work (Davis 2004 and 2006), bedrock geology maps (Fiske et al. 1963, Fiske et al. 1988), surficial geology maps (Crandell 1969a) and field investigations.

Initially, the pattern of contour lines on United States Geological Survey (USGS) 7.5 minute topographic maps, in conjunction with the 1:12,000 scale air photos, are used to outline landforms. Though some landforms (e.g., debris avalanches, bedrock benches and debris cones) are easily identifiable using air photos and contour lines, other landforms (e.g., terraces, floodplain boundaries and small mass movements) require field identification. The minimum size for a mapping unit is approximately 1,000 m^2 with some exceptions for smaller units like slumps.

4.2 Field Methods

Before entering the field, a task list of areas to visit is developed. As much ground as possible is surveyed, but effort is concentrated within the valley bottom. Generally, walking the banks of rivers enables mapping of terraces, slumps, and floodplain boundaries. At places where the valley bottom is wide or complex, cross sections are made from one side of the valley to the other. Some landforms need further exploration and are investigated in more detail as needed. While in the field, geologists draw landform boundaries onto USGS 7.5 minute maps or update boundaries previously mapped in the office. Fieldwork also generates additional information about terrace heights and material type; this information is recorded in field notebooks along with sketches of valley cross-sections. A draft version of the landform description report is used to aid in the identification of landform units while in the field.

4.3 Digitizing Methods

After identifying landforms and drawing the boundaries, each area is peer-reviewed for accuracy and mapping consistency. Landform linework is then transferred onto a new 7.5-minute paper map, which serves as the final map. All boundaries of landforms are then drawn onto Universal Transverse Mercator registered Mylar and a large format scanner transfers lines into digital format. Using GIS software, scans are edited and polygons, which represent landforms, are labeled resulting in a final digitized map (Figure 2). As each polygon is labeled, the shape and location is checked for accuracy. Using the most up to date National Agriculture Imagery Program (NAIP) imagery from the United States Department of Agriculture (USDA), small-scale changes can be made in landform placement. Also, 10 meter digital elevation models (DEMs), along with a 1 meter Light Detection and Ranging (LiDAR) DEM, are overlaid with the landform layer, enabling more fine-tuned editing of placement. If additional editing is needed, on screen digitizing is completed. Landform surveys are occasionally updated as new landforms are identified and new areas are surveyed; the GIS database is then updated to accommodate these changes.

5. Results and Discussion

5.1 General Overview

Mount Rainier is the largest active stratovolcano in the lower 48 states and is composed of lava, volcanic ash, pyroclastic flows and other intrusive rocks. Volcanic activity at this site spans some 700,000 years during which time there have been six or more periods of intense glaciation. Along with mass wasting and the action of rivers, these processes have created 33 distinct landforms.

The volcanic cone of Mount Rainier dominates the skyline of MORA; however, the steep valley walls found throughout the park are the prevailing landform. MORA is just over 50% valley wall, or 483 km^2 (Table 6). The debris apron, which is the zone below the valley wall where colluvial material accumulates along with debris cones, accounts for 12% of the park. The volcanic cone landform occupies 76 km^2, which is 8% of the park (Table 6). The cone is mapped as the area immediately below the volcanic crater and above the valley wall with an elevation range from approximately 4,325 m to approximately 2,130 m. Glaciers cover most of the volcanic cone and descend into the mountain's main river valleys, which are flanked by large Neoglacial moraines and record recent glacial advances. There are 316 Neoglacial moraines at MORA, which is the largest number of any individual landform (Table 6). Including perennial snowfields, glaciers cover ~91 km^2. The percentage of glacier cover listed in Table 6 is only for the glacier cover that extends below the volcanic cone.

Table 6. Summary table of landform results within Mount Rainier National Park.

Landform Type	Number Observed	Area km^2	%of MORA
Valley Wall	74	483.58	50.64
Debris Apron	282	110.90	11.61
Volcanic Cone	1	75.68	7.92
Cirque	138	64.75	6.80
Parkland	55	29.07	3.05
Mass Movement-Debris Avalanche	116	26.89	2.82
Ridge	122	23.04	2.40
Floodplain	30	21.95	2.29
Terrace	296	20.93	2.19
Neoglacial Moraine	316	16.81	1.76
Glacier Ice (Below VC)	8	12.07	1.26
Mass Movement-Fall/Topple	309	9.79	1.03
Bedrock Bench	243	8.56	0.90
Debris Cone	163	8.50	0.89
Valley Bottom	71	8.40	0.88
Amphitheater	2	8.15	0.85
River Canyon	101	6.22	0.65

Table 6 (continued). Summary table of landform results within Mount Rainier National Park.

Landform Type	Number Observed	Area km^2	%of MORA
Pleistocene Moraine	56	4.01	0.42
Debris Fan	12	2.83	0.30
Cleaver	21	2.23	0.23
Arête	44	1.73	0.18
Rock Glacier	18	1.62	0.17
Fan Terrace	13	0.80	0.08
Other Mountain	35	1.54	0.16
Pass	65	1.49	0.15
Undifferentiated	16	1.17	0.13
Horn	25	1.04	0.11
Mass Movement-Debris Torrent	10	0.33	0.04
Crater	2	0.32	0.03
Alluvial Fan	4	0.22	0.02
Debris Cone Terrace	8	0.15	0.02
Patterned Ground	9	0.08	0.01
Mass Movement-Slump/Creep	12	0.04	0.01
Mass Movement-Sackung	1	0.01	0.01
Totals	**2581**	**955**	**100**

Many of the landforms of MORA are of interest even if not extensive, including river canyons, moraines, parklands and terraces. Longmire, Cougar Rock Campground and White River Campground are all located on flat lahar terraces. Box Canyon, Stevens Canyon and other deep gorges and waterfalls throughout the park are popular tourist attractions. Hundreds of towering moraines found in most of the larger valleys and cirques provide clear evidence of the size and extent of glaciers about 100 years ago. Parklands are also distinct features at MORA that cover approximately 30 km^2 (Table 6). These gently sloping surfaces of ancient lava flows have been scoured by glacial erosion during ice ages. Parklands are often found adjacent to the volcanic cone (e.g. Spray Park), but can also extend outward on or near discontinuous ridge tops, valley wall and debris apron benches and cirques; occasionally , parklands can stand alone (e.g. Grand Park). Vegetation on parklands is often subalpine meadow; some of these areas attract many visitors, such as Paradise and Sunrise.

Rivers at MORA typically have large braided floodplains which extend in elevation from up to 1,280 m in the major river valleys, and 1,400 m in tributaries. Although there are numerous large floodplains, they account for only 2.5% of the park. The transition from floodplain to valley bottom occurs between 945 and 1,280 m throughout the park, with valley bottom extending up to 1,525 m where it merges with valley walls, debris aprons, and glaciers at valley heads. Guidelines for determining this transition are based on floodplain width, presence or absence of river terraces and gravel bars and stream gradient (Jarrett 1990). This transition from valley bottom to floodplain typically occurs below the extent of Neoglacial moraines at MORA.

There are several unique landforms that have been mapped at MORA, such as amphitheater, volcanic cone, debris fan, patterned ground and cleaver. Debris fans are most commonly found at the confluence of two relatively large streams (e.g. Tahoma Creek and Nisqually River), where the gradient of a stream abruptly decreases (Figure 9). These fans are often flanked by fan terraces, which are relict features that were deposited during glacial retreat following the last ice age or by ancient lahars. Patterned ground is a high elevation landform characterized by symmetrical geometric shapes (Washburn 1956). Patterned ground features can be found at MORA near, or above, tree line. The types of patterned ground most commonly found at MORA include sorted circles, sorted stripes and non-sorted steps; these features likely formed due to repeated freezing and thawing of the ground (Crandell and Miller 1974). Cleavers are the sharp crested ridges of volcanic bedrock that are distinctly exposed above the surrounding glaciers on the volcanic cone. Cleavers are commonly hydrothermally altered remnants of lava flows from Mount Rainier. The cleavers were often flanked with thick ice when they were constructed and some contain glassy ice-contact features (e.g. Success and Tahoma Cleavers) (Figure 9).

MORA contains 316 Neoglacial moraines. These features formed by advances spanning the past 6,000 years or so. The largest and most extensive were formed in the Little Ice Age between 1450 and 1900 A.D. (Samolcyzk et al. 2010).

Landslides have played a very important role in the geologic history of Mount Rainier; from the overall shape of the volcano to the vast distribution of debris flow deposits, landslides are almost continually altering the landscape of MORA. Large landslides, known as debris avalanches, are of particular importance due to their potential to block streams and deliver massive amounts of large woody debris and sediment to stream systems.

A large rain on snow event, known as a ‘pineapple express,’ dumped 45 cm of rain on MORA in 24 hours on November 6 and 7, 2006. Numerous floods and landslides occurred throughout the park, causing such extensive damage to roads and facilities that the park was forced to close for the first time in more than 60 years. This storm event was a reminder that this dynamic landscape is in a constant state of change. A more detailed discussion of mass movements at MORA is presented below in the Landslide Inventory section of this report and the full landslide inventory is presented in Appendix B.

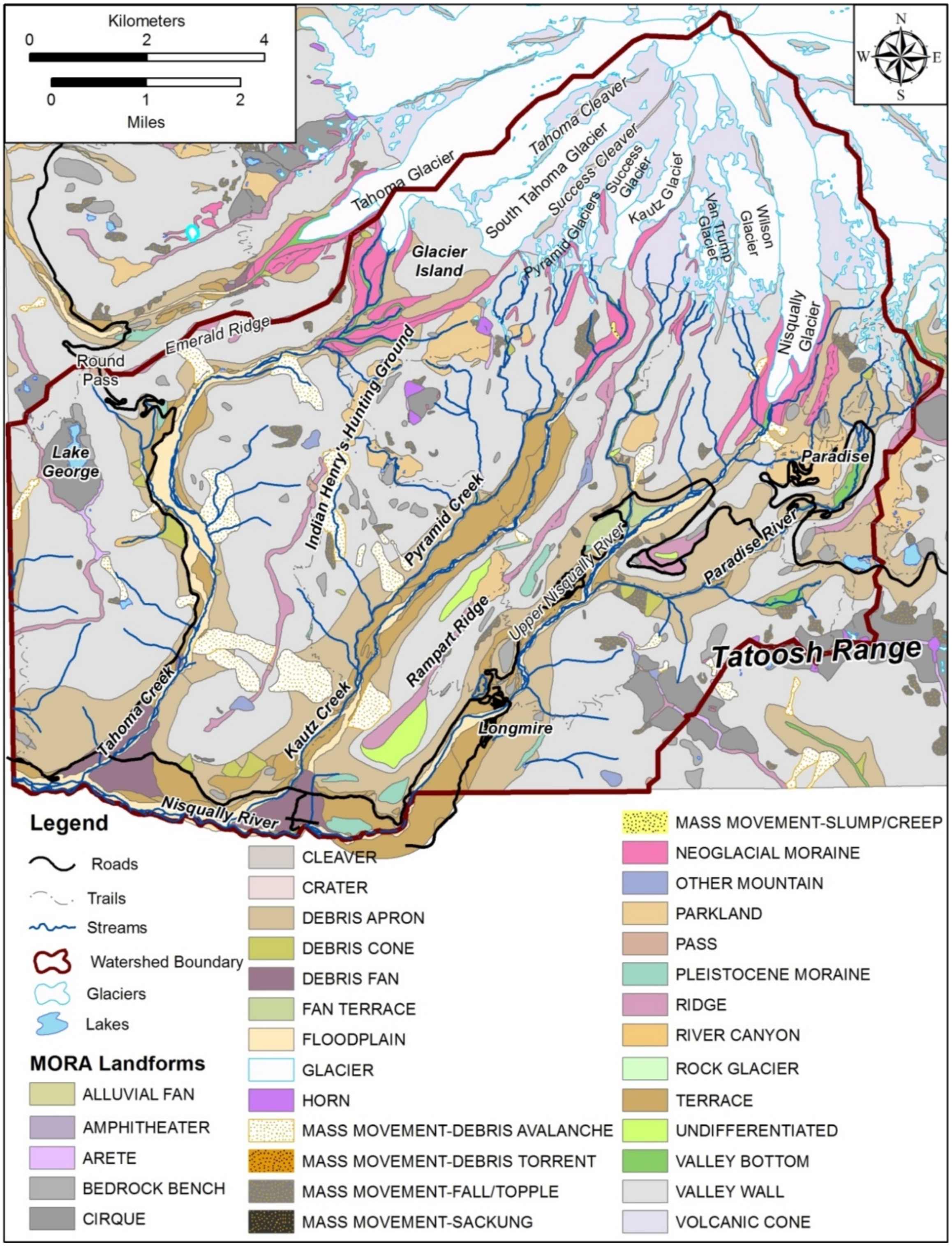

Figure 9. Landform map of the Nisqually River watershed within Mount Rainier National Park showing the localities mentioned in the text.

5.2 Nisqually River Watershed

The Nisqually River flows from the Nisqually Glacier for approximately 125 km before discharging into Puget Sound across a broad delta. The watershed drains an area of approximately 1,970 km^2 but this study focuses on the upper 145 km^2 of the watershed on the southwest flank of Mount Rainier. There are two major tributaries to the Nisqually River in the park: Kautz Creek and Tahoma Creek (Figure 9). The major glaciers that drain into the watershed are (from west to east) Tahoma Glacier, South Tahoma Glacier, Pyramid Glacier, Success Glacier, Kautz Glacier, Van Trump Glacier, Wilson Glacier, and Nisqually Glacier (Figures 4 and 9). Tahoma Cleaver and Emerald Ridge form the upper watershed boundary in the west and in the east the boundary is formed by Cowlitz Cleaver, Mazama Ridge and the Tatoosh Range (Figure 10).

The Nisqually River watershed is 40% (58 km^2) valley wall, attesting to the powerful erosive force of valley glaciers (Table 6). Debris apron is the next most extensive landform at 15% of the watershed. The volcanic cone landform occupies15% of the watershed; there has been no documented edifice collapse within the Nisqually River watershed. Glaciers cover most of the cone and descend into the Nisqually River valley, flanked by large Neoglacial moraines. Glaciers and perennial snowfields cover 0.35 km^2 of the watershed. A more detailed discussion of the landforms in each of the major drainages in the Nisqually River watershed is presented in the following sections.

5.2.1 Nisqually River

The Nisqually River emerges from the Nisqually Glacier approximately 1 km west of Paradise at 1,400 m of elevation (Figure 9). The Nisqually Glacier is a heavily crevassed alpine valley glacier. The glacier has a thick cover of debris, a relatively flat near terminal area, and an abrupt, steep nose. Wilson Glacier is a tributary and is a significant contributor of ice to the lower Nisqually Glacier. The Muir Snowfield is part of the glacier, and is a major climbing route to Mount Rainier’s summit (Figures 4 and 10).

About 25 ka, Nisqually Glacier extended approximately 48 km downvalley from the base of the mountain to near the town of National (Crandell and Miller 1974) (Figure 6). A glacial moraine and till from the last ice age is exposed along the road to Ricksecker Point and forms a lateral moraine at about 1,200 m (Crandell and Miller 1974). The Nisqually Glacier has a long history of observation, particularly at the terminus (e.g. Harrison 1956, Heliker et al. 1983, Sigafoos and Hendricks 1961). The Neoglacial extent of the Nisqually Glacier from tree ring data and moraines places the terminus just downstream from the Nisqually River Bridge in 1840 (Sigafoos and Hendrick 1972).

Paradise Park, Mazama Ridge, and the Tatoosh Range confine the upper Nisqually watershed to the east; broad Rampart Ridge confines the watershed to the west (Figure 11). The south flank of Mount Rainier’s volcano is composed of young lava flows that are less than 40 ka (Pringle 2008). Below the volcanic cone, the upper Nisqually River is flanked by a series of both Neoglacial and Pleistocene moraines (Figure 11). The steep valley walls give way to the more gradual slopes of Paradise Park, which is composed of glacially scoured andesite lava flows. Deposits of the Paradise lahar, which occurred 4,500-5,000 years ago (Scott et al. 1995) mantle the alpine meadows of Paradise Park (Crandell 1969b, Crandell 1971).

Table 7. Summary table of landform results within the Nisqually River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	9	58.17	40.11
Debris Apron	42	21.18	15.09
Volcanic Cone	1	21.65	14.93
Terrace	85	8.45	5.83
Floodplain	1	5.44	3.75
Mass Movement-Debris Avalanche	25	4.35	3.00
Neoglacial Moraine	50	3.85	2.66
Parkland	9	3.19	2.20
Ridge	18	2.88	1.99
Cirque	12	2.45	1.69
Debris Fan	5	2.05	1.41
Glacier Ice (Below VC)	2	1.73	1.19
Mass Movement-Fall/Topple	54	1.66	1.15
Bedrock Bench	62	1.50	1.03
Valley Bottom	10	1.01	0.78
Undifferentiated	7	0.82	0.69
Debris Cone	16	0.69	0.48
Pleistocene Moraine	10	0.69	0.48
Cleaver	8	0.68	0.47
Amphitheater	1	0.40	0.28
Fan Terrace	2	0.41	0.28
Other Mountain	7	0.32	0.22
Arête	14	0.29	0.22
River Canyon	8	0.26	0.18
Horn	7	0.21	0.20
Crater	2	0.18	0.12
Pass	10	0.13	0.11
Alluvial Fan	1	0.03	0.02
Mass Movement-Debris Torrent	1	0.03	0.02
Mass Movement-Slump/Creep	7	0.03	0.02
Mass Movement-Sackung	1	0.01	0.01
Totals	492	145	100

Figure 10. The Nisqually Glacier viewed from the debris-covered ice near the terminus of the glacier; view is looking northwest (NPS Photo).

After exiting the Nisqually Glacier, the Nisqually River flows through a relatively confined valley bottom. The channel then widens considerably into a braided floodplain just downstream from the Nisqually River Bridge. Cougar Rock Campground rests on a terrace composed of several lahar deposits, volcanic ashes and gravel from the Nisqually River. Van Trump Creek has incised into the lahar and formed two distinct fan terraces on the lahar surface (Figure 11). The Nisqually River has also incised into the National Lahar near Cougar Rock Campground. This large lahar terrace is approximately 10 m above the aggrading Nisqually floodplain. This terrace can be traced far downstream of the park and forms a low sandy terrace near Tahoma Woods (Riedel 1997). The National Lahar occurred about 2,285 years ago and was a non-cohesive type flow (Scott et. al 1995).

A main headwater tributary to the Nisqually River is the Paradise River, which is primarily fed by meltwater from the Muir Snowfield (Figure 11). The Paradise Glacier has retreated to the point that it no longer drains into the Paradise River, but now drains into Stevens Creek (Figures 4 and 11). The Paradise flows in a broad valley bottom above Narada Falls where it is confined in a narrow valley. Several small tributary streams, including Tatoosh Creek, drain the north facing cirques of the Tatoosh Range into the Paradise River (Figure 11). The jagged horns and arêtes of the Tatoosh, such as Pinnacle Peak and Plummer Peak, are composed primarily of Tatoosh granite. The steep glacial peaks, cirques and arêtes of the Tatoosh are similar to the landforms of NOCA.

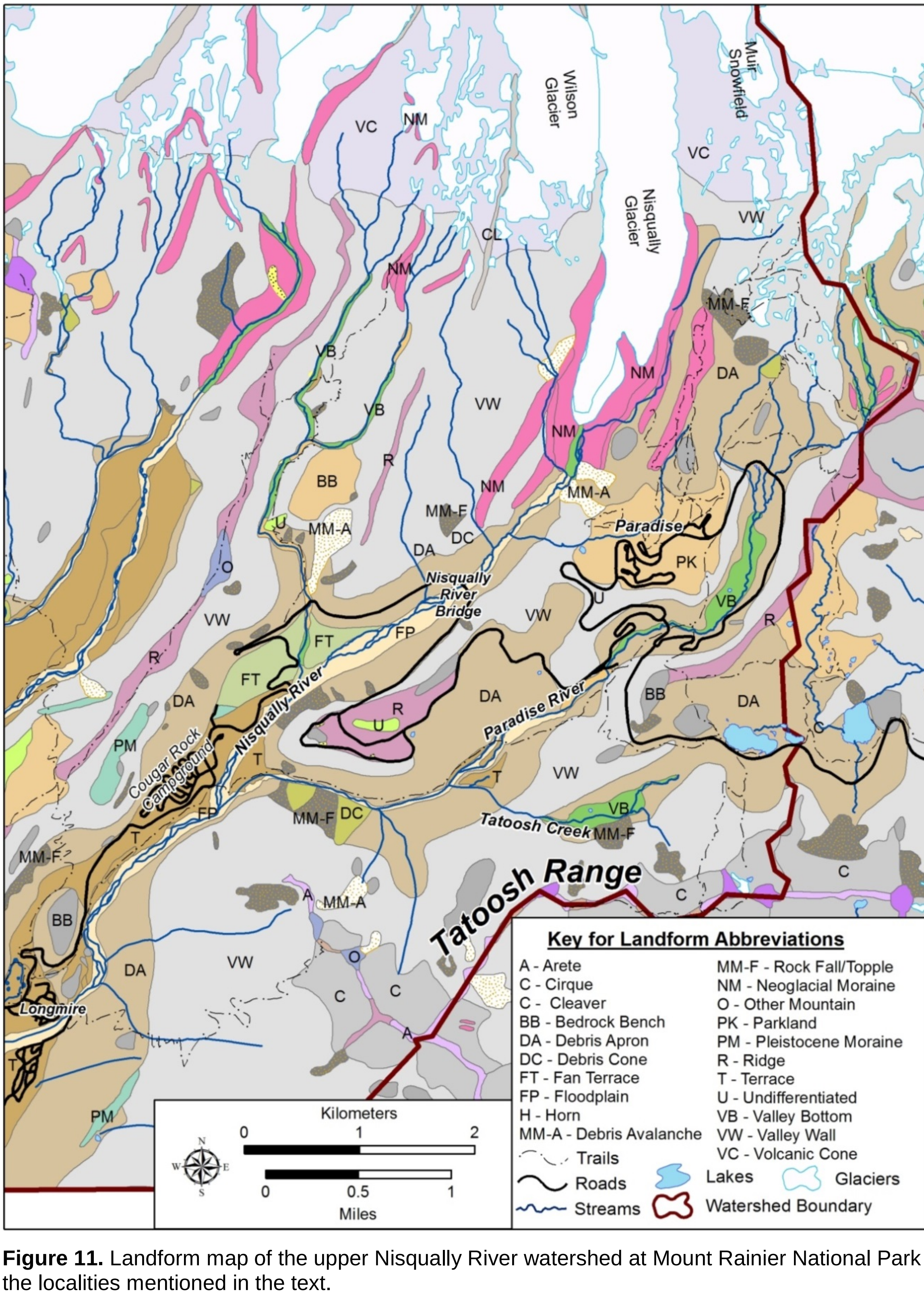

Figure 11. Landform map of the upper Nisqually River watershed at Mount Rainier National Park showing the localities mentioned in the text.

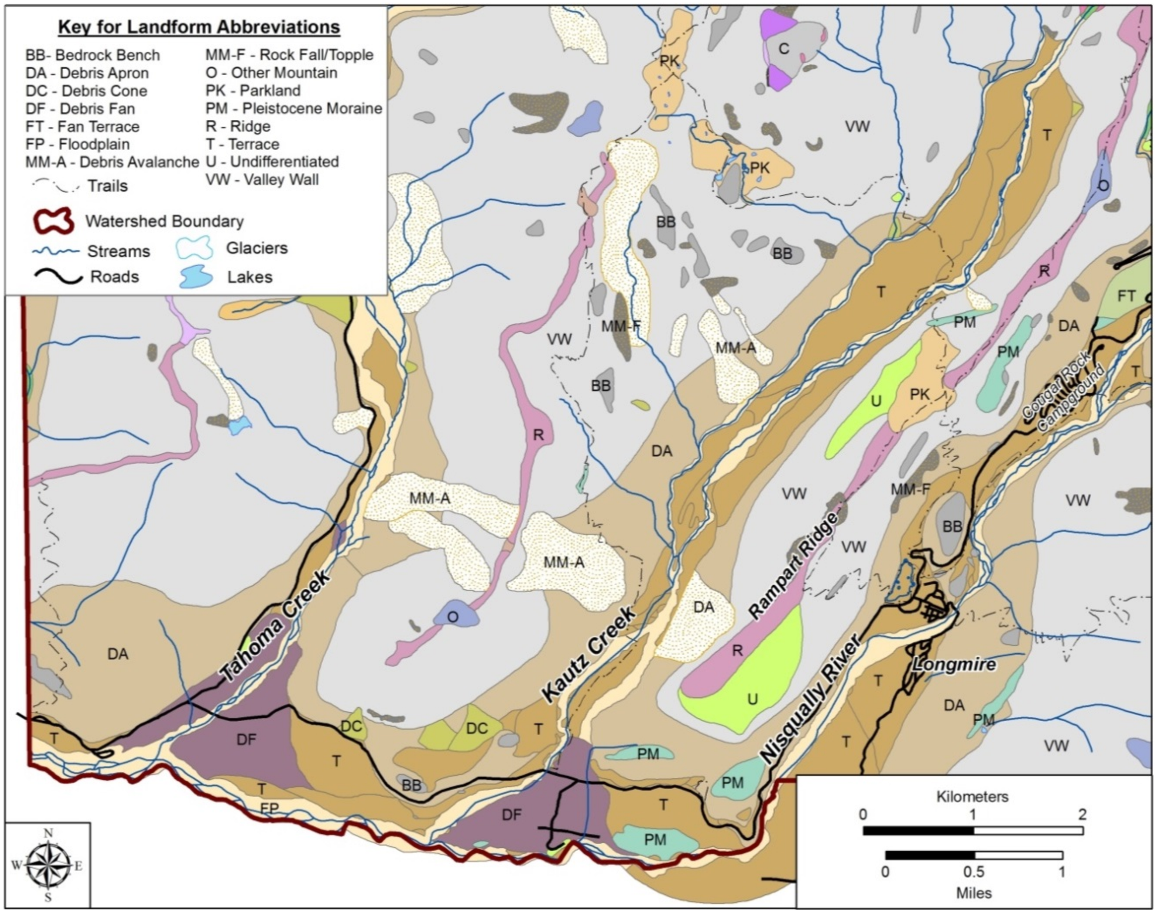

Figure 12. Landform map of the lower Nisqually River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Damage from the 2006 flood event was substantial along the Nisqually River. Near Longmire, the flooding Nisqually River cut into the 3 m high lahar terrace that numerous park facilities are built on; a corner of the Emergency Operations Center was undercut by the river (Figure 13), main sewer lines were destroyed and water supply lines were filled with sediment. Further down river, the Sunshine Point Campground was completely destroyed, along with 200 m of the Nisqually Road (Figure 14).

5.2.2 Kautz Creek

Kautz Creek emerges from the Kautz Glacier at 1,830 m and flows southwest for 10 km before merging with the Nisqually River approximately 4 km southwest of Longmire (Figure 9). Similar to its neighboring glaciers, Kautz glacier has an extensive cover of debris near the terminus, portions of which may be stagnant. Rampart Ridge confines Kautz Creek valley on the east, while the broad bedrock benches and parklands of Indian Henry's Hunting Ground limit the upper Kautz valley to the west (Figure 15). The glacial horns of Iron and Copper Mountains, as well as Pyramid Peak, stand prominently above the flat bedrock benches and parklands of Indian Henry's Hunting Ground (Figures 15 and 18); these horns are composed of rhyodacitic ash flows of the Stevens Ridge Formation. The only sackung mapped at MORA is located on the west side of Iron Mountain.

Figure 13. Emergency operations center at Longmire during the 2006 flood (NPS photo).

Figure 14. The Nisqually Road and the site of the former Sunshine Point Campground, which was destroyed by the 2006 flood (NPS photo).

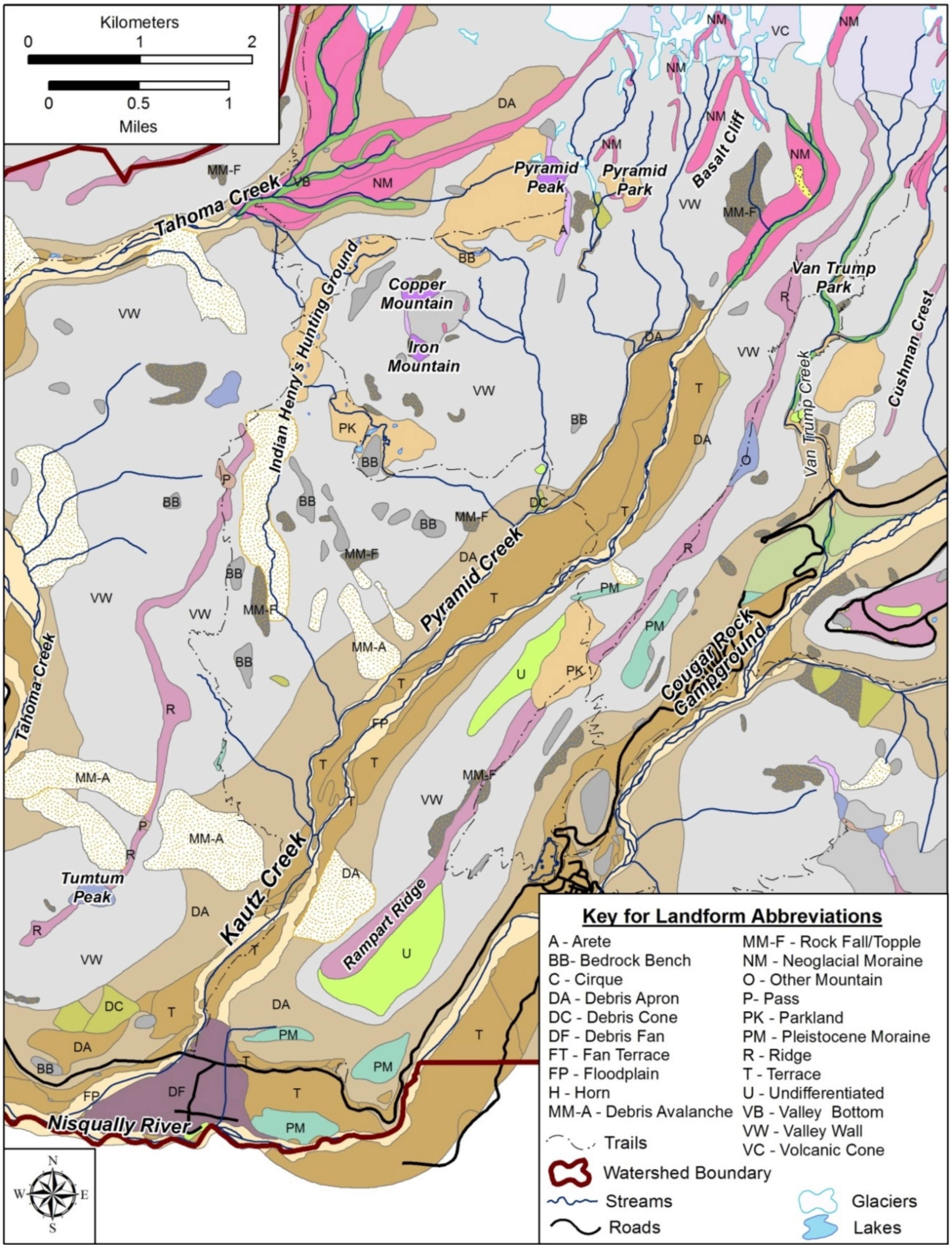

Figure 15. Landform map of the Kautz Creek watershed showing the localities mentioned in the text.

Kautz Creek initially flows in a valley bottom fed by massive amounts of gravel by large Neoglacial moraines. The Kautz Creek valley then widens considerably at 1,400 m to form a braided floodplain flanked by large lahar terraces, which are approximately 12 meters high. Some sections of these terraces are cut into deposits of the 1947 Kautz Creek debris flow, while others are from undifferentiated older lahar flows. The 1947 flows originated as glacial-outburst floods in response to an intense rainstorm that caused the lower 1.6 km of stagnant ice on Kautz Glacier to collapse (Scott et. al 1995). Stagnant ice collapse is a major factor contributing to debris flows at MORA (Crandell 1971, Walder and Driedger 1994, Scott et. al 1995). The 1947 debris flow buried an old park road with 6 m of rock and debris and temporarily dammed the Nisqually River (Figures 15 and 16).

The 2006 flood event caused major channel avulsion of Kautz Creek. The new channel is 0.3 km east of the old channel and has incised into a terrace and debris fan terrace from the 1947 debris flow (Figures 15 and 17). The pre-flood channel filled with sediment and debris, forcing Kautz Creek to the east. Pyramid Creek flows from the meltwater of Pyramid Glacier past the prominent horn of Pyramid Peak and the broad parkland of Pyramid Park (Figures 15 and 18). Pyramid Creek flows almost parallel to Kautz Creek, but they are divided by the large 12 m high lahar terrace mentioned above. Pyramid Creek likely follows an ancient path of Kautz Creek before it was displaced by lahars.

5.2.3 Tahoma Creek

Tahoma Creek flows from the meltwater of the South Tahoma Glacier for approximately 13 km southwest before joining the Nisqually River. The South Tahoma Glacier is a tongue of ice that flows off of Tahoma Glacier. The steep valley walls surrounding Glacier Island (Figure 19) separate the two lobes of ice.

Indian Henry’s Hunting Ground and Success Divide confine the Tahoma Creek valley to the east; broad Emerald Ridge confines the valley to the west (Figure 19). Emerald Ridge is composed of lavas erupted from the Puyallup Cleaver dike system, which was formed during a period of profuse eruptions approximately 280 to 190 ka (Sisson and Lanphere 1999). The volcanic edifice above South Tahoma Glacier is composed of steeply outward dipping lava and pyroclastic units. Intense hydrothermal alteration has occurred along many stratigraphic contacts at this section of the cone, which are potential planes of failure for future landslides (Scott et al. 1995).

Figure 16. Oblique aerial photo of Kautz Creek which shows the extent of the 1947 debris flow. In the right of the image is the upper Nisqually River with Rampart Ridge dividing the two streams. In the left of the image the prominent peaks of Iron and Copper Mountains are all clearly visible in the foreground of Mount Rainier (Photo by Austin Post, USGS, taken on September 22, 1966).

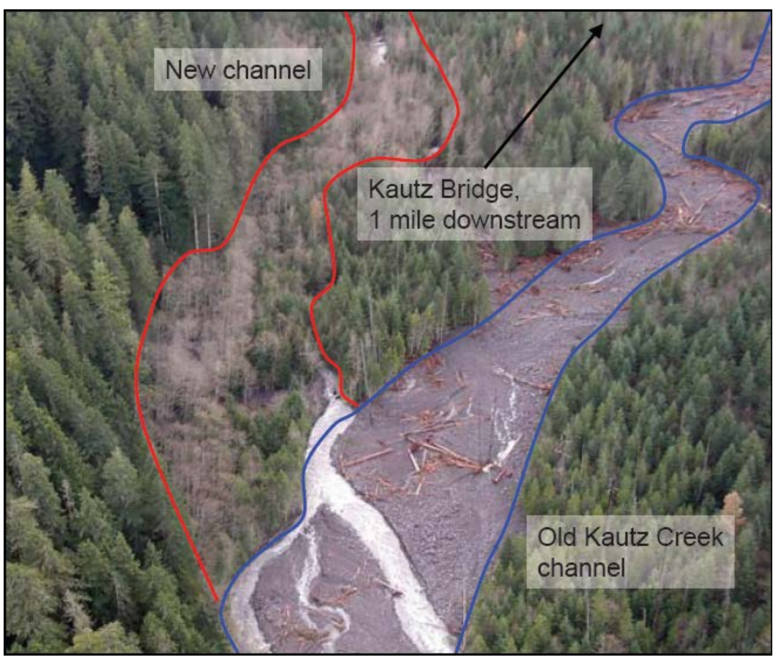

Figure 17. Oblique aerial photo looking south and downstream on Kautz Creek. This photo was taken on November 8, 2006 following a large flood. The old Kautz Creek channel on the right filled with sediment and debris forcing the creek to cut into a terrace of 1947 debris flow material to form a new channel (NPS photo).

Figure 18. View of Pyramid Park, Pyramid Glaciers and Neoglacial moraines looking northeast from Pyramid Peak. Sunset Amphitheater is visible in the upper left portion of the image (NPS Photo).

For the first 2 km, Tahoma Creek flows through valley bottom cut into Neoglacial moraines and unconsolidated sediments. Below this initial reach, Tahoma Creek widens into a braided floodplain and flows southwest for another 11 km before merging with the Nisqually River across a broad debris fan. Archival aerial photographs show that the floodplain of Tahoma Creek has widened considerably since 1960. The sediment and debris from this channel aggradation has been from flood events and debris flows. Debris flows along Tahoma Creek have been recorded since 1967 and have been mostly due to glacial outburst floods, known as jökulhlaups (Walder and Driedger 1994, 1995). Some of the deposits from these and other, older debris flows have since been abandoned as terraces. A series of terraces cut into Tahoma lahar deposits occur near Fish Creek (Figure 19). This area is in a constant state of change as Tahoma Creek's channel migrates into forest from the other side of the valley (Pringle 2008).

The oversteepened valley walls and jagged arêtes of the Mount Wow complex of lava flows tower above the west side of the lower Tahoma Creek valley. Theses lava flows from the Ohanapecosh Formation are thought to be a center of volcanism during the Oligocene (Pringle 2008). A large, blocky and unvegetated complex of debris cones descend from Mount Wow and are crossed by the West Side Road. Five large landslides were mapped in the valley, with four reaching Tahoma Creek.

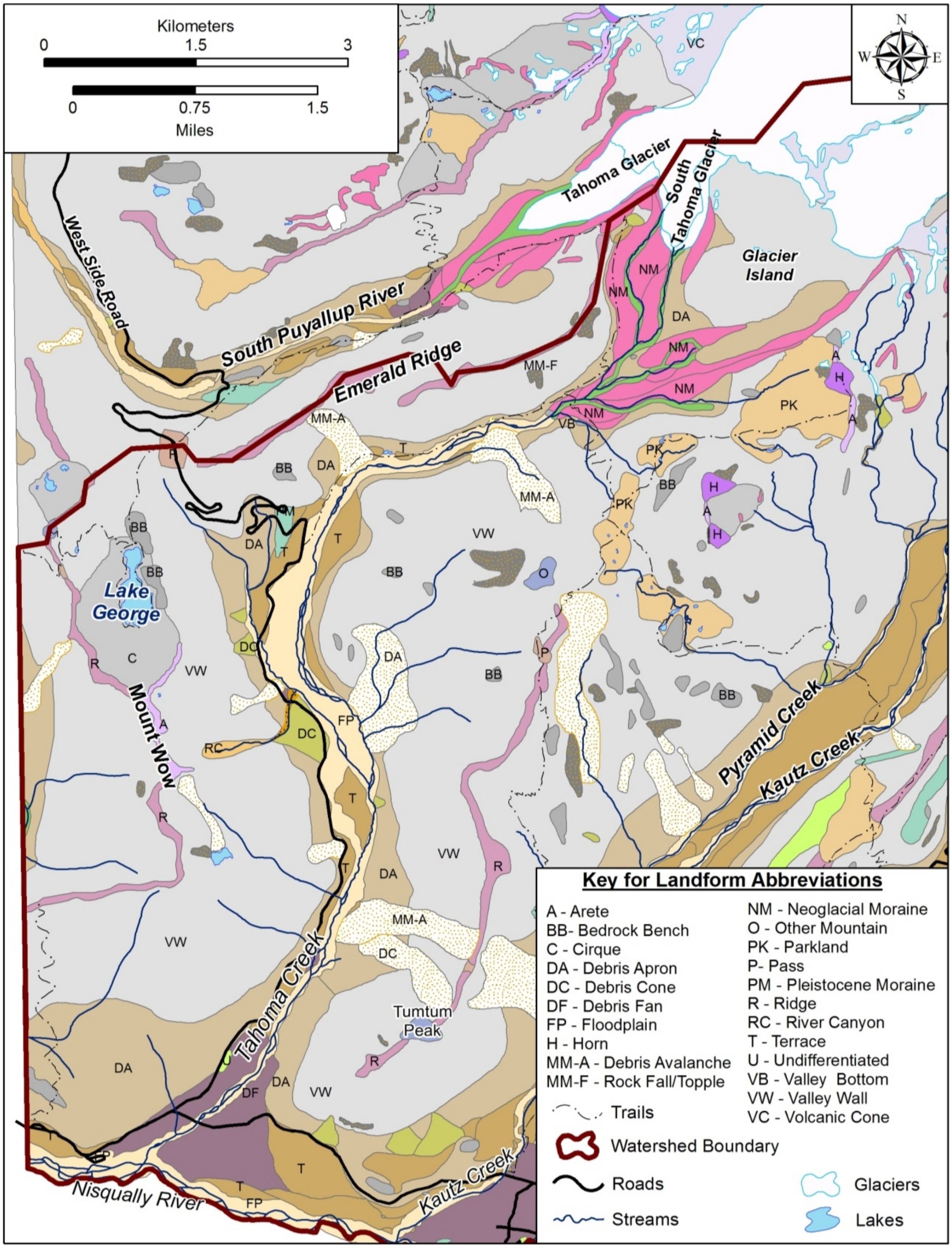

Figure 19. Landform map of Tahoma Creek watershed showing the localities mentioned in the text.

Vehicle access to the western part of MORA has been limited since about 1988 due to ongoing damage from the debris flows described above. Numerous dead trees and the abundant lobes of debris are evidence of the frequency of debris flows in the Tahoma Creek valley. Aggradation of the channel and debris fans continues to damage the West Side Road in response to the large amount of debris from these events. The November 2006 floods also triggered debris flows, caused numerous channel changes, and extensive damage to the West Side and Nisqually Roads.

5.3 Cowlitz River Watershed

The Cowlitz River flows more than 140 km from MORA before entering the Columbia River, making it the only river heading in the park that does not drain into Puget Sound. The Cowlitz River watershed drains an area of approximately 6,698 km^2; this study focuses on the upper 282 km^2 of the watershed that is within MORA. The largest tributaries of the Cowlitz River in the park are the Muddy Fork Cowlitz River and the Ohanapecosh River (Figure 20). These two valleys are very different in that the Muddy Fork heads on the volcanic cone of Mount Rainer, while Ohanapecosh does not. The major glaciers that drain into the watershed are (from west to east) Paradise Glacier, Williwakis Glacier, Cowlitz Glacier, Ingraham Glacier, Whitman Glacier and Ohanapecosh Glacier (Figures 4 and 20). The upper watershed boundary to the west is formed by Cowlitz Cleaver, Mazama Ridge, and the Tatoosh Range and to the north by Whitman Crest and Cayuse Pass. The eastern boundary follows the Pacific Crest south from Chinook Pass. Cowlitz Divide splits the watershed into two main valleys (Figure 20).

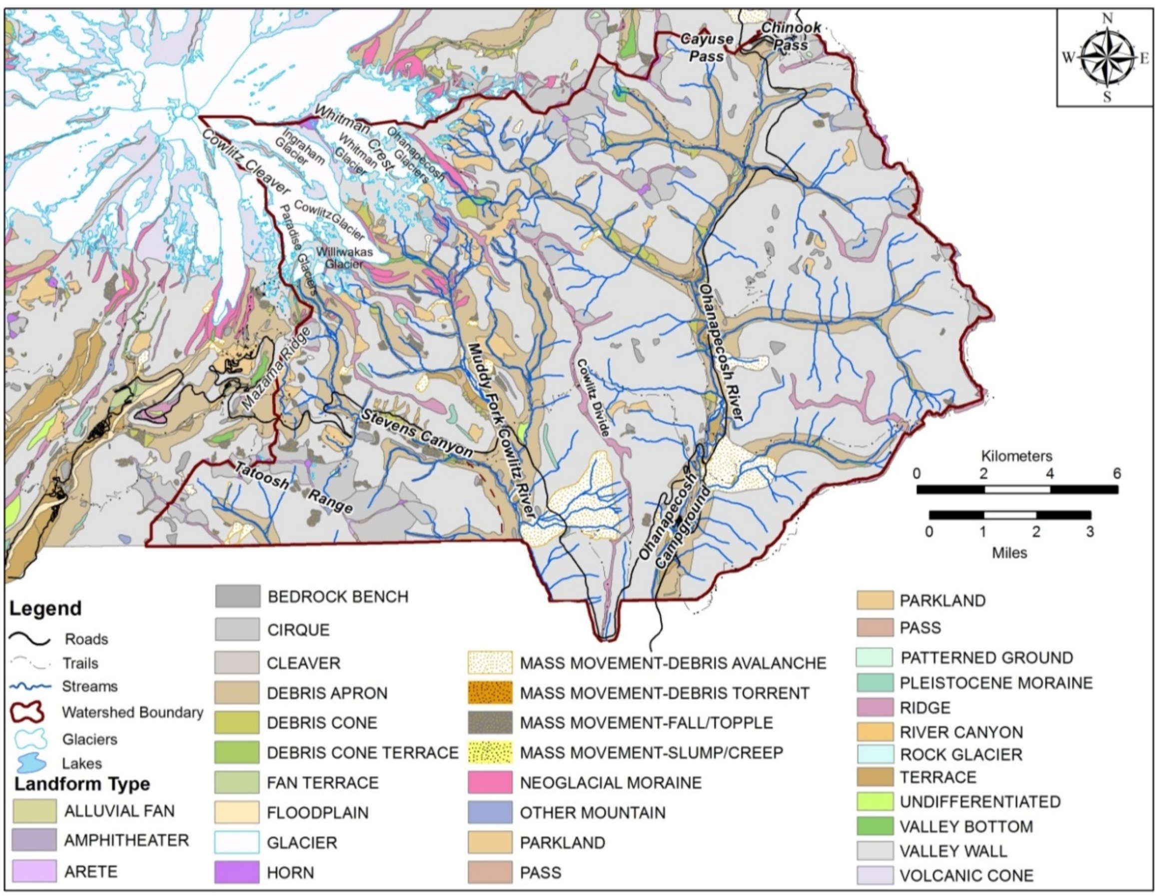

Figure 20. Landform map of the Cowlitz River watershed that is within Mount Rainier National Park showing the localities mentioned in the text.

5.3.1 Muddy Fork Cowlitz River

The Muddy Fork Cowlitz River emerges from the Cowlitz Glacier approximately 5 km northwest of Paradise at 1,600 m elevation (Figures 21 and 22). The Cowlitz Glacier is heavily crevassed and is connected to both the Ingraham and Paradise Glaciers (Figures 4 and 21). Approximately 25 ka, the Cowlitz Glacier extended approximately 67 km down the Cowlitz River valley from the present Cowlitz Glacier (Crandell and Miller 1974, Kiver and Harris 1999). There are several tributary streams to the Muddy Fork Cowlitz within MORA including Steven's Creek, Williwakas Creek and Nickel Creek (Figure 21). The Muddy Fork Cowlitz River drains the southeastern flank of Mount Rainier and flows southeast for approximately 18 km before merging with the Ohanapecosh River approximately 6 km south of the MORA boundary. The Muddy Fork Cowlitz watershed is confined to the west by Mazama Ridge and the Tatoosh Range and to the east by the broad Cowlitz Divide (Figure 21).

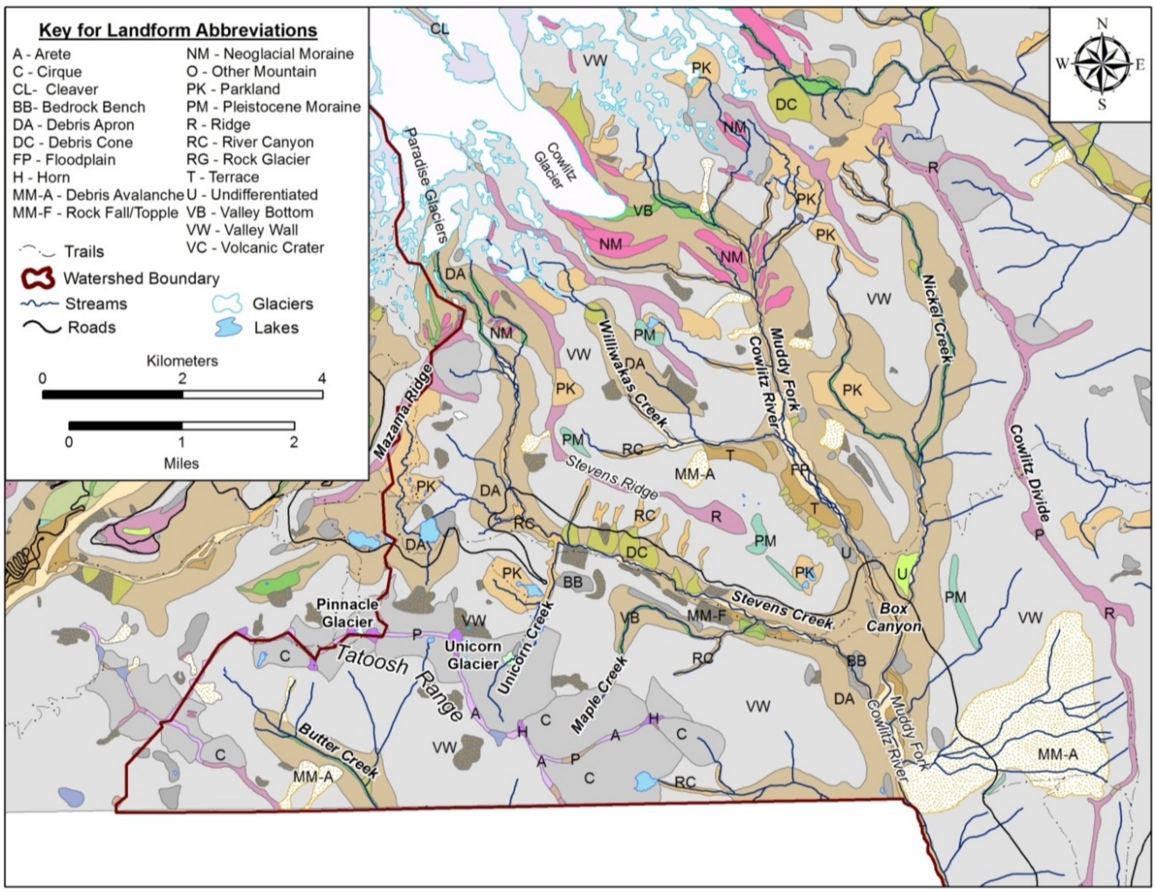

Figure 21. Landform map of the Muddy Fork Cowlitz River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Valley wall is the prevailing landform in the Muddy Fork Cowlitz watershed at 46%, or 52 km^2. Debris apron is the next most extensive landform at 17% (Table 8). The Muddy Fork Cowlitz flows through valley bottom flanked by debris apron, which is composed of primarily glacial till, and large Neoglacial moraines (Figures 21 and 22). The Muddy Fork flows southeast before it enters a relatively short, deeply incised river canyon. The Muddy Fork emerges from the canyon into a wide, braided floodplain (Figure 23) before it enters another deeply incised canyon, known as Box Canyon. The canyon is cut into mudflow breccias of the Ohanapecosh Formation and is locally up to 55 m deep and 5-9 m wide (Pringle 2008). These two river canyons on the Muddy Fork were likely due to postglacial incision of the Cowlitz valley. The wide braided floodplain of the Muddy Fork is flanked by several large terraces, which are composed of a mixture of mudflows and alluvium (Crandell 1969a). There have been numerous lahars that originated in the Cowlitz River watershed. However, none of them were comparable in size to the larger lahars in other drainages at MORA. There is little preserved stratigraphic evidence for Cowlitz lahars within MORA, but a complete flow record is preserved in depositional areas of the valley downstream from the park boundary (Scott 1988).

Table 8. Summary table of landform results within the Muddy Fork Cowlitz River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	16	51.86	45.49
Debris Apron	34	19.06	16.72
Volcanic Cone	1	8.39	7.33
Cirque	17	7.98	7.00
Mass Movement-Debris Avalanche	12	5.22	4.58
Parkland	17	3.73	3.27
Ridge	14	2.55	2.24
River Canyon	31	2.21	1.94
Mass Movement-Fall/Topple	40	1.73	1.52
Glacier Ice (Below VC)	1	1.54	1.35
Neoglacial Moraine	37	1.44	1.26
Floodplain	8	1.25	1.10
Bedrock Bench	34	1.15	1.01
Valley Bottom	7	1.07	0.94
Terrace	35	0.97	0.85
Debris Cone	19	0.84	0.74
Pleistocene Moraine	6	0.46	0.40
Arête	14	0.43	0.38
Cleaver	5	0.42	0.37
Horn	8	0.29	0.25
Amphitheater	1	0.22	0.19
Undifferentiated	1	0.13	0.12
Pass	13	0.12	0.11
Debris Cone Terrace	3	0.07	0.06
Other Mountain	1	0.03	0.02
Rock Glacier	1	0.03	0.02
Patterned Ground	1	0.01	0.01
Totals	353	114	100

Figure 22. View looking northwest of the Cowlitz Glacier and volcanic cone of Mount Rainer (NPS Photo).

Figure 23. View looking southeast down the Muddy Fork Cowlitz River valley from Cowlitz Park. The braided floodplain of the Muddy Fork is visible in the center of the photo. The Tatoosh Range and Mount Adams are visible in the distance (NPS Photo).

Stevens Creek is the largest tributary stream to the Muddy Fork Cowlitz River. Stevens Creek drains the Paradise Glacier, which no longer drains into the Paradise River due to the amount that it has receded (Figure 4). Mazama Ridge forms the drainage divide between Nisqually River watershed and Stevens Creek. Mazama Ridge is a dacite flow that has been dated at approximately 90 ka (Sisson and Lanphere 1999). Stevens Creek emerges from the Paradise Glacier into a valley bottom that is flanked by gently sloping debris apron, which is primarily composed of glacial till (Figure 24). Stevens Creek then widens into a braided floodplain before flowing through a series of river canyons (Figure 21).

There are a series of steep first order streams that descend from Stevens Ridge through narrow river canyons; these streams all have active debris cones at their junction with Stevens Creek. During the 2006 flood, several debris torrents flowed out of the canyons and damaged the Stevens Canyon Road (Figure 25). Several creeks draining the north-facing cirques of the Tatoosh Range also feed Stevens Creek. The assemblages of glacial horns, cirques, and arêtes (Figure 24) are some of the most noteworthy in the park and are composed of predominantly Tatoosh granodiorite, which intruded through older rocks of the Stevens Ridge Formation. There are 15 cirques in the Muddy Fork Cowlitz watershed, most of which are in the Tatoosh Range. These cirques still contain small remnants of cirque glaciers, such as Pinnacle Glacier and Unicorn Glacier (Figure 21). Unicorn Creek and Maple Creek drain two of the north-facing cirques into Stevens Creek; they both have river canyons cut into bedrock where they enter Steven Canyon. The south side of the Tatoosh Range is drained by Butler Creek, which flows into the Cowlitz River approximately 12 km south of the MORA boundary.

Figure 24. Stevens Creek valley bottom and debris apron just downstream from the Paradise Glacier. View is looking southeast. The Tatoosh Range and Mount Adams can be seen in the distance (NPS Photo).

Figure 25. Oblique aerial photo of a debris torrent that covered the Stevens Canyon Road during the November 2006 flood event (NPS Photo).

The juxtaposition of deep canyons and flat bedrock benches and parklands forms unique topography in the Stevens Canyon area (Figure 21) and points out the complex interplay between lava and ice that has occurred throughout the geologic history of MORA. New geologic interpretations of these lava flows suggest that lava was ponded at successively lower levels by tributary glaciers that filled Unicorn Creek and Maple Creek (Lescinsky and Sisson 1998).

5.3.2 Ohanapecosh River

The Ohanapecosh River valley is unique at MORA because it is the largest stream that does not head on Mount Rainier volcano. As a result, it has a different distribution of landform types. The Ohanapecosh valley has a higher proportion of valley wall (71%) than any other valley at MORA and a small amount of floodplain (0.7%). This is likely a result of less extensive erosion by large valley glaciers. The limited influence of glaciers and volcanic processes has allowed hillslope processes to dominate. Floodplains are narrow due to lack of glacial erosion and limited amounts of glacial, volcanic, and lahar debris. The Ohanapecosh also lacks the extensive lahar terraces that dominate most other valleys and owes much of its modern geomorphology to ice age glaciers, landslides and river activity.

The Ohanapecosh River emerges from the Ohanapecosh Glacier at 1,800 m. The Ohanapecosh Glacier is a small glacier located on Mount Rainier's southeastern flanks (Figure 4). The glacier consists of several lobes of ice interconnected by thin snowfields. There are several tributary streams to the Ohanapecosh River within MORA including Chinook Creek, Panther Creek, Deer Creek and Kotsuck Creek (Figure 26). Chinook Creek flows southward from Chinook Pass, which (along with Cayuse Pass, Sheepskull Gap, Barrier Peak and Cowlitz Chimneys) forms the drainage divide between the Ohanapecosh and the White River watersheds (Figure 26). The Ohanapecosh River flows generally southward for approximately 18 km before merging with the Muddy Fork Cowlitz River 6 km south of the MORA boundary to form the Cowlitz River.

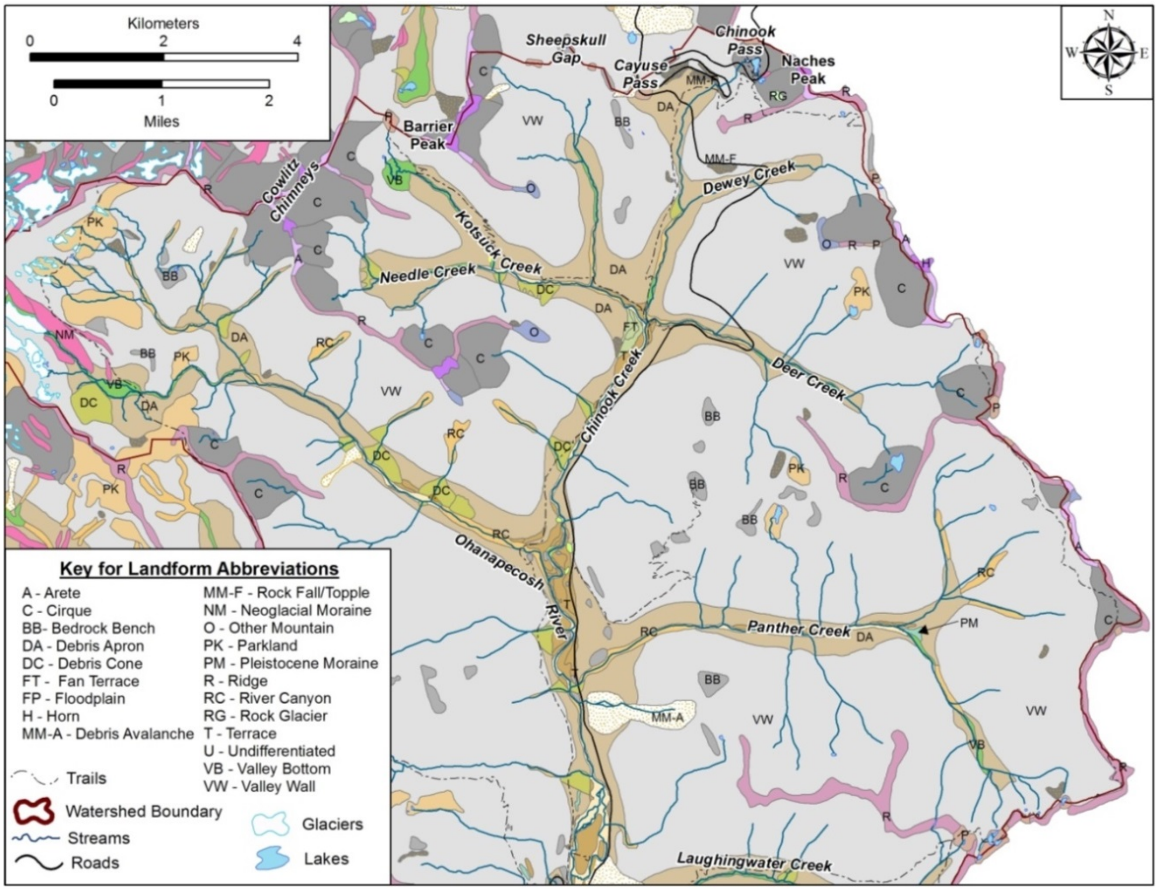

Figure 26. Landform map of the upper Ohanapecosh River watershed showing the localities mentioned in the text.

The main stem of the Ohanapecosh River initially flows in a steep valley bottom before it briefly widens at Indian Bar (Figure 26). It then flows southwest in valley bottom before entering a long river canyon; downstream of the canyon, the river flows in a relatively narrow floodplain. The Ohanapecosh floodplain never develops a braided pattern and remains relatively constricted, which is anomalous when compared to the other major rivers at MORA. This is due to the small amount of glaciated volcanic cone that the Ohanapecosh drains; this represents less than 1% of the watershed compared to an average of approximately 12% for other watersheds at MORA (Table 9). Below this stretch of floodplain, the Ohanapecosh enters another long river canyon. It emerges from the canyon and is joined by its tributary, Chinook Creek, which flows south from Chinook Pass (Figure 26). Chinook Creek is the largest tributary to the Ohanapecosh and is fed by tributaries Deer Creek and Kotsuck Creek; these streams originate from cirques without glaciers on the volcanic cone (Figure. 26).

Chinook Creek originates in west facing cirques below the glacial horn of Naches Peak, with cirque floors down to 1,600 m. Chinook Creek flows south for 4.5 km where it is joined by Kotsuck Creek and Deer Creek. Kotsuck Creek has one headwater tributary, Needle Creek, that originates in east facing cirques below the steep horns and arêtes of the Cowlitz Chimneys. These east facing cirques have floor elevations down to 1,700 m. Needle Creek flows east in valley bottom for 1.5 km until it is joined by Kotsuck Creek. There is a brief floodplain reach on upper Kotsuck Creek before it enters a river canyon. There is a series of fan terraces at the mouth of Kotsuck Creek with heights up to 8 m above the current channel. Directly across from the mouth of Kotsuck Creek is the mouth of Deer Creek, which originates in north and west facing cirques. Deer Creek flows west in valley bottom and then it also enters a long river canyon. After being joined by these two tributaries, Chinook Creek continues to flow south in a meandering floodplain channel.

Table 9. Summary table of landform results within the Ohanapecosh River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	4	118.35	70.45
Debris Apron	57	20.86	12.42
Cirque	27	8.54	5.08
Mass Movement-Debris Avalanche	7	3.59	2.11
Ridge	25	3.59	2.14
Parkland	11	2.69	1.60
River Canyon	26	2.33	1.39
Terrace	74	1.95	1.19
Bedrock Bench	54	1.68	1.00
Debris Cone	20	1.55	0.92
Volcanic Cone	1	1.24	0.74
Floodplain	8	1.22	0.73
Valley Bottom	10	1.16	0.70
Mass Movement-Fall/Topple	21	0.65	0.39
Neoglacial Moraine	7	0.59	0.35
Pass	20	0.36	0.21
Arête	15	0.29	0.17
Other Mountain	5	0.25	0.15
Horn	8	0.24	0.14
Fan Terrace	3	0.13	0.08
Pleistocene Moraine	7	0.12	0.07
Cleaver	1	0.05	0.03
Undifferentiated	5	0.04	0.02
Rock Glacier	1	0.02	0.02
Mass Movement-Debris Torrent	1	0.01	0.01
Mass Movement-Slump/Creep	1	0.01	0.01
Totals	398	168	100

A large debris avalanche (Crandell 1969a) just north of the Ohanapecosh Ranger Station and Campground is mapped in the Laughingwater Creek tributary. This landslide is part of the Laughingwater Creek landslide complex, which has previously dammed the Ohanapecosh River at this site (Pringle 2008). The hummocky topography of the landslide deposit extends for approximately 2 km along SR 123 (Figure 27). The landslide is likely due to the presence of hot fluids and to a lesser extent bedrock weakened by the hot water.

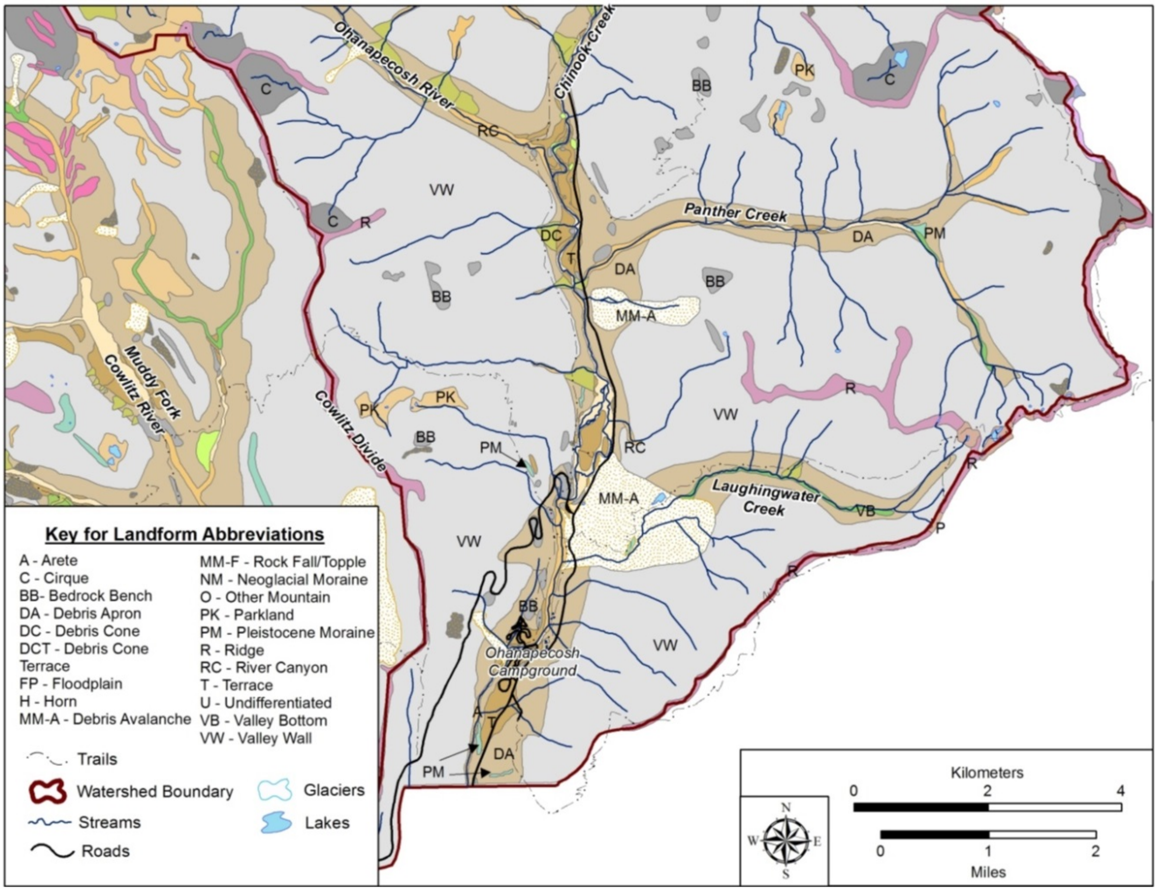

Figure 27. Landform map of the lower Ohanapecosh River watershed within Mount Rainier National Park showing the localities mentioned in the text.

5.4 White River Watershed

The White River watershed is the largest at MORA. The upper part of the valley is dominated by the volcanic cone of Mount Rainier, which is broken by the large amphitheater. The amphitheater was created about 5,700 years ago when a large sector of the volcano collapsed. This event caused the Osceola mudflow, which shaped the White River valley to Puget Sound. Glaciers cut deep canyons which emanate from Mount Rainier. The walls of these canyons form the dominate landform in the watershed.

The White River flows from the Emmons Glacier for 121 km to eventually join the Puyallup River before draining into Puget Sound. The White River watershed drains 285 km^2 and has two major tributaries, Huckleberry Creek and the West Fork White River (Figure 28). The major glaciers that drain into the watershed are (from east to west) Fryingpan Glacier, Emmons Glacier, Inter Glacier and Winthrop Glacier (Figures 4 and 28).

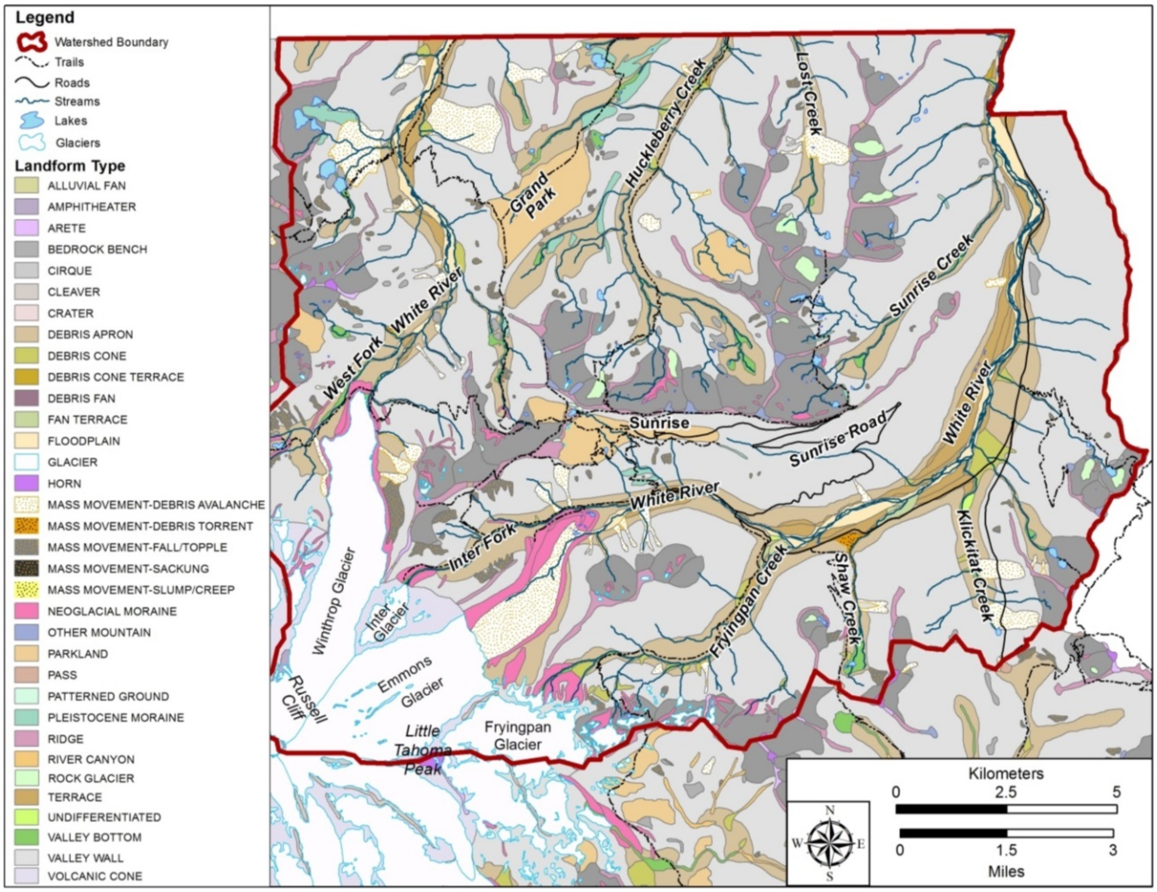

Figure 28. Landform map of the White River watershed within Mount Rainier National Park showing the localities mentioned in the text.

5.4.1 White River

The White River flows east from the Emmons Glacier until turning north just downstream from the White River Ranger Station (Figures 28 and 29). The Emmons Glacier is the largest at MORA, and much of it occupies an amphitheater created by the Osceola Mudflow 5.700 years ago (Hoblitt et al. 1998). Rapid accumulation, flow, and melt of ice on Mount Rainier's glaciers imply that glacial ice on the Emmons is likely less than a few thousand years old.

In December 1963, a large rock avalanche fell from the north side of Little Tahoma Peak covering much of the lower Emmons Glacier with shattered rock (Crandell and Fahnestock 1965). In 1994 remnants of this avalanche covered the lower glacier from the terminus (1,480 m) up to approximately 1,700 m in elevation. This massive landslide may have been triggered by a steam explosion (Crandell and Fahnestock 1965). The White River initially flows through this landslide debris, as well as glacial till from large Neoglacial moraines (Figures 29 and 31). The White River then flows in a braided floodplain just downstream from the Neoglacial moraine extent.

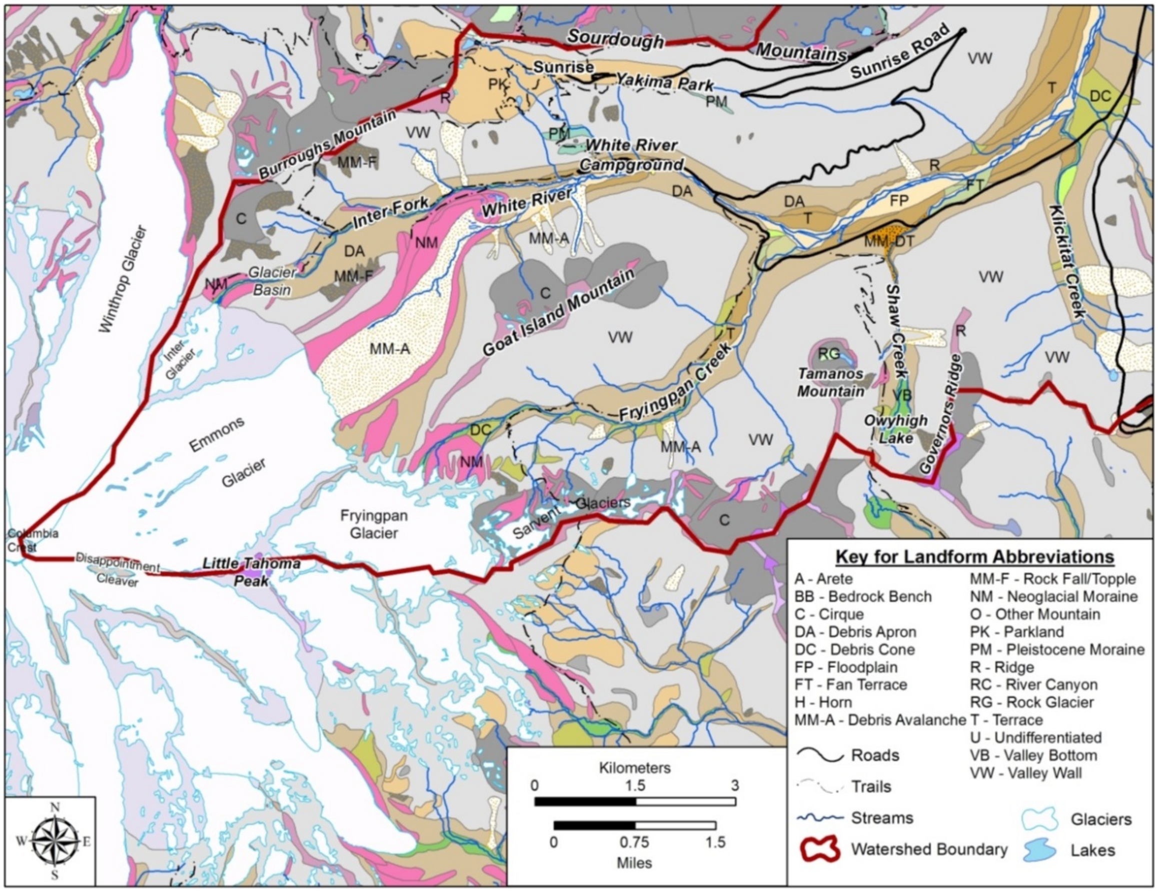

Figure 29. Landform map of the upper White River watershed at Mount Rainier National Park showing the localities mentioned in the text.

The White River emerges from the terminus of the Emmons Glacier at 1,480 m elevation, approximately 3 km southwest of Sunrise (Figure 29). A small headwater tributary of the White River is the Inter Fork, which emerges from the Inter Glacier at 2,135 m of elevation. The Inter Fork initially flows between two large Neoglacial moraines in a brief stretch of sediment-choked valley bottom before it widens to floodplain at 1,890 m in Glacier Basin. There it is confined by debris apron composed primarily of glacial till (Figure 29). Other tributary streams to the upper White River at MORA include Fryingpan Creek, Shaw Creek, Klickitat Creek and Sunrise Creek (Figure 29).

The dominant landforms in White River watershed are valley wall (54%), cirque (9%) and debris apron (10%) (Table 10). Extensive cirques are found in the Sourdough Mountains and the Palisades, as well as on the north aspects of Burroughs Mountain and Goat Island Mountain (Figures 28 and 29). Terraces (3%) and wide, braided floodplain (2.5%) are also extensive landforms in the watershed.

Table 10. Summary table of landform results within the White River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	15	84.75	53.64
Debris Apron	35	16.09	10.18
Cirque	35	14.29	9.04
Volcanic Cone	1	9.50	6.02
Terrace	45	4.82	3.05
Mass Movement-Debris Avalanche	14	4.67	2.96
Floodplain	3	3.82	2.42
Neoglacial Moraine	53	3.77	2.39
Ridge	34	3.32	2.11
Amphitheater	1	2.84	1.80
Parkland	2	2.05	1.30
Debris Cone	22	1.44	0.91
Valley Bottom	7	1.38	0.87
Mass Movement-Fall/Topple	27	1.16	0.73
Rock Glacier	8	0.67	0.42
Bedrock Bench	15	0.43	0.27
River Canyon	6	0.33	0.22
Pleistocene Moraine	7	0.32	0.21
Other Mountain	12	0.31	0.20
Arête	10	0.26	0.17
Fan Terrace	8	0.26	0.17
Pass	17	0.25	0.16
Mass Movement-Debris Torrent	1	0.24	0.15
Alluvial Fan	3	0.19	0.12
Horn	5	0.14	0.09
Cleaver	2	0.11	0.07
Undifferentiated	2	0.11	0.07
Crater	1	0.03	0.02
Patterned Ground	3	0.03	0.02
Mass Movement-Slump/Creep	1	0.01	0.01
Totals	395	158	100

The east face of the volcanic edifice of Mount Rainier is a large amphitheater that was created by the collapse of the volcanic cone and led to Osceola Mudflow. Remnants of the old crater rim can be seen at Point Success, Liberty Cap and the uppermost exposures of Willis Wall (Pringle 2008). The Osceola mudflow was the product of a large debris avalanche composed mostly of hydrothermally altered material. Deposits from the Osceola cover an area of about 550 km^2 in the Puget Sound lowland (Hoblitt et al. 1998), extending at least as far as the Seattle suburb of Kent and to Commencement Bay (now the site of the Port of Tacoma). The mudflow deposited more than 3.7

billion m^3 of material. 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 150 m thick (Crandell 1969b, Crandell 1971). Large terraces along the White River at MORA are composed primarily of Osceola Mudflow deposits and are among the most extensive in the park (Figures 29 and 32). The deposits of the Osceola are clay rich and, locally within the White River valley at MORA, contain large hummocks (Figure 30). They appear as a chaotic jumble of clay, silt, sand and large boulders with a yellowish color.

Figure 30. A good example of the hummocky topography that is found in sections of Osceola Mudlfow deposits; this site is on a terrace along the Fryingpan Creek (NPS Photo).

Prominent lateral moraines from the Evans Creek advance can be observed north of White River Campground and consist of three separate ridges which are 45, 90, and 137 m above the valley floor. The glacier may have grown to a thickness sufficient to cover Burroughs and Goat Island mountains, meaning ice was about 900 m thick above the campground (Crandell and Miller 1974). Approximately 25 ka, three large, separate valley glaciers formed in the White River watershed. The largest was the White River glacier, which terminated about 30 km downvalley from the current terminus of the Emmons Glacier (Crandell and Miller 1974).

Fryingpan Creek is a northeast flowing tributary to the White River that originates from the Fryingpan Glacier. The glacier is on the northeast flank of Little Tahoma Peak, a towering glacial horn that stands prominently above the Fryingpan and Emmons Glaciers (Figures 4 and 31). Little Tahoma Peak is a stack of lava flows with basal flows as old as approximately 195 ka and 130 ka (Pringle 2008).

Figure 31. The debris covered terminus of the Emmons Glacier with Little Tahoma Peak in the background (NPS Photo).

Shaw Creek is a north flowing tributary to the White River that originates from Owyhigh Lake and the north facing cirques of Barrier Peak (Figures 29 and 33). The Shaw Creek valley is confined to the east by Governors Ridge and to the west by the Tamanos Mountains (Figures 29 and 33), which is cored by lava flows of the Ohanapecosh Formation. Large debris flows have filled the Shaw Creek valley bottom and canyon and forced Shaw Creek to flow subsurface (Figures 34 and 35). The debris flow deposits extend for 1.5 km to a large terrace along the White River; debris flows in Shaw Creek seem to be episodic and ongoing. Source material for the flows is likely from debris avalanches on the east side of the valley wall, as well as an abundance of till from Neoglacial moraines in the cirques surrounding Tamanos Mountain.

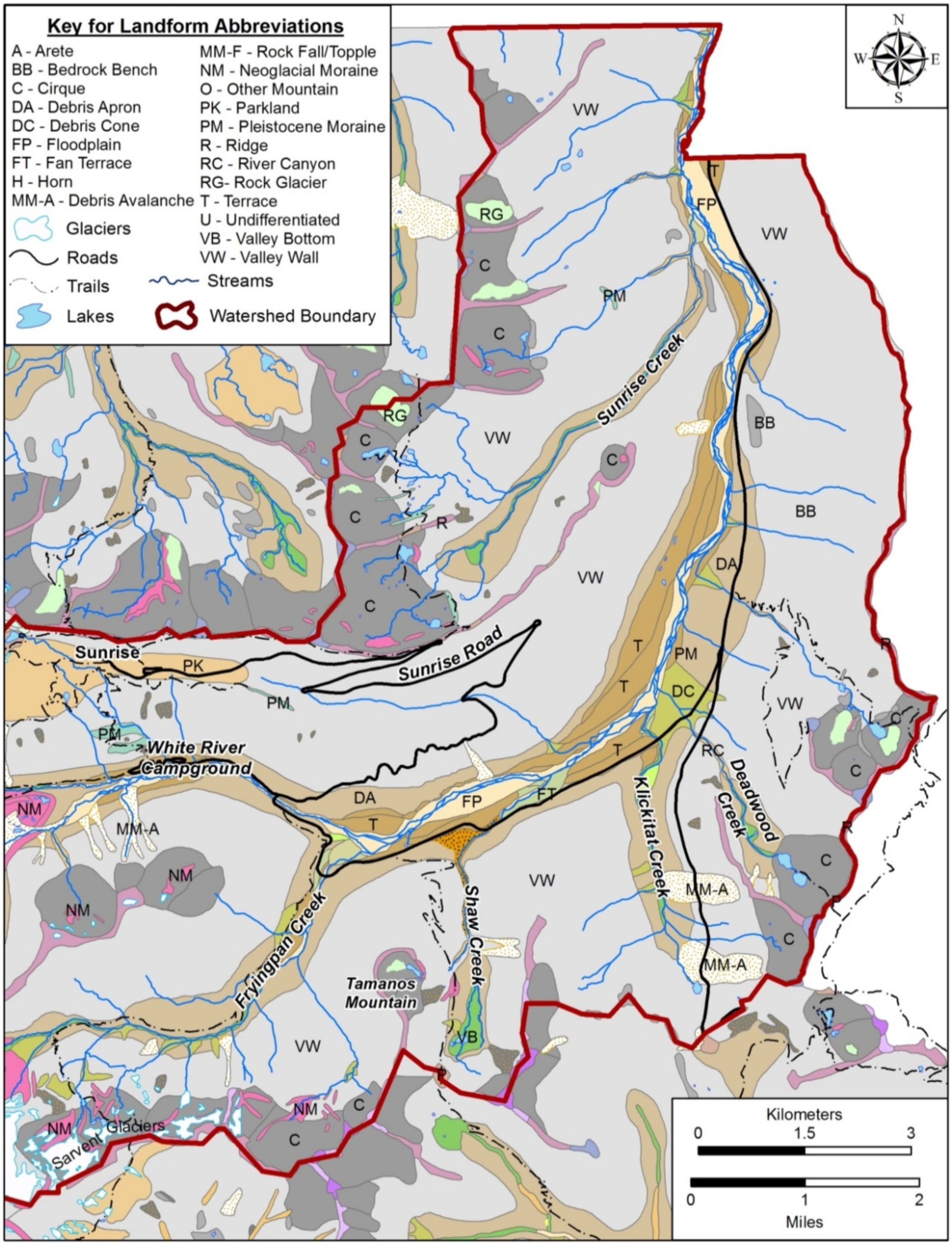

Figure 32. Landform map of the lower White River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Figure 33. Shaw Creek valley looking south from Sunrise Point. Governor's Ridge is in the left of the image with Barrier Peak and the Shaw Creek headwaters in the center, the Tamanos Mountains are on the right and Mount Adams is visible in the distance (NPS Photo).

Figure 34. Shaw Creek debris flow deposits, view is looking south (upvalley) approximately 0.4 km south of the White River Road (NPS Photo).

Figure 35. Shaw Creek debris flow deposits looking south (upvalley) from the Owyhigh Lake trail.

5.4.2 Huckleberry Creek

Huckleberry Creek flows northeast before merging with White River approximately 20 km north of the MORA boundary. Huckleberry Creek watershed does not head on the volcano, but is confined to the south and east by the Sourdough Mountains and to the west by Grand Park (Figure 36).

The headwaters of Huckleberry Creek are in the north-facing cirques of the Sourdough Mountains. These deep cirques have floors that extend down to 1,700 m and hold several small lakes and late ice age moraines. There are several tributary streams to Huckleberry Creek, including Prospector Creek and Lost Creek. The headwaters of Huckleberry Creek are defined by three distinct basins: Cold Basin, Huckleberry Basin, and Huckleberry Park. Each with relatively short 1st order tributaries that flow through glacially scoured headwater basins into Huckleberry Creek (Figure 36). The transition from valley bottom to floodplain occurs at 1,340 m and the floodplain of Huckleberry Creek remains relatively confined within MORA (Figure 36).

Huckleberry Creek is one of the few major streams at MORA that does not originate from a large glacier on the volcanic cone. It lacks the abundant amount of bedload produced by these large glaciers and as a result the meandering floodplain of Huckleberry Creek is notably narrower than the neighboring braided tributaries of the White River. Also lacking are the extensive lahar and glacial outwash terraces found in the other major valleys at MORA. Huckleberry Creek has extensive valley walls (50%) and cirque (15%) with restricted floodplain (0.56%) making its distribution of landforms very similar to the Ohanapecosh valley (Table 11).

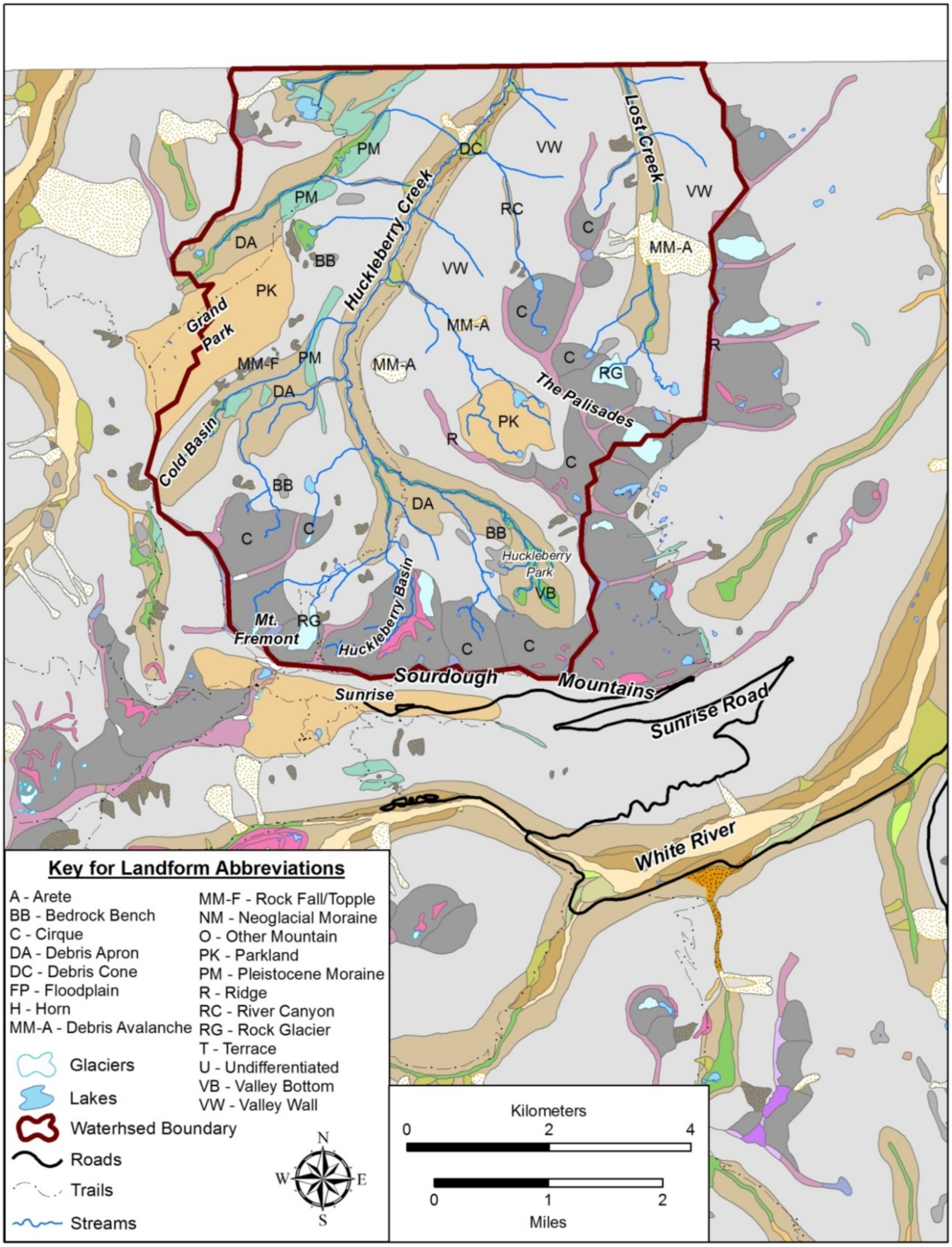

Figure 36. Landform map of Huckleberry Creek watershed within Mount Rainier National Park showing the localities mentioned in the text.

There are several lateral Pleistocene moraines preserved in the Huckleberry Creek valley (Table 11). These landforms are composed of till (Crandell 1969a) and mark the depth that glaciers filled the

Huckleberry Creek valley during the Evans Creek stade. These moraines were originally mapped by Crandell (1969a) and confirmed by LiDAR analysis and field visits. There are also several other moraines in the headwater cirque basins near Sunrise (Figure 36).

Table 11. Summary table of landform results within the Huckleberry Creek watershed.

Landform Type	Number Observed	Area km^2	% of Watershed
Valley Wall	9	27.05	49.18
Debris Apron	14	9.60	17.46
Cirque	18	7.77	14.13
Parkland	2	3.12	5.67
Ridge	20	1.53	2.94
Pleistocene Moraine	8	1.19	2.16
Valley Bottom	7	1.17	2.13
Mass Movement-Debris Avalanche	7	1.02	1.86
Rock Glacier	4	0.49	0.89
Mass Movement-Fall/Topple	28	0.46	0.84
Bedrock Bench	14	0.41	0.75
Floodplain	1	0.31	0.56
Debris Cone	4	0.25	0.46
Other Mountain	12	0.25	0.46
Neoglacial Moraine	8	0.22	0.40
Terrace	8	0.19	0.35
River Canyon	5	0.18	0.33
Pass	9	0.09	0.16
Patterned Ground	2	0.03	0.03
Totals	181	55	100

The aptly named Lost Creek is one of the tributary streams to Huckleberry Creek that flows north in valley bottom before seasonally flowing subsurface for 0.85 km when it crosses a large debris avalanche (Figures 36 and 37). The exact timing and cause of this large landslide is unknown, but it appears to have released from hydrothermally altered rock near the contact of Tatoosh Pluton and Ohanapecosh Formation (Fiske et al. 1963).

There is a large rock glacier near the Palisades that was originally mapped by Crandell (1969a). This deposit covers an area of 0.4 km^2 and is 30-90 m thick. The rock glacier occurs in an east facing cirque and is an accumulation of rock debris derived from the cliffs of The Palisades (Figure 38). These beautiful cliffs are composed of granite from the Tatoosh pluton as well as rhyodacite welded tuff that is as much as 244 m thick (Fiske et. al 1963). Lost Creek merges with Huckleberry Creek approximately 1 km north of the northern MORA boundary.

Figure 37. View of looking down a large debris avalanche in Lost Creek. Debris from this landslide obstructs the flow of Lost Creek and forces it to flow subsurface (NPS Photo).

Figure 38. Rock glacier deposit in the foreground is an accumulation of rock debris derived from the granite cliffs of The Palisades. The deposit covers an area of about 0.4 km2 and is 30-90 m thick (NPS Photo).

5.4.3 West Fork White River

The West Fork White River valley is confined in the east by Burroughs Mountain, Mt. Freemont and Grand Park; to the west, Old Desolate, Sluiskin Mountain and Independence Ridge divide the West Fork from the Carbon River valley (Figure 39). The headwaters for the West Fork White River are 2.5 km southwest of the Winthrop Glacier terminus near Mineral Mountain. This stream flows parallel to Winthrop Creek and joins it after approximately 5 km (Figure 39). Winthrop Creek is the main meltwater stream from Winthrop Glacier at 1,465 m elevation.

The Winthrop Glacier is a large, alpine valley glacier on the northeastern side of Mount Rainier (Figure 4). The Winthrop and Emmons Glaciers are connected from Columbia Crest down to Steamboat Prow (Figure 4). The terminus of Winthrop glacier is debris covered and flanked by large Neoglacial moraines (Figure 35 and Cover Photo). The Winthrop Glacier has the second largest area (9 km^2) of all the glaciers at MORA (Driedger and Kennard 1986). Approximately 25 ka, the Winthrop Glacier extended 23 km from the summit of Mount Rainer to where it merged with smaller glaciers from tributary valleys on the north side of the mountain (Crandell and Miller 1974). A series of Neoglacial moraines flank the Winthrop glacier, which was likely at its maximum Neoglacial extent during the mid-sixteenth century (Crandell 1969a, Sigafoos and Hendricks 1972).

Lahar deposits from the Osceola Mudflow are also found throughout the West Fork White River valley (Crandell 1969a). The West Fork White River initially flows in valley bottom for approximately 2 km alongside a Neoglacial moraine before widening to floodplain just downstream of the moraine (Figure 39). After merging with Winthrop Creek, the floodplain widens briefly before constricting into a short river canyon. The West Fork emerges from the canyon into a wide, braided floodplain, and then flows north for approximately 6 km to the northern MORA boundary. It merges with the White River near the town of Greenwater, approximately 20 km north of the MORA boundary. Numerous large terraces flank the West Fork floodplain; the most prominent of these features are 3 and 8 m above the floodplain and were formed by the Osceola Mudflow (Crandell 1969a).

The expansive Grand Park is a distinctive landform on the eastern edge of the West Fork White River valley (Figure 40). This rhyolitc lava flow was covered in ice during the ice ages, as shown by several exposures of Evans Creek drift (Crandell 1969a). Grand Park is 3 km^2 in size, making it one of the largest parklands at MORA. The northwest portion of Grand Park drains into the West Fork and the remainder of Grand Park drains into Huckleberry Creek. One of the main tributary streams of the West Fork White is Lodi Creek, which flows north from the large cirque of Berkeley Park and is on the north side of Burroughs Mountain. This cirque contains one of the largest moraines of McNeeley drift in the park (Figure 41). Originally described by Crandell and Miller (1974), the moraine extends downvalley slightly below 1,790 m, has about 6 m of local relief and closed depressions as deep as 3 m on the surface. Lodi Creek hangs above the West Fork valley and descends into it via a steep and incised river canyon (Figure 39).

There are 15 debris avalanches mapped within the West Fork White River valley, covering 4 km^2 or 6% of the total watershed area. The largest of these landslides occur at the lower end if the valley within MORA and were originally mapped by Fiske et al. (1963) and Crandell (1969a). Several factors explain the large number of landslides in this area, including glacial oversteepening of the valley walls, bedrock structure (faults and bedding planes) and hydrothermal alteration.

Table 12. Summary table of landform results within the West Fork White River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	13	31.01	42.48
Cirque	16	7.52	10.30
Debris Apron	32	5.87	8.04
Volcanic Cone	1	5.44	7.45
Mass Movement-Debris Avalanche	15	4.11	5.62
Glacier Ice (Below VC)	1	3.33	4.62
Amphitheater	1	2.43	3.32
Neoglacial Moraine	43	2.09	2.86
Parkland	3	1.97	2.70
Floodplain	2	1.51	2.07
Ridge	17	1.46	2.00
Mass Movement-Fall/Topple	39	1.35	1.85
Terrace	13	1.30	1.85
Valley Bottom	7	0.82	1.14
Bedrock Bench	21	0.48	0.66
Pleistocene Moraine	3	0.41	0.56
Debris Cone	6	0.36	0.49
River Canyon	5	0.19	0.26
Arête	6	0.13	0.18
Other Mountain	5	0.08	0.11
Horn	2	0.07	0.10
Pass	13	0.07	0.10
Crater	2	0.05	0.07
Cleaver	1	0.03	0.04
Patterned Ground	4	0.03	0.04
Mass Movement-Slump/Creep	1	0.03	0.04
Mass Movement-Debris Torrent	1	0.02	0.03
Totals	273	73.14	100

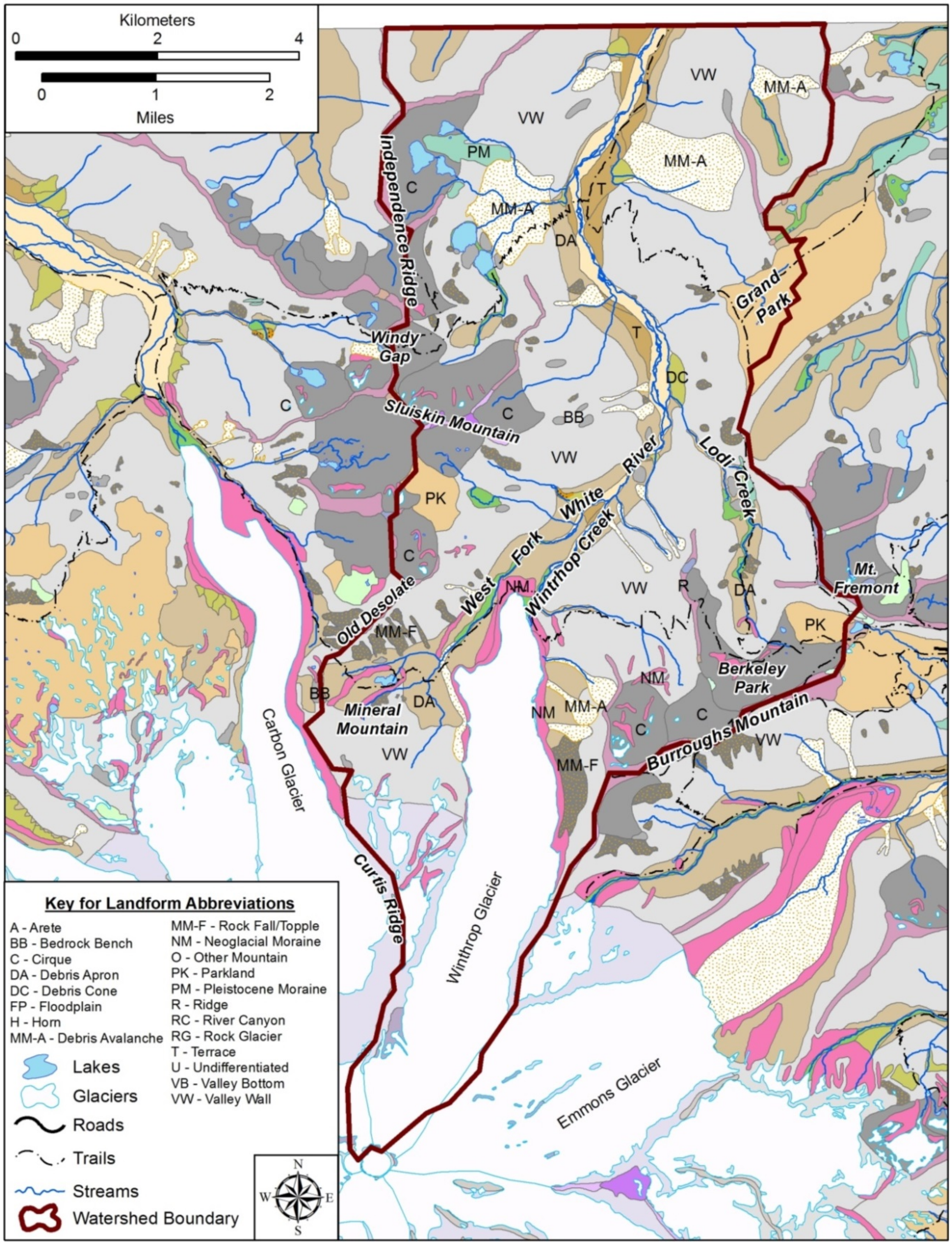

Figure 39. Landform map of the West Fork White River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Figure 40. The expansive, flat parkland of Grand Park (foreground), with Little Tahoma Peak and Mount Rainer in the distance (NPS Photo).

Figure 41. View looking south into the Berkeley Park cirque and a series of Neoglacial moraines. The maximum extent of the McNeeley glacier is marked by the horseshoe shaped moraine that is partially tree-covered in the left center of the image (NPS Photo).

5.5 Carbon River Watershed

The Carbon River watershed has the highest proportion of glacier cover of all MORA watersheds. The Carbon and Russell glaciers feed massive amounts of gravel to the Carbon River floodplain, the largest in the park at almost 6 km^2. The Carbon River valley also hosts some of the most extensive parkland, which covers about 5% of the watershed.

The Carbon River flows from the Carbon Glacier for 48 km where it merges with the Puyallup River before draining into Puget Sound (Figures 6 and 42). The Carbon River watershed drains the northwest flank of Mount Rainier and encompasses 106 km^2 within MORA. Headwater tributary streams include Cataract Creek and Spukwush Creek. Tributary streams to the Carbon River within MORA include Chenuis Creek, Ipsut Creek, Ranger Creek and Tolmie Creek (Figure 42).

5.5.1 Carbon River

The Carbon River emerges from the Carbon Glacier at 1,066 m elevation, the lowest glacier in the contiguous United States (Driedger 1986). The Carbon Glacier is a north facing, alpine valley glacier and has the greatest ice volume (0.8 km^3) and length (9.2 km) of all of the glaciers on Mount Rainier (Driedger and Kennard 1986). In the Carbon valley, ice from the last ice age extended down valley nearly to the town of Fairfax, which is 19 km beyond the present terminus (Crandell and Miller 1974) (Figure 6).

The Carbon River valley at MORA is divided from the West Fork White River valley to the east by the ridge of Old Desolate, the Crescent Mountains and the Chenuis Mountains (Figure 42). Mother Mountain and Spray Park divide the Carbon River valley from the North Mowich River valley to the southwest (Figure 42). The steep north flank of Mount Rainier above the Carbon Glacier is known as the Willis Wall, which is an almost sheer wall of lava 1,097 m high. The oversteepened face of Willis Wall released a major rockfall in 1916, which may be responsible for much of the rock that is visible on the glacier’s surface today (Driedger 1986). Several Neoglacial moraines near the terminus of the Carbon Glacier, just south of Cataract Creek, stabilized about 1500 A.D.; a similar moraine about 60 m to the east stabilized between 1835 and 1850 (Sigafoos and Hendricks 1972). A correlative sequence of Neoglacial moraines is located on the east side of the valley, directly across the Carbon from these moraines (Crandell and Miller 1974) (Figure 43).

The Carbon River briefly flows in a short section of boulder-laden valley bottom (Figures 43 and 44) before widening into a braided floodplain just downstream from the flanking Neoglacial moraines at 975 m. Just upstream from the Ipsut Creek Campground, the braided floodplain of the Carbon River becomes almost 1 km wide (Figures 45 and 47). Following the 2006 flood, recent aggradation increased the width of the floodplain even further downstream from Ipsut Creek. This aggradation destroyed a majority of the Carbon River road (Figure 46) and deposited abundant amounts of sediment into the old growth forest on top of a 3 m high terrace. The Carbon River Ranger station is located on a terrace that is formed in alluvium and contains Mount St. Helens y tephra, making it at least 7,000 years old.

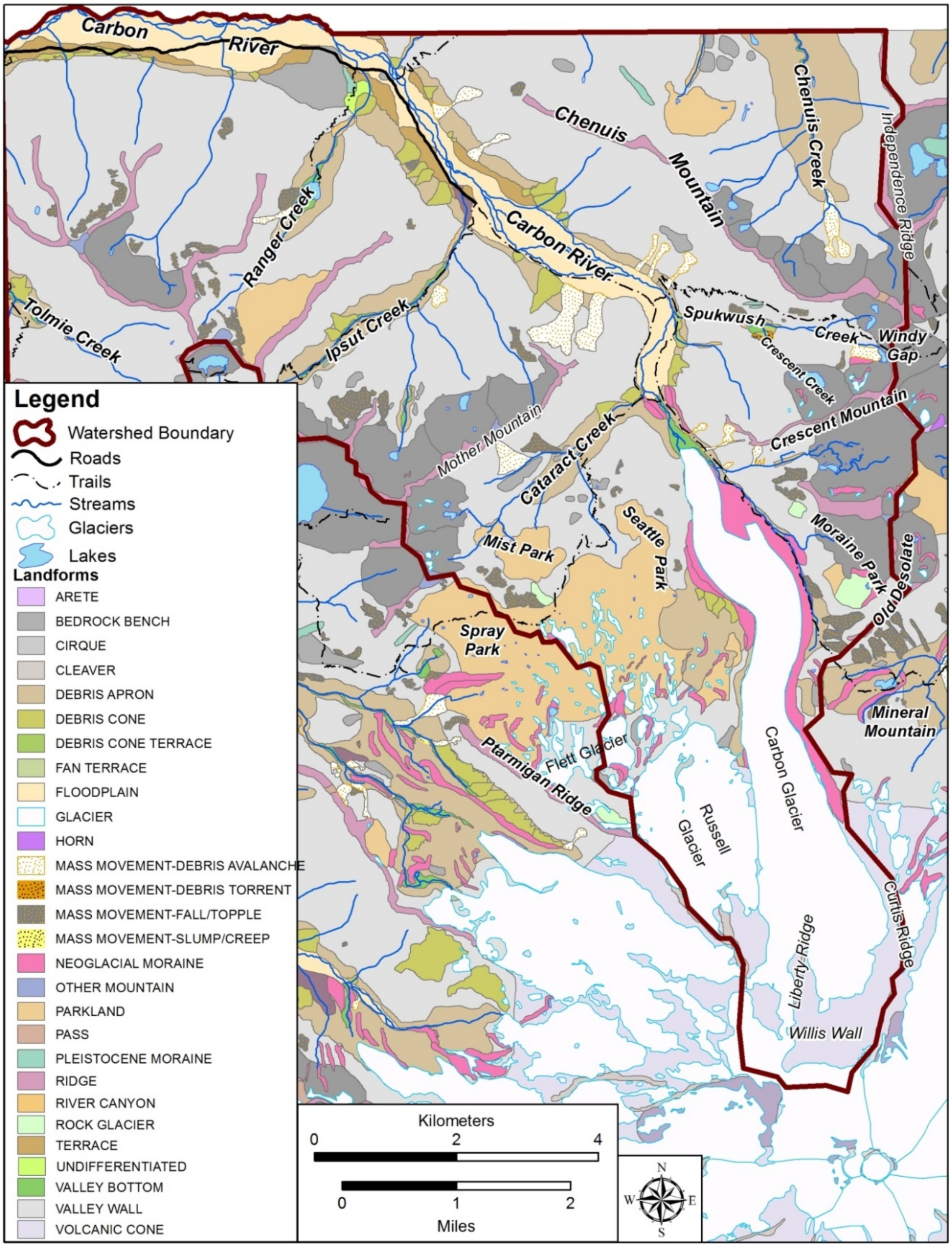

Figure 42. Landform map of Carbon River watershed within Mount Rainier National Park showing the localities mentioned in the text.

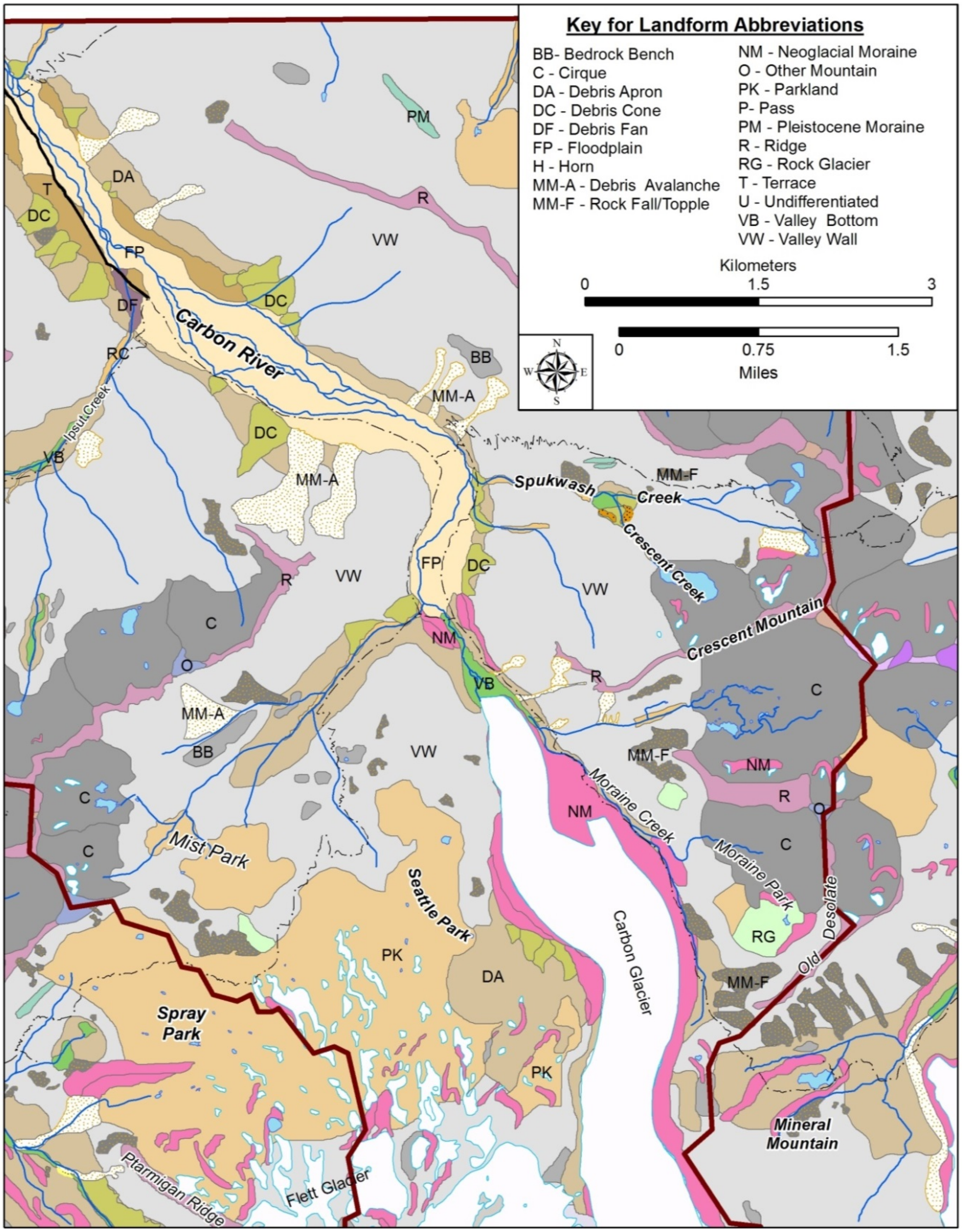

Figure 43. Landform map of the upper Carbon River watershed at Mount Rainier National Park showing the localities mentioned in the text.

Figure 44. View looking southeast at the terminus of the Carbon Glacier and the Carbon River (NPS Photo).

Figure 45. View looking southeast (upstream), from near Ipsut Creek of the braided Carbon River floodplain and the surrounding valley walls (NPS Photo).

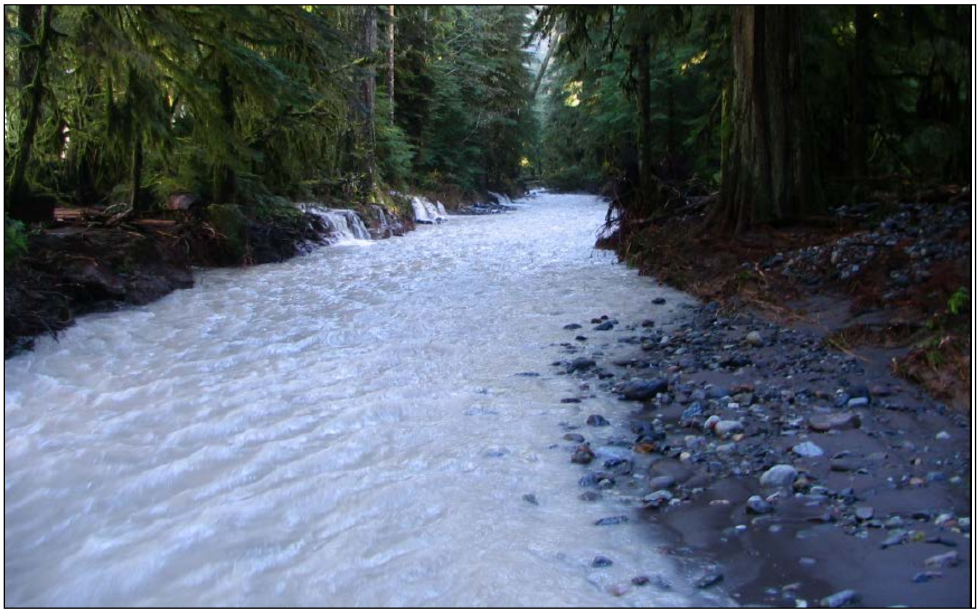

Figure 46. The Carbon River flowing over the remnants of the Carbon River Road following the November 2006 flood (NPS Photo).

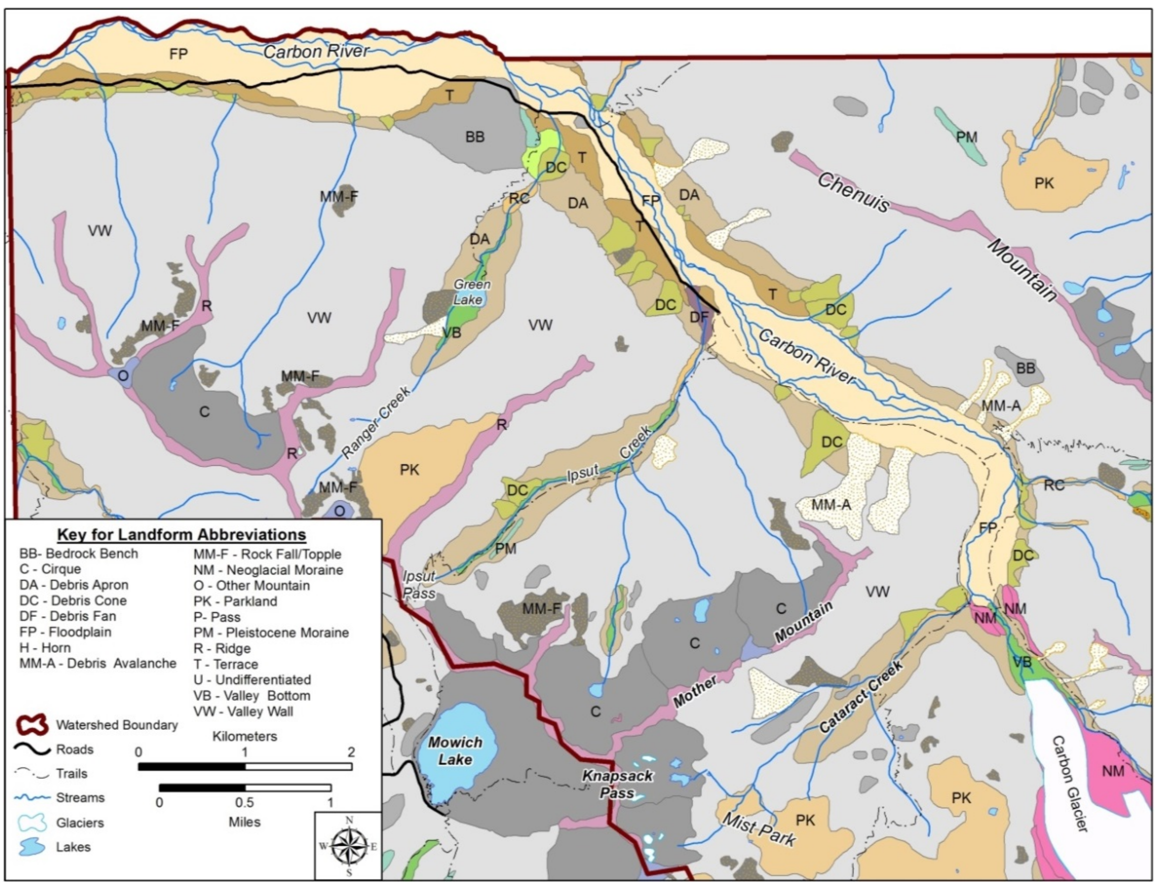

Figure 47. Landform map of the lower Carbon River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Table 13. Summary table of landform results within the Carbon River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	14	50.50	47.20
Volcanic Cone	1	10.11	9.45
Cirque	23	9.19	8.58
Debris Apron	42	7.74	7.24
Parkland	8	5.73	5.36
Floodplain	1	5.62	5.28
Glacier Ice (Below VC)	1	3.29	3.09
Ridge	15	3.08	2.89
Neoglacial Moraine	46	2.22	2.07
Mass Movement-Fall/Topple	41	1.65	1.54
Bedrock Bench	27	1.43	1.34
Mass Movement-Debris Avalanche	20	1.40	1.31
Debris Cone	37	1.36	1.28
Terrace	8	1.09	1.02
Valley Bottom	7	0.56	0.53
Cleaver	4	0.38	0.36
River Canyon	11	0.36	0.34
Rock Glacier	3	0.28	0.26
Other Mountain	5	0.16	0.15
Pleistocene Moraine	5	0.13	0.12
Undifferentiated	1	0.08	0.08
Pass	6	0.06	0.06
Debris Fan	1	0.06	0.06
Mass Movement-Debris Torrent	4	0.02	0.02
Arête	1	0.02	0.02
Patterned Ground	1	0.01	0.01
Totals	333	107	100

A headwater tributary of the Carbon is Moraine Creek, which begins along the eastern flank of the Carbon Glacier, as well as in the glacial cirques of Moraine Park (Figure 43). Above these cirques is the ridgeline of Old Desolate, which is composed of Miocene intrusive rocks and Mount Rainier andesite. As the name suggests, there are numerous small Neoglacial moraines scattered throughout Moraine Park. Moraine Creek also flows between McNeeley (12-10 ka) moraines and younger Neoglacial moraines (Crandell 1969a, Crandell and Miller 1974) as it flanks the east side of the Carbon Glacier (Figure 43). Another headwater tributary of the Carbon River is Cataract Creek, which flows from glacial cirques below Mother Mountain and from the glacially scoured parklands of Mist Park and Seattle Park (Figure 43). During the ice ages, these areas were covered by small ice caps, which fed the larger Carbon valley glacier. Mother Mountain is part of an andesitic sill complex with an average age between 23 and 21 Ma (Hammond 1999). Spukwush and Crescent

Creeks are also headwater tributaries that flow from the glacial cirques of the Crescent Mountains; numerous Neoglacial moraines and tarns occupy these cirques (Figure 43).

5.6 Puyallup River Watershed

The Puyallup River watershed within MORA includes the headwaters of several streams. The upper part of the watershed is dominated by the large glaciers on the volcanic cone. Extensive parklands begin at the base of the volcanic cone and extend out several ridges to the west. Sunset Amphitheater, at the head of the valley, was the source of numerous lahars.

The Puyallup River flows from the west flank of Mount Rainier for 72 km before discharging into Puget Sound. The watershed drains an area of approximately 2,460 km^2, but only 133 km^2 is within MORA. Major tributaries of the Puyallup River in MORA include the South Puyallup, North Puyallup, South Mowich and North Mowich Rivers. The major glaciers that drain into the watershed (from north to south) are North Mowich Glacier, Edmunds Glacier, South Mowich Glacier, Puyallup Glacier and Tahoma Glacier (Figures 4 and 48). The upper watershed boundary to the north is Ptrarmigan Ridge and in the south is Emerald Ridge (Figure 48).

5.6.1 North Mowich River

The North Mowich River emerges from the North Mowich Glacier and flows west for approximately 6 km before merging with the South Mowich River and, eventually, the Puyallup River. The North Mowich Glacier is an alpine valley glacier on the northwest flank of Mount Rainer (Figure 4). Spray Park and Ptarmigan Ridge confine the North Mowich valley to the north; an unnamed ridge divides the North Mowich from the South Mowich in the southern extent of the watershed. Tributaries of the North Mowich include Spray Creek and Crater Creek (Figures 49 and 50).

The North Mowich initially flows in valley bottom flanked by Neoglacial moraines and debris apron composed of glacial till and colluvium (Figure 50); the river then enters river canyon and plunges over Giant Falls. After emerging from the canyon, the North Mowich is joined by tributaries Spray Creek and Crater Creek (Figure 50). The North Mowich then flows in a relatively narrow floodplain before forming a large debris fan at the confluence with the South Mowich River.

Spray Creek drains the gently sloped and glacially scoured parklands of Spray Park and the northeastern flanks of the North Mowich Glacier. The upper portion of Spray Park is a basaltic-andesite ‘mini-shield’ produced by Pleistocene eruptions at Observation and Echo Rocks flank vents (Pringle 2008). The Mowich River watershed is 6% parkland, which is relatively high compared to other watersheds at MORA and is due to the large expanse of Spray Park (Table 14). Crater Creek drains from Mowich Lake, which is inside a large cirque on the southwestern side of Mother Mountain. Mowich Lake is a tarn that is the largest lake in MORA, measuring approximately 50 ha and with a measured depth of 58 m (Wolcott 1961). The surrounding ridges, including Fay Peak and Castle Peak, and valley walls are composed of the Mowich Lake sill andesite complex (Hammond 1999). Several Pleistocene moraines composed of Evans Creek till (Crandell 1969a) flank Crater Creek as it makes a steep descent down to its confluence with the North Mowich (Figure 50).

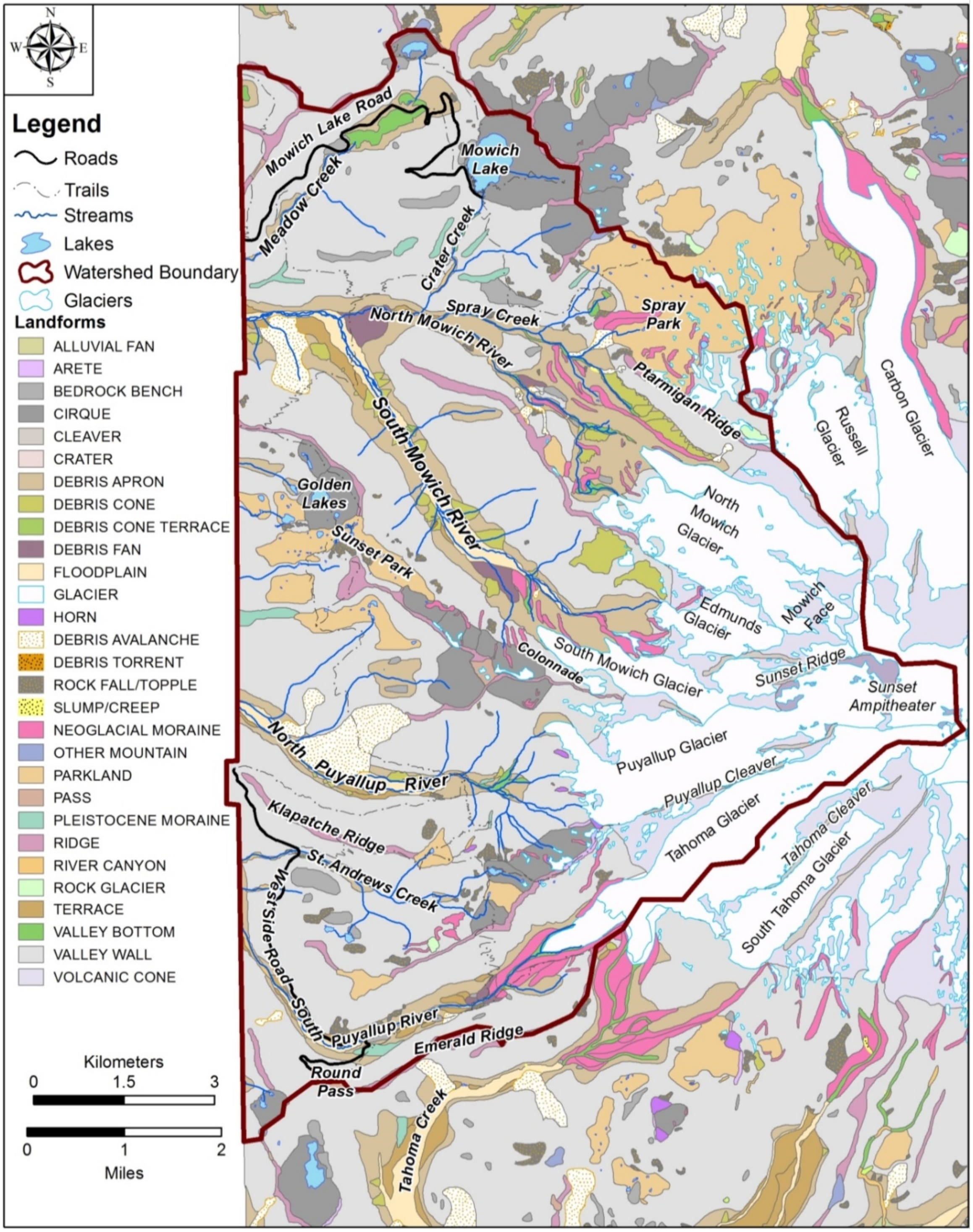

Figure 48. Landform map of the Puyallup River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Figure 49. View looking southwest from Tolmie Peak of the northwest flank of Mount Rainier; the oversteepened Mowich Face and scoured parkland of Spray Park are also visible (NPS Photo).

5.6.2 South Mowich River

The South Mowich River is sourced from the South Mowich and Edmunds Glaciers on the western flank of Mount Rainer (Figures 4 and 50). The South Mowich Glacier begins in the steep cliffs of the Sunset Amphitheater and shares an ice divide with the Puyallup and Tahoma Glaciers (Figure 4). The Edmunds Glacier lies below the steep cliffs of Mowich Face and the cleaver Sunset Ridge. The South Mowich River emerges from the South Mowich Glacier and flows northwest for approximately 7 km, where it joins the North Mowich River. The Mowich River then flows west for approximately 15 km to the Puyallup River, near the town of Electron (Figure 6). The volcanic edifice above the South Mowich Glacier, in Sunset Amphitheater, has undergone intense hydrothermal alteration and has a long history of mass movements that have triggered numerous lahars (Scott et al. 1995).

The South Mowich valley is divided from the North Puyallup River valley to the south by Sunset Park and the glacially oversteepened valley walls of the Colonade (Figure 50). The South Mowich River flows in a wide braided floodplain (Figure 50) which is flanked by several large terraces that are composed of alluvium with interbedded mudflow deposits (Crandell 1969a) (Figure 50).

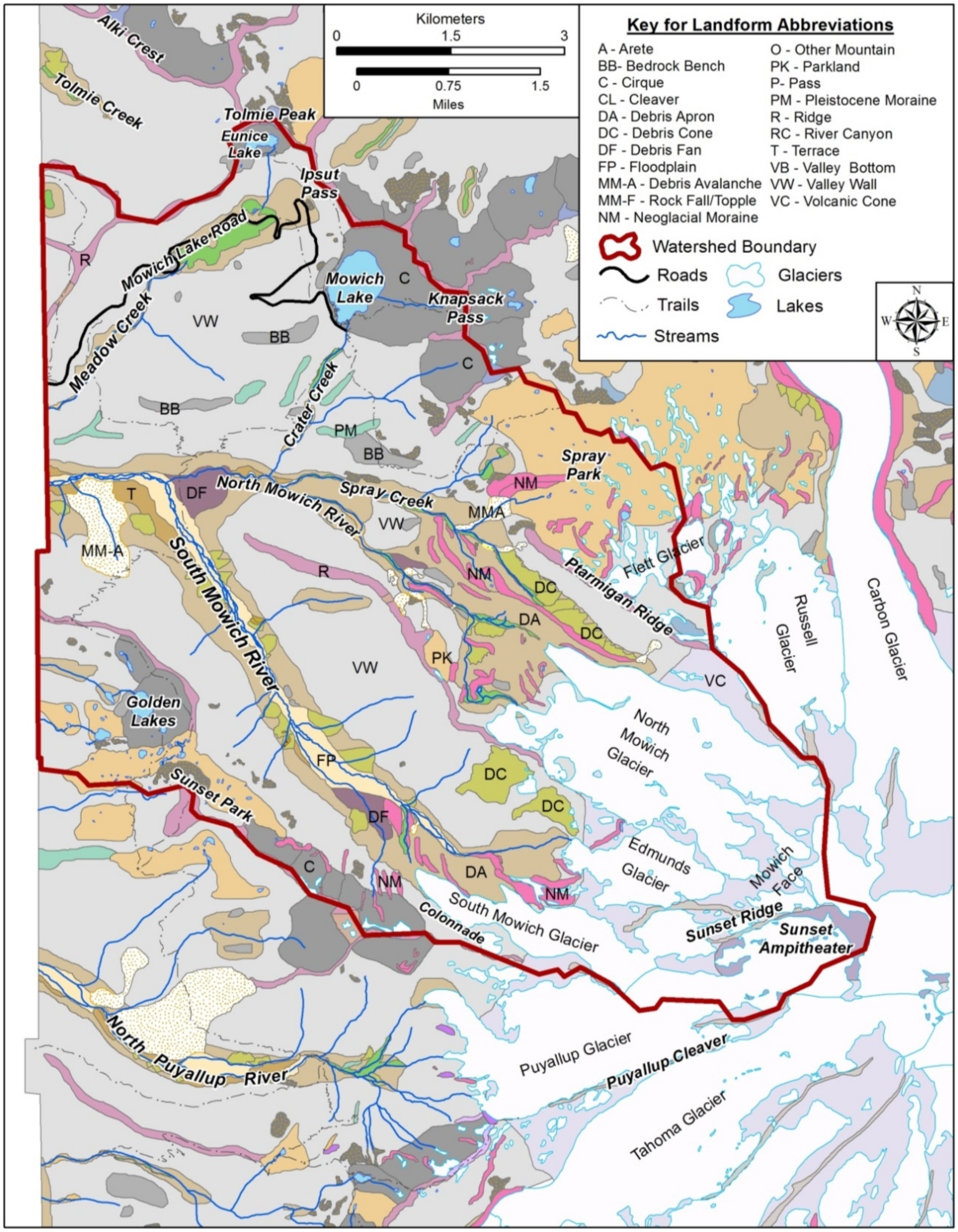

Figure 50. Landform map of the Mowich River watershed within Mount Rainier National Park showing the localities mentioned in the text.

Table 14. Summary table of landform results within the Mowich River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	16	32.47	41.63
Volcanic Cone	1	11.19	14.44
Debris Apron	26	8.98	11.58
Parkland	5	4.65	6.00
Cirque	13	4.56	5.88
Debris Cone	28	1.88	2.41
Ridge	13	1.85	2.39
Amphitheater	1	1.65	2.13
Neoglacial Moraine	59	1.62	2.09
Floodplain	2	1.61	2.08
Glacier Ice (Below VC)	2	1.07	1.38
Mass Movement-Debris Avalanche	11	0.99	1.27
Bedrock Bench	17	0.95	1.23
Valley Bottom	13	0.90	1.16
Debris Fan	3	0.63	0.80
Mass Movement-Fall/Topple	39	0.60	0.77
Terrace	7	0.52	0.67
Pleistocene Moraine	6	0.40	0.51
Cleaver	5	0.37	0.48
River Canyon	4	0.21	0.27
Pass	3	0.06	0.08
Other Mountain	2	0.05	0.06
Debris Cone Terrace	2	0.02	0.03
Mass Movement-Debris Torrent	2	0.01	0.01
Mass Movement-Slump/Creep	1	0.01	0.01
Totals	281	78	100

5.6.3 North Puyallup River

The North Puyallup River begins as meltwater from the Puyallup Glacier on the west flank of Mount Rainer and flows west for approximately 9 km before merging with the South Puyallup River slightly west of the MORA boundary. Sharing the same source of ice as the upper South Mowich Glacier, the Puyallup Glacier begins in Sunset Amphitheater. After splitting from the South Mowich Glacier at approximately 2,600 m (Figure 4), the Puyallup Glacier widens until narrowing into an ice fall above North Puyallup valley (Figures 4 and 52). The North Puyallup River valley is divided from the South Puyallup River to the south by the andesitic lava flows of Klapatche Ridge (Figure 54).

The North Puyallup River begins as numerous tributary streams that flow down the steep valley walls below the Puyallup Glacier (Figures 53 and 54). These streams coalesce into a single channel that flows across valley bottom, beginning at approximately 1,349 m. The channel continues west for 1 km before constricting into a short river canyon where the Wonderland Trail crosses the river. The North Puyallup emerges from the canyon and widens into a braided floodplain. There is a large lahar terrace on the north side of the valley that is likely from the Electron Mudflow. Recent aggradation of the floodplain has forced the river to overtake several forested terraces that are younger and lower than the lahar terrace (Figure 54). The North Puyallup continues to flow in a wide, braided floodplain before it is constricted by a large debris avalanche, which was originally mapped by Crandell (1969a). The North Puyallup then emerges into a braided floodplain for the final 1 km to the MORA boundary.

Figure 51. View of the South Mowich River looking southeast (upstream); the braided floodplain is visible in the foreground, with the steep valley walls of the Colonade and the west face of Mount Rainier visible in the background (NPS Photo).

Figure 52. View of Sunset Park and the west flank of Mount Rainer (NPS Photo).

Figure 53. View of North Puyallup River headwaters and the terminus of the Puyallup Glacier (NPS Photo).

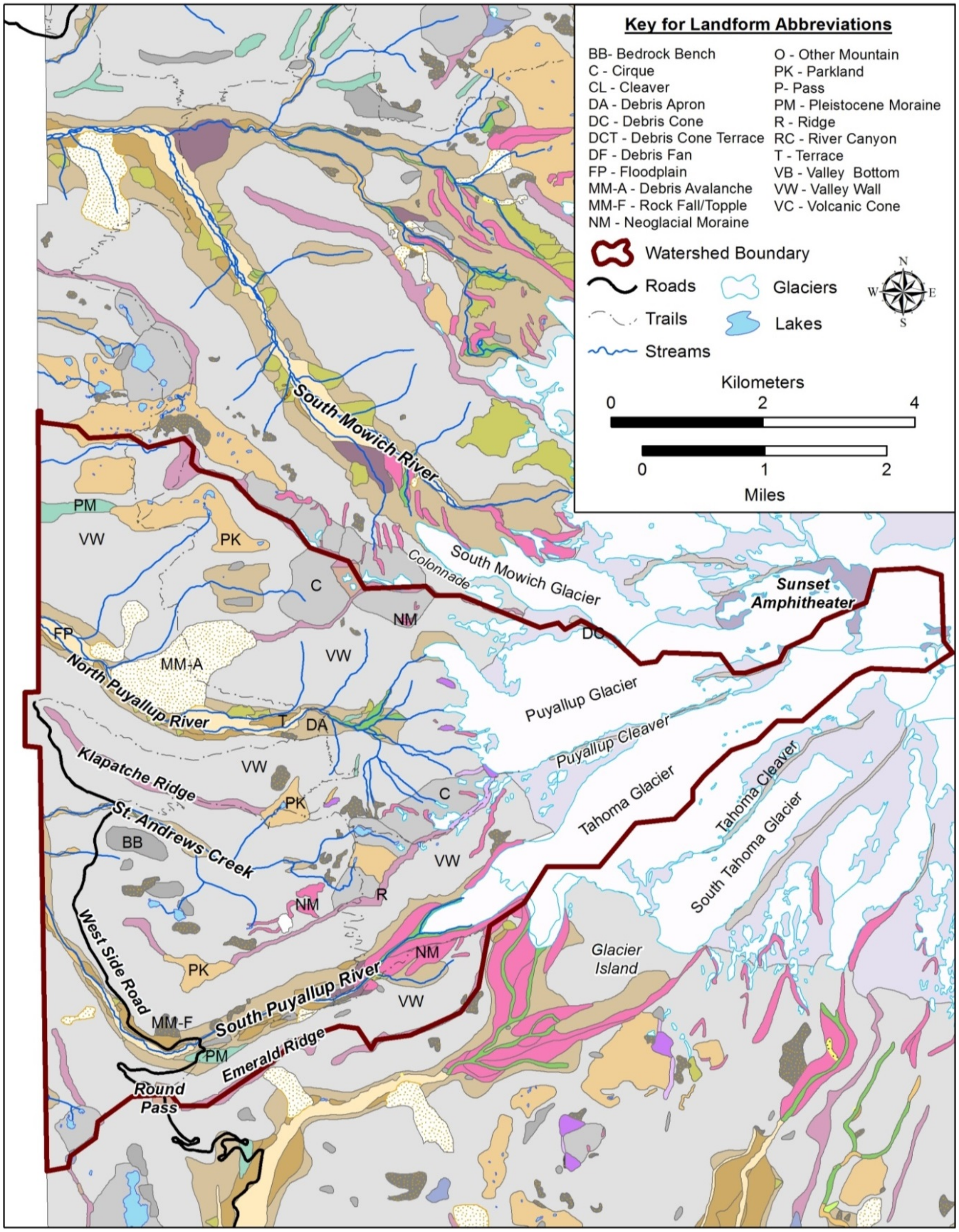

Figure 54. Landform map of the North and South Puyallup Rivers within Mount Rainier National Park showing the localities mentioned in the text.

5.6.4 South Puyallup River

The South Puyallup River starts as meltwater from the Tahoma Glacier on the southwest flank of Mount Rainer. The Tahoma Glacier descends from the summit of Mount Rainier in an icefall from approximately 4,000 m to 3,400 m; here it connects to the Puyallup Glacier near St. Andrews Rock. The Tahoma Glacier splits into two separate tongues of ice, with the southern terminus draining into Tahoma Creek and the northern terminus draining into the South Puyallup River at approximately 1,465 m (Figures 4 and 54). The South Puyallup River initially flows southwest for 4.5 km, and then bends to the northwest for 8 km before merging with the North Puyallup River just west of the MORA boundary. The South Puyallup River valley is divided from the Tahoma Creek valley to the south by the broad Emerald Ridge, which is composed of lavas erupted from the Puyallup Cleaver dike system (Sisson and Lanphere 1999). Beautiful columnar andesite from these flows is exposed in the valley walls along the Wonderland Trail (Figure 56).

Table 15. Summary table of landform results within the Puyallup River watershed.

Landform Type	Number Observed	Area km^2	%of Watershed
Valley Wall	4	28.80	52.37
Volcanic Cone	1	9.50	17.26
Debris Apron	25	3.04	5.52
Cirque	9	2.29	4.16
Parkland	6	1.76	3.20
Mass Movement-Debris Avalanche	4	1.53	2.78
Ridge	10	1.37	2.49
Glacier Ice (Below VC)	2	1.11	2.02
Neoglacial Moraine	28	1.02	1.85
Floodplain	4	0.86	1.56
Terrace	20	0.72	1.31
Amphitheater	2	0.60	1.09
Mass Movement-Fall/Topple	21	0.54	0,98
Bedrock Bench	11	0.48	0.87
Pleistocene Moraine	4	0.31	0.56
Valley Bottom	3	0.26	0.47
Cleaver	3	0.20	0.36
River Canyon	5	0.16	0.29
Debris Cone	11	0.15	0.27
Pass	2	0.13	0.24
Arête	2	0.10	0.18
Horn	4	0.07	0.13
Crater	1	0.06	0.11
Other Mountain	1	0.01	0.02
Mass Movement-Slump/Creep	1	0.01	0.02
Totals	101	55.03	100

Figure 55. Recent aggradation along the North Puyallup River has raised the level of the floodplain. In this photo, an old terrace surface containing old-growth trees is now the location of the active river channel (NPS Photo).

Figure 56. Columnar andesite of from the Puyallup Cleaver lava flows exposed on the valley walls of South Puyallup River valley (NPS Photo).

After emerging from the glacier, the South Puyallup River initially flows in a valley bottom fed with massive amounts of sediment from large, unstable Neoglacial moraines. However, the valley bottom is bedrock lined in some reaches (Figure 58). The channel then widens into a braided floodplain until it constricts into a narrow bedrock channel where the West Side Road crosses the river. Recent aggradation of the channel in this reach has caused only minor damage to the Wonderland Trail thus far (Figure 57). However, the potential for future damage will increase as the channel continues to rise. The South Puyallup emerges from the bedrock walled channel and widens into a braided floodplain (Figures 59 and 60). Just downstream, along the Westside Road, there is a block and ash flow deposit that was first described by Crandell (1969a); the South Puyallup has incised into this deposit and it is mapped as a 60 m high terrace (Figure 54). Here the South Puyallup bends to the northwest and flows in a wide, braided floodplain (Figure 60) before plunging over a waterfall (Figure 61) and into a deeply incised river canyon. The South Puyallup River remains in the river canyon until it emerges into a floodplain channel near the MORA boundary (Figure 54).

Figure 57. Recent channel aggradation has deposited large amounts of boulder debris into the old growth forests along the South Puyallup River; the Wonderland Trail passes through this section of the valley (NPS Photo).

Figure 58. View upstream of South Fork Puyallup bedrock lined valley bottom with the Tahoma Glacier and southwest face of Mount Rainier visible in the background (NPS Photo).

Figure 59. South Puyallup River emerging from a bedrock constriction just downstream from the West Side Road Bridge (NPS Photo).

Figure 60. View northwest (downstream) of the South Puyallup River's floodplain from just downstream of the bedrock constriction shown in the previous figure (NPS Photo).

Major lahars have flowed from Mount Rainier down the South Puyallup River valley, including the Round Pass Mudflow and the Electron Mudflow. The Round Pass Mudflow was a cohesive debris flow and occurred approximately 2,440 years ago (Scott et al. 1995), with deposits up to 16 m thick near the confluence of the Mowich and Puyallup Rivers. Deposits at Round Pass, 170 m above the valley floor, suggest that flow in the South Puyallup valley was deep enough to send a major arm of the flow across Round Pass and into Tahoma Creek (Crandell 1971). The Electron Mudflow was also a cohesive debris flow that occurred approximately 500 years ago, based on radiocarbon dates by Crandell (1971). Evidence of volcanic activity near the time that the Electron mudflow occurred has not been recorded (Crandell 1971, Scott et al. 1995). The lahar began as a collapse of part of the west side of Mount Rainier, near Sunset Amphitheater.

Figure 61. View looking southeast (upstream) of the South Puyallup River plunging over a waterfall and into an incised river canyon (NPS Photo).

5.7 Mount Rainier National Park Landslide Inventory

Large movements of soil, rock and vegetation are common on the steep slopes of MORA. Volcanic landslides, or lahars, are discussed in section 2.4 of this report and in detail in Scott et al. (1995 and 2001), Pringle (2008) and Sisson et al. (2001), among others. These events have shaped the large valleys emanating from the volcano. These large lahars have been estimated to contain enormous volumes of material (greater than 200 million m^3), and their deposits are mapped as terraces in this inventory. Large, non-volcanic landslides at MORA are also important events in the mountain's natural history.

Information on landslides can guide the selection of LTEM reference sites, or locations for building/maintaining public facilities such as trails, campgrounds, and bridges. A landslide database was created to accompany landform maps. Data were collected on 18 characteristics of each landslide, including age, activity, bedrock geology, material type, and area. For large mass movement avalanches, depth of the cavity and the volume of sediment delivered to river/creek were also estimated. Reviewing this data can tell a great deal about the overall stability of a particular area of the watershed, which can be related to factors such as bedrock type, aspect, and proximity to faults (Appendix B). Valley wall landslides can block streams and create lakes, wetlands and fish migration barriers. They also provide large woody debris to streams that helps establish logjams and influence river channel migration and habitat far downstream of the landslide. 448 mass movements constitute 37 km^2 in the park, or 4% of the total area (Table 16). They are classified into five types, as described below and presented in Table 16.

Table 16. Summary of the Mount Rainier National Park landslide inventory data.

Mass Movement Type	Number	Surface Area (km^2)	% of Total Park
Debris Avalanche	116	26.89	2.82
Fall/Topple	309	9.79	1.03
Debris Torrent	10	0.33	0.04
Slump/Creep	12	0.04	0.01
Sackung	1	0.01	0.01
Totals	448	37.06	3.91

5.7.1 Debris Avalanches

Debris avalanches are large landslides that generally include the failure of rock and debris from the side of the volcanic cone or valley wall. They can be triggered by heavy rainfall, earthquakes and freeze/thaw processes. These events are of particular importance due to their large size, potential to block streams, and ability to deliver massive amounts of large woody debris and sediment to stream systems. This material can be disruptive to aquatic ecosystems, creates temporary debris dams, and contributes to the overall bedload of the river systems at MORA. The 116 mapped debris avalanches at MORA cover a total area of 27 km^2 (Table 16).

The largest debris avalanche recorded in the inventory is in the Ohanapecosh valley at the base of Laughingwater Creek (Figure 27). This landslide altered the course of the creek and Ohanapecosh River. Failure of the valley wall at this site is likely due to the glacial oversteepening of the weak, hydrothermally altered bedrock. Several large debris avalanches mapped in the White River watershed have also influenced stream patterns. Two in upper Klickitat Creek reached the stream, while a failure in upper Lost Creek crossed the valley and forced the stream to flow in the subsurface (Figure 36). A 1.5 km^2 debris avalanche about 10 km below Winthrop Glacier is older than the Osceola lahar, since terraces from that flow truncate the toe of the landslide.

Several large landslides in the Nisqually valley are notable. There are three mapped in Tahoma Creek, including one from the south side of Emerald Ridge that left hummocky topography and a swamp along the former trail (Figure 12). Across Tahoma Creek and upstream, a failure started from a fault high on the valley wall. In lower Tahoma Creek, a large debris avalanche from north of Tumtum Creek reached the valley floor (Figure 12). A smaller landslide on the opposite side of the ridge reached the trail, but not Kautz Creek. Two debris avalanches from the south side of the Carbon

River valley wall (below Cataract Creek) reach the edge of the floodplain (Figure 43). Five smaller landslides exist across the valley between Spukwush and Chenuis Creeks and are related to glacial oversteepening of the valley walls as well as bedrock structure.

A very large debris avalanche in the North Fork Puyallup valley constricts the river to the south side of the valley (Figure 54). The largest historic debris avalanche at MORA occurred in 1963 and originated from the side of Little Tahoma Peak. The deposit covered the lower Emmons Glacier in 11 x 10^6 m^3 of landslide debris (Crandell and Fahnestock 1965). The exact cause of the large slide is unknown, but was possibly triggered by a steam explosion and broke along fault fracture surface (Crandell and Fahnestock 1965, Pringle 2008). Sisson et al. (2001) has identified other fractures on Little Tahoma Peak, and it should be expected to produce other rock avalanches in the future. The massive Osceola, Electron and other major collapses of Mount Rainier are the largest debris avalanches that have occurred in the park since the last ice age.

5.7.2 Rock Falls/Topples
Rock falls are one of the most common landforms in MORA. They occur throughout every major watershed, originating from cleavers, horns, arêtes, ridges, and valley walls. Rock falls are typically found on northwest to north to northeast facing slopes because freeze-thaw activity is more pronounced. Rock falls tend to be concentrated around areas that are heavily faulted and below oversteepened valley walls. The 309 mapped rock falls at MORA cover a total area of 10 km^2 (Table 16) and produce talus slopes, which are a favored habitat for pikas.

5.7.3 Debris Torrents
Debris torrents are important contributors to the total amount of sediment delivered to streams systems and present a potential hazard to park staff and visitors. These channelized debris flows are deposited on debris cones and are often found at the mouths of river canyons, along fault controlled streams and below hanging valleys. There are 9 mapped debris torrents at MORA, which is a relatively low number when compared to other parks in Washington State. There are 157 debris cones mapped in the park; most of them are dormant debris systems that could be activated by large precipitation events and/or vegetation disturbance by fire, insects or disease.

5.7.4 Sackungs
Sackungen is a German term describing gravitational spreading or deep-seated gravitational slope deformation at, or near, ridge tops in mountainous terrain. Sackungs, as they are more commonly referred to, form when over steepened, under cut valley slopes create a gravitational spreading or deep-seated gravitational slope deformation away from ridge top (Tabor 1971). There is only one mapped sackung at MORA. It is on the west side of Iron Mountain in the Kautz Creek watershed.

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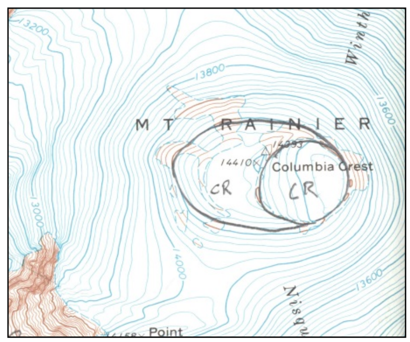
Appendix A: Mount Rainier National Park Landform Unit Descriptions

A. High Elevation Units

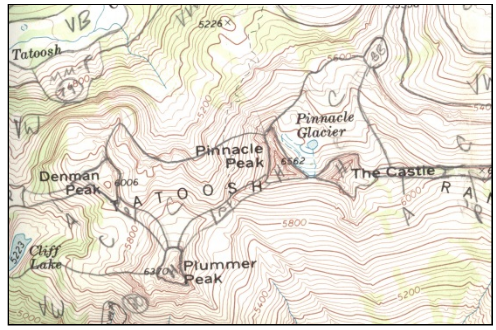
1) CR = Crater (Volcanic). A depression usually ringed with a definitive rim on the very top or on the flanks of a volcanic cone (USDA 2003).

- **Location:** The summit (highest elevation) or near the summit of a volcanic peak.
- **Associated Landforms/ Features**: Volcanic cone, amphitheater, cleaver.
- **Process:** Explosion or collapse associated with volcanism, glacial erosion.
- **Surficial Material:** Bedrock, ash, pyroclastics, ice.
- **Mapping Guidelines:** Mapped from topographic contour lines, the polygon is approximately circular in shape and includes enclosed contour lines.
- **Potential Vegetation:** Typically void of vegetation



2) H = Horn. A high, sharp-pointed, steep-sided, pyramidal mountain peak (massive rock tower) formed by glacial erosion (Ritter 1978, USDA 2003).

- **Location:** Typically found at the highest elevations of the watershed (above ~1800 m), near valley heads.
- **Associated Landforms/ Features**: Rock tower, couloirs, flying buttress, cliff, arête, valley wall, cirque.
- **Process:** Glacial erosion.
- **Surficial Material:** Bedrock, ice.
- **Mapping Guidelines:** Includes primary summit and small portions of the flanks (where arêtes or ridges typically begin). Boundary is marked by break in slope, end of closed contour lines, or glacier. Horns are typically ringed by cirques on three or more sides; they can also stand alone (i.e. Little Tahoma Peak)
- **Potential Vegetation:** Typically void of vegetation, some alpine vegetation possible.

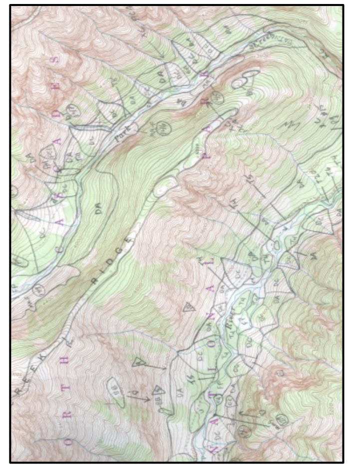


3) A = Arête. A narrow knife-like ridge without a flat top separating cirques and connecting horns (Ritter 1978, USDA 2003).

- **Location:** High elevations (above ~1,650 m), near valley heads, and along the top of watershed divides.
- **Associated Landforms/ Features:** Cliffs, rock towers, horns, cirques, valley wall.
- **Process:** Glacial erosion.
- **Surficial Material:** Bedrock, ice.
- **Mapping Guidelines:** Typically mapped as a long narrow polygon along a watershed divide and attached to horns, broken by passes, and adjacent to cirques. Polygon includes all towers and cliffs and is bounded by the break in slope. In special cases, arête may extend down to glacier, talus, or cirque floor (unglaciated) surface.
- **Potential Vegetation:** Typically void of vegetation, some alpine vegetation possible.

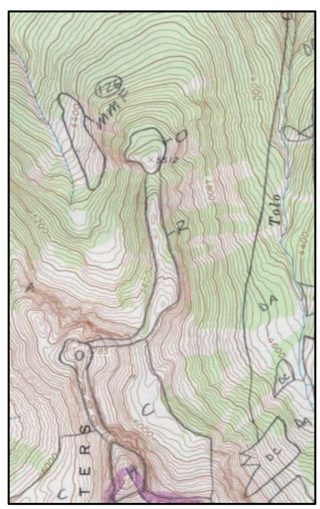
4) R = Ridge. A long, narrow elevation of the land surface, usually sharp crested with steep sides and forming an extended upland between valleys (USDA 2003).

- **Location:** Lower parts of watershed divides (~750-2,000 m) and between large tributaries. Occur lower in elevation than arêtes along the same divide. Can occur above arêtes if there is a high ice field draining multiple directions.
- **Associated Landforms/ Features:** Bedrock benches, valley spurs, patterned ground, parkland, sackung.
- **Process:** Overridden and modified by glaciers.
- **Surficial Material:** Bedrock, till.
- **Mapping Guidelines**: Must be at least ½ km long, boarder by an arête, horn, or pass, and must separate major creeks (3rd order streams = not to be confused with smaller valley spurs). Polygon is narrow and drawn to include only the ridge top; ridge side slopes are part of valley wall polygon. Broken by mountain passes.
- **Potential Vegetation:** Alpine, subalpine, or forest depending on elevation.



5) O = Other Mountain. A rounded lower summit.

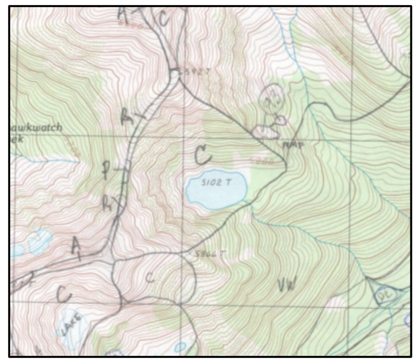
- **Location:** Along mid and lower elevations of watershed divides (~1,500 2,150). Located between adjacent ridges or valley walls.
- **Associated Landforms/ Features:** Ridge, bedrock bench.
- **Process:** Glacial erosion.
- **Surficial Material:** Bedrock, till.
- **Mapping Guidelines:** Polygon includes relatively flat-topped summit to the break in slope (shown by contour line spacing). At least 2-3 closed contours are present.
- **Potential Vegetation:** Alpine, subalpine or forest.



6) P = Pass. A broad low point on a ridge, generally flat on the bottom that separates high mountain divides.

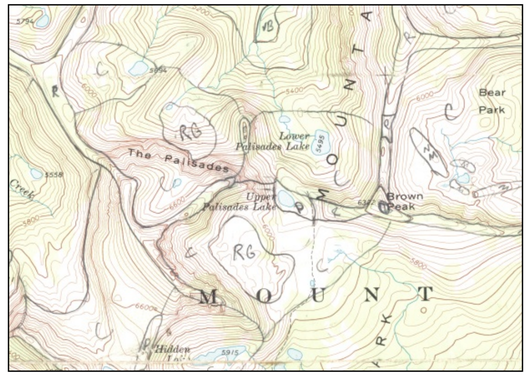
- **Location:** Along major watershed divides (~1,500 - 2,000 m) that separates 3^{rd} and higher order streams. Usually found at valley heads.

- **Associated Landforms/ Features:** Arête, ridge, bedrock bench, col, saddle, valley wall, cirque.
- **Process:** Glacial erosion from ice that flowed across the surface low point from one valley head into another valley.
- **Surficial Material:** Bedrock, till, volcanic ash.
- **Mapping Guidelines:** Polygon includes only flat bench portion of pass and not adjacent ridges or arêtes. Must be bordered by a ridge or arête polygon on either side. Special cases can occur where there is no defined ridge/arête linking the pass, but pass is clearly on a divide.
- **Potential Vegetation:** Alpine, subalpine.



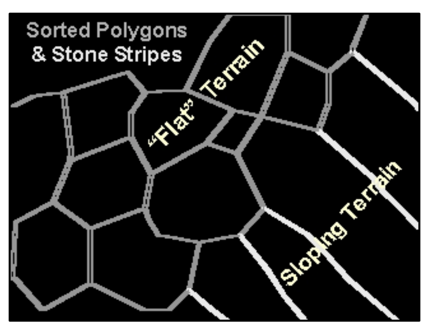
7) C = Cirque. Semi-circular to elongated basin carved into a headwall of a glacial valley (USDA 2003).

- **Location:** High elevation divides (toe of cirque above ~1,150 m) near valley heads. Bordered by horns and arêtes at the top of this unit and valley wall at the bottom of unit.
- **Associated Landforms/ Features:** Talus slope, rock fall, couloirs, Neoglacial moraines, tarn, delta, valley wall, arête, ridge.
- **Process:** Alpine glaciation.
- **Surficial Material:** Bedrock, talus, till.
- **Mapping Guidelines:** Polygon is bordered by rock confining ridges, horns and arêtes and includes headwall cliffs and flat floor. Lower boundary is the break in slope at lip of floor, or in absence of floor feature, lower limit of lateral confining ridges. Lowest elevation contour boundary of a cirque is usually consistent along a particular aspect for a given mountain, which can be used as a guide in poorly defined cirques. North facing cirques are generally lower in elevation than south facing cirques.
- **Potential Vegetation:** Amount and type of vegetation differs from top to toe of single unit. Higher elevations include alpine; lower elevations include subalpine and forest.



8) PG = Patterned Ground. Active and relict stone ground cover in the pattern of stripes, polygons, and circles (Ritter 1978, Washburn 1956).

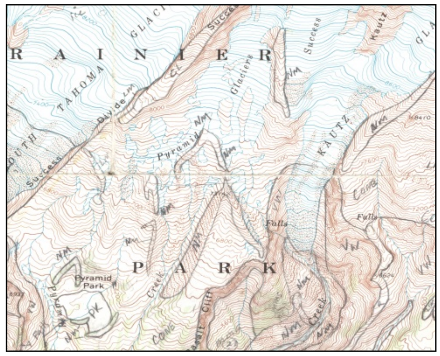
- **Location:** Found in alpine zones where freeze thaw processes occur.
- **Associated Landforms/ Features:** Cirque, ridge, arête, pass, parkland.
- **Process:** Freeze/thaw action sorting of ground cover. Stripes also created by gravitational movement down slope of rock.
- **Age:** 1- 20,000 years old.
- **Surficial Material**: Colluvium, soil
- **Mapping Guidelines:** Usually mapped from air photos. Stone stripes usually occur on slopes where the circular or polygonal pattern becomes elongated. The stripes generally run up and down the slope, as opposed to across the slope. Crandell and Miller (1974) describe numerous different locations of patterned ground at MORA, which was used to help locate and identify these features.
- **Potential Vegetation:** Alpine, subalpine.



9) NM = Neoglacial moraines. Ridge of till deposited by glacier advance/retreat during the Neoglacial period.

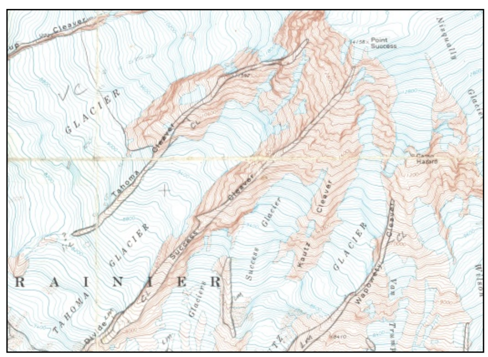
- **Location:** Above tree line and in high elevation cirques. End, lateral and medial moraines are all included in unit.
- **Associated Landforms/ Features:** Cirque, debris apron, glacier, valley wall, ground moraine, rock glacier.

- **Process:** Glacial.
- **Age:** 100-3,000 years old.
- **Surficial Material:** Till.
- **Mapping Guidelines:** Primarily mapped from air photos. They are linear and sharp crested with a fresh appearance (rocky) to sparsely tree-covered. It is not unusual for remnants of recessional (closely spaced) moraines to be present.
- **Potential Vegetation:** Alpine, subalpine.



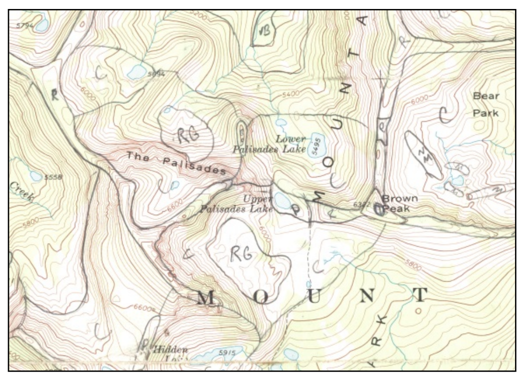
10) CL = Cleaver. Narrow, linear, and sharp crested ridge of volcanic bedrock exposed above surrounding glaciers (USDA 2003).

- **Location:** At high elevations (above treeline), typically within the volcanic cone polygon, and usually separates large glaciers.
- **Associated Landforms/ Features:** Lateral moraine, glacier, volcanic cone, amphitheater.
- **Process:** Lava flows and glacial erosion.
- **Surficial Material:** Bedrock, till, ice.
- **Mapping Guidelines:** Primarily mapped from air photos and 7.5 minute quadrangles. Many are already labeled by the USGS. If Neoglacial moraine covers a portion of the cleaver, usually lower boundary, then the Neoglacial moraine polygon overwrites cleaver polygon.
- **Potential Vegetation:** Typically void of vegetation, alpine.



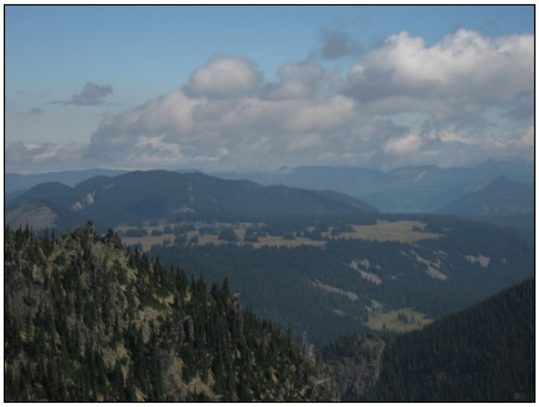
11) RG = Rock Glacier. A mass of poorly sorted angular boulders and fine material, with interstitial ice a meter or so below the surface (ice-cemented) or containing a buried ice glacier (ice-cored) (USDA 2003).

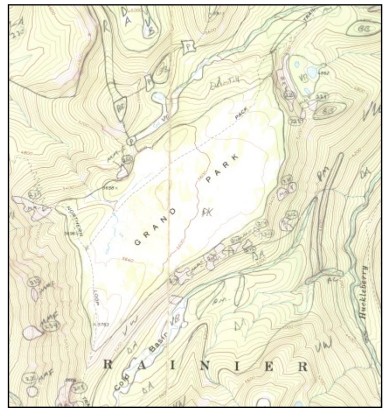
- **Location:** Occurs in high mountains or permafrost areas and is derived from a cirque wall or other steep cliffs or valley walls.
- **Associated Landforms/ Features:** Neoglacial moraines, ponds, ground moraine, valley wall, bedrock bench, ridge.
- **Process:** Mass wasting, rock fall.
- **Surficial Material:** Rock debris, till, ice.
- **Mapping Guidelines:** Rock glaciers may have the general appearance and slow movement of small valley glaciers, ranging from a few hundred meters to several kilometers in length, and having a distal area marked by a series of transverse arcuate ridges. When active, they may be 50 m thick with a surface movement (resulting from the flow of interstitial ice) of 0.5-2 m/yr. However, no active rock glaciers were recognized at MORA; all of the mapped rock glaciers appear to be inactive (Crandell and Miller 1974). Mapping by Crandell (1969a) was used as a basis for identifying these features at MORA.
- **Potential Vegetation:** Subalpine to alpine.



12) PK = Parkland. Gently sloping surface of ancient lava flows scoured by glacial erosion.

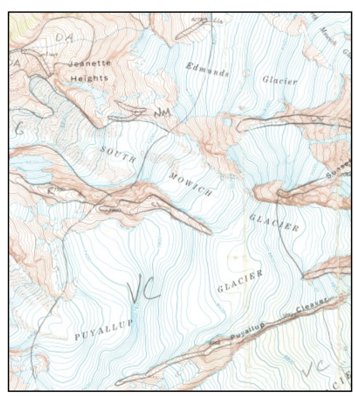
- **Location:** Parklands are often found adjacent to the volcanic cone (e.g. Spray Park), but can also be found on or near discontinuous ridge tops, valley wall and debris apron benches and cirques; or can occasionally stand alone as individual surfaces (e.g. Grand Park).
- **Associated Landforms/ Features:** Neoglacial and Pleistocene moraines, ponds, ground moraine, valley wall, bedrock bench, ridge.
- **Process:** Volcanic processes followed by glacial erosion.
- **Surficial Material:** Bedrock, till, ice.
- **Mapping Guidelines:** Primarily mapped from air photos and 7.5 minute quadrangles. The surface generally does not exceed 10% slope and the polygon area is 0.8 km^2 or larger.
- **Potential Vegetation:** Subalpine to alpine.





13) VC = Volcanic Cone. A conical hill of lava and/or pyroclastics that is built up around a volcanic vent; the sloping to very steep surfaces between the valley floor and summits of adjacent uplands (USDA 2003).

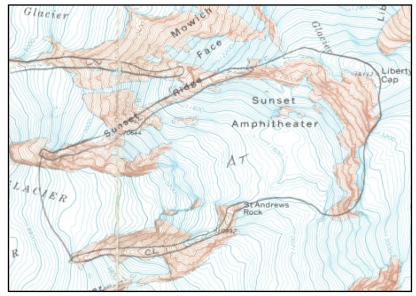
- **Location:** Area immediately below volcanic crater polygon and above valley wall. Ranges in elevation from ~4,330 m down to ~2,150 m. Upland of valley walls and ridges.
- **Associated Landforms/ Features:** Glacier, cleaver, amphitheater, Neoglacial moraine, crater.
- **Process:** Volcanic, glacial erosion.
- **Age:** 1-500,000 years old.
- **Surficial Material:** Bedrock, till, ice.
- **Mapping Guidelines:** Primarily mapped from air photos and 7.5 minute quadrangles. Lowest extent is mapped by the change in slope from relatively gentle to a steep valley wall below.
- **Potential Vegetation:** Mostly void of vegetation, alpine.



14) AT = Amphitheater. Large craters formed from volcanic edifice collapse (John et al. 2008).

- **Location:** Volcanic cone.
- **Associated Landforms/ Features:** Volcanic cone, crater, cleaver, Neoglacial moraine, lahar.
- **Process:** Hydrothermal explosions, sector collapse, lahar, glaciation.

- **Age:** 450-5,600 years old.
- **Surficial Material:** Bedrock, lava flows, till, ice.
- **Mapping Guidelines:** Mapped from air photos, 7.5 minute quadrangles and LiDAR. Osceola amphitheater based on previous extent in Sisson et al. (2001), John et al. (2008) and Pringle (2008).
- **Potential Vegetation:** Mostly void of vegetation, alpine.



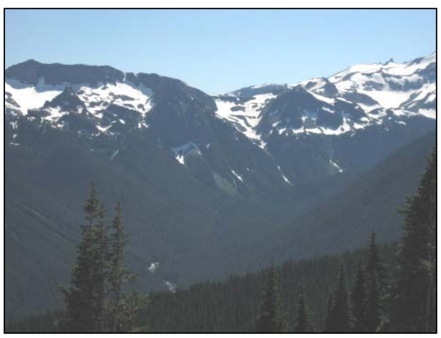
15) G = Glacier. A large mass of ice formed by the compaction and recrystallization of snow, moving slowly by creep downslope or outward in all directions due to the stress of its own weight, and surviving from year to year (USDA 2003).

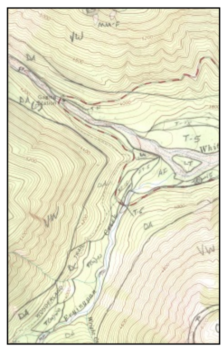
- **Location:** Glacier ice that extends below the volcanic cone polygon.
- **Associated Landforms/ Features:** Volcanic cone, cleaver, Neoglacial moraine, crater, valley bottom, debris apron.
- **Process:** Snow accumulation, glacial erosion.
- **Age:** 1-500,000 years old.
- **Surficial Material:** Ice, till, snow.
- **Mapping Guidelines:** Primarily mapped from air photos and 7.5 minute quadrangles; only the portions of the large valley glaciers that extended below the volcanic cone were mapped as glacier.
- **Potential Vegetation:** Void of vegetation.

B. Transitional Units

16) VW = Valley Wall. The steep sides of mountain valleys ranging from 20 to over 60 degrees of slope.

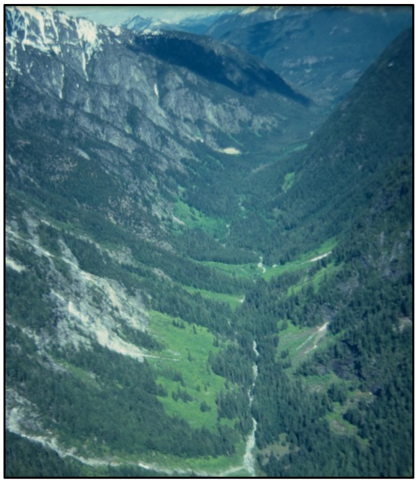
- **Location:** Mid-mountain slopes below cirques, ridges and arêtes, and above debris accumulation zone.
- **Associated Landforms/Features:** Ridge, snow avalanche chute, debris avalanche, rock fall, sackung, bedrock bench, river canyon, cliff, truncated valley spur.
- **Process:** Continental and alpine glaciation.
- **Surficial Material:** Bedrock, till, colluvium.
- **Mapping Guidelines:** Upper polygon line limit determined by watershed divide, arête, or ridge. Lower elevation boundary is typically debris apron zone but can be connected to valley bottom. Areas of bare bedrock may be visible in air photos.
- **Potential Vegetation:** Generally a range that spans from forest to subalpine.

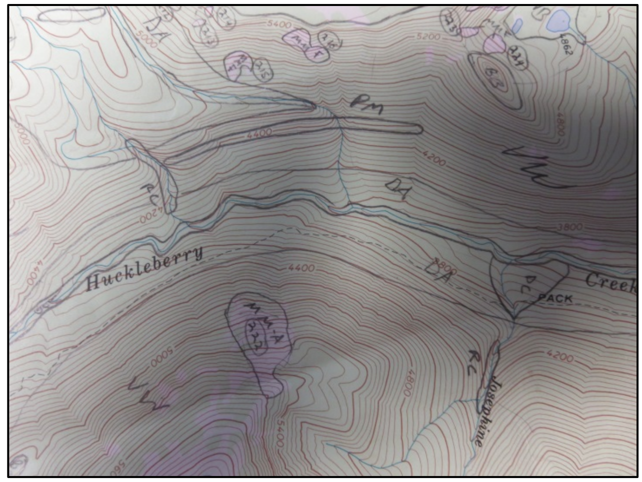




17) DA = Debris Apron. The break in slope zone below the valley wall where colluvial material accumulates.

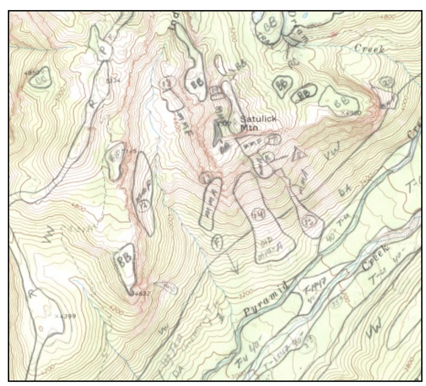
- **Location:** Between the foot of the valley wall and the beginning of the valley bottom, floodplain, or terrace.
- **Associated Landforms/ Features:** Debris cone, debris torrent, mass movement, Pleistocene moraine, gully, bedrock bench.
- **Process:** Debris under gravitational force moving from higher gradient slopes to lower gradient slopes that comes to rest at the break in slope.
- **Age:** Less than ~15,000 years.
- **Surficial Material:** Colluvium, till, talus, volcanic ash.
- **Mapping Guidelines:** Delineation between valley wall, debris apron, and valley bottom/floodplain is mapped by break in slope from change in contour spacing on topographic maps. Composition of DA; colluvium (loose, angular blocks), till (rounded faceted boulders), Undifferentiated talus (vegetated, inactive talus slopes) is noted on field maps when possible, identifications are DAc, DAt, and DAu, respectively.
- **Potential Vegetation:** Forest.





18) BB = Bedrock Bench. Exposed flat or gently sloping bedrock created by glacial activity (Davis and Mathews 1994).

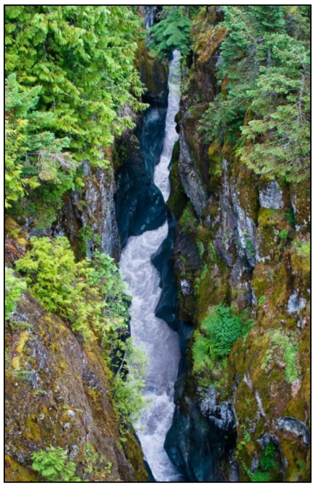
- **Location:** Along valley walls, valley bottoms, along ridges and occasionally in or on the lip of cirques. They are also common where two glacial fed valleys meet usually on valley spurs in glaciated portions of valleys.
- **Associated Landforms/ Features:** Ridge, roches mountonnée, rock drumlin, parkland.
- **Process:** Glacial erosion.
- **Surficial Material**: Bedrock.
- **Mapping Guidelines:** Only the flat (top) surface is mapped and will typically be represented on topographic maps by closed rounded contours or widely spaced contour lines.
- **Potential Vegetation:** Subalpine and forest. Vegetation cover and type varies depending on age and elevation.

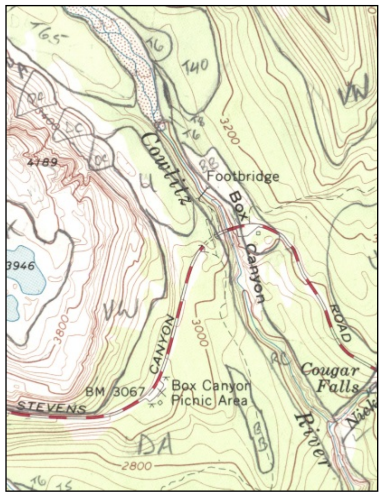


19) RC = River Canyon. A steep-sided valley cut primarily in bedrock (USDA 2003).

- **Location:** On valley walls where 1st and 2nd order streams are located, or along major river valley bottoms composed of bedrock.
- **Associated Landforms/ Features:** Gorge, bedrock, fault, valley wall.

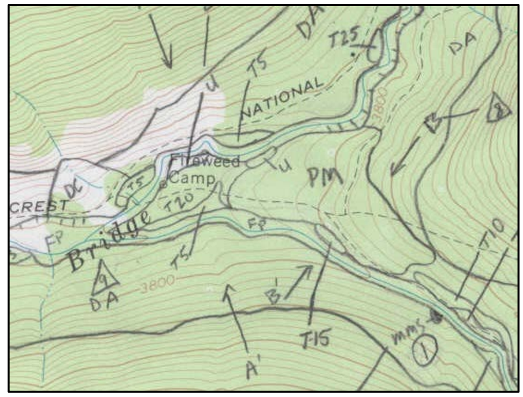
- **Process:** Fluvial erosion incising into bedrock.
- **Surficial Material:** Bedrock, boulders
- **Mapping Guidelines:** A river canyon has a minimum mapping length of approximately 0.40 km. Contours spaced on maps are very close, sometimes overlapping, and usually have a distinct dip (crenulated) down stream. Air photos often show deep shadows in canyons, not to be confused with deep shadows from tall trees. The outline of a river canyon follows contours away from stream only until bedrock stops and/or trees /vegetation begins.
- **Potential Vegetation:** Forest. Sometimes void of vegetation with limited mosses and lichens.





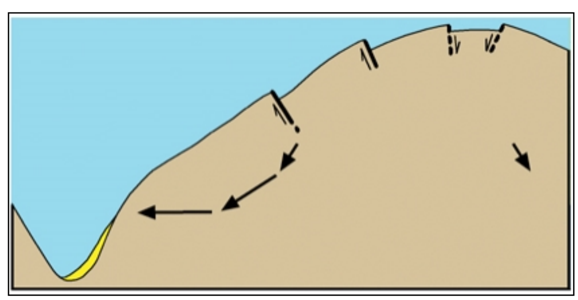
20) PM = Pleistocene Moraine. Ridge composed of till that has been deposited by a glacier; large linear features which are typically greater than 10 m tall with surfaces commonly having hummocky topography with scattered large sub-rounded boulders.

- **Location:** Usually located below tree line along valley walls and valley floor in the debris apron zone.
- **Associated Landforms/ Features:** Hummocky, sharp crested (ridge descends from cirque), kame terrace, end, medial, and lateral moraine, debris apron, valley wall.
- **Process:** Glacial advance and retreat (kame terraces glaciofluvial glaciolacustrine)
- **Age:** Approximately 10,000 – 25,000 years.
- **Surficial Material:** Till.
- **Mapping Guidelines:** Polygons are usually linear, parallel to valley. Contour spacing may be wider than the surrounding contours with a crenulated appearance.
- **Potential Vegetation:** Forest to subalpine.



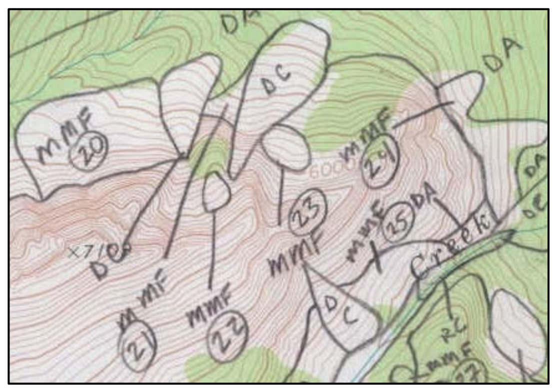
21) MM-SK= Sackung. "Sackungen" is a German term describing gravitational spreading or deep-seated gravitational slope deformation at or near ridge tops in mountainous terrain.

- **Location:** Along major ridges.
- **Associated Landforms/ Features:** Ridge, valley wall.
- **Process:** Over steepened, under cut valley slopes create a gravitational spreading or deep-seated gravitational slope deformation away from ridge top (Tabor 1971).
- **Surficial Material:** Colluvium, bedrock.
- **Mapping Guidelines:** Sackungs are mapped with a line and can usually be mapped via a combination of spaced contour line characteristics and air photos. Linear features trending parallel to ridge tops have visible fissures with uphill-facing scarps and troughs. The most obvious sackungs have giant steps in the landscape or double ridges. Possible dead fallen trees and/or broken bedrock in troughs. Down vegetation may show signs of movement (curved trunks) prior to slope release. Pools of water sometimes develop in trenches to form small ponds. Each sackung is given a number and corresponds to the landslide inventory.
- **Potential Vegetation:** Forest to subalpine.



22) MM-F = Rock Fall or Rock Topple. Type of a landslide involving an accumulation of falling rock in a single or multiple events. Rock falls form an apron of boulders (talus). Topple deposits are marked by a string of boulders (Cruden and Varnes 1996).

- **Location:** Found above floodplain or valley bottom units, generally on valley walls and in high cirques. Rock topples usually originate from towers, rock falls usually originate from cliffs.
- **Associated Landforms/ Features:** Talus, landslide, cliff, tower, cirque, valley wall, bedrock bench.
- **Process:** Detachment of rock falling from bedrock cliffs or rock towers above. Sporadic and shallow. Large rock fall deposits (talus) generally accumulate over long periods of time (vs. debris avalanches).
- **Surficial Material:** Talus, scree, boulders.
- **Mapping Guidelines:** Rock topples can be small and difficult to locate, therefore rock falls and topples have been grouped together into one category. The small size of rock topples are difficult to see in air photos and are usually found at higher elevations where field checking may not be possible. Rock falls are easily viewed in air photos; they are very bright and highly reflective. Rock falls can be distinguished from debris apron because rock fall will have little or no vegetation and the slope is actively accumulating rock debris. Each fall/topple is given a number and corresponds to a landslide inventory.
- **Potential Vegetation:** Generally void of vegetation except for mosses and lichens.



23) MM-A = Debris Avalanche. A large landslide that generally includes the failure of rock and debris (Cruden and Varnes 1996, Orme 1990).

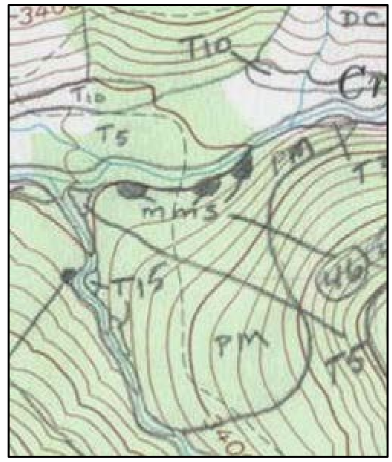
- **Location:** Generally originates from glacially scoured over steepened valley walls and in many cases occur on hydrothermally altered bedrock.
- **Associated Landforms/ Features:** Erosional scar, headwall valley wall, ridge.
- **Process:** Rapid movements, triggered by several factors including precipitation, soil properties, bedrock, slope, sub-colluvial relief, and earthquakes (Orme 1990).
- **Age:** 0 – 25,000 years.
- **Surficial Material:** Soil, colluvium, vegetation all sizes of sediment from boulders to clay.
- **Mapping Guidelines:** Polygon includes headwall scar, path, and deposit. Depositional surface is usually composed of hummocky topography with large angular blocks. These are

the largest of the mass movements and often block streams and create swamps up valley. Each debris avalanche is given a number and corresponds to a landslide inventory.

- **Potential Vegetation:** Recent debris avalanches are typically void of vegetation. Older slides will have vegetation developed that extends from subalpine to lowland forest vegetation.

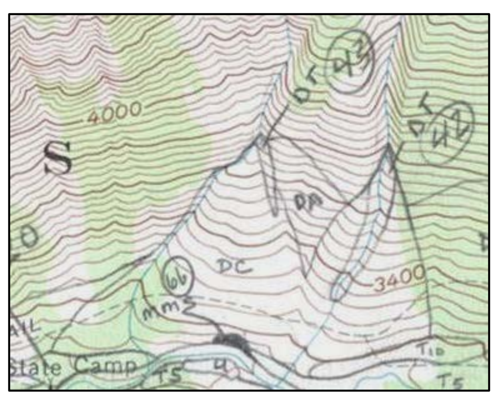
24) MM-S = Slump and Creep. Type of landslide involving rotational slide and/or failure of saturated ground material. Slump and creep landforms are lumped together into one category (Cruden and Varnes 1996).

- **Location:** Slumps are found on over steepened slopes in the Debris Apron zone, along glacial moraines, and river cut banks. Creeps are located at high elevations in the subalpine where snow cover persists into the spring and in the Debris Apron on steep saturated slopes.
- **Associated Landforms/ Features:** Pleistocene moraines, cut banks, debris cones, springs and seeps.
- **Process:** Slumps occur by a rotational slip of cohesive sediments and are usually triggered by undercutting of steep slopes along riverbanks. Creeps are a slow movement induced by saturated ground.
- **Characteristics**: Slumps are typically small and if found adjacent to the river, supply sediment and wood to streams.
- **Surficial Material:** Soil, colluvium, till.
- **Mapping Guidelines:** Slumps are difficult to distinguish on topographic maps. Air photos may show an area with “brighter” deciduous vegetation, compared to adjacent landforms, and fresh new soil indicating disturbance. Slumps (when small, and next to stream) can be mapped as a small half circle, almost a dot. Jackstraw trees (straight trunks falling–in) may be present on slumps. Creeps may contain pistol gripped (curved trunks down slope) trees. Each slump/creep is given a number and corresponds to the landslide inventory.
- **Potential Vegetation:** Forest. Depends on the rate, age and location of disturbance.



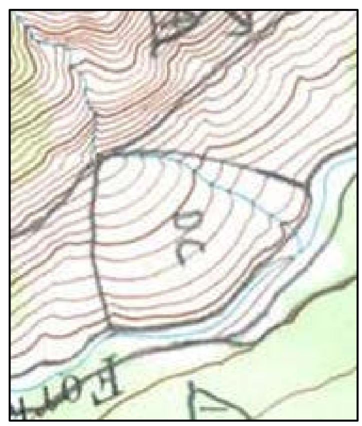
25) MM-DT = Debris Torrent. A channelized debris flow.

- **Location:** Mapped only within the deposit of a debris cone and often found at the base of river canyons, along fault zones, and hanging valleys.
- **Associated Landforms/ Features:** Levee, channel, river canyon, boulders debris cone.
- **Process:** Rapid and shallow**.** Rapid and/or sudden stream flow entrains debris stored in stream channel while moving down slope. Debris is deposited onto gentler slopes below (Eisbacher and Clague 1984, Orme 1990).
- **Surficial Material:** Colluvium (boulders, cobble, gravel), organic debris.
- **Mapping Guidelines:** The debris source should be examined but is not mapped. Debris torrents typically do not extend above or below the debris cone boundary. May contain the active stream. Levees are usually present on either side of the channel and may have a lobe of debris at the toe. Each debris torrent is given a number and corresponds to the landslide inventory.
- **Potential Vegetation:** Recent debris torrents are typically void of vegetation. Older debris torrents will have vegetation developed that extends from subalpine to lowland forest vegetation.



26) DC = Debris Cone. Debris deposited in a conical shape with a surface slope greater than 10 degrees (perpendicular to contours), usually transported by small streams or snow avalanches (Eisbacher and Clague 1984).

- **Location:** Within the debris apron zone and/or at the base of a small stream tributary
- **Associated Landforms/ Features:** Debris torrent (at the mouth of 1st and 2nd order tributaries at the cone apex), scree slopes (at higher elevation zones) that exhibit a conical shape (also known as alluvial cone or talus cone), avalanche chute, avalanche track, levee, SAIL.
- **Process:** Debris transported by small streams or snow avalanches from valley walls and deposited at the break in valley wall slope. Debris is an accumulation of many episodes where the stream channel or avalanche path changes course back and forth creating a conical fan shape.
- **Surficial Material:** Colluvium from bedrock upslope, till, scree, mass movements deposits including boulders.
- **Mapping Guidelines:** Surface is covered with boulders and levees and can often contain rock fall initiated from above. Polygon is drawn around the conical, fan-shaped contour lines on topographic maps verses the straight parallel lines of the debris apron.
- **Potential Vegetation:** Forest; type depends on age.



27) DCT = Debris Cone Terrace. A remnant debris cone surface from past hydrologic conditions.

- **Location:** Typically occurs within the debris apron above an active debris cone.
- **Associated Landforms/ Features:** Debris torrent, avalanche chute, avalanche track, levee, seeps, perched debris cone.
- **Process:** Stream has incised into active debris cone enough so that a remnant surface is left as an inactive terrace.
- **Surficial Material:** Alluvium.
- **Mapping Guidelines:** Features are found usually only by field investigation, or with the aid of LiDAR.
- **Potential Vegetation:** Forest

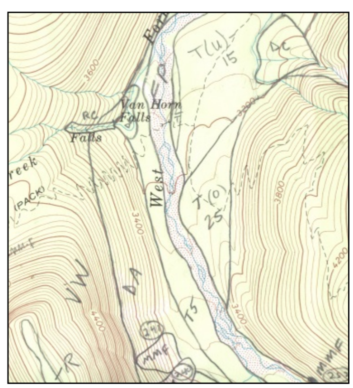
C. Valley Floor

28) FP = Floodplain. The area built of sediments deposited during the present stream regimen and is inundated with water when the river overflows its banks at the 100-year flood stage (Jarrett 1990).

- **Location:** Between terraces on the lowest elevations of the valley. **Associated Landforms/ Features:** River channel, gravel bar, marsh, wetland, braided stream, terrace, side channel.
- **Process:** Frequent disturbance by floods and changes in river channel position.
- **Age:** Less than 100 years.
- **Surficial Material:** Alluvium (sand, gravel).
- **Mapping Guidelines:** Floodplain polygon includes the active river channel, gravel bars, marshes, wetlands and narrow area adjacent to the channel. Mapping can occur at high or extremely low flow depending on the time of year and can be difficult to determine whether an area is a low terrace or floodplain. A clear distinction can usually be made between floodplain and terraces by vegetation type and the presence/absence of water and recent sediment deposition. Floodplain has river rock and/or sand on the surface or under top organic matter, whereas terraces have established soil and limited or no riparian vegetation. Distinction between floodplain and valley bottom units is recognized by the difference in channel restriction, river gradient, and absence/presence of terraces.

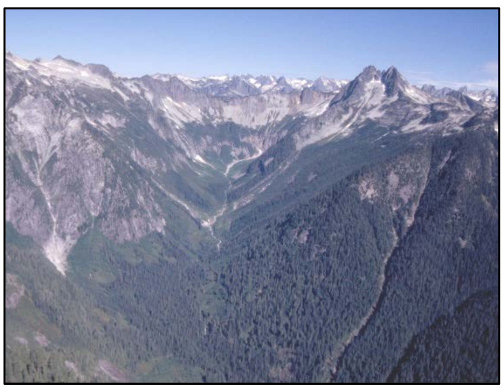
  Tools used to determine floodplain boundary is the presence and location of woody debris. At high flood levels woody debris is carried down the river and is deposited on the banks at the water level surface. Clumps of debris found longitudinally (parallel to the river) may be found in the forest several feet above and away from the current river position indicating the peak flow and possibly a 100-year flood level.

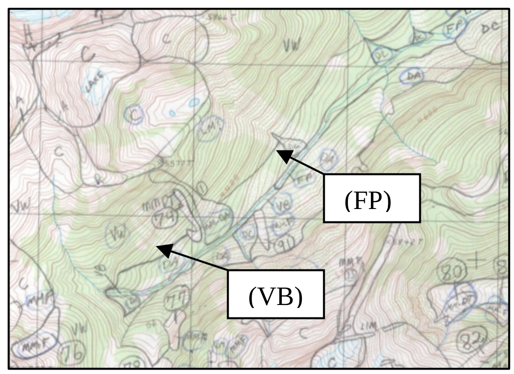
- **Potential Vegetation:** Forest, riparian, wetland; active channel is typically void of vegetation.



29) VB = Valley Bottom. Lowest point of the valley on 3rd order streams or greater with no evidence of floodplain characteristics (Jarrett 1990).

- **Location:** Valley bottom is mapped at elevations above the furthest Neoglacial extent of glaciers within the watershed. Valley bottom polygon does not extend into high elevation cirque basins.
- **Associated Landforms/ Features:** Active channel, cutbank, debris cone, debris apron, SAIL.
- **Process:** Areas at head of valleys where sediment supply generally exceed streams ability to remove. Thus minimal evidence for cut and fill (terraces). Occurs generally above rain on snow zone.
- **Age:** <100 years old
- **Surficial Material:** Alluvium (sand, gravel)
- **Mapping Guidelines:** Polygon is drawn to include the active river and adjacent, gently sloping boundary. Polygon is typically less than several hundred feet wide, merges at lower elevation with floodplain and at the upper elevation with valley wall, cirque, and debris apron. Area contains no terraces or other ways to identify it as floodplain, may have a slightly higher stream gradient than floodplain.
- **Potential Vegetation:** Forest, subalpine.



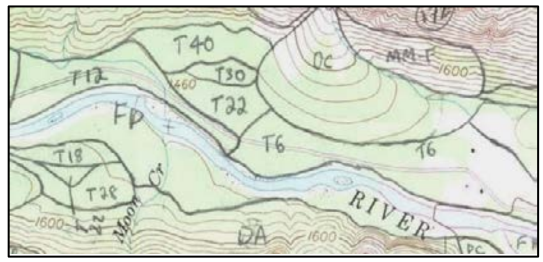


30a) T = Terrace. A relatively flat surface that grades gently downstream and represents the dissected remnants of a previous floodplain (Jarrett 1990, USDA 2003).

- **Location:** On the valley floor between the active river/floodplain and debris apron.
- **Associated Landforms/ Features:** Old side channel, floodplain, escarpment on stream side.
- **Process:** Erosional or depositional feature. River incising into floodplain leaving behind an older surface.
- **Surficial Material:** Alluvium, sand and gravel below soil, glacial outwash.
- **Mapping Guidelines:** Terraces are represented by widely spaced contours adjacent to the active river. Surface gently slopes down valley, verses debris apron, which slopes toward the center of the valley. Remnants of abandoned side channels can cause terrace surface to be slightly uneven. Steep sides are represented by hatched lines on field maps. Terraces at high elevation are generally smaller. All terraces are field checked for height and composition.

Notes of composition, typically alluvium (younger), outwash (older), or lacustrine (clay) deposits are recorded in field notebooks when possible. Terraces are subdivided by the following guidelines; Terrace elevations are marked in feet above stream channel (*i.e.* T-5 or T-12). Terraces can further be described by age using the following guidelines; Terraces <5ft date to the Holocene and are composed of alluvium, terraces >5ft date to the Pleistocene and are composed of outwash.

- **Potential Vegetation:** Vegetation varies with elevation and age of terrace. Higher elevation terraces have montane or subalpine vegetation; lower elevations have lowland forest vegetation. Young terraces have alder or younger conifers. Terraces with many depressions/old side channels may have wetland or riparian vegetation.



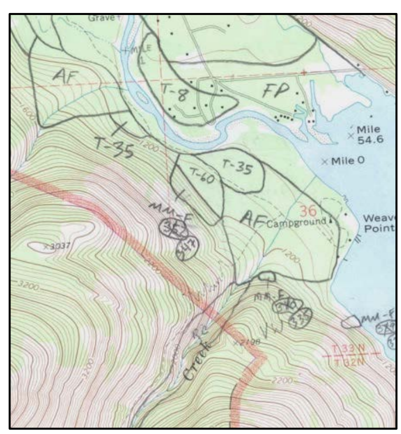
30b) Lahars. Remnants of a large flow, (usually of great speeds with a large volume; possibly a few hundred meters wide and tens of meters deep) which solidified on the flank of a volcano (Crandell 1971, USDA 2003).

- **Location:** Landforms mapped on the flanks of Mount Rainier, usually within the debris apron zone and valley floor as part of a terrace.
- **Associated Landforms/ Features:** Low ridge, mudflow, mass movement, volcanic cone, terrace and debris apron.
- **Process:** Triggered in several ways: water saturated debris, heavy rainfall onto glacial or volcanic deposits, sudden melting of snow or ice associated with volcanism namely by radiant heat at or near a vent or volcanic eruptions, a collapse of hydrothermally altered volcanic edifice, or by sudden discharge of water internally from glaciers.
- **Age:** 0 - 10,000 years.
- **Surficial Material:** Often a poorly sorted matrix consisting of varying material size from clay to blocks (several tens of meters in dimension).
- **Mapping Guidelines:** Lahars are mapped in conjunction with pre-existing geologic, surficial and geologic hazard maps. Slope gradients of 0 to 10% are generally mapped, they are given a height above the river in feet. Surfaces can resemble hummocky topography with height differences of up to 10 feet. Overall surface similarity (debris type, vegetation type and age, etc) is needed for inclusion of a polygon. Terraces are subdivided by the following guidelines; T (fluvial), T-O (Osceola Mudflow),T-E (Electron Mudflow),T-NL (Nation Lahar), T-PL (Paradise Lahar), T-TL (Tahoma Lahar), and T-U (undifferentiated lahars and debris flows).

- Potential Vegetation: Forest

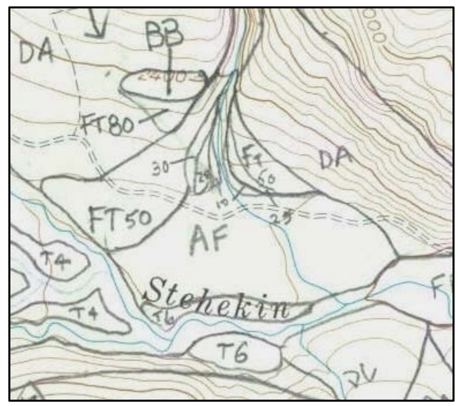
31) AF = Alluvial Fan. Fluvial deposits in the shape of a low broad cone (surfaces are less than 5 degrees) where two rivers meet (USDA 2003).

- **Location:** Found on the lowest elevations of the watershed, bordered by the floodplain and debris apron zones where two large order (2nd, 3rd, or 4th) tributaries join.
- **Associated Landforms/ Features:** Fan terrace, floodplain. Similar morphologically to debris cone but alluvial fans are typically larger and have a lower angle surface slope.
- **Process:** Tributary stream deposits and reworks sediment into a fan shape where it meets the main river valley.
- **Age:** Less than ~200 years.
- **Surficial Material:** Alluvium, sand, gravel.
- **Mapping Guidelines:** Mapped using gently spaced, downward trending, fan shaped contours on topographic maps. Polygon includes deposit from the broad toe to the narrow apex. Only recently active fan is mapped; older parts are fan terraces. Contain many old channels with rounded rocks that are better sorted than on debris cone surfaces. Steep escarpments that occur on upstream side of cone are marked with hatched lines on field maps.
- **Potential Vegetation:** Forest, ranges from dense old growth to open vegetation along streams.



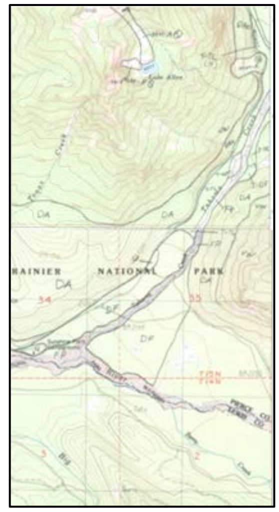
32) FT = Fan Terrace. A remnant surface of an alluvial fan or debris fan that was built under different climatic/hydrologic conditions than present (USDA 2003).

- **Location:** Upstream side of alluvial fans near or next to debris apron zones.
- **Associated Landforms/ Features:** Alluvial fan, terrace, fan remnant
- **Process:** Trunk stream incises tributary alluvial fan, leaving behind an older alluvial fan surface.
- **Age:** 1000 - 25,000 years.
- **Surficial Material:** Alluvium dominates with sand, gravel, and volcanic ash.
- **Mapping Guidelines:** Terrace height is recorded on maps in feet above the alluvial fan. Can be mapped as several polygons with several heights. Cut banks and flat surfaces grade to trunk system.
- **Potential Vegetation:** Forest.



33) DF=Debris Fan. A wedge-shaped deposit of loose rock, debris and vegetation.

- **Location:** Located at or near the junction of streams or where the gradient of a stream abruptly decreases. Usually initiated within the debris apron zone with deposits near or on the valley floor.
- **Associated Landforms/ Features:** Mass movement, floodplain, terrace.
- **Process:** Rapid and sudden debris deposition from lahars and large floods at the mouth of valleys.
- **Surficial Material:** Gravel, sand, soil, organic material.
- **Mapping Guidelines:** Polygon is mapped by a difference (break in slope) in contour spacing. The head of the fan has a steeper apex than the broad low gradient slopes of the toe. The size and amount of material deposited decreases towards the toe. Using the vegetation distinction method may not work if the debris deposits are old. Combines characteristics of alluvial fan and debris cones, debris fan surface is steeper than alluvial fans but less than debris cones.
- **Potential Vegetation:** Forest.



34) U = Undifferentiated. A unique expression that staff cannot explain and may require another senior staff member to visit.

- **Location:** Can occur anywhere in the watershed.
- **Associated Landforms/ Features:** All of the landforms could potentially be associated.
- **Characteristics:** An undifferentiated landform may be created by anthropogenic, or other unexplainable means.
- **Mapping Guidelines:** Mapped when a topographic feature does not clearly fit within one of the other 34 landform definitions.

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Appendix B: Landslide Inventory for Mount Rainier National Park

List of landslide characteristics documented for each landslide is reviewed in this appendix. There are 18 characteristics for all landslides, with an additional four characteristics collected for debris avalanches.

1. Quadrangle Number: Each USGS 7.5 minute quadrangle in MORA was assigned a unique value. Quadrangle values are as follows:

USGS Quadrangle	Value	USGS Quadrangle	Value
Golden Lakes	1	Chinook Pass	8
Mowich Lake	2	Cougar Lake	9
Sunrise	3	Sawtooth Ridge	10
White River Park	4	Wahpemnayo Peak	11
Mount Wow	5	Tatoosh Lakes	12
Mt. Rainier West	6	Ohanapecosh Hot Springs	13
Mt. Rainier East	7		

2. Mass Movement Number: Each mass movement in the watershed is assigned a unique value.

3. Sub-Watershed: Refers to the river or creek name that dominates the drainage where the mass movement is located.

4. Mass Movement Type Number: Each type of mass movement has a number as follows:

USGS Quadrangle	Value
Rock Fall/Topple	1
Creep/Slump	2
Debris Avalanche	3
Debris Torrent	4
Sackung	5
Snow Avalanche Impact Landform (SAIL)	6

5. Identification Number: Consists of the quadrangle number, mass movement number and mass movement type number (e.g. a rock fall on the Copper Mtn. quadrangle with the assigned number of 11 would be 2-11-1)

6. Material Type: Refers to the type of material contained in the mass movement. The four different material types are rock (R), soil (S), till (T) and debris (D).

7. Age: Relative age if known, occasionally specific dates are recorded if the event was observed. When date is recorded, the type of dating will be noted.

8. Sediment Delivered to Stream: A yes or no or blocked category based on NAIP imagery and aerial photographs

9. Bedrock Type: Used Tabor et al (2003) to identify bedrock type of the landslide. Refer to this map for a key to the symbols used in the database.

10. Length: Refers to the average length (from top to bottom) of the total mass movement. For debris avalanches both the cavity and the deposit is included in the average length measurements. For debris torrents and rock falls/topples, only the deposit is measured. Due to the small size of slumps, the length is taken in the field if possible by measuring the height exposure including any cracking above the crown. Measurements are in 2-D. The measurement is taken off GIS with the measuring tool and is recorded in meters.

11. Width: Refers to the average width (generally following on contour) of the total mass movement. For debris avalanches both the cavity and the deposit is included in the average width measurements. For debris torrents and rock falls/topples, only the deposit is measured. Due to the small size of slumps, the length is taken in the field if possible by measuring the width of the exposure. The measurement is taken off GIS with the measuring tool and is recorded in meters.

12. Volume of Sediment of Debris Avalanches: Refers to the amount of material deposited by a debris avalanche. Measurements are taken by calculating volume only of the cavity and are recorded in meters. Formula as follows:

$$((1/6)*3.14*\text{Length of Cavity}*\text{Width of Cavity}*\text{Depth of Cavity})$$

13. Length of Cavity: Used to calculate volume of sediment in debris avalanche. Refers to the average length (from top to bottom) of the cavity and measurement is taken off the GIS and is recorded in meters.

14. Width of Cavity: Used to calculate volume of sediment in debris avalanche. Refers to the average width of the cavity and measurement is taken off the GIS and is recorded in meters.

15. Depth of Cavity: Used to calculate volume of sediment in debris avalanches and refers to the thickness of material. Depth is recorded in the field if possible. If not possible, measurement should be taken by the cavity of the debris avalanche. The cavity can be estimated using a topographic map in lieu of field information. Depth is recorded in meters.

16. Surface Area: Refers to the exposed area in 2-D and is recorded in m^2 and km^2. Measurement is taken off the GIS for all mass movements.

17. Slope Aspect: Refers to the slope aspect that the mass movement originated from and not the deposit. It is measured off the quadrangle using a compass and is recorded in degrees from true north.

18. Percent Slope: Recorded for each landslide, value is calculated by rise over run (45 degrees = 100% slope).

19. Position: Refers to four possible locations of where landslides originated; Valley Bottom (VB) defined as anything below the valley wall unit, Divide (D), Valley Wall (VW), or Channelized (CH) if confined to a channel.

20. Form: Refers to the general slope form of the landslides; concave (CC), convex (CV), flat (FL) and complex (COMP).

21. Top Elevation: Refers to the top most extent of the mass movement. Recorded in meters and measurement is taken from a 7.5 Minute Quadrangle.

22. Toe Elevation: Refers to the lowest extent of the mass movement. Recorded in meters and measurement is taken from a 7.5 Minute Quadrangle.

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
5	1	Tahoma	5.1.1	1	R		Y	Tol	191	86	17069		90	52	FL	VW	1512	1396
5	2	Tahoma	5.2.3	3	D		Y	Tol	791	100	89196	400161.4	330	54	COMP	VW	1817	1396
5	3	Tahoma	5.3.4	4	D		Y	Tol	537	58	28243		20	36	CV	VB	1036	866
5	4	Tahoma	5.4.3	3	D		Y	Tol	547	101	69061	706702.0	60	100	COMP	VW	1341	872
5/6	5	Tahoma	5.5.3	3	D		Y	Qra	628	273	148914	433566.4	330	37	COMP	VW	1280	1036
5	6	Tahoma	5.6.1	1	R		N	Qra	152	100	14124		355	75	FL	VW	1280	1158
6	7	Tahoma	6.7.3	3	D		BLKD	Tol	1149	317	389665	7974363.8	330	56	COMP	VB	1768	1158
6	8	Tahoma	6.8.2	2	T		Y	Tol	32	55	1759		160	33	CC	VW	1170	1158
6	9	Tahoma	6.9.1	1	R		N	Qra	110	275	32999		320	70	FL	VW	1807	1682
5	10	Tahoma	5.10.3	3	D		N	Tol	379	163	65070	91667.6	75	74	COMP	VB	1036	768
6	11	Kautz	6.11.3	3	D		N	Tol	732	231	162269	251655.7	120	23	COMP	VB	1073	939
6	12	Pyramid	6.12.1	1	R		N	Tol	105	461	69235		90	67	FL	VW	1402	1292
6	13	Pyramid	6.13.3	3	D		N	Tol	384	113	37700	36981.3	200	73	COMP	VW	1463	1170
6	14	Pyramid	6.14.3	3	D		N	Tol	676	208	140134	265300.4	160	66	COMP	VW	1463	1036
6	15	Pyramid	6.15.3	3	D		N	Tol	585	66	44025	19198.9	155	58	COMP	VW	1402	1000
6	16	Pyramid	6.16.3	3	D		N	Tol	201	90	18927	7809.7	150	64	COMP	VW	1524	1390
6	17	Pyramid	6.17.1	1	R		N	Tol	123	224	33888		140	88	FL	VW	1646	1487
6	18	Pyramid	6.18.1	1	R		N	Tol	103	177	17859		240	55	FL	VW	1463	1402
6	19	Pyramid	6.19.1	1	R		N	Tol	95	49	4661		260	62	FL	VW	1646	1585
6	20	Pyramid	6.20.1	1	R		Y	Tol	165	103	20513		105	40	FL	VW	1353	1256
6	21	Devils Dream	6.21.1	1	R		N	Tol	53	155	7505		130	58	FL	VW	1573	1548
6	22	Devils Dream	6.22.1	1	R		N	Ts	179	71	13391		170	47	FL	VW	1646	1548
6	23	Devils Dream	6.23.1	1	R		N	Ts	93	117	8625		160	36	FL	VW	1585	1548
6	24	Devils Dream	6.24.6	6	R		N	Ts	27	173	3497		270	42	FL	VW	1865	1853
6	25	Fishers Hornpipe	6.25.1	1	R		Y	Ts	143	105	18359		40	63	FL	VW	1890	1780
6	26	Pearl	6.26.1	1	R		Y	Qs	50	147	7499		230	100	FL	VW	1463	1378
6	27	Kautz	6.27.1	1	R		Y	Tg	348	495	189717		160	74	FL	VW	1951	1524
6	28	Kautz	6.28.2	2	T		Y	Tg	271	65	19719		160	60	CC	VW	1768	1585
6	29	Van Trump	6.29.2	2	T		Y	Qra	26	36	1039		130	87	CC	VW	1670	1646
6	30	Van Trump	6.30.1	1	R		Y	Qra	142	54	8489		240	54	FL	VW	1573	1487

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
6	31	Van Trump	6.31.2	2	T		Y	Tg	16	56	1181		130	61	CC	VW	1366	1353
6	32	Van Trump	6.32.3	3	D		N	Qra	71	40	3219	1711.6	230	57	COMP	VW	1536	1487
6	33	Van Trump	6.33.1	1	R		N	Qra	237	134	32203		210	48	FL	VW	1402	1256
6	34	Van Trump	6.34.1	1	R		N	Qra	124	50	6967		190	64	FL	VB	1341	1256
6	35	Van Trump	6.35.1	1	R		N	Qra	322	67	21274		220	67	FL	VW	1402	1183
6	36	Van Trump	6.36.1	1	R		N	Qra	76	53	4855		210	86	FL	VB	1317	1231
6	37	Nisqually	6.37.1	1	R		N	Qra	86	126	12267		140	68	FL	VW	1439	1366
6	38	Nisqually	6.38.1	1	R		N	Tg	60	187	9769		150	79	FL	VB	1146	1097
6	39	Nisqually	6.39.1	1	R		N	Tg	102	106	7124		140	68	FL	VB	1158	1085
6	40	Nisqually	6.40.1	1	R		N	Tg	194	91	16794		140	66	FL	VB	1219	1073
6	41	Nisqually	6.41.1	1	R		N	Tg	72	45	2748		140	59	FL	VB	1207	1158
6	42	Nisqually	6.42.1	1	R		N	Tg	31	57	1614		140	74	FL	VB	1134	1109
6	43	Nisqually	6.43.1	1	R		N	To	334	46	12682		125	100	FL	VW	1158	1097
6	44	Nisqually	6.44.1	1	R		N	To	99	651	58780		130	68	FL	VB	1036	939
6	45	Nisqually	6.45.1	1	R		N	Qra	109	207	26442		320/115	58	FL	VW	1244	1170
6	46	Nisqually	6.46.1	1	R		N	To	149	44	5377		350	93	FL	VW	1158	1012
6	47	Paradise	6.47.1	1	R		Y	Tg	177	118	24506		350	84	FL	VB	1158	939
6	48	Paradise	6.48.1	1	R		Y	Tg	305	285	91189		355	73	FL	VB	1280	1012
6	49	Paradise	6.49.1	1	R		N	Qra	60	128	7334		210	98	FL	VB	1073	1012
6	50	Paradise	6.50.2	2	T		N	Qra	33	33	1144		210	21	CC	VW	1308	1298
6	51	Paradise	6.51.2	2	T		N	Qra	24	54	1799		190	36	CC	VW	1305	1292
6	52	Nisqually	6.52.2	2	T		N	Qra	27	71	2154		340	76	CC	VW	1292	1268
6	53	Nisqually	6.53.1	1	R		N	Tg	132	488	60760		325	67	FL	VB	1158	1036
6	55	Nisqually	6.55.1	1	R		N	Tg	122	64	7790		330	76	FL	VB	1244	1146
6	56	Nisqually	6.56.1	1	R		N	Tg	162	158	33113		150	88	FL	VW	1524	1366
6	57	Nisqually	6.57.1	1	R		N	Qra	104	72	8395		320	85	FL	VW	1341	1219
6	58	Paradise	6.58.3	3	D		Y	Ts	480	128	54893	311788.3	105	71	COMP	VW	1707	1366
6	59	Paradise	6.59.3	3	D		N	Ts	216	68	16953	123049.7	70	93	COMP	VW	1768	1561
6	60	Paradise	6.60.3	3	D		N	Ts	295	89	28130	243678.5	335	78	COMP	VW	1707	1500
6	61	Puyallup	6.61.1	1	R		N	Qra	40	126	5743		320	60	FL	VW	1753	1719

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
5	62	Puyallup	5.62.1	1	R		Y	Qra	107	164	19654		170	60	FL	VB	1158	1073
5	63	Puyallup	5.63.1	1	R		N	Qra	97	241	21418		180	86	FL	VW	1231	1103
5	64	Puyallup	5.64.1	1	R		N	Qra	63	41	2709		180	80	FL	VW	1268	1219
5	65	Goat Creek	5.65.3	3	D		N	Tol	567	91	51248	1079033.2	220	60	COMP	VW	1561	1207
6	68	Puyallup	6.68.3	3	D		Y	Qra	109	187	28406	80263.5	5	52	COMP	VB	1298	1219
6	69	Puyallup	6.69.1	1	R		N	Qra	46	283	14747		320	55	FL	VB	1280	1231
6	70	Fishers Hornpipe	6.70.1	1	R		N	Ts	114	45	4485		80	69	FL	VW	1719	1631
6	71	Butter Creek	6.71.3	3	D		N	Ts	424	206	82170	772533.1	95	79	COMP	VW	1756	1411
11	72	Kautz	11.72.1	1	R		N	Tol	130	34	4583		330	49	FL	VW	1280	1207
11	73	Kautz	11.73.1	1	R		N	Tol	88	172	15147		200	92	FL	VW	914	792
7	75	Nisqually	7.75.3	3	D		Y	Qra	374	121	56038	7374295.3	300	73	COMP	VW	1585	1305
7	76	Nisqually	7.76.3	3	D		Y	Qra	325	134	47481	3758153.3	320	70	COMP	VW	1597	1341
7	77	Dead Horse Creek	7.77.1	1	R		N	Qra	246	409	95807		225	51	FL	VW	2085	1951
7	78	Tatoosh Creek	7.78.1	1	R		N	Qra	82	156	15816		140	55	FL	VB	1585	1524
7	79	Tatoosh Creek	7.79.1	1	R		N	Tg	203	281	66485		350	59	FL	VW	1515	1366
7/12	80	Butter Creek	7.80.3	3	D		N	Ts	616	93	49125	1768818.3	100	63	COMP	VW	1670	1268
7	81	Sunbeam Creek	7.81.1	1	R		Y	Qra	181	137	23720		155	60	FL	VW	1536	1402
7	82	Unicorn Creek	7.82.1	1	R		N	Ts	80	121	11667		55	52	FL	VW	1500	1439
7	83	Unicorn Creek	7.83.1	1	R		N	Ts	46	50	3224		35	76	FL	VW	1530	1487
7	84	Stevens Creek	7.84.1	1	R		N	Tg	273	198	63913		240	67	FL	VW	1585	1353
7	85	Stevens Creek	7.85.1	1	R		N	Qra/Tg	127	374	54354		100	46	FL	VW	1305	1183
7	86	Stevens Creek	7.86.1	1	R		N	Tg	247	135	34548		175	62	FL	VW	1219	1024
7	87	Stevens Creek	7.87.1	1	R		N	Qra	77	323	23389		20	78	FL	VW	1036	951
7	88	Stevens Creek	7.88.1	1	R		N	Qra	64	270	18032		35	33	FL	VW	975	951
7	89	Stevens Creek	7.89.1	1	R		N	Qra	79	360	29963		35	68	FL	VW	975	914
7	90	Stevens Creek	7.90.1	1	R		N	Qra	145	228	35070		200	45	FL	VW	975	878
7	91	Stevens Creek	7.91.1	1	R		N	Qra	231	511	110726		40	58	FL	VW	1036	878
7	92	Stevens Creek	7.92.1	1	R		N	Ts	89	146	18127		70	71	FL	VW	975	853
7	93	Williwakas	7.93.1	1	R		N	Qra	220	245	53153		60	69	FL	VW	1646	1487
7	94	Williwakas	7.94.1	1	R		N	Qra	224	486	106789		210	85	FL	VW	1597	1356

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
7	95	Williwakas	7.95.1	1	R		N	Qra	90	94	10417		55	68	FL	VW	1475	1396
7	96	Williwakas	7.96.3	3	D		Y	Tg/Ts	502	241	133359	308036.8	25	54	COMP	VW	1451	1146
7	97	Muddy Fork Cowlitz	7.97.3	3	D		Y	Qra	471	130	52538	91113.3	185	72	COMP	VW	1951	1585
7	98	Muddy Fork Cowlitz	7.98.1	1	R		N	Qra	80	111	7513		210	30	FL	VW	1695	1670
7	99	Muddy Fork Cowlitz	7.99.3	3	D		Y BLKD	Qra	105	742	76084	82155.1	60	51	COMP	VW	1646	1158
7	100	Muddy Fork Cowlitz	7.100.3	3	D		Y	Qra	450	88	46214	218551.4	80	86	COMP	VW	1585	1152
7	101	Muddy Fork Cowlitz	7.101.1	1	R		N	Qra	99	109	13269		90	77	FL	VW	1463	1341
7	102	Muddy Fork Cowlitz	7.102.1	1	R		N	Td	180	142	33155		265	44	FL	VW	1366	1225
7	103	Muddy Fork Cowlitz	7.103.1	1	R		N	Qra	85	167	19270		250	51	FL	VW	1158	1084
7	104	Muddy Fork Cowlitz	7.104.1	1	R		N	Qra	76	607	43968		220	65	FL	VW	1158	1097
7	105	Boulder Creek	7.105.1	1	R		Y	Qra	238	122	36410		130	83	FL	VW	1890	1658
7	106	Boulder Creek	7.106.3	3	D		N	Qra	428	134	59489	236894.5	205	73	COMP	VW	2073	1768
7	107	Boulder Creek	7.107.1	1	R		N	Qra	46	225	9295		55	96	FL	VW	1890	1841
7	108	Fryingpan Creek	7.108.3	3	D		N	Tol	251	160	42498	34429.1	40	92	COMP	VW	1780	1481
7	109	Fryingpan Creek	7.109.3	3	D		Y	Tol	696	98	57070	114384.5	355	93	COMP	VW	2012	1390
12	110	Butter Creek	12.110.1	1	R		N	Ts	92	138	16489		20	45	FL	VW	1585	1530
12	111	Butter Creek	12.111.1	1	R		N	Ts	75	182	14636		25	63	FL	VW	1353	1280
12	112	Butter Creek	12.112.3	3	D		Y	Ts	770	143	129210	292864.0	35	66	COMP	VW	1682	1170
12	113	Butter Creek	12.113.3	3	D		Y	Ts	731	148	121087	774108.5	40	50	COMP	VW	1573	1085
13	114	Muddy Fork Cowlitz	13.114.3	3	D		N	To	780	284	224308	47087.9	285	36	COMP	VW	1329	1000
8/13	115	Ohanapecosh River	8.115.3	3	D		Y-BLKD	To	1999	1467	2633570	8805158.1	280	16	COMP	VW	939	622
8	116	Ohanapecosh River	8.116.1	1	R		N	To	50	447	27136		170	88	FL	VW	1512	1439
8	117	Ohanapecosh River	8.117.1	1	R		Y	To	61	53	5025		95	89	FL	VB	756	658
8	118	Ohanapecosh River	8.118.3	3	D		N	To	1153	157	209437	209560.5	275	50	COMP	VW	1414	838
8	119	Deer Creek	8.119.1	1	R		N	Tdi	139	371	50513		300	82	FL	VW	1439	1332
8	120	Nickel Creek	8.120.1	1	R		N	Tol	193	280	64025		220	64	FL	VW	1585	1414
8	121	Ohanapecosh River	8.121.3	3	D		Y	To	738	86	79385	434127.9	50	68	COMP	VW	1353	853
8	122	Ohanapecosh River	8.122.1	1	R		N	To	84	118	11201		140	100	FL	VW	1231	1097
8	123	Boulder Creek	8.123.1	1	R		N	To	123	56	7936		175	57	FL	VW	1707	1597
8	124	Kotsuck Creek	8.124.1	1	R		N	To	81	112	9802		320	27	FL	VW	1597	1567

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
8	125	Deer Creek	8.125.1	1	R		N	Tdi	131	103	14023		30	100	FL	VW	1585	1417
8	126	Chinook Creek	8.126.1	1	R		N	To	110	180	25589		130	64	FL	VB	975	878
8	127	Kotsuck Creek	8.127.2	2	S		Y	To	29	82	1996		175	13	CC	VB	1195	1170
8	128	Dewey Creek	8.128.1	1	R		N	Tdi	262	120	37905		310	55	FL	VW	1707	1536
8	129	Dewey Creek	8.129.1	1	R		N	To	109	327	42916		180	79	FL	VB	1308	1189
8	130	Chinook Creek	8.130.1	1	R		N	To	143	465	69977		200	12	FL	VW	1475	1439
8	131	Chinook Creek	8.131.1	1	R		N	To	174	410	75076		160	67	FL	VW	1579	1426
8	132	Chinook Creek	8.132.3	3	D		N	To	288	72	28204	58587.2	85	45	COMP	VW	1597	1439
8	133	Boundary Creek	8.133.3	3	D		N	To	378	92	38198	131071.0	50	72	COMP	VW	1902	1615
8	134	Chinook Creek	8.134.1	1	R		N	To	128	86	10153		140	82	FL	VW	1311	1207
8	135	Shaw Creek	8.135.1	1	R		N	To	352	250	99325		310	52	FL	VW	1853	1609
8	136	Shaw Creek	8.136.1	1	R		N	Tol	292	198	56954		30	53	FL	VW	1792	1622
9	137	Panther Creek	9.137.1	1	R		N	To	175	270	37556		290	60	FL	VW	1548	1390
9	138	Panther Creek	9.138.1	1	R		N	To	196	84	15440		5	41	FL	VW	1670	1585
8	139	Ohanapecosh River	8.139.1	1	R		N	To	37	35	1082		95	16	FL	VB	671	664
6	140	Twin Falls Creek	6.140.1	1	R		N	Qra	57	83	5806		220	99	FL	VW	1396	1305
8	141	Ohanapecosh River	8.141.4	4	D		Y	Qs	56	123	9120		200	32	CV	VB	832	805
4/8	142	Klickitat Creek	4.142.3	3	D		N	Qls/To	1114	463	510511	4003470.5	290	35	COMP	VW	1707	1280
4	143	Klickitat Creek	4.143.3	3	D		Y	To/Tdi	1057	409	427760	3255652.7	285	45	COMP	VW	1646	1158
4	144	Deadwood Creek	4.144.3	3	D		N	To/Tdi	322	67	22831	39756.8	0	51	COMP	VW	1792	1622
4	145	Deadwood Creek	4.145.3	3	D		N	To/Tdi	201	105	21761	10719.2	5	52	COMP	VW	1731	1585
4	146	Klickitat Creek	4.146.1	1	R		N	To/Tdi	138	131	19325		270	83	FL	VW	1475	1341
4	147	Deadwood Creek	4.147.1	1	R		N	To/Tdi	135	197	21897		5	68	FL	VW	1524	1426
4	148	Crystal Creek	4.148.1	1	R		N	To	149	95	11991		220	88	FL	VW	1902	1786
4	149	Crystal Creek	4.149.1	1	R		N	Tdi	136	92	13480		330	48	FL	VW	1463	1364
4	150	Sunrise Creek	4.150.1	1	R		N	Tg	62	149	9767		330	82	FL	VW	1646	1561
4	151	Sunrise Creek	4.151.1	1	R		N	Tdi/Tg	197	221	38482		70	64	FL	VW	1768	1596
4	152	Sunrise Creek	4.152.1	1	R		N	Tg	86	83	7104		320	56	FL	VW	1719	1658
4	153	Sunrise Creek	4.153.1	1	R		N	Qs/Tg	135	188	25828		90	67	FL	VW	1829	1713
4	154	Lost Creek	4.154.3	3	D		Y-BLKD	Qls/To	1015	401	502092	773773.6	280	58	COMP	VW	1963	1366

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
4	155	Lost Creek	4.155.3	3	D		N	To	411	68	28034	68220.1	90	79	COMP	VW	1829	1500
4	156	Lost Creek	4.156.3	3	D		Y	Tg	442	67	32515	76912.5	85	57	COMP	VW	1682	1396
4	157	Lost Creek	4.157.1	1	R		N	To	164	130	20307		80	61	FL	VW	1487	1366
4	158	Lost Creek	4.158.1	1	R		N	To	266	174	50841		85	47	FL	VW	1524	1366
4	159	Prospect Creek	4.159.1	1	R		N	To	259	91	25253		230	61	FL	VW	2012	1829
4	160	Prospect Creek	4.160.1	1	R		N	To	274	58	13170		230	72	FL	VW	2048	1841
4	161	White River	4.161.3	3	D		Y	Qra	641	116	73157	20213.4	150	46	COMP	VW	1366	1073
4	162	Shaw Creek	4.162.3	3	D		Y-BLKD	To	1217	82	120217	565055.3	335	17	COMP	CH	1317	1097
4	163	Shaw Creek	4.163.3	3	D		Y	To	734	210	146691	205764.1	270	74	COMP	VW	1890	1329
4	164	White River	4.164.1	1	R		N	Qra	89	47	3839		190	94	FL	VW	1768	1670
4	165	White River	4.165.1	1	R		N	Qra	98	50	4822		180	62	FL	VW	1670	1597
3	166	White River	3.166.2	2	T OR S?		Y	Qs	61	68	5652		350	31	CC	VB	1280	1256
3	167	White River	3.167.1	1	R		N	Tg/Qra	206	209	43005		170	76	FL	VW	1707	1536
3	168	White River	3.168.1	1	R		N	Tg/Qra	368	90	27639		185	79	FL	VW	1884	1585
3	169	White River	3.169.1	1	R		N	Tg	44	60	2685		160	49	FL	VW	1524	1500
3	170	White River	3.170.1	1	R		N	Tg	96	50	4722		170	46	FL	VW	1414	1359
3	171	White River	3.171.3	3	D OR T?		Y	To	1020	210	215602	126958.7	355	55	COMP	VW	1902	1305
3	172	White River	3.172.3	3	D OR T?		N	To	681	109	65194	94686.3	335	59	COMP	VW	1792	1347
3	173	White River	3.173.3	3	D OR T?		N	To	664	108	58136	36100.8	340	74	COMP	VW	1853	1378
3	174	White River	3.174.3	3	D OR T?		N	Tg/To	432	84	37080	37011.9	0	91	COMP	VW	1878	1426
3	175	Inter Fork	3.175.1	1	R		N	Qra	197	96	17930		170	100	FL	VW	1890	1670
3	176	Inter Fork	3.176.1	1	R		N	Qra	100	67	6549		170	84	FL	VW	1878	1780
3	177	Inter Fork	3.177.1	1	R		N	Qra	268	89	21678		165	71	FL	VW	1829	1622
3	178	Inter Fork	3.178.1	1	R		N	Qra	96	95	11755		180	78	FL	VW	1951	1786
3	179	Inter Fork/White River	3.179.3	3	T		Y	Qs	3435	651	2545235		45	9	COMP	VW	1731	1378
3	180	Inter Fork	3.180.1	1	R		N	To/Qra	163	399	79354		0	97	FL	VW	1999	1731
3	181	Inter Fork	3.181.1	1	R		N	To/Qra	174	466	102332		340	54	FL	VW	2012	1841
3	182	Inter Fork	3.182.1	1	R		N	Qra	257	519	170708		175	75	FL	VW	2243	1890
3	183	Inter Fork	3.183.1	1	R		N	Qra	221	159	39404		150	49	FL	VW	2128	1975
3	184	Inter Fork	3.184.1	1	R		N	Qra	236	446	110999		140	37	FL	VW	2134	1987

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3	185	Inter Fork	3.185.1	1	R		N	Qra	143	95	11412		70	38	FL	VW	2097	2036
3	186	Winthrop Creek	3.186.1	1	R		N	Qra	174	622	138456		160	74	FL	VW	2256	1963
3	187	Winthrop Creek	3.187.1	1	R OR T?		Y	Qra	351	1235	400726		280	74	FL	VW	2146	1829
3	188	Winthrop Creek	3.188.3	3	D OR T?		Y	Qra	594	161	98510	313742.5	310	60	COMP	VW	2134	1731
3	189	Winthrop Creek	3.189.3	3	D OR T?		Y	Qra	848	159	144713	911336.7	310	54	COMP	VW	2073	1597
3	190	Winthrop Creek	3.190.3	3	D OR T?		Y	Qra	1024	184	170961	1042107.8	320	45	COMP	VW	2073	1561
3	191	West Fork White River	3.191.3	3	D OR T?		Y-BLKD	Qra	1782	103	175294	248277.2	0	15	COMP	VW	1829	1567
3	192	West Fork White River	3.192.1	1	R		N	Qra	387	57	19946		160	48	FL	VW	1890	1682
3	193	West Fork White River	3.193.1	1	R		N	Qra	339	116	39536		140	55	FL	VW	1829	1622
3	194	West Fork White River	3.194.1	1	R		N	Qra	163	71	12775		120	69	FL	VW	1692	1573
3	195	West Fork White River	3.195.1	1	R		N	Qra	64	41	2923		115	55	FL	VW	1658	1622
3	196	West Fork White River	3.196.1	1	R		N	Qra	73	55	3460		115	63	FL	VW	1646	1597
3	197	West Fork White River	3.197.1	1	R		N	Qra	135	82	10239		135	69	FL	VW	1634	1536
3	198	Winthrop Creek	3.198.1	1	R		Y	Qs	48	62	3359		320	84	FL	VW	1451	1402
3	199	Winthrop Creek	3.199.3	3	D		N	Tdi	957	70	58168	92606.3	320	65	COMP	VW	1890	1280
3	200	West Fork White River	3.200.3	3	D		N	Tdi	1141	62	67708	112015.7	310	63	COMP	VW	1963	1256
3	201	West Fork White River	3.201.3	3	D		N	Tdi	1187	108	105110	190167.3	340	63	COMP	VW	2012	1256
3	202	West Fork White River	3.202.4	4	D		N	Tdi/Qra	181	93	20685		130	68	CV	VW	1475	1305
3	203	Lodi Creek	3.203.1	1	R		N	Tdi	164	64	10139		80	37	FL	VW	1780	1707
3	204	Lodi Creek	3.204.1	1	R		N	Tdi	146	80	12490		60	22	FL	VW	1829	1795
3	205	Lodi Creek	3.205.1	1	R		N	Tdi	67	60	3560		270	64	FL	VW	1939	1890
3	206	Lodi Creek	3.206.1	1	R		N	Qs	98	49	5667		270	53	FL	VB	1780	1719
3	207	Lodi Creek	3.207.1	1	R		Y	Tdi	142	207	34670		310	66	FL	VW	1829	1707
3	208	Lodi Creek	3.208.1	1	R		N	Tdi	192	368	58440		260	60	FL	VW	1670	1487
3	209	Huckleberry Creek	3.209.1	1	R		N	Qra	105	89	17365		140	54	FL	VW	1695	1609
3	210	Huckleberry Creek	3.210.1	1	R		N	Qra	117	173	29960		140	54	FL	VW	1682	1585
3	211	Huckleberry Creek	3.211.1	1	R		N	Qra	65	56	5732		170	51	FL	VW	1646	1597
3	212	Huckleberry Creek	3.212.1	1	R		N	Qra	57	101	5926		140	45	FL	VW	1634	1597
3	213	Huckleberry Creek	3.213.1	1	R		N	Qra	56	28	1860		175	67	FL	VW	1634	1597
3	214	Huckleberry Creek	3.214.1	1	R		N	Qra	62	30	1917		140	39	FL	VW	1658	1634

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3	215	Huckleberry Creek	3.215.1	1	R		N	Qra	121	125	13850		110	45	FL	VW	1536	1475
3	216	Huckleberry Creek	3.216.1	1	R		N	Qra	74	225	17528		160	100	FL	VW	1658	1536
3	217	Huckleberry Creek	3.217.1	1	R		N	To	57	125	6725		140	60	FL	VW	1804	1768
3	218	Huckleberry Creek	3.218.1	1	R		N	Tdi	127	155	22949		355	33	FL	VW	1951	1890
3	219	Huckleberry Creek	3.219.1	1	R		N	To	55	42	2495		160	40	FL	VW	1817	1792
3	220	Huckleberry Creek	3.220.1	1	R		N	To	128	170	21610		355	86	FL	VW	1829	1707
3	221	Huckleberry Creek	3.221.1	1	R		N	To	171	102	21411		90	91	FL	VW	1817	1646
3	222	Huckleberry Creek	3.222.3	3	D		N	To	478	186	80835	24328.8	280	59	COMP	VW	1707	1426
3	223	Huckleberry Creek	3.223.1	1	R		N	Qra	95	53	5809		5	70	FL	VW	1597	1524
3	224	Huckleberry Creek	3.224.1	1	R		N	Qra	104	81	8278		345	42	FL	VW	1561	1512
3	225	Huckleberry Creek	3.225.1	1	R		N	Qra	236	376	58748		50	65	FL	VW	1646	1500
3	226	Eleanor Creek	3.226.1	1	R		N	Tf	171	60	9861		60	51	FL	VW	1646	1548
3	227	Eleanor Creek	3.227.3	3	D		Y	Tf	731	125	83229	277582.8	60	35	COMP	VW	1768	1512
3	228	Eleanor Creek	3.228.1	1	R		N	Tf	171	103	18981		50	65	FL	VW	1768	1646
3	229	West Fork White River	3.229.3	3	D		N	Qls/Tf	889	240	230475	1184874.3	285	44	COMP	VW	1829	1402
3	230	West Fork White River	3.220.3	3	D		Y-BLKD	Qls/Tf	1471	984	1371491	14076997.8	280	39	COMP	VW	1585	975
3	231	West Fork White River	3.231.1	1	R		N	Ts	132	231	41504		280	68	COMP	VW	1707	1512
3	232	West Fork White River	3.232.1	1	R		Y	Tdi	37	59	2965		230	80	COMP	VW	1082	1036
3	233	West Fork White River	3.233.1	1	R		N	Qra/Tdi	57	132	7376		270	97	COMP	VW	1378	1317
3	234	West Fork White River	3.234.1	1	R		N	Qra/Tdi	154	95	20892		270	55	COMP	VW	1341	1219
3	235	West Fork White River	3.235.1	1	R		N	Tdi	109	88	10014		275	45	COMP	VW	1402	1347
3	236	West Fork White River	3.236.3	3	D		Y	Tdi	702	128	74862	89811.6	90	74	COMP	VW	1658	1109
3	237	West Fork White River	3.237.1	1	R		Y	Tdi	74	74	8172		85	40	FL	VB	1158	1109
3	238	West Fork White River	3.238.3	3	D		Y	Tdi	664	52	40262	41672.5	70	73	COMP	VW	1646	1097
3	239	West Fork White River	3.239.1	1	R		N	To	159	88	15537		90	54	FL	VW	1622	1512
3	240	West Fork White River	3.240.3	3	D		N	Tdi	561	88	44878	13054.5	85	54	COMP	VW	1475	1207
3	241	West Fork White River	3.241.1	1	R		N	Tdi	184	154	33033		70	56	FL	VW	1158	1018
3	242	Van Horn Creek	3.242.1	1	R		N	Tdi	154	208	27878		310	63	FL	VW	1548	1439
3	243	Van Horn Creek	3.243.1	1	R		N	Tdi	101	147	16153		100	47	FL	VW	1634	1573
3	244	Van Horn Creek	3.244.1	1	R		N	Qra	164	105	18303		100	25	FL	VW	1804	1762

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3	245	Van Horn Creek	3.245.1	1	R		N	Tdi	79	72	5630		80	97	FL	VW	1426	1341
3	246	Van Horn Creek	3.246.1	1	R		N	Qra	137	78	10786		30	36	FL	VW	1579	1500
3	247	Van Horn Creek	3.247.1	1	R		N	Qra	80	123	9219		120	52	FL	VW	1585	1524
3	248	Van Horn Creek	3.248.1	1	R		N	Tdi	68	61	4570		10	100	FL	VW	1347	1244
3	249	Winthrop Creek	3.249.2	2	S		Y	Qs	41	58	2622		340	32	CC	VB	1268	1253
3	250	Van Horn Creek	3.250.1	1	R		N	Qra/Tdi	176	220	40247		40	54	FL	VW	1585	1463
3	251	West Fork White River	3.251.1	1	R		N	Qra	99	107	11441		340	46	FL	VW	1707	1640
6	252	Tahoma	6.252.1	1	R		N	Tol	144	143	19750.0		170	60	FL	VW	1500	1390
5	254	Goat Creek	5.254.1	1	R		N	Tol	79	143	11405.0		325	72	FL	VW	1670	1603
7	255	Frying Pan Creek	7.255.1	1	R		N	Tol	244	120	29121.0		10	66	FL	VW	1951	1768
3	256	West Fork White River	3.256.1	1	R		N	Tdi	113	87	12661.1		15	51	FL	VW	1463	1366
3	257	Van Horn Creek	3.257.1	1	R		N	Tdi/Qra	76	201	13290.2		80	47	FL	VW	1366	1280
3	258	West Fork White River	3.258.1	1	R/T		N	Qs	124	152	18860.4		120	44	FL	VW	1341	1280
3	259	West Fork White River	3.259.3	3	D		N	Tdi	785	157	136913.7	2606311.5	30	37	COMP	VW	1219	908
3	260	West Fork White River	3.260.1	1	R		N	Tdi	613	144	84795.9		185	92	FL	VW	1878	1670
6	261	West Fork White River	6.261.1	1	T		Y	Qra	464	423	191854.7		165	64	FL	VW/D	2057	1695
6	262	West Fork White River	6.262.1	1	T		N	Qra	260	244	52478.4		175	73	FL	VW	1999	1792
6	263	West Fork White River	6.263.1	1	T		Y	Tg	208	338	48182.4		345	67	FL	VW	1902	1743
6	264	West Fork White River	6.264.1	1	T		N	Tg	49	32	1753.8		10	49	FL	VW	1780	1750
6	265	West Fork White River	6.265.1	1	T		N	Tg	63	83	3911.8		30	46	FL	VW	1762	1731
1	266	Carbon River	1.266.1	1	R		N	Tf	142	141	16716.6		280	60	FL	VW/D	1536	1451
1	267	Carbon River	1.267.4	4	D		Y	Ts/Qs	61	27	1492.2		355	25	CV	VW	579	570
1	268	Carbon River	1.268.4	4	T		Y	Ts/Qs	38	30	986.6		345	9	CV	VB	573	570
1	269	June Creek	1.269.1	1	R		N	Tf	171	696	81966.8		330	41	FL	VW	1573	1366
1	270	June Creek	1.270.1	1	R		N	Tf	243	330	49009.2		290	46	FL	VW	1463	1292
1	271	June Creek	1.271.1	1	R		N	Tf/Ts	127	86	9493.0		265	57	FL	VW	1366	1286
1	272	Falls Creek	1.272.1	1	R		N	Tg	186	267	40429.5		300	56	FL	VW	975	829
1	273	Falls Creek	1.273.1	1	R		Y	Tf/Ts	155	118	21128.7		35	63	FL	VW	1366	1244
1	274	Falls Creek	1.274.1	1	R		N	Tf	230	77	14970.3		345	74	FL	VW	1561	1378
1	275	Falls Creek	1.275.1	1	R		N	Tf	340	391	58232.2		345	39	FL	VW/D	1548	1426

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2	276	Ranger Creek	2.276.1	1	R		Y	Ts	274	264	67432.6		90	80	FL	VW	1219	975
2	277	Ranger Creek	2.277.3	3	D		Y	Tf/Ts	618	73	57398.6	242973.2	85	81	COMP	VW/D	1512	988
2	278	Ranger Creek	2.278.1	1	R		N	Tf	286	70	17341.4		155	66	FL	VW/D	1573	1378
2	279	Ranger Creek	2.279.1	1	R		N	Tf	63	308	20311.0		50	100	FL	VW	1634	1512
2	280	Ranger Creek	2.280.1	1	R		N	Tf	170	237	28615.8		45	72	FL	VW	1487	1366
2	281	Ranger Creek	2.281.1	1	R		Y	Tf	253	258	41630.9		350	48	FL	VW	1713	1573
2	282	Ranger Creek	2.282.1	1	R		N	Tf	254	409	77863.8		70	57	FL	VW	1728	1487
2	283	Carbon River	2.283.1	1	R		N	Ts	97	118	11307.2		35	79	FL	VW	1292	1195
2	284	Carbon River	2.284.1	1	R		N	Ts	182	107	20222.0		50	65	FL	VB	829	707
2	285	Carbon River	2.285.3	3	D		Y	Tg	673	126	96797.7	1749398.7	200	84	COMP	VW	1317	683
2	286	Carbon River	2.286.1	1	R		N	Ts/Tg	163	203	28619.8		340	65	FL	VW	1475	1366
2	287	Chenuis Creek	2.287.3	3	D		Y	Ts	926	185	166595.2	648580.1	355	36	COMP	VW	1561	1207
2	288	Carbon River	2.288.3	3	D		N	Ts/Tg	576	115	61727.4	83348.2	220	65	COMP	VW	1116	707
2	289	Ipsut Creek	2.289.3	3	D		N	Ts	239	215	51147.4	97327.4	345	72	COMP	VW	1079	890
2	290	Ipsut Creek	2.290.1	1	R		N	Tf	370	628	191005.2		345	85	FL	VW	1780	1402
2	291	Doe Creek	2.291.1	1	R		N	Tf	139	439	53376.5		80	62	FL	VW	1634	1463
2	292	Carbon River	2.292.3	3	D		Y	Tf/Ts	839	320	331588.0	3227726.4	15	80	COMP	VW	1585	792
2	293	Carbon River	2.293.3	3	D		Y	Tf/Ts	819	227	188433.4	1058556.8	5	96	COMP	VW	1585	792
2	294	Ipsut Creek	2.294.1	1	R		N	Tf	449	105	70508.9		275	51	FL	VW	1536	1256
2	295	Carbon River	2.295.3	3	D		Y	Ts	579	60	37017.4	29531.7	190	77	COMP	VW	1292	847
2	296	Carbon River	2.296.3	3	D		Y	Ts	524	66	39784.6	205638.6	190	74	COMP	VW	1244	853
2	297	Carbon River	2.297.3	3	D		Y	Ts	580	91	67175.1	477964.5	195	80	COMP	VW	1366	866
2	298	Spunkwash Creek	2.298.1	1	R		Y	Ts	150	206	41040.4		260	54	FL	VW	1402	1268
2	299	Crescent Creek	2.299.4	4	D		Y	Ts	172	39	7578.9		355	43	CV	VB	1451	1381
2	300	Crescent Creek	2.300.4	4	D		Y	Ts	150	82	10766.1		350	45	CV	VB	1451	1378
2	301	Spunkwash Creek	2.301.1	1	R		N	Ts	41	55	1845.7		195	59	FL	VW	1500	1475
2	302	Spunkwash Creek	2.302.1	1	R		N	Ts	89	272	21352.7		165	98	FL	VW	1670	1561
2	303	Spunkwash Creek	2.303.1	1	R		N	Ts	257	73	16528.7		5	65	FL	VW	1853	1682
2	304	Cataract Creek	2.304.1	1	R		N	Tf	443	146	78301.1		100	61	FL	VW	1512	1225
2	305	Cataract Creek	2.305.3	3	D		Y	Tf	494	242	13214.3	170464.3	155	77	COMP	VW	1756	1366

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
2	306	Cataract Creek	2.306.1	1	R		N	Qra/Qroa	97	134	12471.0		35	56	FL	VW	1707	1646
2	307	Cataract Creek	2.307.1	1	R		N	Qra/Qroa	260	206	50160.9		30	38	FL	VW	1731	1628
2	308	Cataract Creek	2.308.1	1	R		N	Qra/Qroa	352	574	14333.9		350	57	FL	VW	1890	1676
2	309	Cataract Creek	2.309.1	1	R		N	Ts	122	62	6524.2		340	49	FL	VW	1524	1451
2	310	Cataract Creek	2.310.1	1	R		N	Ts	117	140	14171.4		350	98	FL	VW	1524	1414
2	311	Cataract Creek	2.311.1	1	R		N	Ts	61	190	10433.4		290	99	FL	VW	1451	1378
2	312	Carbon River	2.312.3	3	D		Y	Ts	293	50	16431.3	204186.4	220	100	COMP	VW	1439	1073
2	313	Carbon River	2.313.3	3	D		Y	Ts	594	38	17683.2	8591.0	260	74	COMP	VW	1597	1140
2	314	Carbon River	2.314.3	3	D		Y	Ts	248	104	29011.4	102948.0	185	100	COMP	VW	1731	1378
2	315	Dick Creek	2.315.3	3	D		Y	Ts	149	65	9205.9	9533.0	215	79	COMP	VW	1390	1237
2	316	Dick Creek	2.316.3	3	D		Y	Ts	292	61	23496.6	218393.3	185	100	COMP	VW	1756	1430
2	317	Dick Creek	2.317.3	3	T		Y	Ts	81	18	1524.8	2826.0	185	70	COMP	VW	1506	1445
2	318	Dick Creek	2.318.3	3	T		Y	Ts	70	23	1681.9	2713.0	185	91	COMP	VW	1524	1451
2	319	Dick Creek	2.319.3	3	T		Y	Ts	112	22	2643.1	4182.5	185	41	COMP	VW	1573	1524
2	320	Dick Creek	2.320.1	1	R		N	Ts	107	384	32112.1		170	59	FL	VW	1817	1701
2	321	Dick Creek	2.321.1	1	R		N	Qroa	318	291	62145.0		285	41	FL	VW	1853	1682
2	322	Carbon River	2.322.1	1	T		N	Qroa	184	395	45206.1		230	68	FL	VW	1847	1719
2	323	Carbon River	2.323.1	1	R		N	Qra	128	47	6994.5		95	100	FL	VW	1463	1305
2	324	Carbon River	2.324.1	1	R		N	Qra	91	85	7990.8		25	65	FL	VW	1548	1481
2	325	Carbon River	2.325.1	1	T		N	Qra	120	149	13273.6		45	94	FL	VW	1707	1585
2	326	Carbon River	2.326.1	1	T		Y	Qs	231	207	43850.6		265	61	FL	VW	1804	1670
2	327	Carbon River	2.317.1	1	R		N	Qra	453	206	90539.3		275	47	FL	VW	2018	1753
2	328	Carbon River	2.328.1	1	R		N	Qra	271	119	34135.6		270	64	FL	VW	1926	1756
2	329	Carbon River	2.329.1	1	R		N	Qra	360	137	39861.2		260	61	FL	VW	1963	1756
2	330	Meadow Creek	2.330.1	1	R		N	Tf	99	129	11822.2		255	70	FL	VB	1439	1366
2	331	Meadow Creek	2.331.1	1	R		N	Tf	87	26	2435.6		270	100	FL	VW	1573	1475
2	332	Meadow Creek	2.323.1	1	R		N	Tf	44	42	2104.4		270	100	FL	VW	1591	1530
2	333	Meadow Creek	2.333.1	1	R		N	Tf	82	112	8914.5		340	98	FL	VW	1524	1439
2	334	North Fork Mowich River	2.334.1	1	R		N	To	63	196	15133.1		15	85	FL	VB	1109	1012
2	335	Spray Creek	2.335.1	1	R		Y	To	94	472	38585.4		190	100	FL	VW	1183	1061

Quad #	MM #	Sub-watershed	I.D. #	MM Type	Material Type	Age (If known)	Sediment Delivered?	Bedrock Type	Length (m.)	Width (m.)	Surface Area (sq. m.)	Volume of MM-As (cubic m.)	Slope Aspect (°)	Percent Slope (%)	Form	Position	Top Elev. (m.)	Toe Elev. (m.)
2	336	Crater Creek	2.336.1	1	R		N	Ts	108	46	7077.1		250	45	FL	VW	1426	1390
2	337	Crater Creek	2.337.1	1	R		N	Ts	96	326	27112.5		260	60	FL	VW	1670	1439
2	338	Crater Creek	2.338.1	1	R		Y	Tf	293	271	64941.6		295	46	FL	VW/D	1841	1609
2	339	Grant Creek	2.339.1	1	R		N	Tf	246	97	21472.6		160	61	FL	D	1939	1756
2	340	Grant Creek	2.340.1	1	R		N	Tf	118	72	7015.8		160	69	FL	VW/D	1890	1804
2	341	Spray Creek	2.341.1	1	R		N	Qroa	50	57	2184.7		190	55	FL	VW	1707	1670
2	342	Spray Creek	2.342.1	1	T		N	Qroa	178	180	20505.8		280	31	FL	VW	1689	1615
2	343	Spray Creek	2.343.1	1	R/T		N	Qra	121	23	2498.3		265	76	FL	VW	1634	1545
2	344	Spray Creek	2.344.1	1	R/T		N	Qra	194	130	17026.3		270	66	FL	VW	1585	1457
2	345	Spray Creek	2.345.1	1	R		N	Qra	134	60	5716.9		270	84	FL	VW	1426	1362
2	346	Spray Creek	2.346.1	1	R		N	Qra	64	39	2292.5		185	28	FL	VW	1402	1366
2	347	Upper Spray Creek	2.347.3	3	R/T		Y	Qroa/Qra	812	161	126550.9	3810858.9	205	49	COMP	VW	1719	1317
2	348	Upper Spray Creek	2.348.1	1	T		N	Qra	337	78	35523.8		330	56	FL	VW/D	1878	1634
2	349	Upper Spray Creek	2.349.1	1	R/T		N	Qra	96	35	2979.5		340	57	FL	VB	1475	1420
2	350	Upper Spray Creek	2.350.3	3	R		Y	Qra	148	36	3761.8	77884.6	270	71	COMP	VW	1841	1426
2	351	Upper Spray Creek	2.351.2	2	R		Y	Qra	605	72	32766.8		340	50	CC	VB	1524	1445
2	352	Upper Spray Creek	2.352.3	3	R		N	Qra	369	80	32835.8	242470.8	200	72	COMP	VW	2316	2024
2	353	North Fork Mowich River	2.353.3	3	T		Y/BLKD	Qra	83	32	3048.9	2625.0	45	94	COMP	VB	1536	1457
2	354	North Fork Mowich River	2.354.3	3	R		Y	Qra	609	56	37089.2	63698.0	0	69	COMP	D	1780	1387
2	355	North Fork Mowich River	2.355.1	1	R		Y	Qra	108	167	11081.6		340	52	FL	VW	1509	1420
2	356	North Fork Mowich River	2.356.3	3	R		Y	Qra	198	172	34641.1	29013.6	0	74	COMP	D	1622	1390
2	357	North Fork Mowich River	2.357.3	3	R		Y	Qs	252	72	16485.8	21226.4	275	69	COMP	VW	1451	1256
2	358	North Fork Mowich River	2.358.3	3	R		N	Qra	140	64	8032.4	7008.5	30	92	COMP	VW	1426	1292
2	359	North Fork Mowich River	2.359.3	3	R		N	Qra	163	46	10145.5	2684.7	25	93	COMP	VW	1433	1280
2	360	Grant Creek	2.360.1	1	R		N	Qroa/Tf	97	33	4585.8		150	53	FL	VW	1875	1817
2	361	Grant Creek	2.361.1	1	R		N	Qroa/Tf	115	45	3108.1		160	52	FL	VW	1905	1844
1	362	Mowich River	1.362.1	1	R		N	Qra	165	66	14605.3		30	61	FL	VW	1317	1183
1	363	South Fork Mowich River	1.363.1	1	R		N	Qra/Ts	112	64	6385.2		105	63	FL	VW	1469	1378
1	364	South Fork Mowich River	1.364.1	1	R		N	Qra	48	29	993.9		40	48	FL	VW	1390	1366
1	365	South Fork Mowich River	1.365.1	1	R		N	Qra	51	38	1237.8		45	64	FL	VW	1402	1372

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1	366	South Fork Mowich River	1.366.1	1	R		N	Qra	41	87	2963.6		45	32	FL	VW	1366	1350
1	367	South Fork Mowich River	1.367.1	1	R		N	Qra	115	100	210345.0		20	43	FL	VW	1481	1402
1	368	South Fork Mowich River	1.368.1	1	R		N	Qra	117	157	15913.1		0	59	FL	VW	1500	1420
2	369	South Fork Mowich River	2.369.4	4	D		Y	To	83	17	1610.7		75	22	CV	VB	1073	1055
2	370	South Fork Mowich River	2.370.4	4	D		Y	To	158	38	5379.1		35	25	CV	VB	1109	1067
6	371	South Fork Mowich River	6.371.1	1	R		N	Qra	114	202	19111.1		45	62	FL	VW	1609	1524
2	372	South Fork Mowich River	2.372.1	1	R		N	Qra	80	50	3461.6		260	43	FL	VW	1475	1439
6	373	South Fork Mowich River	6.373.3	3	D/T		Y	Qs	186	68	11478.6	20328.4	20	30	COMP	VB	1387	1329
1	374	South Fork Mowich /Rushingwater Creek	1.374.1	1	R		N	Qra	747	244	144157.4		340/30	48	FL	VW	1658	1524
1	375	Rushingwater Creek	1.375.1	1	R		N	Qra	98	119	10248.6		200	76	FL	VW	1305	1231
1	376	Rushingwater Creek	1.376.1	1	R		N	Qra	72	85	4748.0		230	72	FL	VW	1286	1231
1	377	Rushingwater Creek	1.377.1	1	R		N	Qra	78	77	3485.9		225	84	FL	VW	1366	1317
1	378	Rushingwater Creek	1.378.1	1	R		N	Qra	105	186	14329.1		190	5	FL	VW	1378	1426
1	379	Rushingwater Creek	1.379.1	1	R		N	Qra	187	81	8818.4		255	17	FL	VW	1695	1375
5	380	North Puyallup River	5.380.3	3	D		Y	Tol	973	224	207083.8	2179888.5	350	100	COMP	VW	1426	829
5	381	North Puyallup River	5.381.3	3	D		Y/BLKD	Tol	1636	729	1256166.1	9565699.1	340	100	COMP	VW	1430	853
6	382	North Puyallup River	6.382.2	2	D		Y	Tol	13	32	552.1		290	25	CC	VB	1030	1024
6	383	North Puyallup River	6.383.1	1	T		Y	Tol	72	204	13039.0		295	34	FL	VB	1091	1024
6	384	North Puyallup River	6.384.1	1	R		N	Tol	116	50	4081.2		180	69	FL	VW	1923	1838
6	385	North Puyallup River	6.385.1	1	R		N	Tol	154	49	6988.9		140	67	FL	VW	1823	1713
6	386	North Puyallup River	6.386.1	1	R		N	Tol	372	79	16690.7		0	70	FL	VW	1853	1585
6	387	North Puyallup River	6.387.1	1	R		N	Tol	250	339	64139.3		355	77	FL	VW	1853	1585
6	388	St. Andrews Creek	6.388.1	1	R		Y	Qra	82	99	5851.8		205	51	FL	VW	1731	1682
6	389	St. Andrews Creek	6.389.1	1	R		Y	Qra	157	85	16183.9		200	62	FL	VW	1622	1512
6	390	St. Andrews Creek	6.390.1	1	R		Y	Qra	146	156	14685.4		275	71	FL	VW	1682	1561
6	391	St. Andrews Creek	6.391.1	1	R		N	Qra	87	44	4672.4		300	44	FL	VW	1524	1475
6	392	St. Andrews Creek	6.392.1	1	R		N	Qra	129	340	44810.2		350	44	FL	VW	1670	1548
5	393	St. Andrews Creek	5.393.1	1	R		N	Qra	146	512	59267.6		335	41	FL	VW	1341	1247
5	394	South Puyallup River	5.394.3	3	D		N	Tol	453	96	43027.0	95418.3	80.000	60	COMP	VW	1298	1003

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5	395	South Puyallup River	5.395.1	1	R		N	Qra	285	234	60006.3		180	83	FL	VW	1317	1073
3	396	Josephine Creek	3.396.3	3	D		Y	To	478	81	47112.0	135497.3	265.000	71	COMP	VW	1756	1414
6	397	Muddy Fork of Cowlitz	6.397.3	3	D		N	Td	499	105	52891.8	118378.0	210.000	65	COMP	VW/D	1707	1390
7	398	Tahoma Creek	7.398.3	3	D		Y	Tol/To	1323	254	428581.4	2964318.0	285.000	30	COMP	VW	1158	744
13	399	Ohanapecosh River	13.399.3	3	D		Y-BLKD	To	847	120	111858.9	320303.6	100.000	36	COMP	VW	878	549
3	401	Huckleberry Creek	3.401.1	1	R		N	To	86	95	6797.9		105.000	50	FL	VB	1606	1564
3	402	West Fork White River	3.402.1	1	R		N	Tdl	152	55	7864.9		340.000	47	FL	VW	1609	1573
2	403	Mowich River	2.403.1	1	R		N	Qra	41	88	3113.3		250.000	49	FL	VB	1323	1292
3	404	West Fork White River	3.404.1	1	R		N	To/Ts	78	57	4341.4		40.000	49	FL	VW	1567	1530

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U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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