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Geomorphology of Coastal Olympic National Park

Natural Resource Report NPS/NCCN/NRR—2021/2260



ON THE COVER
Near Hole-in-the-Wall, Olympic National Park, Washington
NPS / Jon Riedel

Geomorphology of Coastal Olympic National Park

Natural Resource Report NPS/NCCN/NRR—2021/2260

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North Cascades National Park
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Executive Summary

The surficial geology of coastal Olympic National Park (OLYM) was surveyed from 2012-2016 to help meet the goals of the Natural Resources Challenge Inventory Program of 1998. Coastal OLYM contains a rich collection of landforms created by the intersection of a variety of processes. The influence of glaciation and active tectonic processes on coastal processes makes this unit unique in NPS managed coastlines.

This coastline is a stunning landscape created by the interaction of dynamic tectonic, coastal, glacial, mass-wasting and fluvial processes of erosion and deposition. These processes created 802 distinct landforms, from the rare (two tombolos) to the plentiful (hundreds of sea stacks) and the inviting (74 sand beaches) to the treacherous (26 headlands). Glacial landforms, including moraines, ice-walled lake plains and drift mantled bedrock hills are the most extensive landforms. Second in abundance are glacial outwash terraces deposited during the ice age at the mouths of the Hoh and Quillayute rivers. Landforms common on most coastlines that we did not observe, due to the Olympic coast's active tectonics and high wave energy, include long barrier islands, deltas at the mouths of large rivers and extensive sand dunes.

We identified three distinct sections of coastline, where certain types of foreshore landforms are associated with backshore and tectonic conditions. In the northernmost section, from Shi Shi Beach to Cape Johnson, the Cordilleran ice sheet (CIS) inundated the coast, bringing erratic rocks from Canada and shaping the hills and valleys. Thrust faults are also common near the coastline in this section. These faults are linked to the formation of headlands, sea stacks and wave cut platforms. Point of the Arches stands out due to its many sea stacks, an unusual collection of folded thrust faults and igneous rocks of Mesozoic age. The sedimentary bedrock along most of the coastal zone is much younger. From Cape Johnson to Hoh Head, glacial deposits are absent or severely eroded, giving this section of coast a slightly different geomorphology although the thrust faults (and associated landforms) remain. Coastal bluffs in this area are mostly composed of intensely weathered bedrock that is failing by deep-seated slumping, particularly where undercut by winter waves. Beaches are smaller and crescent shaped, tending to be coarser-textured. South of Hoh Head to Kalaloch, the coastal bluffs consist of layers of alpine glacial outwash and occasional beds of peat and lacustrine deposits of silt and clay. No nearshore thrust faults have been mapped in this section of coastline and there are few wave-cut platforms. Instead, long wide sandy beaches are the dominant landform.

Along the entire coast backshore zone, coastal bluffs are 37% bedrock and 41% glacial drift, with approximately 15% of the backshore area composed of floodplains and terraces, concentrated near the mouths of the Hoh and Quillayute rivers. Many of the coastal bluffs are failing due to wave undercutting and pervasive chemical and physical weathering under several hundred inches of rain that falls annually and mild coastal temperatures. We identified 45 individual landslides, but many of these are features that include many other smaller landslides, or those that have coalesced and were not distinguishable as individual failures. Glacial landforms such as moraines and outwash terraces also occur throughout the backshore zone and an unusual landform called an ice-walled lake plain

occurs west of Ozette Lake. These features form where large masses of the ice sheet stagnated in and near the lake basin and underlie the modern-day prairies.

In addition to sea stacks and wave cut platforms, the foreshore area has a diverse collection of landforms including 174 beaches. The largest and most common beaches are composed of sand and are found adjacent to bluffs composed of glacial outwash from Kalaloch north to Hoh Head, and fronting the glacial drift bluffs west of Ozette Lake. Gravel beaches are associated with the mouths of large rivers, where bluffs are composed of glacial drift, or where small bays are divided by headlands and wave energy is high. Boulder and cobble gravel dominated beaches are not that common and cover only about 1% of the park's foreshore zone. Beaches at OLYM are also renowned for their collections of large wood from the peninsula's rain forests. The beaches north of the Hoh and Quillayute river mouths are covered in hundreds of giant logs.

The age of the coastal landforms varies substantially. Most of the glacial sediments date to the last great ice age. North of Cape Johnson the ice sheet deposits are about 15,000 years old. South of Scott Creek, to the Hoh River and to Kalaloch, the glacial deposits are from alpine glaciers and much older, with some bluff sediments as old as 70,000 years or more. The age of glacial deposits between Cape Johnson and Scott's Creek would be a rich area for further research. Age of bedrock landforms such as headlands, sea stacks and wave cut platforms is difficult to determine. However, on this high-energy coast, rates of coastal recession are probably near 10-30 m per century, or more. At this rate of erosion, most of these landforms are not enduring and are likely less than a few centuries in age. The ages of two important landforms, marine terraces and wave-cut platforms, may be related to cycles of coastal up-lift and down-drop. These events are associated with large and powerful subduction earthquakes, the last of which occurred in January 1700 A.D.

Data contained in this report has several important management implications. Landforms provide critical information on three of five soil forming factors, including parent material, time and relief and are also closely linked to vegetation. Combining landform, soils and vegetation data will allow park staff to unlock important ecological relationships, identify habitat for key species of plants and animals and guide ecological reference site selection and restoration. Many of the landforms mapped provide information on past climate change and destructive subduction zone earthquakes. Data included in this report will also assist with cultural resource management because landform age and topography are directly related to the density of archeological sites. Many areas of further study are identified related to dating prominent landforms along the coast. Finally, this report contains many stories about the natural history of the park that interpreters can share with the public. These stories include prehistoric use of the park, the evolution of the coast, the interaction of glacial, tectonic and coastal processes and the unique natural history of OLYM's coastline.

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Introduction

Background

Landforms of coastal Olympic National Park (OLYM) were mapped to help meet the goals of the national Geologic Resource Inventory (GRI) program (Figure 1). The goals included production of digital geology maps and a geologic resource inventory report. The North Coast and Cascades Network (NCCN) resource managers and scientists chose to emphasize surficial geology mapping over bedrock geology as the focus of the GRI at a late 1990s scoping meeting in Seattle organized by the Geologic Resources Division. This emphasis was made because information on surficial deposits has a greater relevance to management of land and water resources in mountain parks (e.g. geologic hazards, soils, floodplains). Further, the bedrock geology at OLYM was being mapped at an appropriate scale of 1:100,000 to meet management needs (Gerstel and Lingley 2000, Schasse 2003). Mapping protocols were developed by staff at North Cascades National Park and emphasized mapping of landforms as an accurate, useful way to capture the diverse surficial geology and dynamic landscape at the 922,881-acre park. Landforms are created by discreet geologic processes of erosion and deposition, including coastal, glacial, fluvial and mass wasting. Many of these landforms are common features of coastal areas and include beaches, headlands, bluffs, arches, sea stacks and marine terraces (Figure 2; Appendix A).

Landforms provide a physical basis for understanding coastal ecosystems and can guide the selection of long-term reference sites. They also contain information to help manage geologic hazards, floodplains, facility locations, cultural resources, fisheries and terrestrial and aquatic ecosystems. Landforms summarize the park's more recent geologic and climatic histories, including the last ice age. Landforms are inherently linked to vegetation and soils, providing information on three of the five soil forming factors, including time, parent material and topography (climate and vegetation are the others). Therefore, the landform mapping at OLYM was integrated with the soil resource inventory, as it was at other NCCN parks.

The remainder of this inventory report is organized into six main parts. There is a brief summary of the geology and geologic history of the coastline obtained from published literature. It includes a discussion of how tectonic, coastal, glacial, fluvial (river) and hillslope processes create landforms. Next is a short review of climate and vegetation. Methods used to map the landforms are described in section four. Results are summarized in two parts, including a standard results section as well as a synthesis which links distinct geologic processes to the assemblage of landforms. Appendix A provides a description of the landform units identified and mapped. In addition to this report, digital landform shapefiles form the other main deliverable to OLYM.

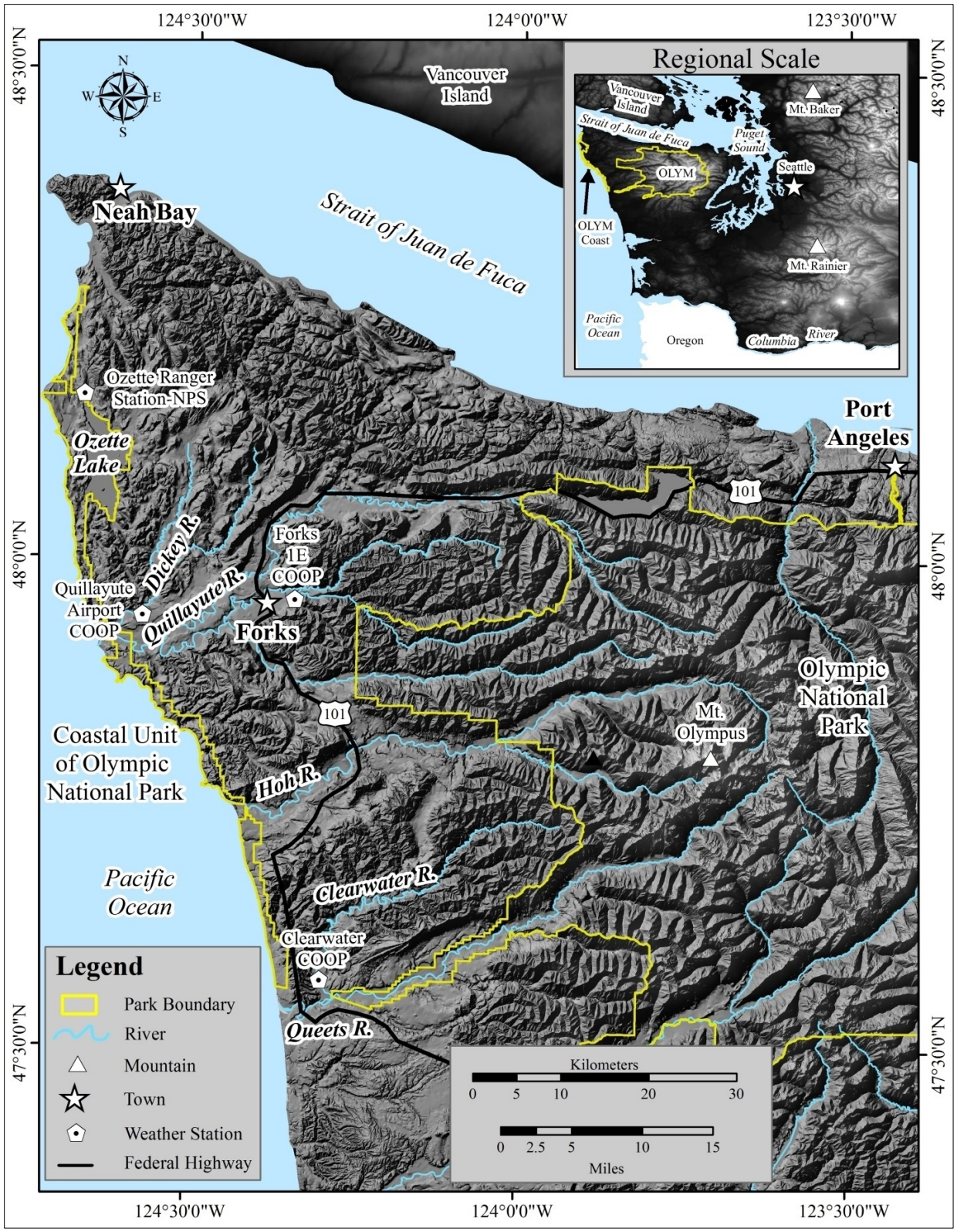


Figure 1. Location of the coastal unit of Olympic National Park.

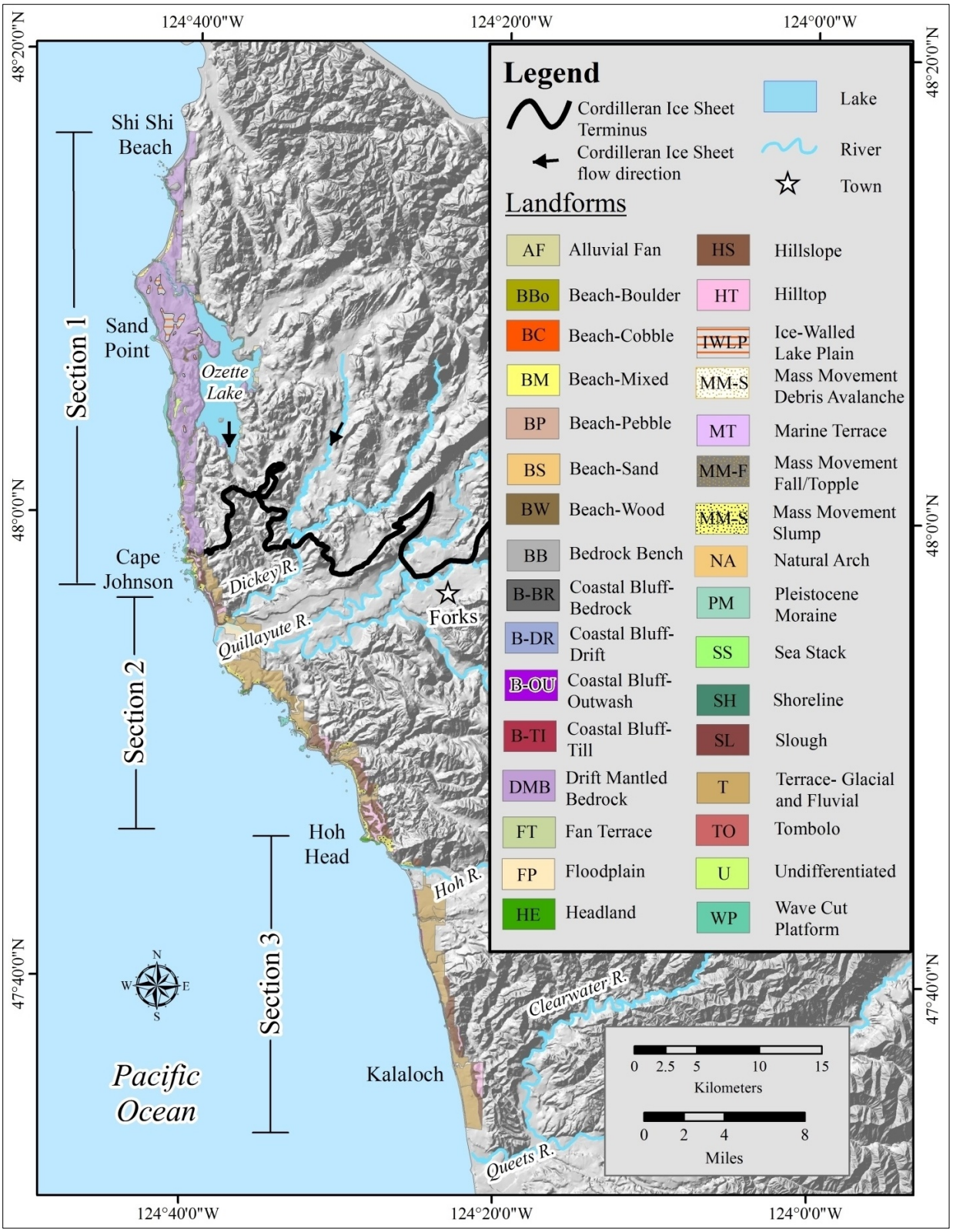


Figure 2. Coastal Olympic National Park landforms and Cordilleran ice sheet terminus (black line).

Geologic Setting

The geology of the Olympic Peninsula was created largely by the collision of the Juan de Fuca oceanic plate with North America (Figures 3 and 4). The ocean plate moves beneath the continent by a process called subduction. Subduction of the Juan de Fuca plate created a thick accretionary wedge of sediment added to the continental margin (Tabor and Cady 1978b). The accretionary wedge is formally designated as the Olympic Structural Complex (OSC) by Stewart and Brandon (2004). The OSC was formed at the edge of the continent were sediments were successively peeled off and stacked; basaltic oceanic crust was also incorporated. The heat and pressure of burial caused low-grade metamorphism, forming the shales, schists, phyllites and greenstones found in the inner core of the peninsula. Subduction also led to the uplift of the Olympic Mountains and parts of the coastline (Brandon and Vance 1992).

The coastline has been greatly shaped over the past 6,700 years by large subduction zone earthquakes, which have an estimated reoccurrence interval of 500 years (Atwater et al. 2005). Subduction earthquakes have been dated in coastal marshes along the coastline and occurred 0.3, ~1.1, ~1.3 and 1.7 Ka (Atwater et al. 2004; ages of landforms are reported in thousands of calibrated years before present). Tsunami waves generated by these earthquakes have reached as high as 11.5 m above modern sea level near Sand Point (Peterson et al. 2013). The last major subduction earthquake occurred on January 26, 1700 and had a magnitude of 9 on the Richter scale (Atwater 1987, Satake et al. 1996).

Bedrock on the coast is exposed in headlands, sea stacks, natural arches and bluffs. The coastal unit of OLYM is mapped within the coastal structural sheet as defined by Gerstel and Lingley (2000) and the majority of the bedrock is mapped as the Coastal Unit of the OSC, formerly known as the Hoh Formation (Weaver 1916) and the Hoh lithic assemblage (Rau 1973, Tabor and Cady 1978a). This unit is composed of turbidites and mélange (mixed) sedimentary deposits that contain deep-water microfauna. Mudstones make up a majority of the mélange, along with sandstones and siltstones. The sediments were deposited by rivers into the Pacific Ocean and lithified to varying degrees (Peterson et al. 2010). They have undergone metamorphism and deformation due to burial and tectonic forces. Basalts erupted mostly in a marine environment are also present (Figure 3).

Bedrock on the Olympic Peninsula is primarily of Tertiary age, apart from Point of the Arches along the northern coast, where the bedrock is Mesozoic (> 66.4 Ma; Figure 3). Most of the sediments were deposited in the early Miocene (ca. 24 to 16 Ma; Stewart and Brandon 2004). Some deposits are of Eocene age (ca. 58-36 Ma) and are only found in shear zones (Gerstel and Lingley 2000).

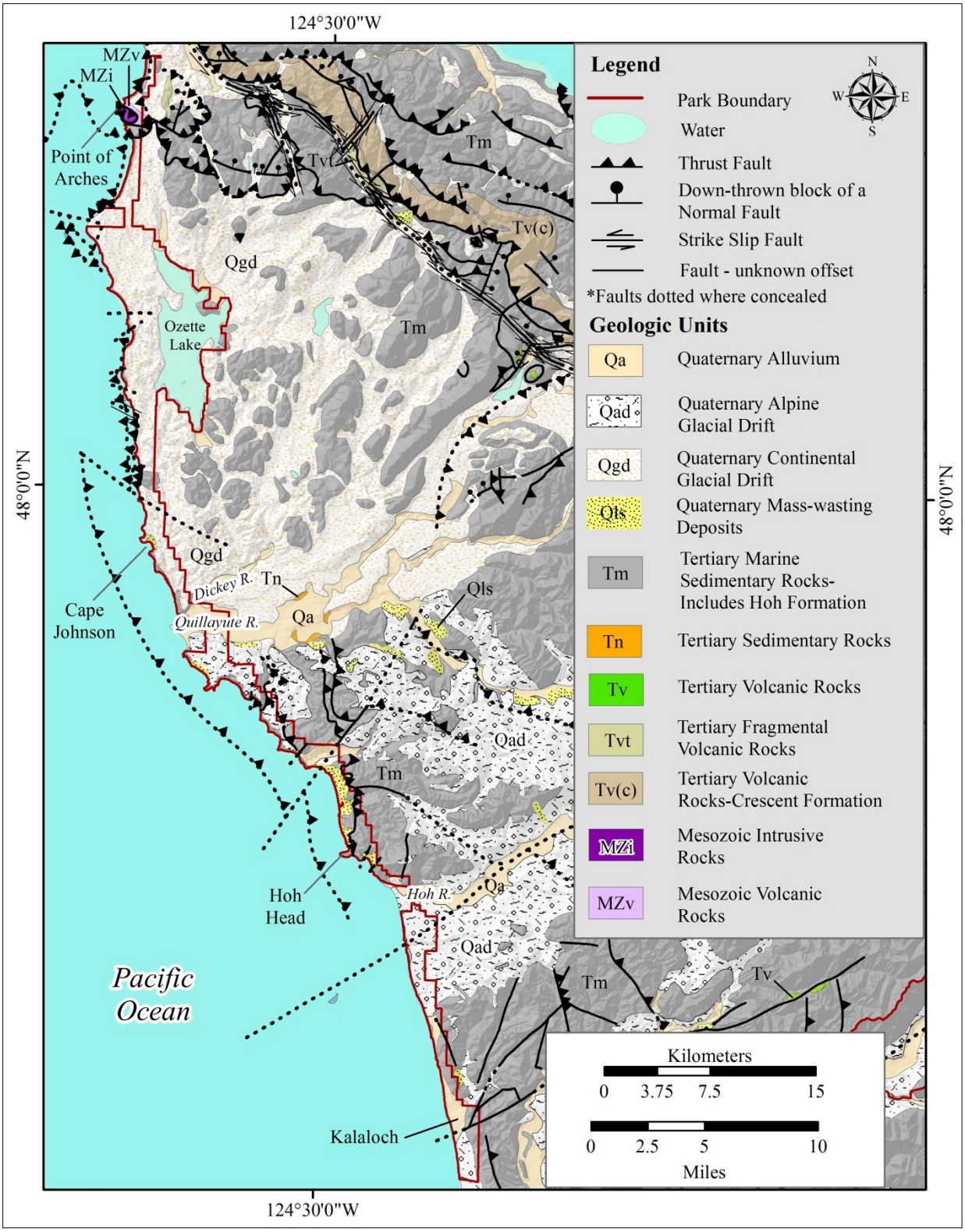


Figure 3. Geology of coastal Olympic National Park. Modified from 1:100,000 scale maps by Gerstel and Lingley (2000) for area south of Ozette Lake and by Schasse (2003) to the north of Ozette Lake.

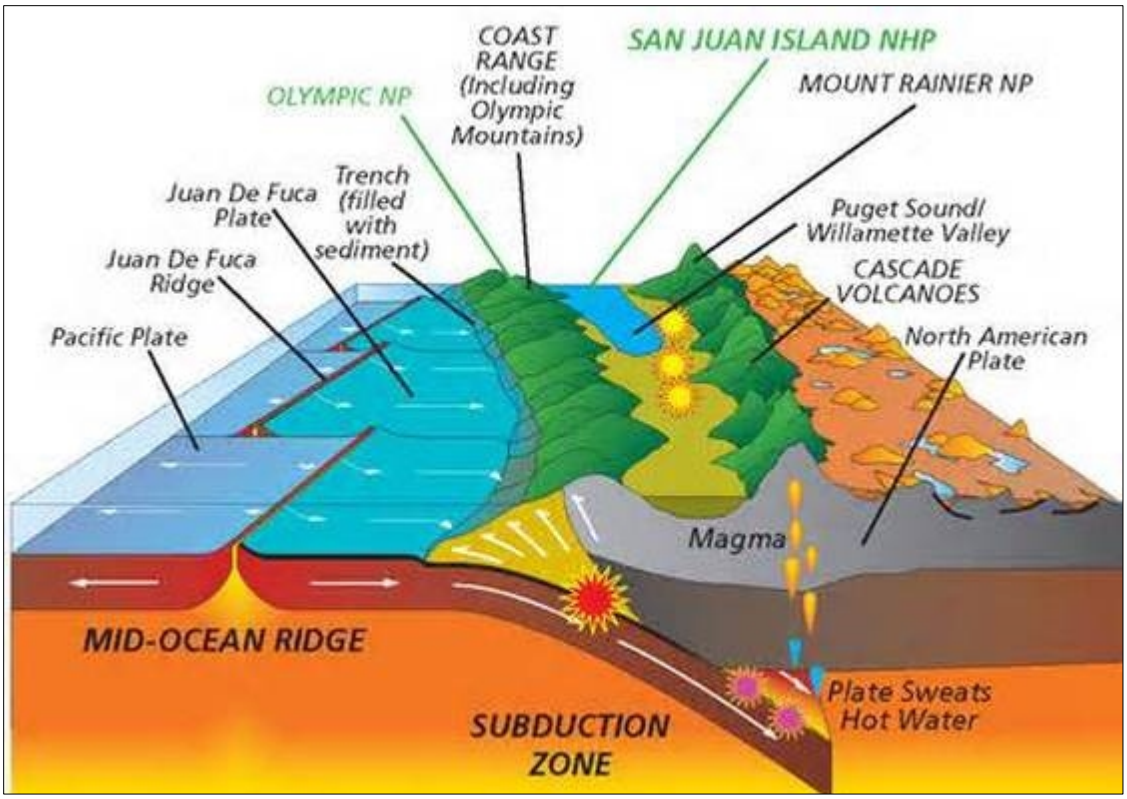


Figure 4. Subduction of tectonic plates in the Pacific Northwest. Starbursts show three types of earthquakes, including subduction (red), deep ocean plate (purple) and shallow crustal (yellow) (Lillie 2005).

Stress exerted on these volcanic and sedimentary rocks by tectonic forces caused by subduction creates breaks in the crust called faults, which are mapped throughout the study area (Gerstel and Lingley 2000, Schasse 2003). Thrust faults are where older layers are thrust atop younger layers by compressive forces of plate collision. Normal faults also occur along the coast, often perpendicular to the thrust faults, and occur in areas where the crust is being stretched (Figure 5). These breaks in the earth's crust occur as rock on one side of the fault moves downward relative to the other side.

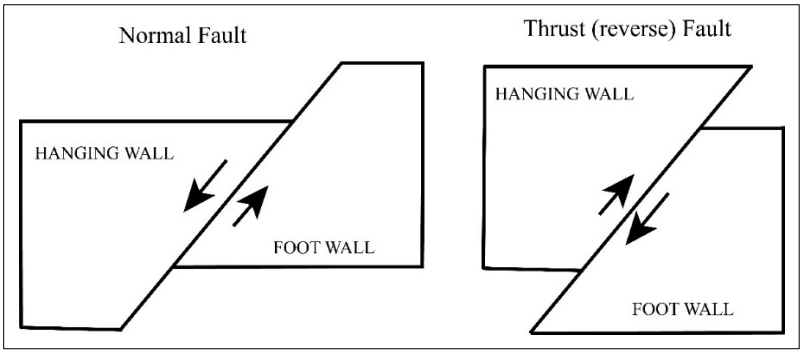


Figure 5. Types of faults along the Olympic Coast.

Glacial Geology

The majority of the coastline is dominated by Quaternary deposits of sand, gravel, silt and clay left by continental and alpine glaciers during multiple glacial episodes over the past 2.6 Ma (Figure 3). These large glaciers also fed massive amounts of sand and gravel down major coastal rivers such as the Quillayute and Hoh.

Alpine glaciers flowing down Olympic Mountain valleys and continental ice sheets from Canada reached to and across the modern coastline on multiple occasions at several locations (Figure 6). At the south end of the coastal strip, meltwater from alpine glaciers in the Hoh, Quinault and Queets valleys deposited vast sheets of sand and gravel (outwash) along the coast. The oldest exposed are known as the pre-Wolf Creek Formation, thought to be middle Pleistocene in age (~1 Ma; Thackray et al. 2015). Most of the coastal bluffs south of Hoh Head are made of outwash and lake deposits that are from the late Pleistocene, about 120 to 14 Ka. At least five periods marking the advance of the alpine valley glaciers are recorded by layers of outwash, including the most extensive advance known as the Lyman Rapids that occurred about 70 Ka (Thackray 2001). These glaciers also reached advanced positions and built moraines within 15 km of the modern coastline about 35 Ka (Hoh Oxbow advance) and about 21 Ka (Twin Creeks advance). Smaller advances after that time were limited by the influence of continental glaciers on climate (Thackray 2001). Following the end of the last ice age about 11.6 Ka, alpine glaciers in the Olympic Mountains probably reached their minimum extent since the last ice age about 8 Ka (Heusser 1958 and 1977, Osborn et al. 2012). In the next several thousand years they advanced and retreated several times during the Neoglacial Period (Porter and Swanson 1998). None of these advances came close to the coastal unit of the park, however, and were instead limited to within 10 km of valley heads.

Continental ice sheets also reached the northern coast multiple times. Only deposits from the most recent glaciation have been recognized (Figure 3; Schasse 2003. Gerstel and Lingley 2000). Sometime after about 16.3 Ka the Cordilleran ice sheet (CIS) reached its maximum extent on the Olympic Coast (Haugerud and Hendy 2016, Troost 2016). It flowed west along the Straits of Juan de Fuca, southwest across the northwestern tip of the peninsula, then south along the coast to Cape Johnson, terminating near the Quillayute River (Figure 6; Waitt and Thorson 1983). The ice was at least 1065 m thick on the northern edge of the Olympics (Tabor and Cady 1978b). It generally subdued the pre-existing topography, filling valleys and rounding ridges.

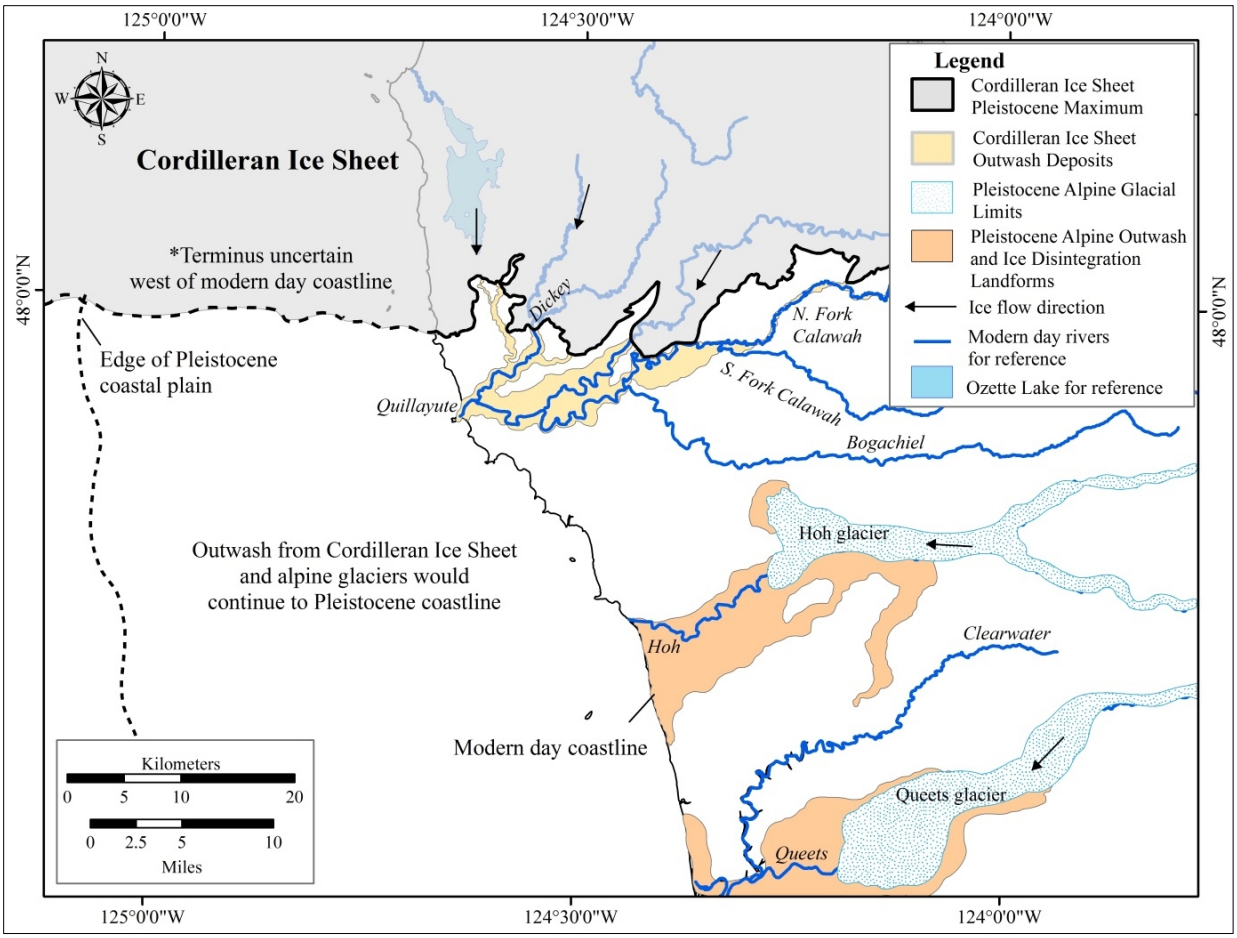


Figure 6. Glacial Map of the Cordilleran ice sheet terminus and associated outwash deposits and marine isotope stage 4 (Lyman Rapids) limits for alpine glaciers in the Hoh and Queets valleys (Thackery 1999 and 1996). Extent of Bogachiel alpine glacier advance and outwash unknown.

Coastal Geology and Processes

Plate subduction along the coast of OLYM is currently raising the coast 1.2-3 mm/year, with higher rates to the north (Verdonk 2006). Subduction earthquakes may drop the coastline by a meter or more (Atwater et al. 1997, Clague 1997). Modern sea level is rising about 0.7 ±0.2 mm/year in the southern part of the OLYM coast and is currently stable at the north end (Engelhart et al. 2015). The higher rate of uplift to the north is out-pacing sea level rise, with sea level falling at Neah Bay. About 600 years ago relative sea level on the northern OLYM coast was 0.5 m higher than today (Engelhart et al. 2015).

Unrelenting, powerful waves erode coastal bluffs and headlands leading to recession of the coastline. Coastal recession of bluffs and headlands has not been measured directly at OLYM but is probably episodic. Greater rates of erosion likely occur after subduction earthquakes because lowering of the coast effectively brings waves into direct contact with steep landforms (Brown et al. 2003). The rate of coastal recession at other sites globally is about 20-30 m/100 years in glacial drift, 10-20 m/100 years in sedimentary rocks and less than 1 m/100 years in crystalline and volcanic rocks (King 1972).

More recent estimates in mudstone and conglomerate cliffs in New Zealand are an order of magnitude higher at 230-440 m/100 year, respectively, but these cliffs are not fronted by beaches and end in deep water (Gibb 1978). Coastlines dominated by sandy beaches were examined at >1200 transects from La Push south past the boundary of OLYM; the results indicated an average retreat rate of 40 m/100 years from the 1920s and 1930s to 2002 for sand beaches (Ruggiero et al. 2013). Higher rates of erosion were noted to the south, with roughly half of the beach transects examined eroding.

Erosion of steep slopes at the base leads to landslides and the introduction of cobbles and boulders to adjacent beaches. Sediments brought to the coast by rivers and bluff erosion are redistributed by longshore currents, tides and waves. The tidal range at La Push is about 3.9 m, and high tides are increased by strong offshore winds (NOAA 2018). Waves reaching the coast from the open Pacific Ocean are large and powerful. Waves taller than 10 m occur during winter storms, with 95th percentile mean winter wave power approaching 3 Joules/m (personal communication, Ian Miller, Coastal Hazards Specialist for the Washington Sea Grant program, email, 2018.). This amount of force is enough to move sand and pebble gravel seasonally and daily up, down and along the beaches.

Waves directly control the texture, shape and stability of beaches. Summer beach profiles tend to be shallower, and coastal bluffs are protected by berms (Komar and McDougal 1994). In winter, high-energy storms reshape the beaches and create steep gravel beach profiles. Gravel and mixed beaches are steeper because wave energy stacks up gravel coming in, but swash/return waves are smaller because water percolates into gravels with relatively high porosity. The null line is a point near the wave breaker zone; offshore from this point, sediment is not transported by waves, and landward the net movement is toward the shore (Figure 7). Sand erosion occurs beneath breakers and in the swash zone on shore where waves collide with backwash. At OLYM the null point changes with the diurnal tide cycle and during winter storms with bigger waves, and with each passing large earthquake that could lower the coast by 1-2 m or more (Gibb 1978, Atwater and Hemphill-Haley 1997). Wave refraction around headlands is an important process that moves sediments from eroding bluffs and rivers to create drift cells and beaches (Komar and McDougal 1994). Wave energy generally converges on headlands and diverges in bays.

Drift cells form between each headland and are controlled to some extent by the angle at which waves reach the coast. At points where longshore currents merge, rip currents are formed that move off the coast. These currents are narrow and strong (2 m/second; Sonu 1972) and move sediments offshore where longshore drift moves them along the coastline. Nearshore ocean currents are also influenced by large rivers that punctuate the coastline, with diverging longshore currents near river mouths.

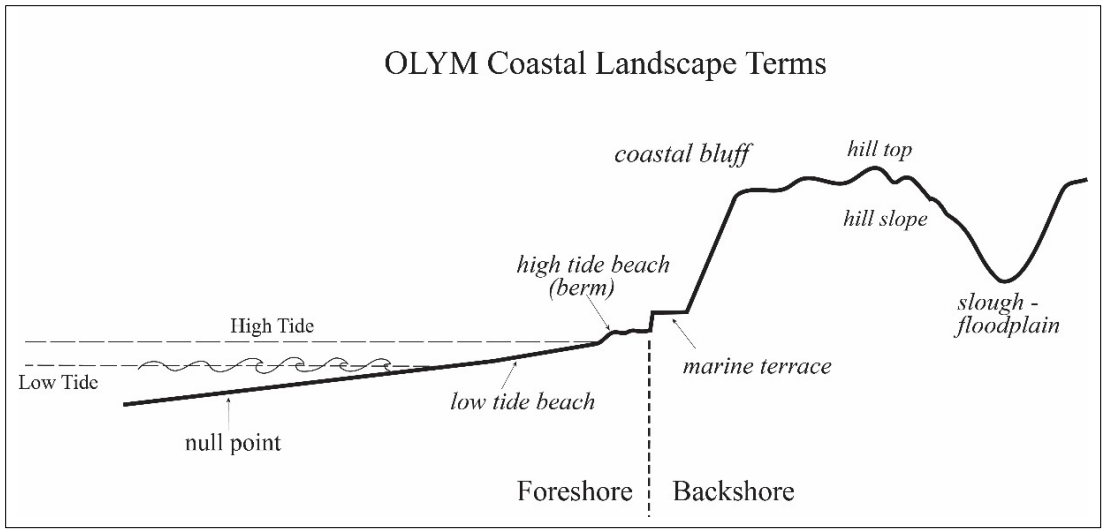


Figure 7. Schematic cross-section of coastal landforms and zones related to tides.

Tsunami waves are much larger than wind-driven waves and are a product of large submarine earthquakes. Peterson et al. (2013) found that the 1.3 Ka subduction quake led to an 11.5 m high tsunami wave on the peninsula coastline. This wave reached as far as 4.5 km inland in the Waatch Creek valley near Cape Flattery. Presumably, similar sized waves would reach several kilometers inland along the estuaries of all OLYM coastal rivers.

Beaches are nourished with sand laterally along the coast in the longshore currents that reach 100 cm/second and move sand parallel to the coast (Ingle 1966). Longshore currents redistribute sand up the coast from south to north (Swartz et al. 1985, Peterson et al. 2013). Beaches south of the Quinault River are fed by the Columbia River Littoral Cell and show net aggradation (Ruggiero et al. 2013). It is not clear how far north sediment from this littoral cell reaches. Sand and finer gravel at OLYM is likely from more local sources, including erosion of glacial sediment in coastal bluffs and the Hoh and Quillayute Rivers (Peterson et al. 2010). The strength of longshore currents also change with the seasons as summer winds shift to the northwest. Small, south-directed longshore currents tend to be shorter, and are found at the south end of Shi-Shi Beach, south of Ozette Reservation, just north of Sand Point, at Rialto Beach and at Strawberry Bay (Washington Department of Ecology 2018).

Climate

Climate at OLYM is primarily influenced by latitude and proximity to the Pacific Ocean, and secondarily by the mountain topography to the east (down-wind). It is the dominant driver of the physical and ecologic processes at OLYM (Davey et al. 2006). The climate along the coast is monitored by rainfall and temperature data from both National Weather Service Cooperative Network stations (NWS-COOP) and NPS Ranger Stations along or near the coast (Figure 1). A summary of that data is presented below (Tables 1 and 2).

Table 1. Summary of site data for NWS-COOP and NPS stations.

Station Name*	Station Type	Elevation (m)	Forest Zone	Temperature Record	Precipitation Record
Kalaloch Ranger Station	NPS	13	Coastal	2011-2015	1966-2015
Ozette Ranger Station	NPS	9	Coastal	2003-2015	1982-2015
Quillayute Airport	NWS-COOP	55	Coastal	1966-2015	1966-2015
Clearwater	NWS-COOP	25	Lowland	1895-2012	1895-2012
Forks 1E	NWS-COOP	107	Lowland	1931-2008	1931-2008

*Sources: National Weather Service 2015 and William D. Baccus, National Park Service, email, 2015. Data are provisional and subject to revision.

Table 2. Summary of temperature and precipitation data from NWS-COOP and NPS stations.

Watershed	Average High Temperature (°C) / Month	Average Low Temperature (°C) / Month	Average High Precipitation (cm) / Month	Average Low Precipitation (cm) / Month	Mean Annual Precipitation (cm)
Queets	14.4 / August	4.78 / January	34.65 / December	5.36 / July	248.36
Ozette	15.1 / August	5.31 / January	32.89 / January	5.56 / July	223.52
Quillayute	20.4 / August	1.44 / December	37.34 / November	5.54 / July	259.36
Clearwater	21.4 / August	1.06 / January	43.56 / November	5.99 / July	295.93
Calawah	22.5 / August	7.17 / January	47.27 / December	5.82 / July	299.44

*Sources: National Weather Service 2015 and William D. Baccus, National Park Service, email, 2015. Data are provisional and subject to revision.

Winter rain and summer drought characterize the temperate, maritime climate of the Olympic coast. About 93% of annual precipitation falls between September and May when the Pacific storm track brings rain in the lowlands and snow in the mountains (Henderson et al. 1989). A high-pressure area eventually develops off the coast of Oregon and Washington and keeps the Olympic coast drier during late spring into early fall. Based on climate data there appears to be little difference in temperature or precipitation between sites on the north and south ends of the coast (Baccus et al. 2013). There is a noted difference between sites closest to the coast (Kalaloch and Ozette) and those inland (Quillayute, Clearwater and Forks). Coastal fog generally envelops the coast during the month of August and has a strong effect on temperature. This moderating effect of the Pacific Ocean results in cooler summer and warmer winter temperatures along the coast compared to inland (Baccus et al. 2013). Precipitation increases inland due to orographic uplift over the mountains.

Vegetation

The Pacific coastal temperate rainforest, extending from northern California to southeast Alaska, is characterized by some of the highest biomass accumulation and most productive forests in the world (Franklin and Dyrness 1973). OLYM is in the Northwest Coast ecoregion which includes the Coast Ranges from Oregon north to Vancouver Island, British Columbia. Climate, topography and

elevation strongly influence vegetation patterns. The coast contains vegetation of varying types and growth habits that are different than are found in the interior of the peninsula (Crawford et al. 2009). Some landforms have strong associations with vegetation types or are characterized by the absence of vegetation due to wave action.

Tree species that are present in the maritime strip along the Pacific Ocean mountains include Sitka spruce (*Picea sitchensis),* western hemlock (*Tsuga heterophylla)* and western red cedar (*Thuja plicata)*. These species are found below 500 feet where there is a strong summer fog layer that can reach up to 2000 feet in elevation in valleys along the coast (Henderson et al. 1989). The coastal forest thrives in 200-300 cm of annual precipitation, with Sitka spruce either being the dominant tree species or co-dominant with western red cedar on hillslopes, hilltops and terraces. In these coastal forests, red alder (*Alnus rubra*) is present in recently disturbed sites, such as debris cones, floodplains and sometimes slumps. Other tree species mapped along the coast in smaller numbers are Bigleaf maple (*Acer macrophyllum*), Pacific silver fir (*Abies amabilis*), Douglas-fir (*Pseudotsuga menziesii ssp. menziesii*), Shore pine (*Pinus contorta* var. *contorta*) and Western Yew (*Taxus brevifolia*) (Crawford et al. 2009). Several of these species are common on marine terraces.

The understory vegetation on the Olympic coastline and adjacent lowlands is a significant ground cover on most landforms, with beaches, wave-cut platforms, tombolos and natural arches being the exception. Common species within these groups includes red huckleberry (*Vaccinium parvifolium*), Alaska huckleberry (*Vaccinium alaskaense*), salmonberry (*Rubus spectabilis*), salal (*Gaultheria shallon*), vine maple (*Acer circinatum*), sword fern (*Polystichum munitum*), lady-fern (*Athyrium felix-femina*), oxalis (*Oxalis oregana*), false lily-of-the-valley (*Maianthemum dilatatum*), Siberian miner's lettuce (*Claytonia sibirica*) and foamflower (*Tiarella trifoliata*) (Henderson et al. 1989). It should be noted that all of these species exhibit vigorous growth and an overall increased size from their counterparts east of the Olympics. Near the coast there are also small patches of upland vegetation that are strongly affected by high winds and sea spray, which can be found on top of bluffs, hilltops, and headlands. These zones consist of small grasslands in a mosaic with stunted trees and shrub lands (Crawford et al. 2009). In the area around Ozette Lake, lowland forest and bog-type vegetation are present as well on the shoreline and sloughs, with a notable population of rare and threatened plant species (Acker and Olson 2009). For an extensive summary of vegetation associations found on various landforms along the coast, refer to Crawford et al. 2009.

The prairies near Ozette Lake are primarily a mix of bog and wetland species, such as sedge, bog laurel, and Labrador tea, that can tolerate the wet and acidic nature of the soils such as sedge, bog laurel and Labrador tea. The persistence of these open prairies has been attributed to anthropogenic activity in the form of burning. At about 2000 years before present, forested swamps were replaced by wetland vegetation and the record shows a frequent fire return interval, suggesting human-caused low-intensity burns (Bach and Conca 2004). Bach and Conca (2004) have also documented encroachment of forest on both Roose's and Ahlstrom's Prairies' that correspond with the abandonment of homesteads (80 years ago for Roose and 50 years ago for Ahlstrom). Areas around the wetland on higher ground with drier soils include Western red cedar, Western hemlock, yellow cedar and Sitka spruce, with an understory primarily of salal.

Methods

We focused on mapping of landforms to complete the GRI at coastal OLYM (Figure 2). Landforms provide a convenient, accurate way to map surficial geology because they are recognizable and provide important information on how and when the landscape was created. A total of 31 distinct landforms were identified to map the surficial geology of the coastal zone at OLYM (Figure 2). During the inventory we modified original list of landforms to include newly discovered features. Sources for the landform units include several geomorphology textbooks and features noted on the NPS GRD coastal inventory features list for Point Reyes National Seashore (Ritter 1982, Bloom 1978). A list of these units is given in the legend on Figure 2, with detailed descriptions of each landform provided in Appendix A.

Our approach to the landform inventory included a mix of office and field methods used to map landforms at other parks in the NCCN. This included a three-step process:

1) Initial mapping on topographic maps and Light Detection and Ranging (LiDAR) hillshades using aerial photographs and a review of published maps and reports;

2) Field reviews of the coastline, focusing on landform identification on the nearshore and coastal bluffs; and

3) Verification of the landform boundaries and digitizing in GIS.

This inventory also includes a brief synthesis linking landforms to geologic processes of erosion and deposition that have direct relevance to park management, including earthquakes, faults, waves, glaciers, rivers and landslides. The synthesis is based on review of literature on coastal geomorphology, previous geologic mapping at OLYM and field observations.

Initial Mapping

Initial mapping at 1:24,000 scale was based on USGS topographic maps, 1:12,000 scale, National Agricultural Inventory Program aerial photographs, published geologic maps and reports, a 10 m digital elevation model, and where available, LiDAR data. Though some landforms (e.g., beaches and shorelines) are easily identifiable using air photos, other landforms that are beneath a closed tree canopy require field verification (e.g., terraces, landslides). The minimum size for a mapping unit is approximately 1,000 m^2. Individual tide pools, sea caves, small sea stacks and many other important coastal features are not mapped at this scale. They are often associated with individual landforms, however, and these associations are described in the unit descriptions and in this report.

Field Methods

Before entering the field, a task list of areas to visit, logistics and access was developed. As much ground as possible was surveyed, but effort was concentrated along the foreshore and coastal bluffs, and the area surrounding Ozette Lake. These areas were chosen because of landform diversity and access. Two geologists field checked these areas in 2012-2013, and another geologist revisited all of the foreshore in 2016 to assess changes in beach texture. The main mapping was conducted by two

geologists with extensive landform mapping experience at all six other units in the NCCN, including coastal areas at Ebey's Landing and San Juan Island.

Areas that were not mapped include most of the Quillayute, Hoh, or Ozette Reservations. We also infrequently explored deep into the backshore or off trail around Ozette Lake due to time and access (dense vegetation, steep slopes). We did survey a short distance up coastal rivers to identify terraces. In areas we did not visit we relied on published geologic maps and LiDAR bare-earth and 10m NED digital elevation models. Some areas outside, but adjacent to the park were mapped to include entire landform units, and to provide important context for the landforms and processes operating in the park. We mapped most of the low tide beaches and wave-cut platforms visible during late summer low tides, but our mapping focused on the foreshore (tidal limits) and adjacent coastal bluffs (Figure 7). We did not systematically map offshore islands since they are outside OLYM, but we include them on our map for reference.

While in the field, geologists drew landform boundaries on USGS 7.5-minute maps or adjusted boundaries previously mapped in the office. We periodically drew cross-sections to understand landform relationships. Interesting landforms were noted and additional information about terrace heights, landform associations, buried wood and landform sediment type were recorded in field notebooks and archived at the NPS office in Marblemount, Washington.

The Wentworth scale for classifying beach texture was used, and assignments were made qualitatively based on experience. The use of three different geologists to classify beach texture likely introduced some error. All geologists working on this project have advanced degrees in geology and many years of experience mapping landforms at North Cascades, Mount Ranier and Olympic National Parks; and at Ebey's Landing National Historical Reserve. The primary and secondary authors are licensed geologists in the State of Washington. The geologists mapped the coastline by working together in the field, working independently and then comparing results in the office, and by using lidar to refine landform designations and line placement.

Digitizing and Verification

After identifying landforms and drawing their boundaries on base maps, each area was peer-reviewed for accuracy and mapping consistency. Landform line-work was then transferred into a Geographic Information System by heads-up digitizing in ArcMap. As each polygon is labeled, the shape and location were checked for accuracy. Also, landforms are compared again to 10-meter digital elevation models (DEMs) and in some cases with Light Detection and Ranging (LiDAR) DEMs, enabling more fine-tuned editing. We used the Washington State Department of Natural Resources LiDAR portal and the Puget Sound LiDAR Consortium, both provided data from several surveys. We found the coastal LiDAR obtained by the US Army Corps of Engineers to be of limited use due to its low resolution and data gaps.

Error introduced into the LiDAR datasets is reviewed in individual reports associated with these LiDAR surveys (TerraPoint 2002, Watershed Sciences 2011, WSI 2012, Woolpert 2014, Quantum Spatial Inc. 2015). Each report contains relative and absolute accuracy assessments for review. Relative accuracy refers to the internal consistency of the data set; the ability to place a laser point in

the same location over multiple flight lines, GPS conditions and aircraft attitudes. Absolute accuracy is the consistency of the data with external data sources, such as the ground surveyed quality check points (Watershed Sciences 2011). Relative accuracy may be a greater concern in detailed geomorphic mapping; feature recognition and definition are carried out on the basis of height differences between points (Jones et al. 2007). Error associated with relative accuracy for all LiDAR surveys used was less than 0.01m.

Within the GIS dataset all quantitative, qualitative and topological errors were assessed and corrected when found. Positional accuracy is likely highest within areas covered by LiDAR datasets. The most recent coverage layers were used in mapping to increase positional accuracy as well (i.e. recent aerial imagery).

Results

Landform Distribution

Coastal OLYM contains a rich collection of landforms created by the intersection of multiple processes of erosion and deposition. The influence of glaciation and active tectonic processes on coastal processes makes this unit unique in NPS managed coastlines in the lower 48 states.

More than 90% of the OLYM coastal strip is in the backshore area (Figure 2). The geology of the backshore at OLYM is dominated by glacial deposits (41%), with approximately 37% of the coastline composed of sedimentary bedrock, and most of the remainder sand and gravel deposits at the mouths of coastal rivers (Table 3). In the area inundated by the CIS north of Cape Johnson, glacial deposits make up 47% of the coastline, while they account for less than 30% south of Cape Johnson. Alluvial landforms, including floodplains, terraces, gravel barriers and beaches account for most of the remaining areas intersecting the Pacific Ocean (Table 3).

Table 3. Summary of the geology of coastal OLYM and in the three geologically different reaches.

Material Type*	Entire Coastline	Shi Shi to Cape Johnson	Cape Johnson to Hoh Head	Hoh Head to Kalaloch
Bedrock	37%	30%	44%	41%
Glacial	41%	67%	26%	22%
Other	15%	2%	11%	37%

*Table is based on the linear distance measured in GIS along the coastline in four material types. Other is mainly gravel barriers, terraces and floodplains at the mouths of the Quillayute and the Hoh rivers.

The most dominant landforms in the backshore lands managed by NPS are the glacial drift-mantled bedrock hills (Table 4). River and glacial outwash terraces are also prominent, and Ozette Lake is the single largest feature. Weathered bedrock hills, including hill tops and hill slopes that may have a thin, discontinuous mantle of glacial drift, also cover much of the backshore.

Backshore coastal bluffs are largely unstable, especially those composed of glacial deposits and weak bedrock composed of silt and clay. Along these coastal bluffs a type of landslide known as slumps are common. We identified 43 slumps, but many of these are long features consisting of many individual landslides that are very difficult to distinguish (Table 4). The bedrock headlands can produce rock-falls and adjacent cobble and boulder beaches that are not common landforms, accounting for less than 1% of the total area (Table 4).

Glacial landforms cover more than 50% of coastal OLYM, with drift mantled bedrock the most dominant landform overall, followed by glacial outwash terraces at the mouths of the Hoh and Quillayute rivers (Figure 2; Table 4). The largest single feature, Ozette Lake, occupies a deep basin created at least partially by CIS erosion. South of the Hoh Head to Kalaloch, coastal bluffs are largely composed of deposits from alpine glaciers (Thackray 2001). These thick accumulations of sand and gravel provide sediment to nourish the wide sandy beaches south of Hoh River.

Table 4. Summary of landform distribution across the coastal unit of OLYM. Unit descriptions and mapping criteria are provided in Appendix A.

Landform Type	Number Observed	Area (km^2)	% of Total
Drift-Mantled Bedrock	11	54.84	29.77
Terrace	76	39.24	21.30
Lake Ozette	1	30.07	16.32
Hillslope	22	15.53	8.43
Floodplain	24	6.49	3.52
Hilltop	17	6.17	3.35
Beach-Sand	74	5.49	2.98
Mass Movement-Slump	43	4.60	2.50
Wave Cut Platform	33	4.13	2.24
Ice-walled lake plain	11	3.41	1.85
Shoreline	9	1.95	1.06
Bluff-Bedrock	30	1.89	1.02
Bedrock Bench	8	1.59	0.87
Headland	26	1.32	0.72
Bluff-Drift	13	1.22	0.66
Beach-Mixed	47	0.96	0.52
Alluvial Fan	8	0.72	0.39
Undifferentiated	6	0.68	0.37
Sea Stack	228	0.67	0.36
Marine Terrace	14	0.58	0.31
Bluff-Outwash	7	0.39	0.21
Bluff-Till	11	0.51	0.28
Beach-Pebble	17	0.51	0.28
Slough	4	0.49	0.27
Pleistocene Moraine	7	0.32	0.17
Beach-Boulder	19	0.12	0.06
Beach-Wood	6	0.11	0.06
Beach-Cobble	11	0.06	0.03
Natural Arch	12	0.06	0.03
Mass Movement-Debris Avalanche	1	0.04	0.02
Mass Movement-Fall/Topple	1	0.01	0.01
Tombolo	2	0.01	0.01
Fan Terrace	3	0.01	0.00
Totals	802	184.2	100.0

The foreshore area of OLYM is dominated by beaches, but sea stacks are the most numerous landform (Table 4). We identified 174 beaches that account for less than 4% of the total area of coastal OLYM. Sand beaches are the most common and cover more area than all the other beach types combined. We identified only 37 gravel beaches that cover 0.4% of coastal OLYM; 47 beaches have gravel mixed with sand.

Processes of erosion and deposition by the larger coastal rivers strongly influence the coastal geology. River landforms account for about 25% of the total area at coastal OLYM, including terraces 21% and floodplain 4% (Table 4). The Hoh and Quillayute rivers have particularly large floodplains and the highest and most extensive terraces. Stream deposits of sand and gravel create gravel barriers and offshore bars and shoals. Gravel and sand barriers are found at the mouths of most coastal streams at OLYM; the barriers at the mouths of the Hoh and of Quillayute rivers are particularly large.

Detailed landform mapping results are presented in four geologically distinct areas of coastal OLYM. At a broad scale, we identified three distinct sections of coastline demarcated by changes that occur near Cape Johnson (Norwegian Memorial) and at Hoh Head, and a fourth distinct backshore area surrounding Ozette Lake (Figure 2 and 3). Detailed results are presented in recognition of these four sections.

Ozette Lake

Near its northern boundary coastal OLYM turns several kilometers inland to include Ozette Lake and the surrounding glacial landscape created by the CIS (Figures 2, 6 and 8). This area contains landforms including the ice-walled lake plains (modern-day prairies), glacial drift mantled hills and hummocky glacial moraines (Table 5; Figures 9 and 10). Ozette Lake is the third largest natural lake in Washington at 30.6 km^2 (11.8 mi^2; Walcott 1973) and has a maximum depth of 97.5 m (320 ft), 88 m (290 ft) below sea level (Dlugokenski et al. 1981). Given its great depth, Ozette Lake may rest in a structurally controlled basin, but no faults are mapped nearby (Figure 3). An alternative explanation for the lake's great depth is that it was excavated by the CIS, where subglacial meltwater under high pressure created a positive feedback loop, with deeper erosion bringing in more ice and meltwater.

The lake basin has a pronounced topographic asymmetry, with a steep shoreline fronting glacially shaped hills on the west and south, and a more gently sloping shoreline composed of ice age deltas, moraines, and modern broad floodplains on the northeast (Figures 9 and 10). The elongate, coast-parallel hills on the west side are occasionally cut by sloughs draining to or from the lake. The lake has one modern outlet, the Ozette River at its north end (Figure 10). Bedrock occurs beneath the channel at several locations along the river, and keeps the lake level near its present elevation, controlling the stream channel gradient and depth of incision.



Figure 8. Ozette Lake (Ritchie and Bourgeois 2010).

Table 5. Coastal section 1 summary of landform distribution near Ozette Lake and along the coast north of Cape Johnson.

Landform Type	Number Observed	Area	% of Section
Drift-Mantled Bedrock	11	54.85	52.23
Lake Ozette	1	30.07	28.64
Ice-Walled Lake Plain	11	3.41	3.25
Wave Cut Platform	16	2.57	2.45
Bluff-Bedrock	20	2.35	2.23
Shoreline	9	1.96	1.87
Beach-Sand	62	1.79	1.70
Floodplain	11	1.36	1.30
Bluff-Drift	10	0.97	0.93
Terrace	18	0.84	0.80
Alluvial Fan	8	0.72	0.69
Undifferentiated	6	0.68	0.64
Mass Movement-Slump	11	0.55	0.52
Beach-Mixed	19	0.55	0.52
Slough	4	0.49	0.47
Headland	11	0.47	0.44
Marine Terrace	5	0.32	0.31

Table 5 (continued). Coastal section 1 summary of landform distribution near Ozette Lake and along the coast north of Cape Johnson.

Landform Type	Number Observed	Area	% of Section
Pleistocene Moraine	5	0.31	0.29
Bluff-Till	6	0.28	0.27
Sea Stack	68	0.25	0.24
Beach-Pebble	7	0.14	0.13
Natural Arch	5	0.03	0.03
Beach-Cobble	3	0.02	0.02
Beach-Boulder	3	0.01	0.01
Fan Terrace	3	0.01	0.01
Tombolo	1	0.01	0.01
Totals	334	105.0	100.0

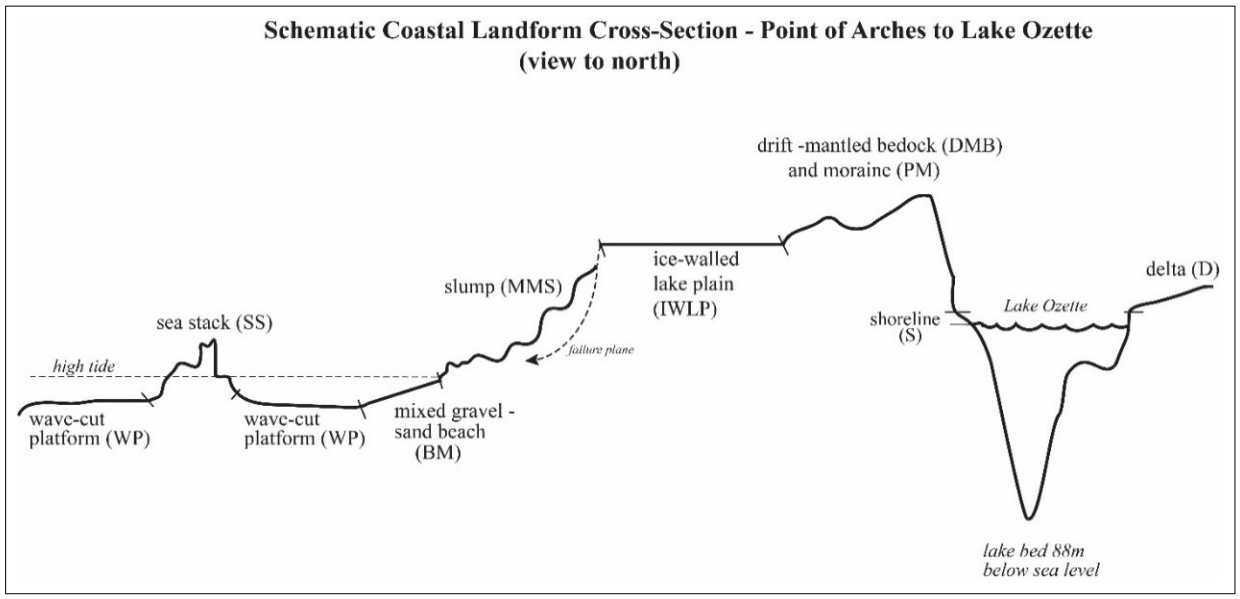


Figure 9. Schematic coastal landform cross-section looking north from near Point of the Arches to Ozette Lake.

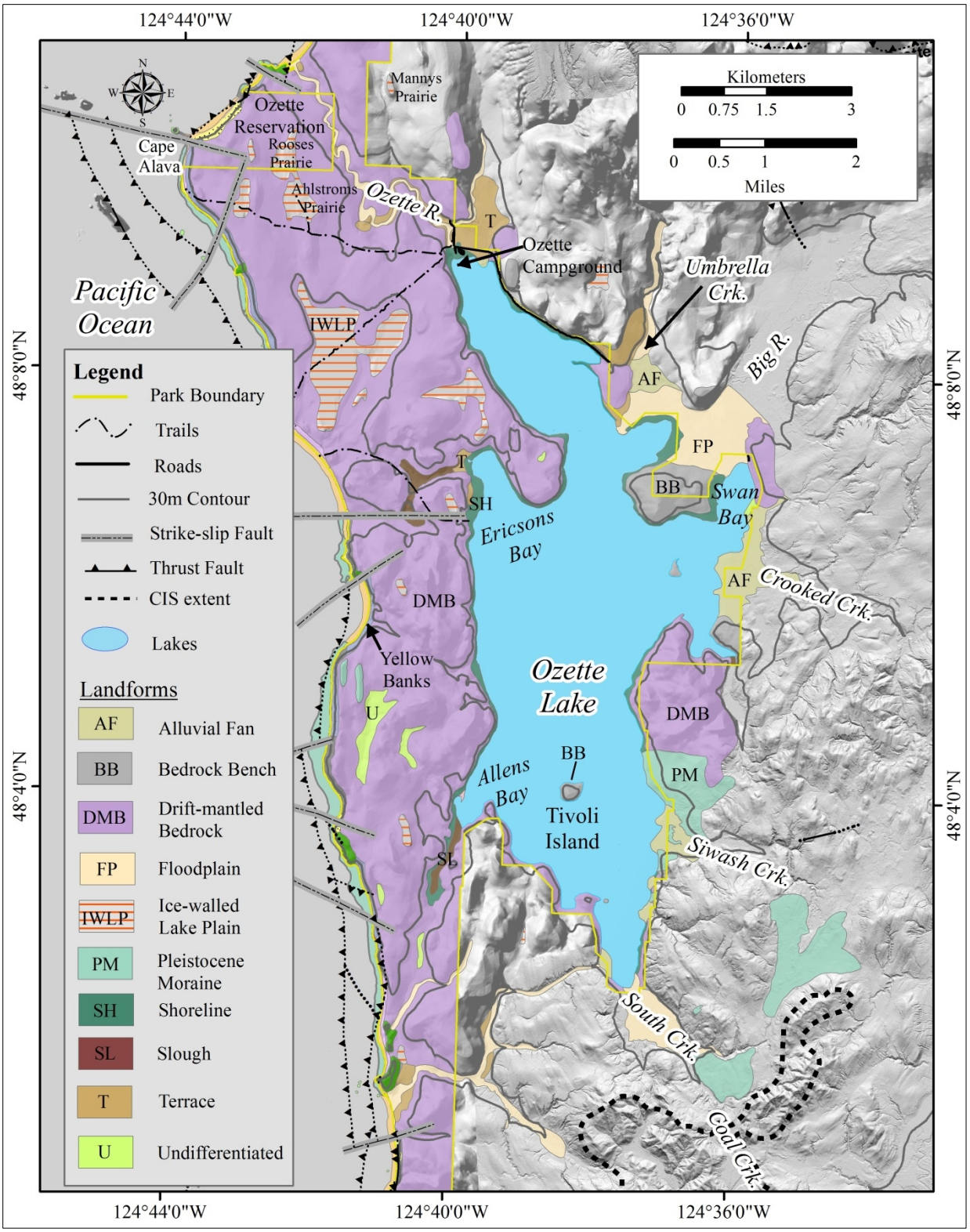


Figure 10. Coastal landforms near Ozette Lake. Faults mapped by Schasse (2003).

The lake surface level today is 10.4 m (34 ft) above sea level. Lake level fluctuates up to 3.4 m each year, flooding parts of the campground and parts of the shoreline around the entire lake. A line of shrubs and wetland plants along many parts of the lake identify the seasonally flooded shoreline. Large tsunami waves known to be 11.5 m high (Peterson et al. 2013) could have reached the lake and Ozette Campground.

The watershed and shoreline of Ozette Lake is undergoing changes related to disturbances in land cover. About 17% of the lake shore is undergoing net deposition because sedimentation rates into the lake from eastern parts of the watershed have increased due to logging (Ritchie and Bourgeois 2010). An estimated 400,000 m^3 of sediment has accumulated since the 1950s on the delta of Umbrella Creek alone. Due to relatively consistent lake levels, approximately 80% of the shoreline is stable and not undergoing erosion (Ritchie and Bourgeois 2010).

Most of the landforms around Ozette Lake were created by glacial processes in the last ice age (Table 5). Published geology maps classify the area around the lake as 'glacial drift', a broad term for all material deposited by a glacier and its meltwater during both ice advance and retreat (Figure 3; Gerstel and Lingley 2000, Schasse 2003). These sediments are well exposed in coastal bluffs south of Sand Point and include layers of outwash and till. The general flow direction of the ice sheet was north to south, with ice locally following the deep trough that holds Ozette Lake. During deglaciation ice flow changed and flowed into the lake basin from the east, as shown by the orientation of low hills adjacent to Crooked Creek.

During this study we identified the terminal moraine of the ice sheet about 1.5 km south of Ozette Lake (Figure 2 and 10). The terminus is marked by a small moraine at the head of Coal and South Creeks, and by a change in the landscape from drift-mantled, fluted hills to a more dissected landscape with a higher drainage density. Lobes of the ice extended farther south along the coast almost to Cape Johnson and down Dickey River valley to the east (Figure 6).

The ice sheet had a dramatic impact on the landscape, producing several glacial landforms. The most prominent of these are the elongate (fluted) drift mantled bedrock hills formed at the base of the flowing ice (Table 5). The hills are bedrock-cored in most cases, and their orientation parallel to the ice flow enhanced overall structural (fault) control on their orientation (Figure 10). They are covered by glacial till and outwash several meters thick that is exposed along coastal bluffs where it includes sand and gravel and glacial till with granitic erratics derived from the Coast Mountains in British Columbia (e.g. Yellow Banks). Five small moraines were also found throughout the area on both sides of the lake, including lateral moraines deposited against hills as the glacier wasted. Tivoli Island is composed of bedrock, with a gentle up-ice side and steep down ice face (south). While we mapped it as a bedrock bench because of its flat top, its asymmetry is similar to a landform known as a roche mountonee (Benn and Evans 1998).

On the north-west side of Ozette Lake, elongate bedrock-cored hills are interrupted by broad flat prairies, that are composed of silt and clay (sediments deposited in a lake) overlying glacial drift (Figure 10; Bach and Conca 2004). Some of the prairies are perched 10 m or more above the surrounding landscape, and most are not forested because a high groundwater table precludes growth

of trees (Figure 11). The origin of Roose's, Ahlstrom's and Manny's prairies has previously not been clear, but we suggest they are a landform known as ice-walled lake plains (Clayton et al. 2008). They form where glacial ice stagnates and is buried by sediment, often near the terminus of a glacier. Ephemeral lakes form trapped within and between the melting ice and bedrock ridges and moraines. Where LiDAR data is available, there is evidence around Ozette Lake of widespread ice stagnation in the form of hummocky topography near the mouth of Siwash Creek. We identified 11 ice-walled lake plains, but there are likely more in the landscape west of Ozette Lake that were not identified.



Figure 11. Ahlstrom's Prairie, an ice-walled lake plain. The plain is underlain by silt and clay from a former lake bed that rests on top of glacial till (Bach and Conca 2004).

Coastal Section 1-Shi Shi Beach to Cape Johnson.

The northern end of the OLYM coastal unit begins at the Makah Reservation at the north end of Shi Shi beach and extends south to Cape Johnson, the southern limit of the CIS (Figures 1 and 6). A wide range of coastal landforms were observed in this section from Shi Shi Beach south to Cape Johnson (see Table 5; Figures 12-15). We observed 15 different foreshore landforms, with sea stacks the most numerous (68) and wave-cut platform the most extensive, covering more than 2% of the total area in this section. We observed 94 distinct beaches, with a majority classified as sand, 19 mixed sand and gravel and 13 gravel. The backshore is dominated by drift-mantled bedrock hills and Ozette Lake (Table 5).

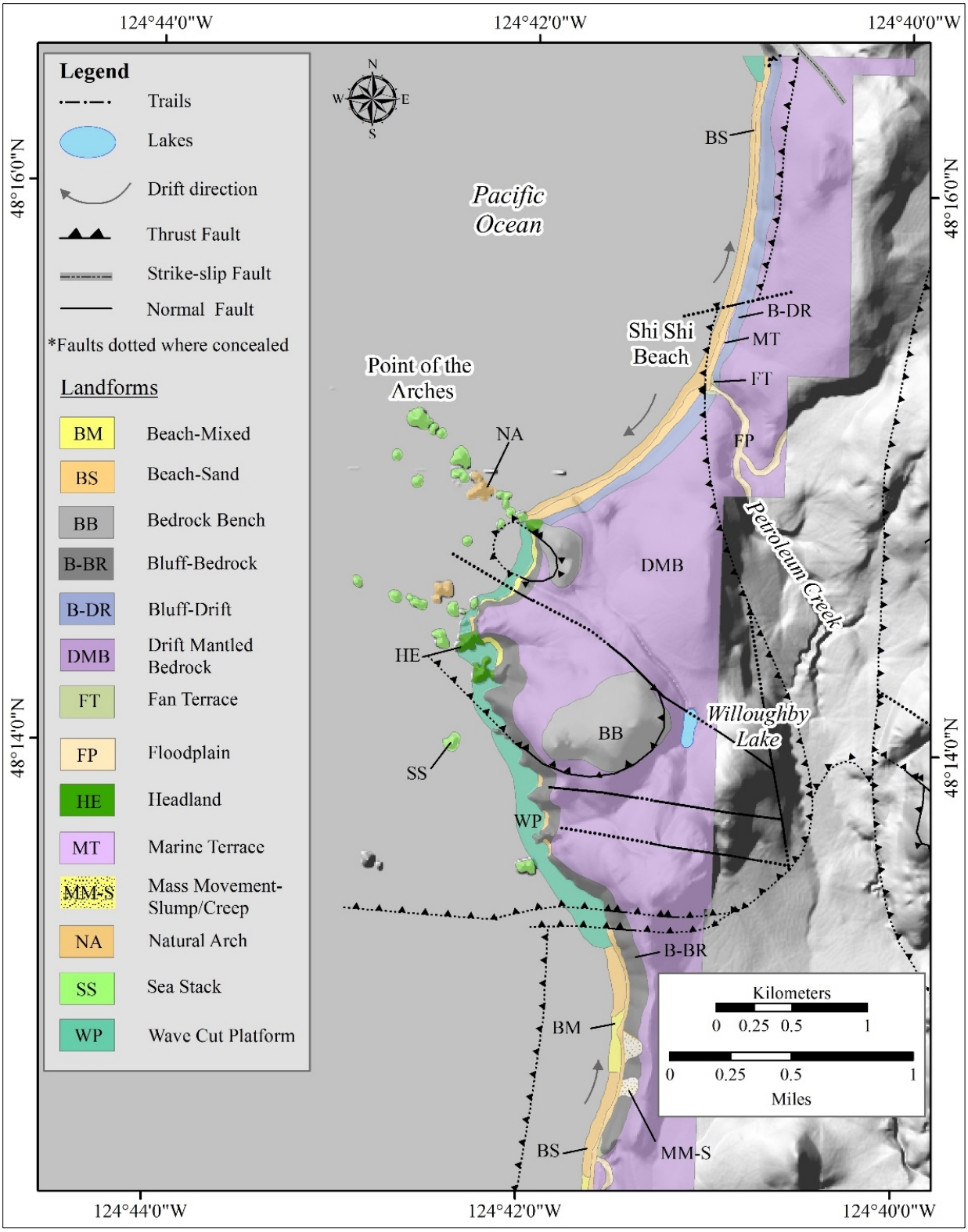


Figure 12. Coastal landforms near Point of the Arches and Shi Shi Beach. Faults mapped by Schasse (2003).

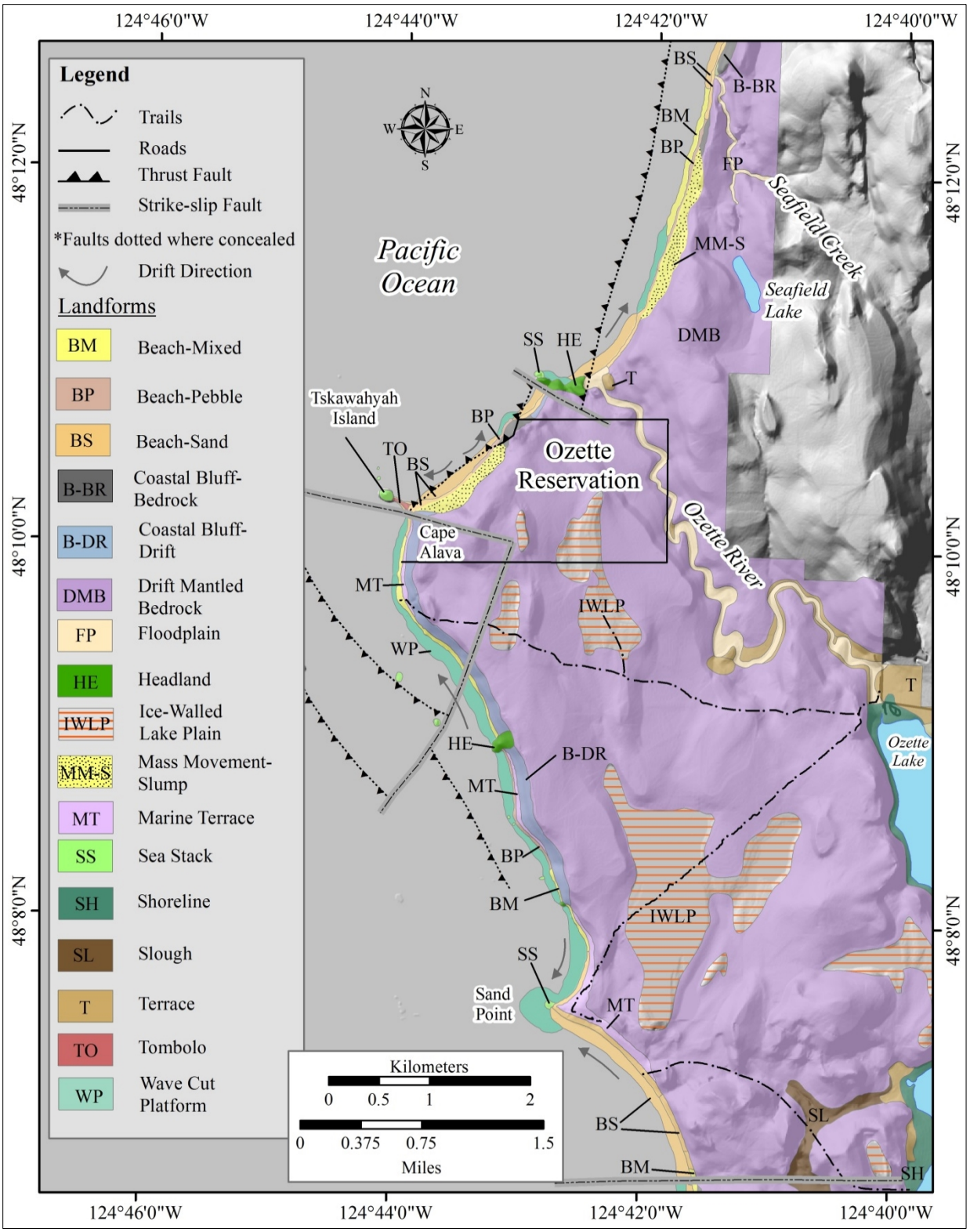


Figure 13. Coastal landforms near Cape Alava and Sand Point. Faults mapped by Schasse (2003).

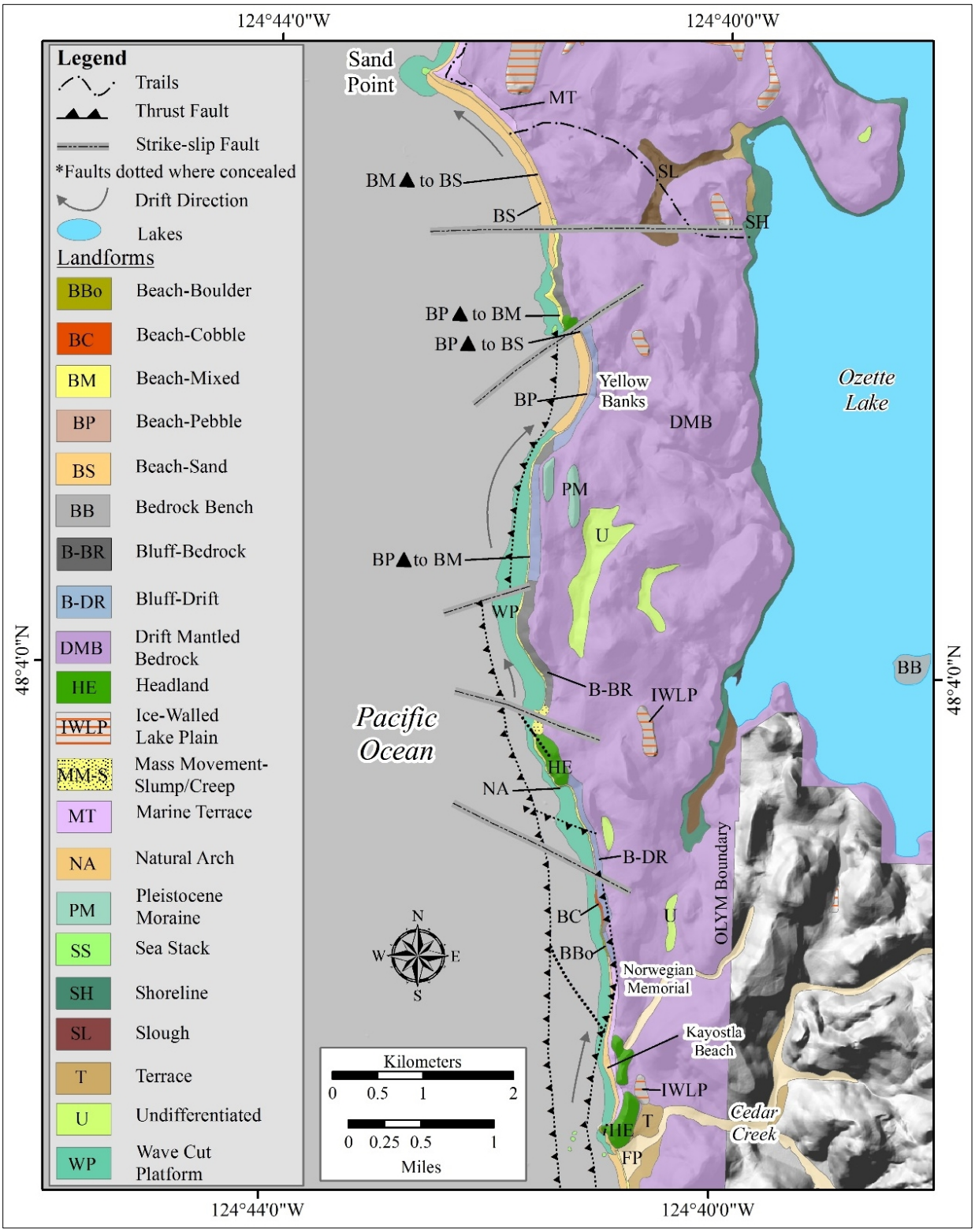


Figure 14. Coastal landforms from Sand Point to Cedar Creek. Note backshore dominance of ice sheet drift-mantled bedrock hills, and in the foreshore wave-cut platforms. Thrust faults along the coast are thought to be related to the formation of wave cut platforms. Triangles represent beaches that underwent a change in texture in winter 2015. Faults mapped by Schasse (2003).

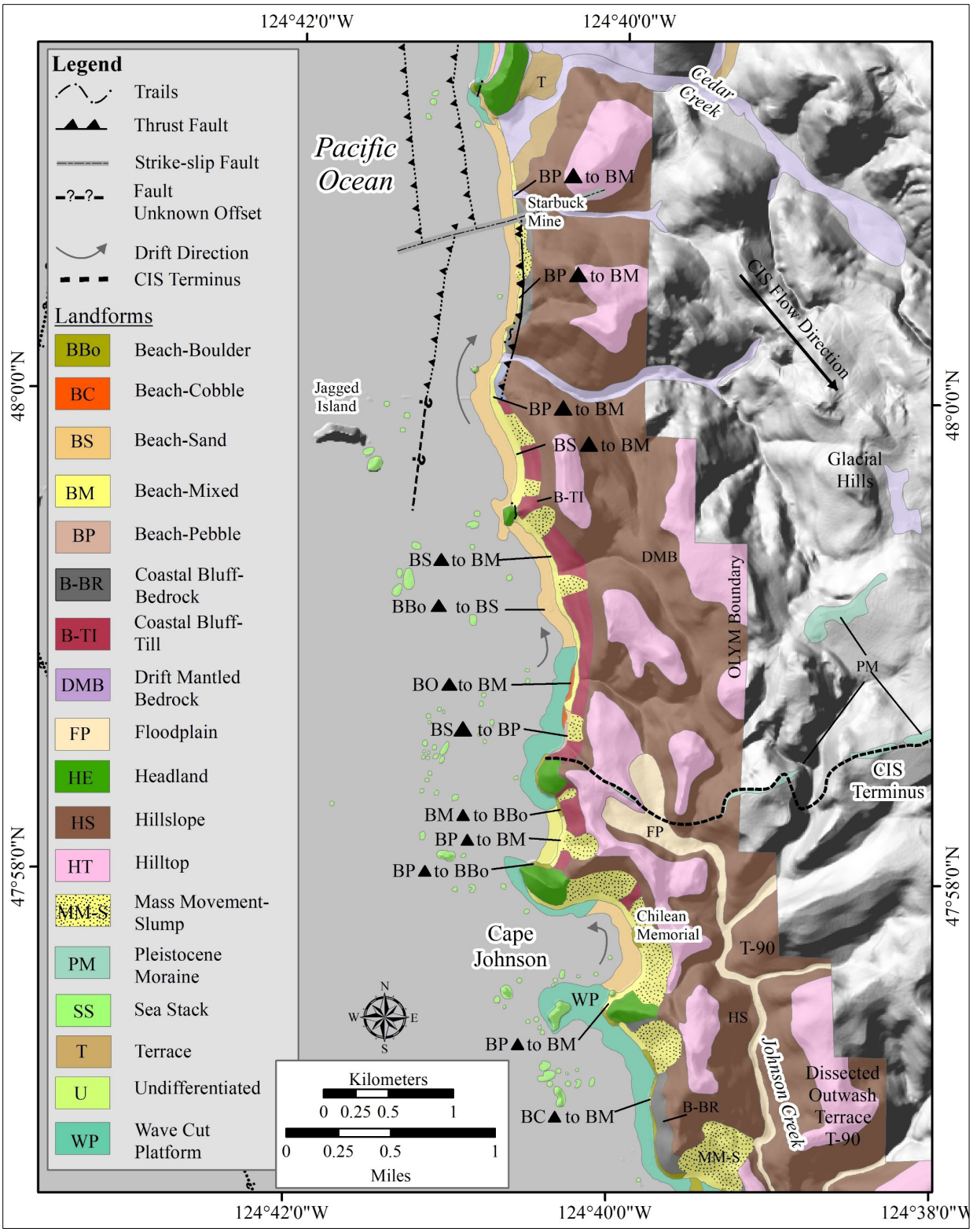


Figure 15. Coastal landforms from Cedar Creek to Cape Johnson. Note ice sheet terminus and glacial erosion of drift mantled hills to form SSE-directed (fluted) landscape. Triangles represent beaches that underwent a change in texture in winter 2015. Faults mapped by Gerstel and Lingley (2000).

Highlights in the northern part of this section include unusual bedrock that forms the dense concentration of sea stacks and arches at Point of the Arches, a tombolo at Cape Alava, wide sandy beaches north of Ozette River and a long wave-cut platform and adjacent marine terrace from Cape Alava to Sand Point (Figures 12 and 13). There are also interesting associations between thrust faults and the type and distribution of coastal landforms that are discussed in the synthesis section of this report.

The coastline south of Sand Point is slightly different than the reach to the north because there is no evidence of widespread stagnation of the ice sheet in the backshore (i.e. no ice-walled lake plains or hummocky topography). Highlights south of Sand Point include the continuation of extensive wave-cut platforms, a wide, low-tide sand beach south of Sand Point, strike-slip faults that break the thrust faults into short blocks, and the terminus of the CIS (Figures 14 and 15). The large coastal headland Cape Johnson is a prominent landform.

Shi Shi Beach is framed by headlands on either end that are made of breccia and conglomerate bedrock (Figure 3). At Point of the Arches the bedrock includes a number of rock types not found elsewhere on the coast that were placed against each other by a complex series of thrust and strike-slip faults (Figure 12). The folded thrust faults wrap the conglomerate and breccia around crystalline rocks gabbro and pillow basalt that were invaded by a series of dikes and sills (Tabor and Cady 1978a). Wave erosion of the uplifted rock at Point of the Arches has produced the many sea stacks, arches, and extensive wave cut platforms (Figures 12 and 16). South of the Point of the Arches, the bedrock exposed at headlands and composing some of the coastal bluffs is sandstone with less than 40% siltstone. This type of bedrock dominates the coastline all the way to the Quillayute River and forms headlands, sea-stacks and wave-cut platforms. We mapped 11 distinct headlands in Section 1 of the coastline, representing slightly less than half of the total in coastal OLYM (Tables 4 and 5). We mapped five natural arches, including one small natural arch at the north end of Kayostla Beach. Many more arches were inaccessible offshore at Point of the Arches.



Figure 16. Sea stacks and wave-cut platform near Point of the Arches.

Thrust faults are mapped along the northern end of Shi Shi beach, but the fault line is broken and offset just north of Petroleum Creek (Figure 12). To the north the thrust fault is behind the coastal bluffs, while to the south it is just offshore before it sweeps inland parallel and to the southwest of Petroleum Creek. Thrust faults continue south of Cape Alava to Cape Johnson, but they are interrupted every 1-2 km and offset by strike-slip faults (Figures 13-15). Movement along the strike-slip faults has offset the thrust faults by several hundred meters in some cases. The different faults and locally different bedrock uplift have produced a series of smaller bays south of the ice sheet terminus.

About two thirds of the coastal bluffs north of Cape Johnson are formed in bedrock, and glacial till and outwash compose the other third. Cape Alava was over-ridden by the CIS, eroding the base of the headland into a bedrock bench. The ice sheet terminus is marked by a low, discontinuous ridge that runs roughly east-west across the backshore, and its passage across the landscape marked by the subglacial fluting of the low coastal hills. Near the ice sheet terminus, the glacial till gets thicker and composes the coastal bluffs south of Jagged Island to Cape Johnson. South of Ozette Lake we did not observe ice-walled lake plains in the backshore. One of the few named bluffs on the coast known as Yellow Banks was formed in thick, dense glacial till with a cap of outwash. The color is imparted by the weathering and groundwater staining of glacial deposits at the top. The thickest accumulations of ice sheet till occur near Starbuck mine and continue to the Cape Johnson. At one site 8 m of glacial drift is exposed and includes 7 m of glacial till at the base of the bluffs (Figure 17). The till was deposited beneath the ice sheet, known as lodgement till, and includes a mix of cobbles, gravel, sand, silt, and a small amount of clay. Glacial erratics are common on the beach and include pink and tan quartzite from eastern British Columbia and granite from the Southern Coast Mountains.



Figure 17. Glacial drift forming coastal bluffs and a pebble gravel beach near Norwegian Memorial. The base of the bluff is composed of about 8 m of compact glacial lodgement till, and the top meter or so glacial outwash and ablation till.

Extensive slope failures in both bedrock and glacial drift bluffs were observed north of Ozette River mouth. North of Seafield Creek two bedrock landslides were observed (Figure 12). Where the bluffs and headlands are composed of un-weathered bedrock, landslides are often rockfalls that add boulders to beaches of mixed sediment. The extent and number of landslides generally increases south of Cedar Creek where backshore slopes are steeper and glacial drift is thicker (Figures 14 and 15).

From Point of the Arches to Cape Johnson, wave-cut platforms dominate the shoreline in association with headlands and thrust faults (Table 5). The wave-cut platforms surround headlands such as Sand Point and Point of the Arches, where the thrust faults are near the coastline (Figures 12 and 13). Most of the sea stacks are ‘rooted’ in wave cut platforms exposed at low tide (Figure 7). Some of the wave-cut platforms have more than one level, which may be related to tectonics, faults and/or long-term fluctuations in sea level.

Marine terraces occur above the narrow beaches and wide wave cut platforms on both sides of Sand Point headland (Figure 13). The flat terraces stand a meter or more above the high tide line and are covered by deciduous trees and grasses. Many campsites are located on these landforms. The marine terrace at Sand Point is described by Peterson et al. (2013) as an uplifted beach plain that contained other landforms such as berms (a.k.a. foredune ridge). These features were too small for us to map but illustrate the complexity of some landforms. Other marine terraces that we mapped in this section are located south of Cape Alava and north of a small headland near the mouth of Ozette River

(Figure 12). A 2 km long marine terrace begins just north of Norwegian Memorial and continues south to the headland at the mouth of Cedar Creek (Figures 14 and 15).

There are two long beaches in this section of the coast. The largest single beach is 3.8 km long Shi Shi Beach at the north end of the park (Figures 12 and 18). Shi Shi is a wide, sandy, low-sloping beach at low and high tides. Its backshore is composed of bluffs formed in ice sheet deposits, and in places a narrow marine terrace (Figure 12). The only other large continuous beach in this section of coast is between Cape Alava and the Point of the Arches. Much of the beach is sand, but a section of mixed beaches runs from the unstable bluffs to Seafield Creek (Figure 13). Small, narrow, crescent-shaped cobble, pebble and mixed beaches occur in bays between headlands and above wave-cut platforms offshore (Figure 19). Unlike the sand beaches, the cobble beaches have steep slopes and often large wood accumulations.



Figure 18. Shi Shi sand beach looking south toward Point of the Arches.



Figure 19. Pebble and cobble mixed high tide beach, and sand low-tide beach near Cape Alava.

Longshore currents generally run from south to north between Shi Shi Beach and Cape Johnson (Figures 12-15). They feed sediment from unstable bluffs formed in glacial drift to beaches. Near the mouth of Petroleum Creek is a point of divergence in the longshore currents (Figure 12; Washington Department of Ecology 2018). Currents move to the north and south from this point, forming separate drift cells. Sand is fed to the beach by longshore currents and erosion of the glacial drift sea cliffs, and to a lesser extent by Seafield Creek and Ozette River. Two other points of diverging longshore currents near here occur at Cape Alava and just north of Sand Point. The converging drift cells deposited an unusual landform called a tombolo at Cape Alava (Figures 13 and 20). A tombolo is a beach than connects an island or sea stack to the shoreline. In this case the tombolo connects the mainland to Tskawahyah Island. This tombolo formed because drift cells converge on Cape Alava from the north and south, creating a pebble and sand beach that connects the island to the mainland (Washington Department of Ecology 2018).



Figure 20. Tombolo and sea stack near Cape Alava.

Thrust faults continue for a few kilometers to the south of Starbuck mine (Figure 15). The change in tectonic setting leads to two very different coastlines in this section. To the north and south of Starbuck mine, coastal bluffs are dominated by glacial sediments prone to mass wasting, and crescentic beaches are common. From Cedar Creek south past Jagged Island, there is no wave-cut platform, but instead the coastline is a wide sand beach. Kayostla Beach is a narrow sand beach near Norwegian Memorial. It transitions to a cobble beach to the north, and eventually to mixed beach. Most of the other beaches in this section of coast are mixed and narrow above wave-cut platforms. Starbuck Beach south of Cedar Creek is interesting because of the large number of granitic and occasional pink quartzite gravels brought by the CIS from the Southern Coast Mountains north of Vancouver. The incredible variety of rock types in the beach gravels distinguishes this section of coastline from gravel beaches to the south (Figures 15 and 17).

Rivers that reach the sea on this section of coastline are generally small and include the Ozette, River, Seafield Creek, Petroleum Creek and Cedar Creek (Figures 12-15). There are wide, mostly sand beaches and small mixed texture barrier beaches located adjacent to and across each of the river mouths, and small accumulations of wood on adjacent beaches. Alluvial terraces were identified at the mouth of Petroleum Creek and along the Ozette River. The age and texture of these terraces is variable and several include buried wood.

Coastal Section 2: Cape Johnson to Hoh Head.

This reach of coastline extends south from the ice sheet terminus near Cape Johnson to Hoh Head River (Figures 2 and 6). The coastline here is different than to the north due to the absence of recent glacial landforms and change in tectonic setting, with fewer thrust faults mapped near the shore (Figure 2). Section 2 is interrupted by the large estuary of the Quillayute River and associated

landforms, as well as a change in tectonic and glacial settings to the south of the river mouth (Figures 3 and 21-23).

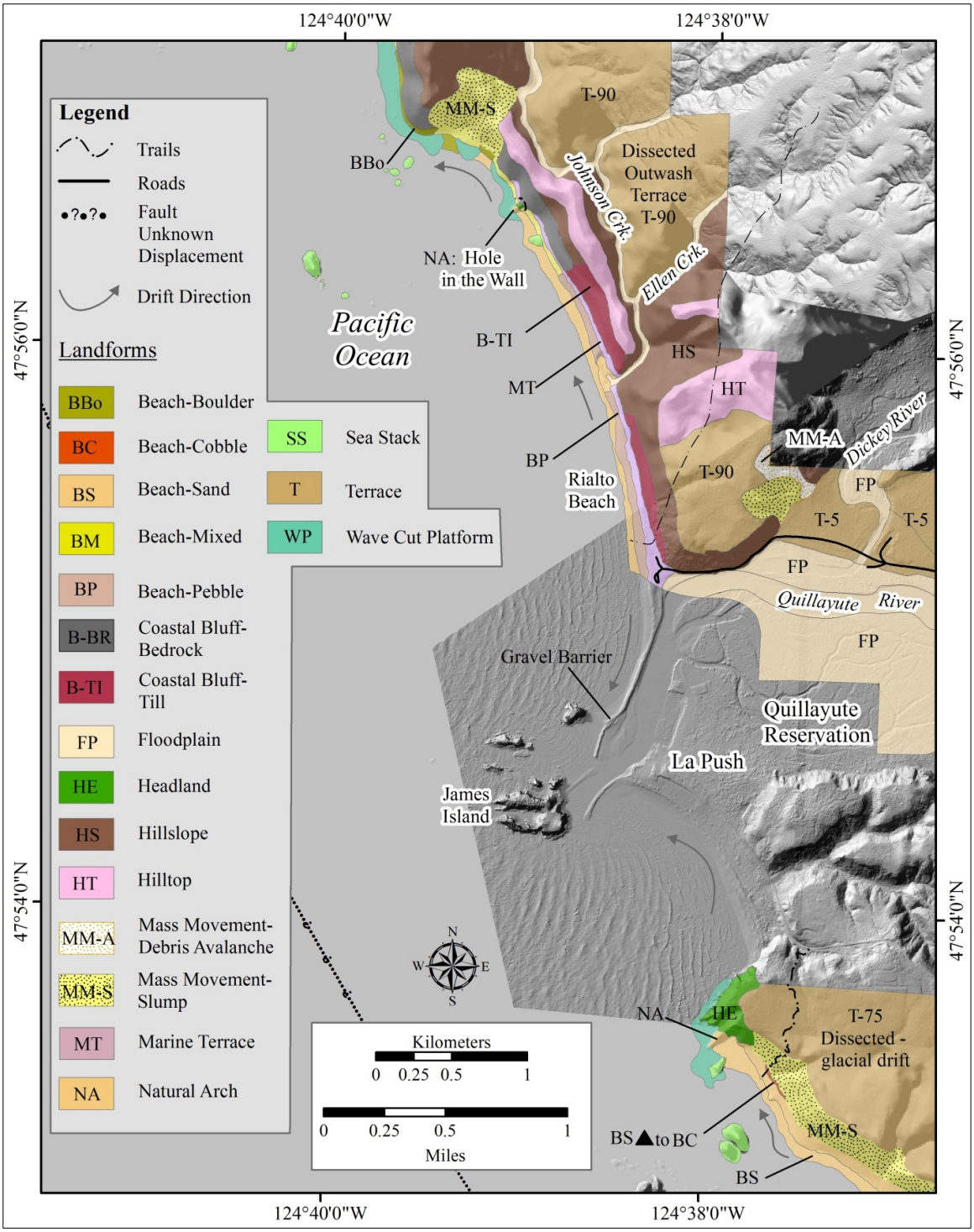


Figure 21. Coastal landforms near the Quillayute River mouth. Triangles represent beaches that underwent a change in texture in winter 2015. Note large terraces near the river mouth. Faults mapped by Gerstel and Lingley (2000).

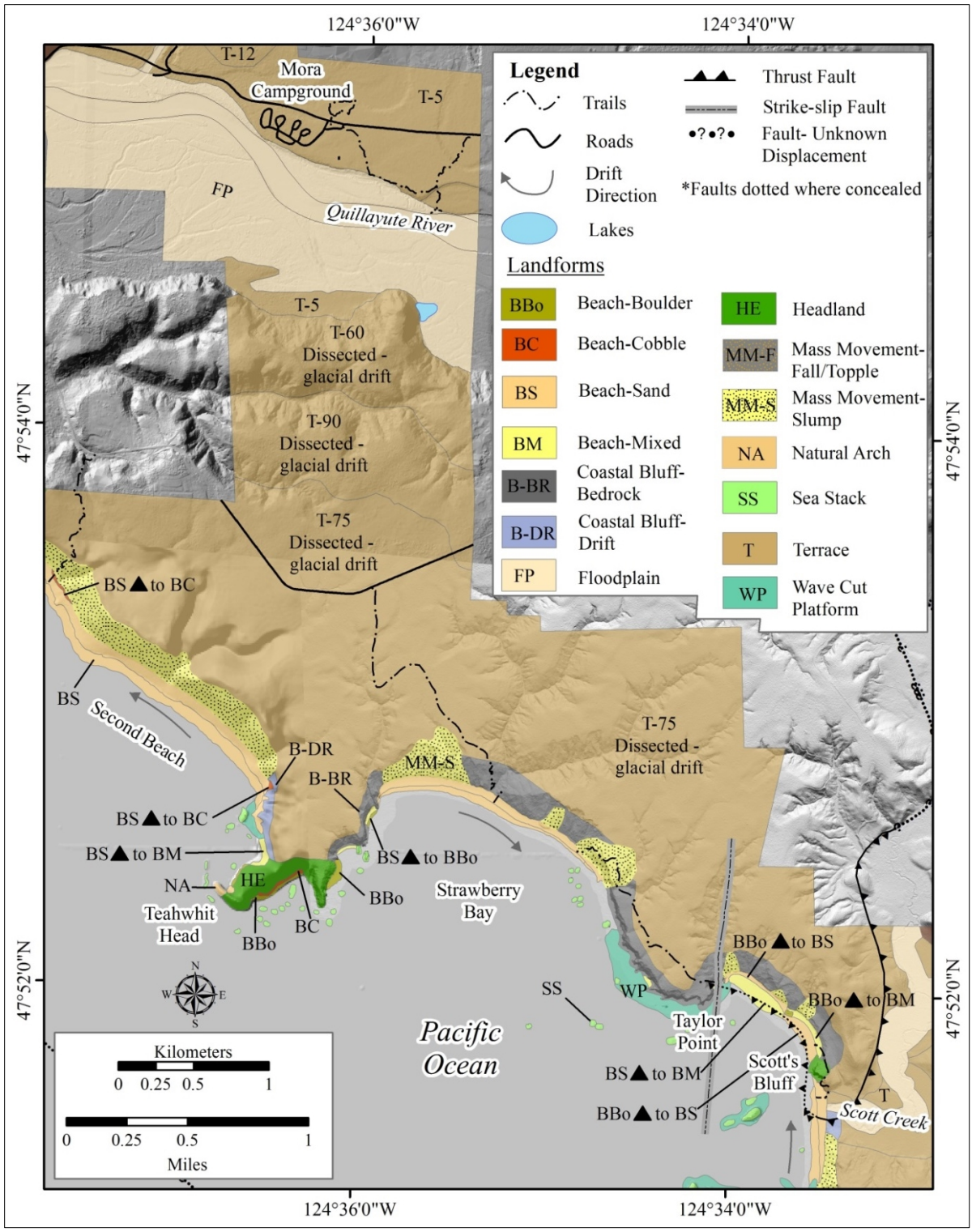


Figure 22. Coastal landforms from Quillayute River south to Scott Creek. Triangles represent beaches that underwent a change in texture in winter 2015. Faults mapped by Gerstel and Lingley (2000).

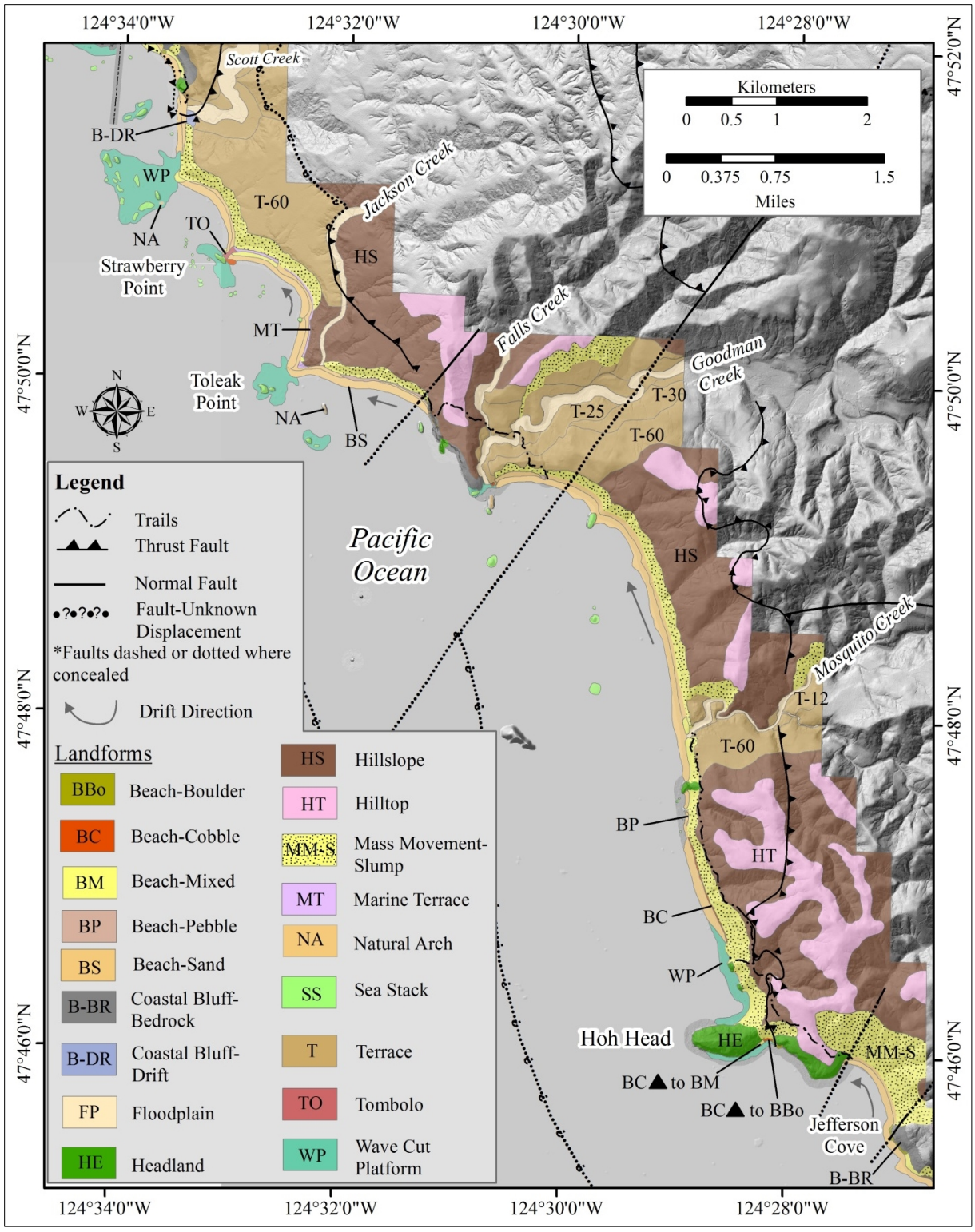


Figure 23. Coastal landforms from Goodman Creek south to Hoh Headland. Triangles represent beaches that underwent a change in texture in winter 2015. Faults mapped by Gerstel and Lingley (2000).

Highlights include numerous headlands, sea stacks, arches and wave-cut platforms (Table 6). Accessible Rialto Beach has exceptional wave energy and an impressive accumulation of large wood from the Quillayute River. Teawhit Head, Toleak Point and Hoh Head are prominent features that isolate relatively small crescentic beaches. There is a tombolo at Strawberry Point, and a collection of terraces at multiple elevations around the mouths of Mosquito Creek and Goodman Creek.

Table 6. Coastal Section 2 summary of landform distribution along the Olympic coast from Cape Johnson to Hoh Head.

Landform Type	Number Observed	Area (km^2)	% of Section
Terrace	45	19.91	41.68
Hillslope	17	9.88	20.67
Floodplain	7	4.54	9.49
Hilltop	13	4.30	9.00
Mass Movement-Slump	23	3.02	6.33
Beach-Sand	28	1.93	4.04
Wave Cut Platform	14	1.48	3.10
Bluff-Bedrock	11	0.75	1.57
Headland	11	0.46	0.97
Sea Stack	158	0.40	0.83
Beach-Mixed	25	0.34	0.71
Bluff-Till	5	0.23	0.48
Marine Terrace	6	0.16	0.33
Beach-Pebble	5	0.12	0.26
Beach-Boulder	14	0.09	0.19
Bluff-Drift	2	0.04	0.09
Mass Movement-Debris Avalanche	1	0.04	0.09
Beach-Cobble	7	0.03	0.07
Natural Arch	7	0.02	0.05
Mass Movement-Fall/Topple	1	0.01	0.03
Pleistocene Moraine	2	0.01	0.03
Tombolo	1	0.01	0.02
Totals	403	47.8	100.0

We observed 10 different coastal landforms in the foreshore of coastal Section 2 (Figures 24 and 25). As in Section 1, sea stacks were the most numerous foreshore landform (158), while wave-cut platform were the most extensive, covering more than 3% of the total area in coastal Section 2 (Table 6). We observed 79 distinct beaches, but they are coarser-grained in general than in Section 1 to the north. Most low tide beaches are dominated by sand with several long high tide sand beaches south of the Quillayute River. Boulder beaches were present mostly around prominent headlands. In the

backshore, terraces and floodplain along the Quillayute River and drift-mantled hills account for about 80% of the NPS land in Section 2.

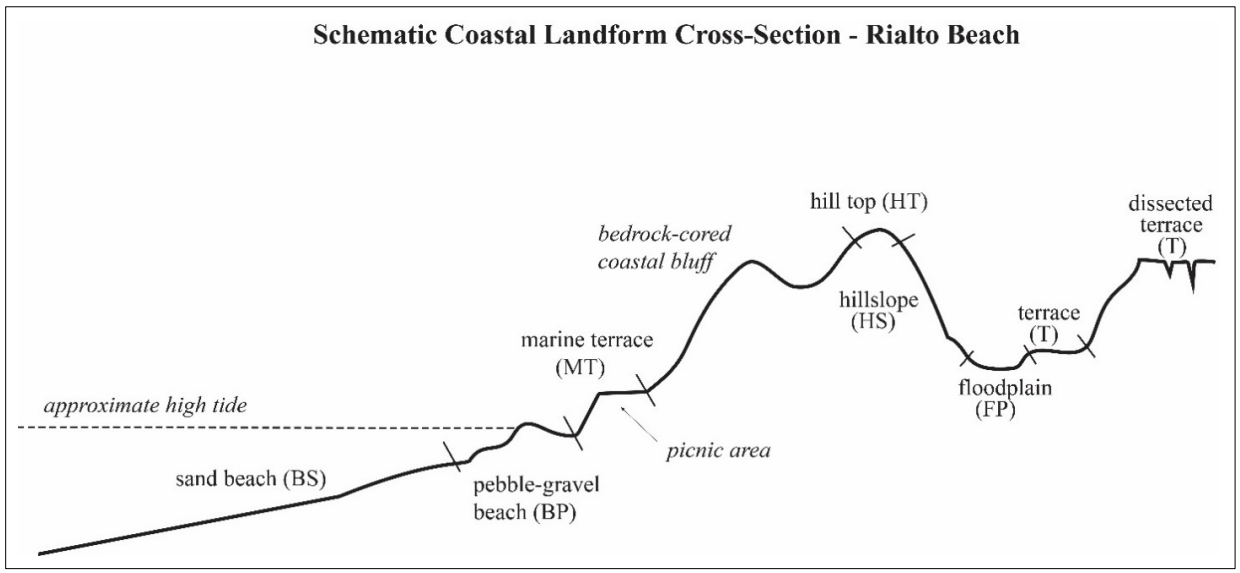


Figure 24. Schematic coastal landform cross-section through Rialto Beach.

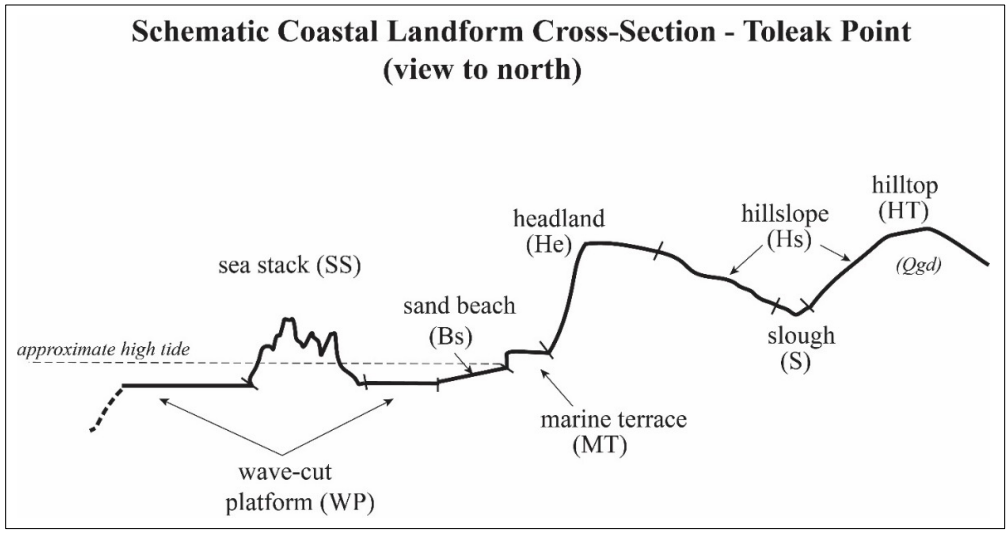


Figure 25. Schematic coastal landform cross-section looking north near Toleak Point.

The backshore hills and coastal bluffs from Cape Johnson to the south are composed mainly of sandstone and siltstone bedrock, with some conglomerate (Tabor and Cady 1978a). Coastal erosion of the bedrock has created multiple headlands that represent about ½ of the OLYM coast's total (Figures 21 and 22). Prominent headlands include Teahwhit, Toleak and Hoh, and there are smaller headlands Taylor Point and Strawberry Point. The section of coast from Hoh Head north to Teahwhit Head is particularly rocky and contains hundreds of beautiful sea stacks that are the erosional remnants of former headlands. Glacial deposits have been mapped south from Cape Johnson to

Toleak Point (Gerstel and Lingeley Jr. 2000), but their age and origin is not clear. South of Scott Creek the glacial sediments are outwash sand and gravel that came from Olympic Mountain alpine glaciers flowing down the Hoh and Quinault valleys (Figures 6 and 23).

A fault running parallel to the coast at the mouth of the Quillayute River is about 3 km offshore. A thrust fault was mapped that is about 1 km landward of the coastline from south of Third Beach to Hoh Head where it intersects the coast (Figure 23). As with areas to the north, the thrust faults are associated with development of a number of landforms, including headlands, sea stacks and wave-cut platforms. Movement along this fault has resulted in the uplift of the area between Scott and Mosquito Creeks. South of Hoh Head two faults truncate the thrust fault, and run perpendicular to the coast, extending from 0.5 km offshore and about 1 km inland. These faults define the limits of Jefferson Cove. A short section of beach runs between the faults, with a corresponding break in the bedrock sea cliffs.

The sedimentary bedrock in the backshore is intensely weathered and prone to mass wasting, as shown by the unstable bluffs near Hole-in-the-Wall arch and elsewhere in this section of the coast. Unstable coastal bluffs are nearly continuous from the headland north of Cape Johnson to Hole-in-the-Wall Arch (Figure 26). These landslides are classified as slumps, which are deep-seated and occur slowly compared to debris flows and rock falls. Slow movement of the deposits disturbs the soil so that the main tree is alder on this landform, most of which lack vertical tree-trunks (i.e. jack-strawed).



Figure 26. Photo of unstable coastal bluffs and jack-strawed trees tilted by slow movement of the bluff face near Cape Johnson.

Inland, terraces, hills and floodplains are the most extensive landforms (Figures 21-23). The bedrock hills behind Rialto Beach have a mantle of glacial drift we suspect may be from an earlier ice age. The area was mapped as continental drift by Gerstel and Lingley (2000), but is south of the ice sheet terminus we identified near Cape Johnson (Figure 6). Some of the hill tops are relatively narrow, while others are flat-topped terraces that stand 75-90 m above the Quillayute River. They are isolated by steep gullies and small floodplains; therefore they were mapped as dissected terraces. More work is needed to identify the source of these sediments by examining their age, texture and lithology. Many of the valley bottoms hold swamps and marshes. Lower down in the larger valleys, including Johnson and Ellen creeks, floodplains were identified.

Near the mouth of the Quillayute River, high terraces are the dominant landform in the backshore on the south side of the river (Figures 21; Table 6). Gerstel and Lingely mapped these landforms as deposits from the Whale Creek advance some 200 ka ago. These features continue south to Goodman Creek.

In the foreshore zone, sand beaches and wave-cut platforms around headlands are the most extensive landforms, with sea stacks the most numerous (Table 6). Pebble and cobble beaches are more common in this section of coast than to the south of Hoh Head. North of Jackson Creek some of the coastal bluffs are formed in glacial deposits, but to the south of the creek they are more typically formed in bedrock (Figure 23; Tabor and Cady 1978a). The bedrock weathers to silt and clay and produces very unstable slopes, particularly where undercut by wave erosion. More stable bedrock cliffs are confined largely to the headlands north of Scott Creek. The bedrock hills of the backshore are more-or-less level at an elevation of about 100 m above sea level and form a long, discontinuous flat hilltop from Hoh Head north to Mosquito Creek. The landform extends about 1 km inland from the coast to near the park boundary and has far less relief than the hills farther inland outside of the park. Rounded cobbles and boulders were observed along the Hoh Head trail on this feature. It is not clear what processes have created this landform. It is possible that Mosquito Creek carried glacial outwash from the Hoh River alpine glacier (Figure 6). It is also possible the gravel clasts were rounded on the coast then uplifted to their present elevation. A thrust fault runs along the west edge of this feature (Figure 23).

Wave erosion of bedrock formed wave-cut bedrock platforms from just north of Cape Johnson to Hole-in-the-Wall arch. The wave-cut platforms are studded with sea stacks, an iconic feature of the wild Olympic coast. Some of the wave-cut platforms are continuous while others are isolated. Near several headlands, including Cape Johnson, we observed two levels of wave-cut platforms. Wave-cut platforms are also found near the headlands and surrounding most sea stacks and small offshore islands farther south of the Quillayute River (Figures 22, 23 and 27). They are not nearly as extensive in this section of the coastline as they are north of Hole-in-the-Wall. Prominent offshore platforms were mapped surrounding large sea stacks at Hoh Head and at Giants Graveyard north of Strawberry Point. They are only exposed at low tide. It is noteworthy that with fewer thrust faults and bedrock bluffs and headlands, there are fewer and smaller wave cut platforms and more beaches in Section 2 of the OLYM coast.



Figure 27. Wave-cut platform in rhythmically bedded sedimentary rock tilted 90º (left) and Hole-in-the-Wall Arch and surrounding wave-cut platform at low tide (right).

One marine terrace was observed along the section of coastline north from Quillayute River to Hole-in-the-Wall (Figures 21 and 28). In the 300-plus years since the last subduction earthquake, many of the marine terraces have been uplifted enough to raise them above the high tide line, allowing trees and grasses to grow on their relatively flat surfaces. We observed wood buried in the Rialto marine terrace that could be radiocarbon dated to constrain the timing of coastal tectonic events. Marine terraces are not extensive between the Quillayute River and Hoh Head; we counted only six. They are located between Strawberry Point and Toleak Point, at the north end of Third Beach, and north of Jackson Creek. The Strawberry-Toleak terrace is 30 m wide and stands >1.5 m above the high tide line and beach. It is composed of sandy mud with abundant shell fragments.



Figure 28. Marine terrace adjacent to Rialto Beach being invaded by driftwood and beach gravel pushed landward by winter storm waves. Burial of the tree roots by gravel has killed the spruce trees.

Coastal rivers, erosion of coastal bluffs and longshore currents are the primary source of sediment for the beaches. Longshore currents generally move sediment to the north in this section of coastline, but there are two south-moving offshore currents at the north end of Strawberry Bay and the south end of Rialto Beach (Figures 21-23). Longshore currents diverge at the south end of Rialto Beach, moving river sediment north to nourish the beach, and south to the barrier island.

Rialto Beach is among the most popular and accessible beaches in the park (Figure 21). A wide, flat sand beach exposed at low tides merges landward with a steeper, narrower pebble and mixed sediment beach, and eventually a marine terrace (Figure 28). The pebble beaches have relatively steep ocean-facing slopes unlike the sand beaches, and form when strong winter storms pile-up coarse sediment. Rialto Beach has a spectacular accumulation of large wood largely from the Quillayute River. Winter storms have racked up an impressive number of giant logs 1 m or more in diameter.

Boulder beaches are small, discontinuous landforms on this section of shoreline, and were observed in small coves near headlands adjacent to Cape Johnson and north of Hole-in-the-Wall (Figures 15 and 21). Cobble and boulder beaches form beneath headlands where rock fall accumulates at the base of bluffs and high energy waves quickly round the edges off the sharp rocks. Most of the beaches south of the Quillayute River are sand with smaller cobble, pebble and boulder beaches. (Table 6).

We also observed a small pebble beach south of Toleak Point that contained the southernmost granitic erratics from the CIS. There was also a more extensive cobble beach north of Hoh Head. The coarser grain sized beaches often have berms that have steep ocean-side slopes that extend down to sand beaches. One of only two tombolos mapped in the park attaches Strawberry Point to the coast (Figure 23).

The mouth of the Quillayute River is one of the most diverse and dynamic places on the coastline because of the wide variety of landforms created by the interaction of glacial, coastal and river processes (Figures 21 and 29). The gravel barrier beach across the river mouth is massive and has been known to be breached by severe winter storms, only to be repaired by the next large flood on the river. The threat to the La Push harbor when the barrier was breached in the early 1990s led to the placement of many hundreds of yards of large angular rock (a.k.a. rip-rap) by the U.S. Army Corps of Engineers.

The National Park boundary turns inland at the mouth of the Quillayute River. The river mouth includes a collection of fluvial landforms, including the river floodplain. The floodplain contains a number of other features too small for us to map, including oxbow ponds, gravel bars and logjams. Recent river deposits compose the lower terraces 5 m and less above the river. Taller terraces at 12, 60, 75, and 90 m are likely to include glacial outwash (Figures 21 and 29). Outwash was likely deposited by the Quillayute and Dickey rivers when they were large, braided streams carrying melt water from the ice sheet (Figure 6). It is also possible that some of the outwash was from alpine glaciers from the Sol Duc or Bogachiel valleys.

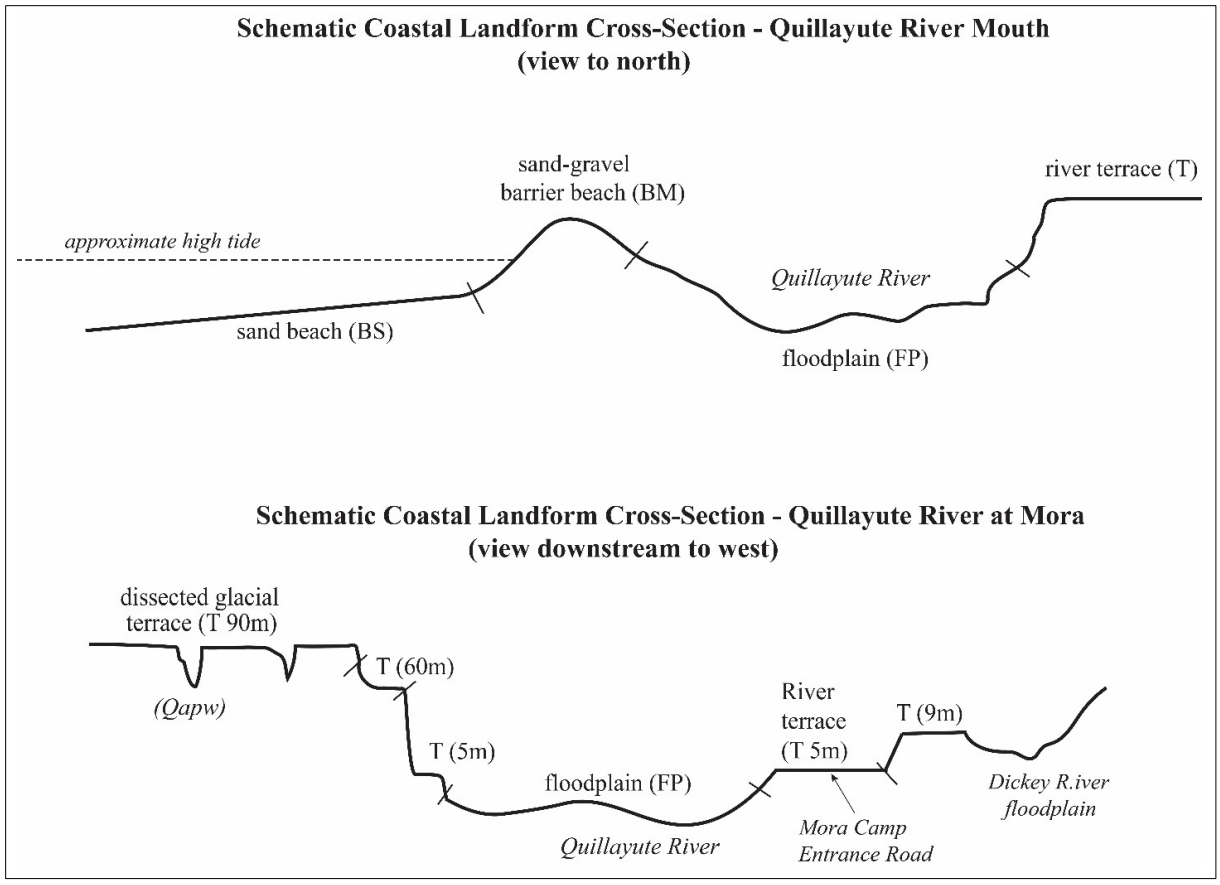


Figure 29. Schematic landform cross-sections near the mouth of the Quillayute River.

There is a sand barrier beach across the mouth of Mosquito Creek, which has a small, deep estuary (Figure 23). The river has cut a wide, flat bench in bedrock on its south bank about 60 m above river level. This type of terrace is called a strand terrace and may date to a time when this section of the coastline was lower in elevation. There is a small marsh on top of the terrace, and another terrace stands about 12 m above the river. Just upstream from the estuary, the stream has cut deeply into the hills.

Goodman Creek enters the Pacific Ocean through an interesting bedrock canyon that included small rock towers and other features too small to map (Figure 30). Falls Creek enters the canyon as a beautiful waterfall that can be seen from the trail. Tidal influence reaches into the canyon to the base of the falls. About 1 km above the river mouth the bedrock canyon ends and a series of alluvial terraces descend from about 60 m above the river to another terrace at 25 m and a smaller one about 3 m above the river. A gully cut into the 3 m terrace exposed a layer of buried wood observed just above the floor of the gully. There is a layer of well-rounded cobble beneath the wood, and 1 m of silt, sand and clay above it. Future research on the history of the coastline could use the buried wood layer to date a flood or coastal tectonic event. A natural arch and small cave are mapped north of Goodman Creek near a small headland. The mouth of Scott Creek enters the coastline through a

narrow, colluvial valley. There is a small sulphur spring on the beach near the south end of Scott's Bluff.



Figure 30. Bedrock smoothed by waves and floods near the mouth of Goodman Creek.

Coastal Section 3 Hoh Head to Kalaloch

This southern section of the coast differs markedly from the reaches to the north because the backshore is dominated by thick outwash sand and gravel deposits from multiple excursions of an alpine glacier down the Hoh valley (Figures 3 and 6). Thrust-faults are rare along this coastline, perhaps explaining the absence of large wave-cut platforms, and beaches are long, straight and sandy. Another highlight is the ever-changing mouth of the glacial-fed Hoh River (Figures 31 and 32). In contrast to coastal Sections 1 and 2, this section has only four headlands compared to 11 in Sections 1 and 2 where there are more bedrock bluffs in the back shore. Due to the lack of headlands, there are also only three small wave-cut platforms and two sea stacks.

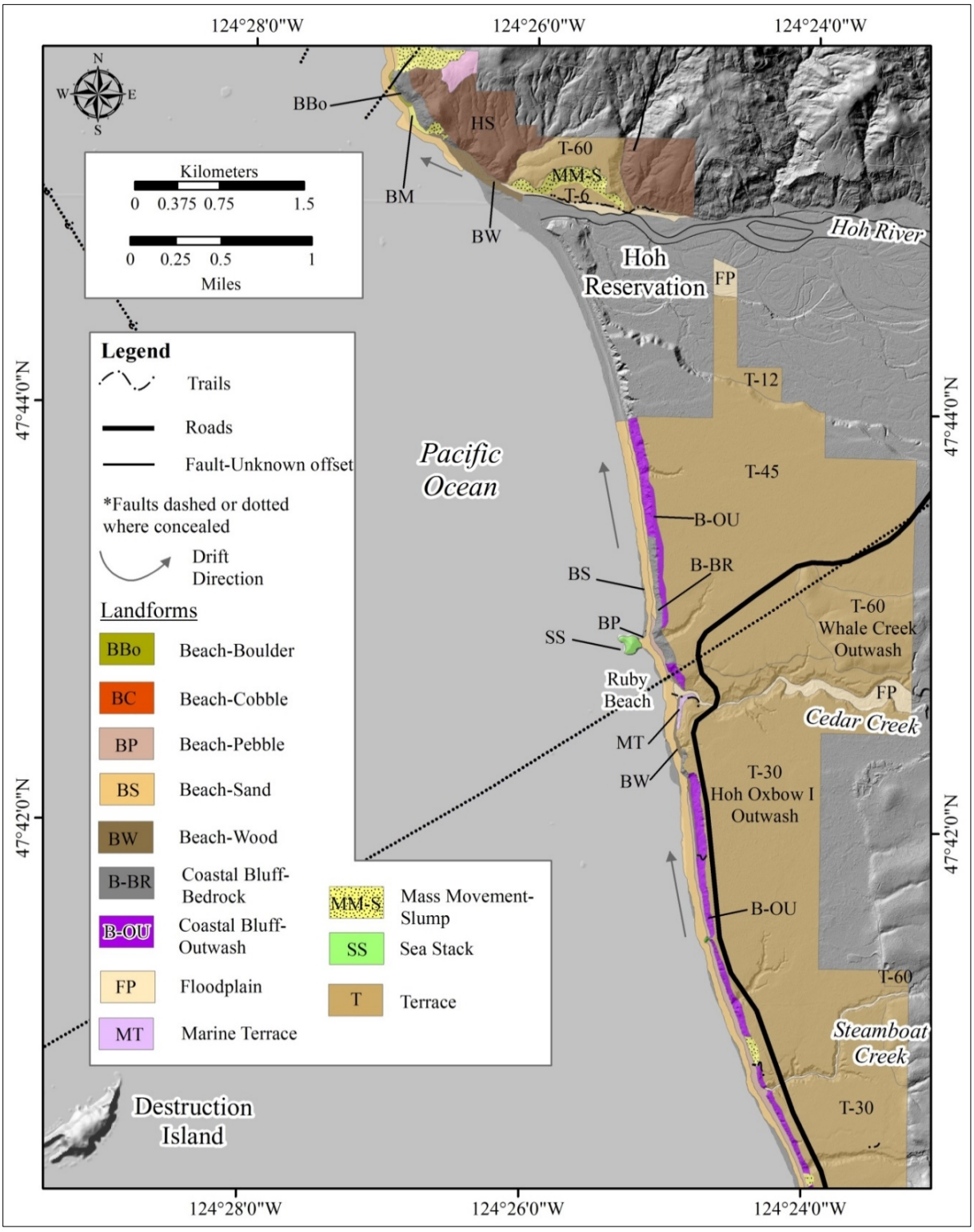


Figure 31. Coastal landforms from Hoh River to Steamboat Creek. Faults mapped by Gerstel and Lingley (2000).

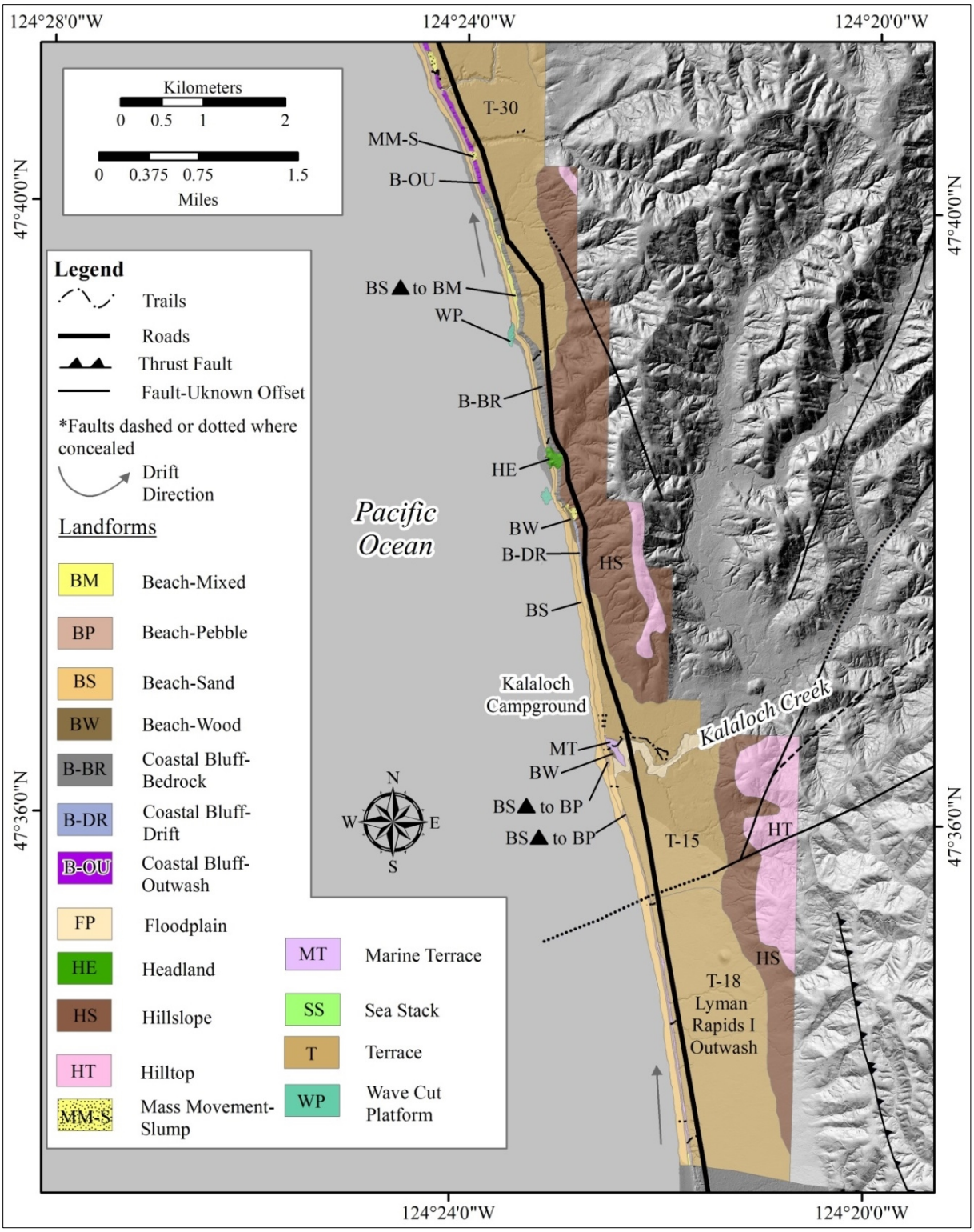


Figure 32. Coastal landforms from Steamboat Creek to Kalaloch and southern boundary. Triangles represent beaches that underwent a change in texture in winter 2015. Faults mapped by Gerstel and Lingley (2000).

In the backshore, the Hoh River mouth floodplain, associated terraces and backshore hills are the main landforms, accounting for 87% of the total area (Figure 31; Table 7). In the foreshore zone we counted nine distinct landforms, with long, wide sand beaches the most numerous and extensive (Table 7). Sand beaches are the most extensive foreshore landform, unlike the coast north of Hoh Head where there is more variety in beach type. The long straight beaches cover more than 3% of this section of coastline.

Table 7. Coastal Section 3 summary of landform distribution from Hoh Head to Kalaloch.

Landform Type	Number Observed	Area (km^2)	% of Section
Terrace	13	18.49	59.13
Hillslope	5	5.66	18.09
Hilltop	4	1.87	5.99
Beach-Sand	14	1.77	5.67
Mass Movement-Slump/Creep	9	1.03	3.28
Floodplain	6	0.59	1.89
Bluff-Outwash	7	0.39	1.26
Headland	4	0.39	1.25
Bluff-Bedrock	7	0.39	1.23
Beach-Pebble	5	0.25	0.81
Beach-Wood	6	0.11	0.36
Marine Terrace	3	0.10	0.33
Beach-Mixed	4	0.08	0.25
Wave Cut Platform	3	0.07	0.24
Bluff-Drift	1	0.02	0.07
Sea Stack	2	0.02	0.07
Beach-Boulder	2	0.01	0.04
Beach-Cobble	1	0.01	0.01
Totals	96	31.3	100.0

Conspicuous by their low numbers and limited extent are landforms associated with thrust faulting and bedrock hills, such as wave-cut platforms, headlands, sea stacks and small, coarse-textured crescent shaped beaches. We mapped two headlands and two sea stacks between the Hoh River and Kalaloch (Table 7). Bedrock bluffs were observed for a short distance at the mouth of Cedar Creek and just north of Kalaloch Creek (Figures 31 and 32).

Most of the coastal bluffs between the Hoh and Queets rivers are formed in glacial outwash and peat deposits that form a series of prominent terraces 30-60 m above sea level (Figure 31-34). Wave erosion has exposed the western edge of the sediments, which used to form a continuous sheet of sand and gravel to Destruction Island (Pazzaglia et al. 2003). The upper part of the bluffs is

composed of sand and gravel deposited during the Lyman Rapids and Hoh Oxbow glacial advances from 70 to 23 Ka (Thackray 2001). Many of the costal bluffs are stable and have near vertical faces. An exception is a several hundred-meter-wide landslide that occurred in 2016 one kilometer south of Steamboat Creek. Four kilometers south of Steamboat Creek until one km north of Kalaloch Creek, coastal bluffs are formed in bedrock composed mainly of sandstone, with minor siltstone and conglomerate (Tabor and Cady 1978a).

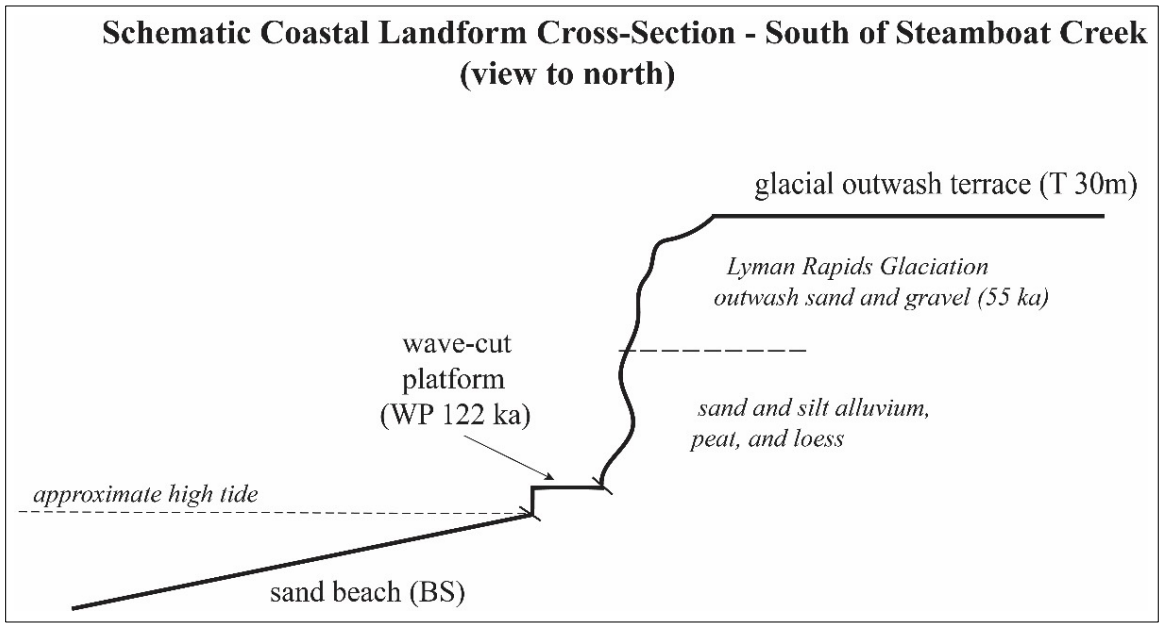


Figure 33. Schematic coastal landform cross-section looking north near Ruby Beach. Sediments composing coastal bluffs described by Thackray (2001) and wave-cut platform age from Pazzaglia et al. (2003).



Figure 34. Coastal geomorphology near Kalaloch, with a wide sand low-tide beach, gravel beach/berm, large wood accumulation, and coastal bluff in glacial outwash.

Only small wave cut platforms were observed in this section, which we relate to the lack of thrust faults and headlands. Pazzaglia et al. (2003) describe a wave-cut unconformity exposed 2.7 m above sea level at the base of Beach Trail 4, about 2 km north of Kalaloch (see their Figure 10A). It is about 12 m above sea level near Ruby Beach to the north and also present 52 m above sea level to the south near the Queets River. They suggest that this landform was created about 122 Ka, based on the age of overlying sediments of the Brown's Point Formation and its deformation along the coast (Figure 33). More research is needed to determine if the wave-cut platform near Hoh Head is the same landform, but if it is, the once-level wave-cut platform has been severely deformed in the past 100,000 years.

The inviting long sandy beaches in this section of coastline are fed by erosion of the bluffs and by rivers that provide sediment for the longshore drift current that runs south to north (Figures 31, 32 and 35). A narrow pebble beach occurs near the high tide line and the base of the outwash bluffs from Cedar Creek and continues about 5 km to the south. The gravels are left as a lag deposit by waves that moved sand offshore. Near where the pebble beaches end the backshore is dominated by bedrock hills and colluvium instead of the outwash bluffs to the north. The bedrock cliffs end south of a small headland.



Figure 35. Wide sandy low-tide beach looking north near Kalaloch to a small headland.

At the north end of Jefferson Cove, in a marine terrace, a possible volcanic ash was observed in the eroding shoreline and is most likely layer 'O' from the eruption of Mt. Mazama in Oregon (Crater Lake) 7.6 Ka (Bacon 1983; Zdonowiecz et al. 1999). The only other site along the coast where we observed the tephra is on the glacial moraines west of Ozette Lake. A small marine terrace was mapped on the south (left) bank of Cedar Creek at its mouth. There is another long, narrow marine terrace about 1 km south of Kalaloch Creek that continues for 2.5 km to the south. Cedar, Steamboat and Kalaloch creeks are the only perennial streams that drain to the coast of Olympic National Park south of the Hoh River.

The mouth of Hoh River is a dynamic place due to the interaction of glacial, river and coastal processes of erosion and deposition. We identified an alluvial terrace at 6 m, and what may be glacial outwash terraces at 12, 45, and 60 m above the floodplain. There are more, but we did not map in the Hoh Reservation. South of the river bedrock hills also are common and intersect the coast north of Kalaloch (Figure 32). Gravel and sand delivered by the river have built a large beach and gravel barrier on the coastline. The barrier extends across the mouth of the river from south to north. This landform is likely not stable and could be breached by strong winter storms and reshaped by new waves of sand and gravel deposited by the river during floods.

In the foreshore of this section of coast we observed six wood-covered beaches. The largest collection of drift wood we encountered was observed north of the Hoh River mouth (Figure 36), where logs more than 30 m long and 1.5 m wide cover the beach for 500 m. In places the driftwood is stacked 3 m high and is built on a mixed sand and gravel beach.



Figure 36. Large logs dominate the beach north of the Hoh River mouth in the foreground, with bedrock coastal bluffs in the distance.

Landslide Inventory

Large movements of soil and vegetation are common on the steep coastal slopes of OLYM. Information on landslides can guide the selection of ecological reference sites or locations for facilities such as trails, campgrounds and bridges. Coastal bluff instability also feeds sediment to nourish beaches and large wood to provide shoreline protection. All the landslides we mapped are active, but it was beyond the scope of this effort to determine when they became active (i.e. their age). This data provides information of overall stability of a section of coastline, and its influence on other processes such as beach morphology and texture.

The coastal region of OLYM contains 45 mapped mass movements that cover 4.65 km^2, or 2.77%, of the total coastal unit (Table 4). The exact number of landslides is not as important as the area they cover because in many sections of coastline long stretches of coastal bluffs are failing and it is difficult to map individual landslides since they have coalesced. Landslides were classified into slow-moving slumps, rapid debris avalanches and rock falls/topples (Table 8; Appendix A). Of the 45 mass movements, 43 are slumps, with one rock topple and one debris avalanche. A majority of slides (56%) are concentrated between the Quillayute and Hoh Rivers. The coastline to the north and south of this region overall contains fewer mass movements because bluffs are not as tall or they are composed of more stable glacial material.

Table 8. Summary of the OLYM coastal unit landslide inventory data.

Mass Movement Type	Number	Surface Area (km^2)	% of Total Park
Debris Avalanche	1	0.04	0.02
Fall/Topple	1	0.01	0.01
Slump/Creep	43	4.60	2.50
Totals	45	4.65	2.53

The primary controls on mass movements are topography, proximity to faults, slope material, high rates of weathering and wave erosion of the toe of slopes. Most of the coastal bluffs at OLYM (41%) are composed of glacial sediments (till, outwash, and lake beds), and 37% are bedrock. Sandstone and siltstone of the Hoh Formation is the primary bedrock, although some intrusive and volcanic units are present, mostly near the as area around Point of the Arches. Gerstel (1999) found that large debris avalanches on the peninsula involved bedrock failures along bedding surfaces, along zones of mineralogical alteration and along faults and other structural weaknesses.

We also observed high rates of bedrock weathering, and in many instances, siltstones were chemically and physically weathered to silt and clay at several meters depth, resulting in deep-seated failures of bedrock bluffs undercut by waves (e.g. Figure 26). An excellent example is found along the coastal bluffs north of the Hoh River to Second Beach, where weathered siltstone has produced a nearly continuous strip of coastal bluffs failing by deep-seated slumps and creeps.

Glacial sediments are also prone to failure, particularly when they include silt and clay, such as in till and glacial lake sediments. Thick, dense glacial till was found in the coastal bluffs north of Cape Johnson to the northern boundary, where it is often topped by sand and gravel (Figure 17). The layering of outwash over dense till creates conditions for slope failure because water is trapped on top of the till, leading to oversaturation and failure of the overlying soils. For long sections of the coastline north of Cedar Creek, coastal bluffs are failing due to wave undercutting slopes. In some cases, the dense till protects the slope from wave undercutting and results in a near vertical bluff, such as in Figure 17. Coarser-grained glacial outwash, dominated by sand and gravel, is less likely to fail by deep-seated slumps and instead fails less-frequently by shallow debris flows. Coastal bluffs in glacial outwash are generally more stable and form steep cliffs along the coast south of the Hoh River.

Slumps account for 96% of landslides on the Olympic coast within OLYM. These 43 mass movements range in individual size from <.01 km^2 to 0.82 km^2. Most commonly, slumps occur on flat to concave seaward slopes which face south to west. However, there are examples of slumps which occur on convex or complicated slopes and on slopes which do not terminate at beaches. Slump material varies widely to contain all types of available material on the coast including tectonic breccia, marine sedimentary rocks, conglomerates and Quaternary deposits such as glacial drift, till and outwash.

Debris avalanches are large slope failures that were not frequently observed in this inventory, with only one mapped along the coast. This landform is on a southeast facing slope that drains towards Dickey Creek and is composed of glacial drift overlying bedrock. The drift is dense to extremely dense with cobbles, gravel and scattered boulders supported by a clay and silt matrix (Gerstel and Lingley 2000). Underlying this debris avalanche are deposits of marine rhythmic thin-to-medium-bedded sandstone, siltstone and shale. This early Miocene unit is stretched and rotated. It is likely that erosion undercut the slope and caused the development of this debris avalanche. Restriction of groundwater flow into the upper till unit may have also been a contributing factor. The reported area of the debris avalanche underestimates its true size, since it is cross-cut by a slump and there is a component of the avalanche outside park boundaries. Overall, debris avalanches are considered atypical coastal mass movements due to short slope lengths and rapid removal of sediments along the coastline. In contrast, they are common landforms in the mountains of OLYM.

Rock falls and topples are small, ephemeral landforms. Rock towers fail and deposit a series of boulders that are quickly diminished by waves. They occur most often near headlands and sea stacks. In this setting waves tend to remove the rocks, or in some cases to reorganize them at the base of cliffs as boulder-gravel beaches. As a result, we only mapped one topple in this survey near Hoh Head, and they are clearly not a key component of the coastal landform inventory. This topple is in heavily altered rocks, including breccias, that are either mélange injected along fault planes or as thick sequences of intensely sheared sandstones and siltstones (Gerstel and Lingley 2000). All tectonic breccia deposits along the coast are in fault contact with surrounding rocks, adding to their vulnerability to rock falls and topples.

Synthesis

The wild, rugged Olympic Peninsula coastline is shaped by the intersection of tectonic, glacial, hillslope, coastal and river processes of erosion and deposition. Different combinations of these processes make the OLYM coast unique within the lower 48 states and have created three distinct sections of coastline. Tectonic, glacial and fluvial processes have shaped the backshore, including the formation of the large and deep Ozette Lake, along with its peculiar landscape. In this section we link distinct geologic processes to the assemblage of landforms discovered at OLYM. We conclude this report by providing a brief assessment of landform age and by examining the stability of beaches.

Landform – Process Associations

Tectonics and Bedrock Geology

Subduction of the Juan de Fuca oceanic plate beneath North America continues to raise and lower the OLYM coast and creates a setting where waves impinge on steep uplands composed of sedimentary rocks and glacial deposits. This results in rapid rates of coastal recession of 20-30 m or more every 100 years (King 1972), creating many of the iconic features of this coastline, including headlands, sea stacks, natural arches and wave-cut platforms. Erosion is also rapid because of weathering processes that are intense in the wet, mild climate along the coast. Bedrock and glacial sediments that compose the bluffs (backshore) are all pervasively weathered to a meter or more in depth and prone to landslides. Yellow Banks west of Ozette Lake is an example of the intense weathering of glacial sediments since the end of the last ice age (Figure 14).

It is clear from this landform inventory that thrust faults near the coast control local uplifting of bedrock and the creation of bedrock landforms. The cluster of thrust faults north of Hoh Head led to the creation of many headlands, countless sea stacks, and the second most common foreshore landform, wave–cut platforms (Table 4). This rocky reach of coastline contains 22 of 26 headlands and most of the park's sea stacks.

Larger headlands are called capes, and they often mark major changes in coastal geology, such as at Cape Johnson and Hoh Head. Headlands at OLYM are evidence of greater resistance to erosion by bedrock than by glacial sediments. Most of the main capes and headlands at OLYM have been eroded to produce dense concentrations of sea stacks and arches just offshore. These landforms mark the landward retreat of the coastline. We identified several hundred sea stacks in our survey, but note that there are many hundreds more offshore, outside of the park boundary (Table 4).

Wave-undercutting of bedrock bluffs and headlands leads to rock falls and the formation of boulder and cobble beaches. These are not common features; we mapped 19 boulder beaches and 11 covered in cobbles that combined cover less than 0.1% of coastal OLYM.

The base of headlands and sea stacks are often surrounded by wave cut platforms. These landforms are the second most common in the foreshore after sand beaches and are created by a combination of bedrock resistance, weathering, tectonics, sea level and wave erosion. We identified 33, many of which contain tidal pools, channels and abundant marine life (Table 4). Wave-cut platforms are created between the high and low tide lines by wave erosion of bedrock by the processes of abrasion,

plucking and mainly water-level weathering (i.e. shore platforms, wave-cut bench; Wentworth 1938, Bloom 1978). They are often submerged during high tides but are exposed during low tide connecting sea stacks and headlands. They can be temporarily obscured by a cover of sand and gravel and exposed during large storms (cover photo).

Wave cut platforms are also interesting because their formation is controlled to some extent by changes in sea level and by uplift/down-drop of the coastline. Subduction earthquakes every 300-500 years move the platforms into or out of the wave erosion zone (Atwater et al. 2004). Some wave-cut platforms could also be related to higher stands of sea level before the last ice age. We observed multiple platforms at some sites, including near Hole-in-the-Wall, but we did not map them separately.

Near Kalaloch, a 122 Ka wave cut platform in the Steamboat Creek Formation can be observed in the coastal bluffs (Pazzaglia et al. 2004). At the mouth of the Hoh River, this wave cut platform is now below sea level, but it rises to 12 m above sea level at Ruby Beach, and 52 m above sea level near the mouth of the Queets River. This wave cut platform vividly illustrates how much tectonic deformation is occurring on the OLYM coast.

Changes in the type and orientation of faults directly influence the type of coastal landforms. Slabs of crust offshore that are being thrust shoreward are fragmented by faults that generally run north to south (Figure 3). Near-shore thrust faults lead to rock that is uplifted and eroded by waves to form capes, headlands, arches, caves, sea stacks, wave cut platforms and bedrock sea cliffs. Erosion of the uplifted coastline is dominated by the power of waves against rocks and glacial deposits that are physically and chemically weathered in the wet mild climate (Bloom 1978).

Hillslope Geology

Where the backshore intersects the foreshore, coastal bluffs form. Many of the bluff faces are unstable due to wave undercutting, weathering and heavy rainfall. The 45 individual landslides we mapped are contributing gravel, sand, large wood and organic material to the foreshore. A majority of the landslides (56%) occur between the Hoh and Quillayute rivers, where more weathered glacial deposits and bedrock occur. Most of the landslides are classified as slumps and are slow moving, limiting the threat they pose to hikers on the beach. Many do accelerate during periods of heavy rainfall, however, and should be avoided as campsites.

Glacial Geology

Changes in the style and age of glaciation help define the three different sections of coastline. Widespread evidence of stagnation of the ice sheet around the Ozette Lake basin during deglaciation created a unique set of backshore landforms.

The coast north of Cape Johnson was inundated by the most recent excursion of the CIS, which left glacial deposits as thick as 40 m mantling the bedrock hills and coastal bluffs. The glacial landscape around Ozette Lake is dominated by moraines, drift-mantled bedrock hills and widespread evidence of ice stagnation, including the prairies, an unusual feature in this forested landscape. We identified the terminus of the Juan De Fuca Lobe of the CIS just south of Ozette Lake, near the headwaters of

Dickey River and extending west to Cape Johnson (Figure 6). LiDAR data clearly show the ice moved south parallel to the coastline, following the topography of the lake basin and terminating along the coast just north of Cape Johnson. The ice sheet shaped lowland deposits to create a fluted surface characterized by low, long ridges oriented parallel to ice flow. Landforms east of Ozette Lake also record a reorientation in flow from southerly to westerly as the ice retreated. During retreat, large masses of the ice sheet stagnated in and around Ozette Lake to form areas of hummocky topography and the ice-walled lake plains (Clayton et al. 2008). These are unusual landforms locally and regionally in a coastal setting. The ice-walled lake plains have prairie vegetation in an otherwise densely forested landscape, likely maintained for the past 2,000 years by anthropogenic activity in the form of burning (Bach and Conca 2004). That study also concluded that the area was deglaciated about 14,000 years ago, with lakes occupying the prairie sites. These landforms have been recognized in the Midwestern U.S. (Clayton et al. 2008).

Some sloughs and valleys around the lake likely carried glacial meltwater, while some also may have served as temporary outlets for drainage of Ozette Lake when the lake level was higher, and the Ozette River was blocked by ice. Allen's Slough was likely another outlet when the lake level was about 20 m higher while Cedar Creek at the south end of the lake also may have been a spillway when the lake level was 50 m or higher, which was probably only at the end of the ice age when ice blocked the other outlets to the north. The northeast shoreline of the lake fronts a series of ancient deltas, where Umbrella Creek, Trout Creek and Big River emptied into the lake at the end of the ice age. At that time the lake's surface elevation was about 30 m (100 ft) higher than today. A series of terraces that stand 3 m above the Ozette River at the lake outlet indicate that the lake level may have been stable near 12.2 m elevation a.s.l. for a long time (Figure 10). However, tectonic events that change the elevation of the outlet may also have influenced the lake level.

Beaches between the headlands in this northern section are often composed of coarser grain-sizes, and composed of an incredible variety of rock types, many of which are from Canada. The exceptions are two larger sand dominated beaches adjacent to the area of ice stagnation near Ozette Lake north, including Shi Shi Beach.

South of Cape Johnson to Hoh Head, the backshore is dominated by backshore hills in bedrock with a thin, discontinuous cover of highly weathered, possibly older, glacial sediments. On the coast, thrust faults continue, along with small headlands and associated sea stacks and wave cut platforms. Beaches are small and dynamic, with more cobble and boulder beaches than in the other sections of coastline. Beyond the most recent ice sheet limit a series of dissected outwash terraces and drift mantled hills may date to an earlier glaciation. They are mapped as continental glacial till north of the Quillayute and alpine glacial till, pre-Wisconsin, south of the Quillayute by Gerstel and Lingley (2000), but more work is needed to determine the age and origin of these landforms.

From Hoh Head to Kalaloch, the tectonic setting, character of the glacial landscape, and landform distribution all change. The backshore is dominated by glacial outwash terraces consisting of layers of sand and gravel deposited by the meltwaters of alpine glaciers flowing down the Hoh, Clearwater and Queets rivers during the last 100,000 years (Figure 3; Gerstel and Lingley 2000, Thackray 2001).

Glacial deposits that mantle bedrock bluffs and hills north of the Hoh River estuary to the north are likely older alpine glacial deposits that spilled down Mosquito Creek from the Hoh River (Figure 6).

In the absence of thrust faults and bedrock near the coastline, headlands, sea stacks and wave cut platforms are not common from Hoh Head to Kalaloch. We identified only four headlands, two sea stacks, and three wave-cut platforms (Table 7). Instead, long, straight sand beaches replace the small crescentic gravel beaches.

Coastal Geology

Coastal processes directly influence the shape of the coastline and the type of landforms found in the foreshore zone. From Cape Alava south, multiple headlands define a scalloped coastline with isolated crescent-shaped, coarse-grained beaches at the high tide line (Figure 2). North of Cape Alava and south of Hoh Head, glacial outwash bluffs and fewer uplifted bedrock landforms result in long, straight, sandy beaches.

The 174 beaches at OLYM are dynamic landforms that change with the season and passage of winter storms, and with the occurrence of vertical changes in land elevation due to subduction earthquakes. They are fed sediment from local, regional and distant sources. Many gravel beaches receive sediment directly from adjacent landslides, small streams and erosion of coastal bluffs. Others are fed sediment by nearby coastal rivers, particularly the large Hoh and Quillayute Rivers. It is also possible that all of the beaches receive sand from more distant rivers, including the Queets, Quinault and Columbia Rivers. The sand is moved along the coast from south to north by longshore currents. Peterson et al. (2010) found that headlands extending more than 2.5 km from the coastline tend to block sand moving northward, while smaller headlands are bypassed by littoral drift of sand from coastal rivers. Only Cape Alava comes close to this threshold. Hoh, Toleak, and several other headlands protrude 1 km or less from adjacent coasts. Therefore, it seems likely that sand is moving along the entire coast south of this point, and perhaps from as far as the Columbia River (Ruggerio et al. 2012).

Marine terraces represent sections of the coast that were, or are, being uplifted above the tideline (Peterson et al. 2013). In some cases, they merge with stream terraces (e.g. Ellen Creek). Some are protected by large wood accumulations, such as the one near Rialto Beach. They in turn protect glacial sediments from direct wave erosion, keeping the coastal bluffs stable. Buried wood observed in some of the marine terraces could provide information on when and how they formed.

Peterson et al. (2013) found small sand dunes and tsunami deposits on the marine terrace north of Sand Point (Figure 15). They described the assemblage of landforms as a ‘raised beach plain’. They concluded that the aggradation of sand initiated about 1.5 Ka and ended about 600 years ago. The relatively short period of beach plain deposition was related to the instability of these small beaches on the high-energy coast. A pebble gravel tsunami deposit was also found inland on a sand ridge on the marine terrace as high as 10 m above modern sea level. It was created by a subduction quake about 1.3 Ka. The dunes were too small to include at our mapping scale, but along with the marine terraces are important landforms because they attest to vertical changes in the coast and can preserve

evidence of past tsunamis. There are likely others along the section of coast north of Sand Point where the backshore is not steep due to the bedrock and glacial geology.

Beach Stability

Beaches are dynamic, relatively young landforms that may change in texture during one powerful winter storm. Of the 174 beaches we mapped, 70% were fine textured sand and pebble gravel that may be more sensitive to change. Winter 2015-16 witnessed the largest El Nino in 145 years, and some of the highest wave energy recorded on the west coast of the U.S. (Barnard et al. 2017). These events are known to raise mean monthly winter sea level by tens of centimeters and alter the storm track (Ruggiero et al. 2013).

Along the Olympic Coast at Buoy 46041, located west of the Quinault River, wave energy was the highest it has been since 2007, and wave power was the second highest since measurements began in 1987 (personal communication, Ian Miller, Coastal Hazards Specialist for the Washington Sea Grant program, email, 2018.). Several powerful storms produced an average monthly wave height of 10 m at coastal buoys (Figure 37). Combined with an 11 cm average increase in water elevation during these events, we anticipated changes in beaches and more landslides due to undercutting of coastal bluffs.

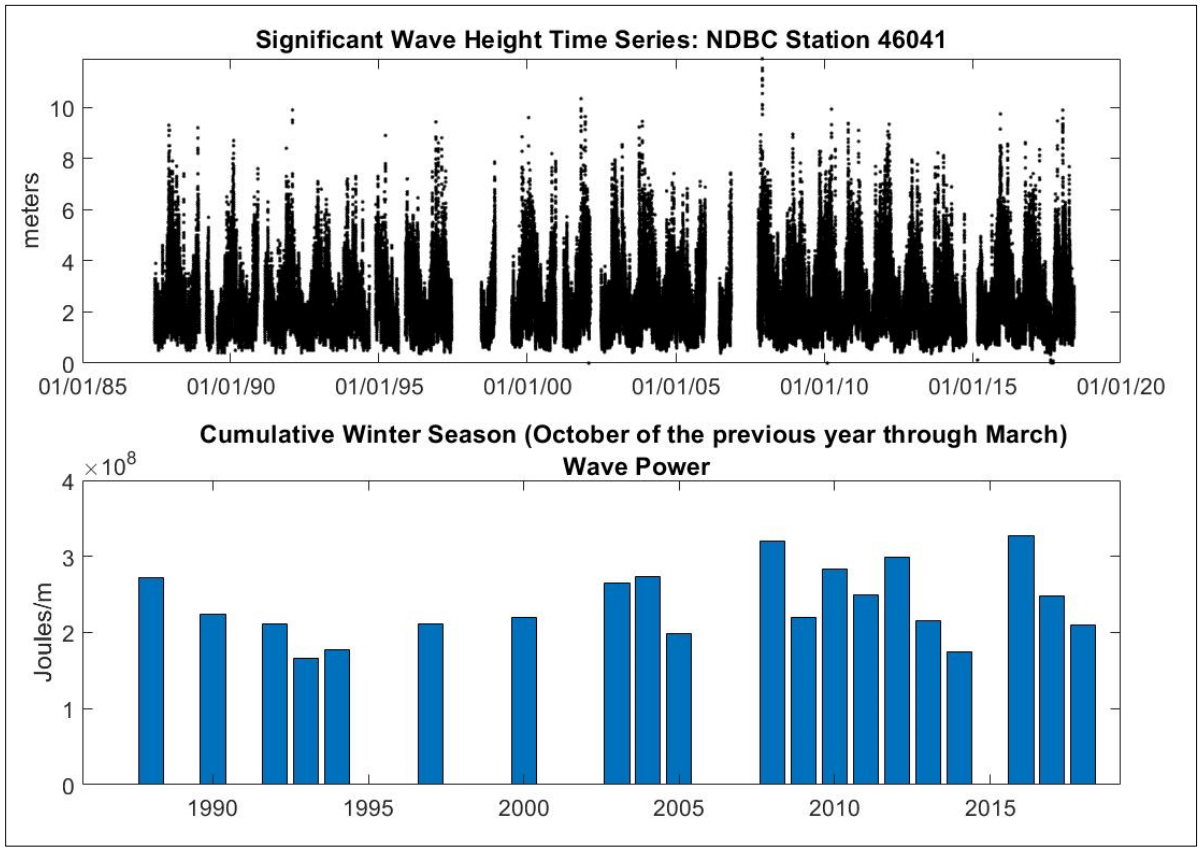


Figure 37. Winter wave power time series at coastal buoy 46041 near Cape Elizabeth. Data from Ian Miller, Coastal Hazards Specialist for the Washington Sea Grant program, email, 2018.

To assess changes in beaches, most of which were likely caused by the winter 2015-16 storms, we re-visited the beaches to look for changes in their composition (i.e. gravel vs. sand vs. mixed). Changes were observed in all settings, from small, crescent-shaped sand and gravel beaches between headlands to long, straight, relatively flat sand beaches. We observed changes at various scales at 44 sites, with the most common changes on small (< 1 km long) crescentic beaches at high-tide sites near Cape Johnson, Teahwhit Head and Hoh Head (Table 4). Twelve of 16 beaches near the three headland sites became coarser-textured, changing from mixed to gravel (pebble, cobble and boulder) and from sand to mixed (sand and gravel). These beaches should be expected to continue to be more dynamic given the focus of wave energy at the headlands.

Several beaches north of Cape Johnson became finer-textured, changing from mixed to sand, and from pebble to mixed, presumably as a result of deposition during the winter storms. Just to the south of Sand Point, a wave cut platform exposed at low-tide accumulated sand for several hundred meters along shore below the high-tide beach. The deposition of sand at these sites was likely due to longshore transport of sediment from feeder bluffs and beaches to the south that were eroded during the winter 2015-16 storms. The long beach south of Yellow Banks accumulated sand over a distance of 1.5 km and was remapped from a pebble beach to a mixed beach.

No changes in texture were noted for the large (> 1km) crescentic beaches north of Sand Point. Only minor changes in texture were noted at three small beaches south of Hoh River. In two cases near Kalaloch Creek sand was eroded from the beaches, as it was at another site 6 km to the north. South of the Quillayute River, two small sand beaches at either end of Second Beach changed from sand to cobble dominant and follow the general trend toward beach erosion and coarsening near headlands where wave energy is concentrated.

Only seven changes in texture were observed at beaches exposed at low tides. Low tide beach changes were observed between Taylor and Strawberry Point, but exhibited no trend indicating sand erosion or accumulation.

In summary, the winter of 2015-16 likely brought changes in the type of sediment composing 44 beaches along the OLYM coast. The general trends were toward erosion (coarsening) of small beaches near headlands, and deposition of sand on high tide beaches to the north. The locations of the beaches that changed in texture are marked by black triangles on the large-scale landform maps.

Coast section 1: Beach texture changes can occur seasonally, as noted above. In this section of beach, the only changes observed from 2013-2016 occurred to the beaches near Yellow Banks and north of Cape Johnson (Figures 14 and 15). At Yellow Banks, small sections of beach became finer textured; in one case a mixed beach became sand dominant, and in another a pebble gravel beach became mixed. Beach texture changes seasonally as winter storms eroded some beaches while bringing new loads of sand to others. The shifting sands also can cover wave cut platforms for various lengths of time. North of Cape Johnson, all high tide beaches underwent changes in winter 2015.

Coast section 2: Several small sections of sand beach near the high tide line at Second Beach changed to cobble beach between 2013 and 2016, most likely during the winter 2015 storms (Figure

22). The small crescent-shaped beach south of Taylor Point also underwent changes. The low tide beaches changed from sand to cobble dominant, and the sand appears to have been moved shoreward and converted cobble beaches to sand and mixed beaches.

Coast section 3: The beaches in this area are relatively stable compared to some of the steeper shorelines, at least as far as changes in texture in winter 2015. Two minor changes were observed near Kalaloch Creek, where the 2015 storms removed some sand and changed to pebble dominant (Figure 32).

Fluvial Geology

All the moderate to large coastal streams have created similar sets of diverse landforms where they intersect the coast. These include barrier beaches, river terraces, local drift cells and accumulations of wood. The river terraces are the second most extensive landform at coastal OLYM, and floodplains the fifth (Table 4). The estuaries of the Hoh and Quillayute rivers have particularly large floodplains and terraces, but they differ in that the Hoh carries glacial meltwater and drains a large undisturbed area in OLYM. The Quillayute is the merger of several large rivers and carries no glacial meltwater.

These rivers also contribute large wood to adjacent beaches that typically accumulates on the north side of the mouths due to longshore currents. We identified six beaches covered in large woody debris. Combined, they cover only 0.11 km^2, with the largest found just north of the Hoh and Quillayute rivers (Figure 31; Table 4).

We observed wood buried in river terraces at several sites, including Ozette River and Goodman Creek. Near the outlet of Ozette Lake on the right bank tributary entering from the north, we observed an interesting record of deposition in a terrace. Sediments included mostly silt and clay, but also buried wood and sand. Tsunami waves may be recorded several kilometers upstream from river mouths along the coast (Peterson et al. 2013).

Powerful waves preclude development of some coastal landforms. The dominance of wave erosion over river deposition on the OLYM coast is illustrated by the absence of deltas, tidal mud flats, or large linear offshore barrier islands. Instead, waves rapidly erode sediments from large rivers that might otherwise form a delta and longshore currents redistribute it rapidly along the coast. We also did not observe large sand dunes like those farther south along the Pacific coast at Oregon Dunes.

Landform Age

The scope of this study precluded determination of the ages of individual landforms, but it is possible to bracket the age of some based on process. The coastal landforms at OLYM have a variety of ages depending on whether they were formed by glaciers, rivers, mass-wasting or wave processes. For example, most of the sea cliffs in glacial deposits are prone to frequent landslides. We observed three large slope failures between 2012-2016, all of which delivered trees and sediment across high-tide beaches and into the surf zone. Most landslides are probably less than 100 years old since the rate of shoreline erosion in glacial sediment is about 20-30 m/100 years (King 1972). This conclusion is supported by the fact that unstable bluffs are covered by alder and other young vegetation.

At the other end of the spectrum, moraines and outwash terraces date to the last ice age. North of the Quillayute River, the glacial landforms were left by the CIS between 16 and 14 Ka (Haugerud and Hendy 2016). South of the Quillayute River, the deposits were left by alpine glaciers moving down west-side valleys over a long period of time in the last ice age. For example, six glacial sequences are recognized in the western Olympic Peninsula since the last interglacial between 100 and 11.6 Ka (Thackray et al. 2015). Each of the sequences is represented by moraines and associated outwash sand and gravel that form fluvial terraces and coastal bluffs. Near the mouth of the Hoh, the bluffs are capped by glacial outwash from the Lyman Rapids (75-55 Ka) and the Hoh Oxbow (50 to 23 Ka) alpine glacier advances.

The ages of other landforms observed are in-between those created within the past decade or from the last ice age. Of interest to managers are wave cut platforms, river terraces and marine terraces. It is likely that the age of these landforms is related to tectonic activity and the occurrence of coastal uplift and down-drop events. Subduction earthquakes occurred 0.3, ~1.1, ~1.3 and 1.7 Ka (Atwater et al. 2004). Therefore, some of these landforms may date to the one of these events, including the last major subduction earthquake in January 1700 A.D. (Satake et al. 1996).

Marine terraces are particularly interesting from several perspectives. They can include shell middens, colluvial material, swamp mud, sand and wood. Wood buried in marine terrace deposits and in riverine terraces in estuaries was observed at several sites. Peterson et al. (2014) recovered wood from a beach plain (marine terrace) north of Sand Point and suggested that the landform was formed between 1.5 and 0.6 Ka. We strongly urge the park to investigate the age of the buried wood to provide some indication of landform age, slope stability and the effect of subduction earthquakes. It is possible that erosion or down-drop of the coastline could destroy these deposits.

Headlands and arches may not be the enduring landforms they appear to be. The rate of shoreline erosion of bedrock has not been measured at OLYM, but 10 m/100 years in sedimentary rocks (King 1972) would mean that some these features are not more than a few thousand years old.

Gravel and sand barrier beaches, like marine terraces and wave cut platforms are important landforms because they protect the bluffs from the direct impact of waves. Gravel barriers can be enduring, but also dynamic features known to be temporarily breached during winter storms. The winter erosion of the barrier beach at the mouth of the Quillayute River in the early 1990s led to a breach of the landform and a threat to La Push harbor. As a result, the barrier was armored on the seaward face with large, angular rocks.

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Appendix A. Description of Landform Mapping Units

1) HT = Hilltop:

The broad high point of a hill that rises prominently above the surrounding area, generally less than 300 m from base to summit (USDA 2003, Bates and Jackson 1984). Along the Olympic National Park (OLYM) coastline, the hills are uplifted bedrock that has been shaped by erosion processes.

- **Location:** The first broad highs inland from the Pacific Ocean coastline.
- **Associated Landforms/Features:** Hillslope and slump mass movements.
- **Process:** Elevated by tectonic process, and overridden and modified by alpine glaciers or continental glaciers depending on location within OLYM.
- **Surficial Material:** Typically bedrock at the core with or without a mantle of glacial deposits such as till or drift.
- **Mapping Guidelines**: Only the flatter top surface is mapped as a hiltop, typically represented on topographic maps by closed contours.
- **Potential Vegetation:** Lowland forest with dense understory. Near the coast there are also small patches of upland vegetation that are strongly affected by high winds and sea spray, which can be found on hilltops. These zones consist of small grasslands in a mosaic with stunted trees and shrub lands, possibly with a carpet of lichens and mosses (Crawford et al. 2009).



Rounded hilltop in the distance (NPS)

2) BB = Bedrock Bench:

Exposed flat or gently dipping bedrock eroded by glacial activity (Davis and Mathews 1994).

- **Location:** Common where two glacial fed valleys meet usually on valley spurs in glaciated portions of valleys. In the coastal unit of OLYM they are found mostly around Ozette Lake and to the north, since these areas were overridden and scoured by the Cordilleran ice sheet. An example is Tivoli Island pictured below.

- **Associated Landforms/Features:** Terraces, sloughs, floodplains, shorelines and coastal bluffs-bedrock.
- **Process:** Glacial erosion abrades and plucks bedrock, often leaving it exposed.
- **Surficial Material**: Bedrock, often striated or polished.
- **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:** Lowland forest with thin understory, along with a carpet of grasses, mosses and lichens (Crawford et al. 2009).



Tivoli Island – Bedrock Bench (Washington Department of Ecology)

3) HS = Hillslope:

The sides of a hill, that rise up to less than 300 m from base to summit (USDA 2003, Bates and Jackson 1984).

- **Location:** The first broad high slopes extending from the coastline to hilltops.
- **Associated Landforms/Features:** Hilltops and slump/creep landslides.
- **Process:** Could have been modified by alpine glaciers or the Cordilleran ice sheet or by weathering and slope processes such as mass wasting.
- **Surficial Material:** Bedrock, till, drift, colluvium
- **Mapping Guidelines**: Delineation between hilltop and hillslope is mapped by break in slope from change in contour spacing on topographic maps.
- **Potential Vegetation:** Lowland forest with dense understory (Henderson et al. 1989).

4) DMB = Drift Mantled Bedrock.

Terrain that was shaped by erosion and deposition of the Cordilleran ice sheet.

- **Location:** In the area north of Cape Johnson, particularly around Ozette Lake.
- **Associated Landforms/ Features:** Slough, bedrock benches, ice-walled lake plains and moraines.

- **Process:** Erosion and deposition beneath or along the margins of the Cordilleran Ice Sheet
- **Surficial Material:** Glacial till and outwash, including lodgement and melt-out till
- **Mapping Guidelines**: Gentle topography north of the Cordilleran ice sheet terminus.
- **Potential Vegetation:** Lowland forest with dense understory (Henderson et al. 1989).

5) IWLP = Ice-walled Lake Plain:

A glacial landform created when the Cordilleran ice sheet stagnated in the lowlands west of Ozette Lake. Typically, flat and underlain by silt and glacial drift (Clayton et al. 2008). Striking at OLYM due to the lack of forest.

- **Location:** West of Ozette Lake against moraines and drift mantled hills.
- **Associated Landforms/ Features:** Drift-mantled bedrock, Pleistocene moraines, meltwater channels.
- **Process:** Form where glacial ice stagnates and is buried by sediment, often near the terminus of an ice sheet. Ephemeral lakes then form, trapped within and between the melting ice and bedrock ridges and moraines (Clayton et al. 2008).
- **Surficial Material:** Fine-grained deposits, silt or clay, lacustrine.
- **Mapping Guidelines:** Broad flat areas with no forest cover; tend to have marsh conditions.
- **Potential Vegetation:** The ice walled lake plains have prairie vegetation in an otherwise densely forested landscape, likely maintained for the past 2,000 years by anthropogenic activity in the form of burning (Bach and Conca 2004).



Ahlstroms's Prairie, mapped as an ice-walled lake plain (NPS)

6) MM-A = Debris Avalanche:

A large landslide that generally includes the failure of rock, soil and vegetation (Cruden and Varnes 1996, Orme 1990).

- **Location:** Typically found on glacially scoured over-steepened valley walls and hillslopes. There is only one mapped in the coastal unit of OLYM. This avalanche occurred in dense till that was deposited by the Cordilleran ice sheet (Gerstel and Lingley Jr. 2000).
- **Associated Landforms/ Features:** Hillslope, terrace and hilltop.
- **Process:** Rapid movement of hillslopes or headlands, triggered by several factors including heavy precipitation, soil properties, bedrock, slope, groundwater and earthquakes (Orme 1990).
- **Surficial Material:** Soil, colluvium, till, vegetation debris of all sizes and boulders.
- **Mapping Guidelines:** Polygon includes headwall scar, path, and deposit. Depositional surface is usually composed of hummocky topography with large angular blocks. These largest mass movements often block streams and create swamps. 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 developed lowland forest vegetation with variable understory.



Example of a debris avalanche (NPS)

7) MM-F = Rock Fall/Topple:

A type of a landslide involving the failure of a rock tower or cliff in 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:** Occur from headlands, sea stacks and coastal bluffs.
- **Associated Landforms/ Features:** Sea stacks, headlands or coastal bluffs composed of bedrock.
- **Process:** Detachment of rock falling from bedrock coastal bluffs or headlands. Large rock fall deposits generally accumulate over long periods of time.
- **Surficial Material:** Boulders and cobbles.

- **Mapping Guidelines:** Observed in the field, most of a significant accumulation of boulders at the base of a headland or coastal bluff.
- **Potential Vegetation:** Generally void of vegetation except for mosses and lichens.

8) MM-S = Slump and Creep:

Type of landslide involving rotational slide, typically slow and deep-seated, and/or failure of saturated soil, colluvium and glacial till. Slump and creep landforms are lumped together into one category (Cruden and Varnes 1996).

- **Location:** Slumps are found at the base of steep hillslopes along the coastline. They occur in unstable geologic deposits such as glacial till and deeply weathered bedrock. Preferential flow of water from seeps or springs can also be key to the development of creeps and slumps.
- **Associated Landforms/ Features:** Hillslopes, coastal bluffs, beaches.
- **Process:** Slumps occur by slow rotational movement of cohesive sediments 5 m or more in thickness. They are usually triggered by saturation of undercut steep slopes along the beach or riverbanks.
- **Characteristics**: Slumps are typically small and if found adjacent to the river, they supply sediment and wood to beaches and streams.
- **Surficial Material:** Soil, colluvium, till, outwash, drift.
- **Mapping Guidelines:** Slumps can be 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. Jackstrawed trees (crooked) are usually present on slumps that may also contain pistol gripped (curved trunks down slope) trees.
- **Potential Vegetation:** Recent slumps are typically covered in alder or other young vegetation. Older slides will have lowland forest vegetation developed or species that can tolerate high disturbance. Trees will typically be pistol-gripped, moving slowly down-slope with gravity.



Slumps along the OLYM coastline (NPS)

9) FP = Floodplain:

Low-lying area adjacent to a river composed of sediments deposited by a stream. Inundated with water during seasonal and large floods (Jarrett 1990).

- **Location:** On valley floors between river terraces adjacent to a river.
- **Associated Landforms/ Features:** River channel, gravel bar, marsh, wetland, braided stream, terrace, side channel, oxbow lake.
- **Process:** River erosion and deposition that moved sediment from the uplands toward the coast.
- **Surficial Material:** Alluvium (sand, silt and gravel).
- **Mapping Guidelines:** Floodplain polygon includes the active river channel, gravel bars, marshes, wetlands, oxbow ponds and other features adjacent to the stream 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. Usually, a clear distinction can be made between floodplain and terraces by vegetation type and the presence/absence of flowing water and/or freshly deposited alluvium. The floodplain is typically composed of rounded gravel and/or sand.
- The floodplain boundary is also identified by the presence and location of woody debris. Clumps of debris found longitudinally (parallel to the river) may be found in the forest several feet above the current river level indicating areas subject to recent flooding.
- **Potential Vegetation:** Lowland forest, riparian, wetland; active channel is typically void of vegetation but may contain vegetated island (Crawford et al. 2009).



Floodplain of the Quillayute River (NPS, left; Washington Department of Ecology, right)

10) SH = Shoreline:

Area bordering a large lake where the water level fluctuates seasonally.

- **Location:** A well-developed shoreline occurs around Ozette Lake where water level fluctuates several meters, or more, seasonally
- **Associated Landforms/ Features:** Drift-mantled bedrock, alluvial fan, terrace.

- **Process:** Waves redistribute sediment to form a beach where lake surface intersects upland landforms
- **Surficial Material:** Sand, gravel, silt and clay.
- **Mapping Guidelines:** The shoreline extends landward from the low-water line through a gently sloped beach covered in grasses and sedges. Shoreline polygon ends at change in ground cover, to trees and shrubs.
- **Potential Vegetation:** Type of vegetation is dependent on topography and length of the year flooded. See Ritchie and Bourgeois (2010) for detailed shoreline analysis of Ozette Lake.



Shoreline around Ozette Lake (Washington Department of Ecology)

11) SL = Slough:

A marsh or shallow undrained depression that usually contains a wetland or open water (Bates and Jackson 1984).

- **Location:** Between hills in the backshore zone of OLYM where low gradient streams meander through dense forest.
- **Associated Landforms/ Features:** Hillslope, floodplain, terrace.
- **Process:** Slow erosion and deposition by streams
- **Surficial Material:** Alluvium (sand, cobble, gravel, silt, clay) tends to be finer-grained.
- **Mapping Guidelines:** Topographic depressions between hillslopes and in drift-mantled bedrock. Typically do not have significant stream discharge.
- **Potential Vegetation:** Wetland, riparian. Amount of vegetation is dependent on micro-topography and depth to water table (Crawford et al. 2009).



Slough near the coastline (NPS)

12) T = Terrace:

A relatively flat surface that grades gently along a river. Can represent the dissected remnants of a previous floodplain or glacial outwash deposit (Jarrett 1990, USDA 2003).

- **Location:** On the valley floor between the active river floodplain and debris apron, or, hillslope.
- **Associated Landforms/ Features:** Floodplain.
- **Process:** Erosional or depositional feature. Rivers can cut into its floodplain and abandon terraces, or, build a new terrace surface by overbank flooding and deposition of silt and sand.
- **Surficial Material:** Alluvium composed of sand and gravel, glacial outwash.
- **Mapping Guidelines:** Terraces are represented by widely spaced contours of surfaces perched above and adjacent to a river. Surface gently slopes down valley. Remnants of abandoned side channels can cause terrace surface to be slightly uneven. Steep sides are represented by hatched lines on field maps. All terraces are field checked for height and composition from young alluvium to older outwash, to lacustrine (clay). Terrace elevations are marked in meters above stream channel (*i.e.* T-3 or T-30).
- **Potential Vegetation:** Vegetation varies with elevation and age of terrace. Higher elevation terraces have mature stands of lowland forest. Lower terraces may include generally younger, less mature, forests. Low terraces may have many depressions/old side channels with wetland or riparian vegetation (Crawford et al. 2009).



Low-lying terrace (NPS)



Elevated outwash terraces (Washington Department of Ecology)

13) PM = Pleistocene Moraine:

Ridge composed of till deposited at the margin or terminus of a glacier. These are large linear features usually > 5 m tall with surfaces commonly having hummocky topography. Usually have a single ridge, but on other occasions exhibit multiple ridges covered with large sub-rounded boulders scattered on the surface (Benn and Evans 1998).

- **Location:** Usually located below tree line near valley floors at the terminus of the Cordilleran ice sheet or alpine valley glaciers. Pleistocene moraines are often found at major stream junctions.
- **Associated Landforms/ Features:** Drift-mantled bedrock, terraces, hillslopes.
- **Process:** Glacial deposition of mud, sand, gravel and boulders from debris-laden ice.
- **Surficial Material:** Till, ice-contact stratified drift.
- **Mapping Guidelines:** Contour spacing and site visits distinguish PMs. Polygons are usually linear, parallel to valley. Contour spacing may be wider than the surrounding contours with a crenulated appearance.
- **Potential Vegetation:** Lowland forest vegetation (Crawford et al. 2009).

14) AF = Alluvial Fan:

Fluvial deposits in the shape of a low broad cone, with surfaces sloping less than 5 degrees.

- **Location:** Found where a mid-sized or large stream merges with a larger valley.
- **Associated Landforms/ Features:** Fan apron, fan collar, fan terrace, braided channel. Similar to a debris cone however an alluvial fan is typically larger, has a lower angle surface slope, and supports more mature vegetation.
- **Process:** Tributary stream deposits sand and gravel into a fan shape as the stream migrates back and forth.
- **Surficial Material:** Alluvium composed of sand and coarse 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 lowest elevation active part of the fan is mapped; older parts are fan terraces. Contain many old channels. Steep escarpments that occur on upstream side of cone are marked with hatched lines on field maps.
- **Potential Vegetation:** Lowland, riparian. Ranges from dense old growth to shrubs and open vegetation along streams (Crawford et al. 2009).



Example of an alluvial fan (NPS)

15) FT = Fan Terrace:

Remnants of an alluvial fan built under different climatic/hydrologic conditions than present, often during paraglacial sedimentation at the end of the last ice age (Church and Ryder 1972).

- **Location:** Lateral part 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.
- **Surficial Material:** Alluvium composed of sand and gravel.

- **Mapping Guidelines:** Terrace height is recorded on maps in feet above the active stream on an alluvial fan. Can be mapped as several polygons with several heights. Cut banks and flat surfaces grade to trunk system.
- **Potential Vegetation:** Lowland forest with dense understory (Crawford et al. 2009).



Fan terraces on either side of an alluvial fan (NPS)

16) B-S = Beach-Sand:

A coastal landform in the foreshore zone where waves and longshore currents deposit sediment. Typically have a gentle slope that can be flat or concave, extending landward from the low-tide line to a change in slope or perennial vegetation.

A sand beach is composed of particles with a size range of 0.0626 – 2 mm (Wentworth 1922).

Beaches at OLYM are also classified by other dominant particle sizes and other distinguishing characteristics:

17) B-B = Beach-Boulder

Gravel > 256 mm

18) B-C = Beach-Cobble

Gravel between 65-256 mm

19) B-P = Beach-Pebble

Gravel between 2.1 – 64 mm

20) B-M = Beach-Mixed

Beaches composed of varying combination of sand and gravel.

21) B-W = Beach-Wood

Beaches that contain high concentrations of large woody debris. Typically found at the mouths of major rivers.

- **Location:** Along shorelines with an abundant supply of sand or gravel and sufficient wave action to rework this material (Bird 2000, Woodroffe 2002).

- **Associated Landforms/ Features:** Wave cut platform, marine terrace, headlands and coastal bluffs.
- **Process:** Wave sorting and deposition of wood from coastal rivers and coastal bluffs.
- **Surficial Material: Large trees typically void of branches over beach sediments that range** in size from boulders to sand, cobble, gravel, silt and clay).
- **Mapping Guidelines:** Adjacent to coastal rivers that supply the large wood.
- **Potential Vegetation:** Typically void of vegetation although small shrubs, moss and lichen common.




Beach - Sand (NPS, left) and Beach - Pebble (NPS, right)




Beach - Cobble (NPS, left) and Beach - Mixed (NPS, right)




Beach - Wood (NPS, left) and Beach - Boulder (NPS, right)

22) HE-Headland:

A prominent landform along the coast that often has a cliff facing the ocean that protrudes from the coastline into the ocean (Bates and Jackson 1984). Larger headlands are often called capes.

- **Location:** Rocky protrusions from the land into the ocean.
- **Associated Landforms/ Features:** Wave-cut platform, sea stacks, coastal bluff, and marine terraces.
- **Process:** Erosional processes of wave action or glaciers against the mainland. Isolates sections of coast with wave refraction, re-enforcing erosion and isolation of headlands.
- **Surficial Material:** Bedrock with some colluvial or glacial sediment.
- **Mapping Guidelines:** Identified in air photos and maps as extending out from the coast with steep contours rising hundreds of feet above sea level.
- **Potential Vegetation:** Lowland forest and/or sea-spray vegetation zone. Where the bedrock meets the sea there may be little vegetation. Common to find dense understory along the back-slopes of headlands (Henderson et al. 1989).



Headland in the distance - left, seastacks on the right (NPS)

23) MT = Marine Terrace:

A coastal landform created by deposition and uplift of beaches that are flat and run parallel to the coast, contains silt, sand and fine gravel. Marine terraces are perched by lowering of sea level or the uplifting of land (Bates and Jackson 1984).

- **Location:** In the backshore above wave-cut platforms and beaches, below coastal bluffs.
- **Associated Landforms/ Features:** Beaches, wave-cut platforms, slump/creep and elevated terraces.
- **Process:** Depositional feature, made by the tectonic uplift of beaches.
- **Surficial Material:** Sand, gravel, shells and wood.
- **Mapping Guidelines:** Often too narrow to see on topographic maps, are usually mapped in field. Identified by elevation above the coast, are vegetated.
- **Potential Vegetation:** Lowland forest with a thin understory community (Crawford et al. 2009). Maybe void of major vegetation and have beach logs deposited by the highest of tides.



Marine terrace near at Rialto Beach (NPS)

24) NA = Natural Arch:

A landform created by wave erosion of headlands and sea stacks to form a round opening in sea stacks and headlands.

- **Location:** Part of eroded headlands or sea stacks.
- **Associated Landforms/ Features:** Wave-cut platforms, headlands and sea stacks
- **Process:** Wave erosion of bedrock. Tidal action and mass-wasting also can contribute to formation.
- **Surficial Material:** Bedrock
- **Mapping Guidelines:** Identified from topographic maps, but usually in the field, near headlands and sea stacks in foreshore zone.
- **Potential Vegetation:** Void of vegetation



Hole-in-the-Wall arch at Rialto Beach (NPS)

25) B-BR: Coastal Bluff Bedrock

A coastal bluff is a backshore landform where the upland rises above the beach (Shipman 2008). Bluffs include only high and steep features. The morphology of the bluff is greatly influenced by the composition of the shoreline materials and geologic history. At OLYM coastal bluffs are broken into four categories to reflect variability in material. In addition to bedrock there are:

26) B-TI = Coastal Bluff Till

27) B-DR = Coastal Bluff Drift

28) B-OU = Coastal Bluff Outwash

- **Location:** Along the coastline, in the backshore zone, either directly next to the ocean or upland of beaches.
- **Associated Landforms/ Features:** Headland, hillslope, slump/creep and other landslides.
- **Process:** Coastal bluffs formed by wave erosion at base of slope, weathering of bluff in heavy rainfall and mass-wasting. Bluffs of drift or outwash reflect glacial (alpine and continental) deposition.
- **Surficial Material:** Bedrock, drift, till or outwash.
- **Mapping Guidelines:** Material type observed from field or inferred from the geologic map (Gerstel and Lingley Jr. 2000, Schasse 2003) and Washington Coastal Atlas (Washington Department of Ecology 2018). Contours often closely spaced reflecting steep slopes. Large features usually mapped from topographic maps or aerial photographs.
- **Potential Vegetation:** Vertical features that can have lowland forest or sea-spray zone vegetation (Henderson et al. 1989).




Coastal Bluff - Bedrock (NPS, left) and Coastal Bluff - Outwash (NPS, right)



Coastal Bluff - Drift (NPS)

29) SS = Sea stack:

A tower or small island of rock along the coast (Bates and Jackson 1984).

- **Location:** In the foreshore zone adjacent to headlands and islands. Stand above wave-cut platforms and beaches.
- **Associated Landforms/ Features:** Wave-cut platform, headlands, tombolo and natural arches.
- **Process:** Erosional processes of wave action against bedrock that is no longer attached to the mainland.
- **Surficial Material:** Bedrock
- **Mapping Guidelines:** Identifiable in air photos and large-scale topographic maps.
- **Potential Vegetation:** While sea stacks tend to be void of vegetation, the tops of stacks can have lowland forest and/or sea-spray vegetation zone (Crawford et al. 2009).



Numerous sea stacks in the distance (NPS)

30) TO = Tombolo:

A sand or gravel beach or barrier that connects an island with the mainland or with another island (Bates and Jackson 1984).

- **Location:** In the foreshore zone between sea stacks and the mainland.
- **Associated Landforms/ Features:** Sea stacks, beaches and wave-cut platforms.
- **Process:** Depositional feature created by longshore currents and drift cells.
- **Surficial Material:** Sand or gravel.
- **Mapping Guidelines:** Connection of beaches to sea stacks observable on large scale topographic maps and in the field at low tide.
- **Potential Vegetation:** Typically below high tide line with no vegetation.



Tombolo connecting sea stack to the beach (Washington Department of Ecology)

31) WP = Wave-cut Platform:

A gently sloping bedrock surface produced by wave erosion (Bates and Jackson 1984). Can have multiple levels of wave-cutting in tectonically active sites where sea level rises and falls.

- **Location:** In foreshore zone below high tide line, adjacent to beaches, headlands and sea stacks.
- **Associated Landforms/ Features:** Beaches, sea stacks and headlands. Typically contain tidal pools and small tidal channels.
- **Process:** Wave erosion of bedrock in tidal zone.
- **Surficial Material:** Bedrock
- **Mapping Guidelines:** Observed in the field at low tide.
- **Potential Vegetation:** Often covered in kelp.




Examples of wave-cut platforms (NPS)

32) U = Undifferentiated:

Features that are often created by human alteration of the landscape, or that are not easily recognized by topography or exposure.

- **Location:** Anywhere.
- **Associated Landforms/ Features:** Drift-mantled bedrock and other inaccessible backshore areas.
- **Process:** Unknown.
- **Surficial Material:** Any type.
- **Mapping Guidelines:** Mapped by aerial photographs or topographic maps, typically not visited in the field.
- **Potential Vegetation:** Any type.

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