



# National Park Service Geologic Type Section Inventory

## *North Coast and Cascades Inventory & Monitoring Network*

Natural Resource Report NPS/NCCN/NRR—2022/2366



**ON THE COVER**

Type locality exposures of the Cretaceous Shuksan Greenschist at Mount Shuksan, North Cascades National Park. The Shuksan Greenschist comprises portions of Mount Shuksan including the prominent Summit Pyramid (NPS/DEBY DIXON).



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March 2022

U.S. Department of the Interior  
National Park Service  
Natural Resource Stewardship and Science  
Fort Collins, Colorado

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Please cite this publication as:

Henderson, T. C., V. L. Santucci, T. Connors, and J. S. Tweet. 2022. National Park Service geologic type section inventory: North Coast and Cascades Inventory & Monitoring Network. Natural Resource Report NPS/NCCN/NRR—2022/2366. National Park Service, Fort Collins, Colorado. <https://doi.org/10.36967/nrr-2293013>.

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## Executive Summary

A fundamental responsibility of the National Park Service (NPS) is to ensure that park resources are preserved, protected, and managed in consideration of the resources themselves and for the benefit and enjoyment by the public. Through the inventory, monitoring, and study of park resources, we gain a greater understanding of the scope, significance, distribution, and management issues associated with these resources and their use. This baseline of natural resource information is available to inform park managers, scientists, stakeholders, and the public about the conditions of these resources and the factors or activities which may threaten or influence their stability and preservation.

There are several different categories of geologic or stratigraphic units (supergroup, group, formation, member, bed) that form a hierarchical system of classification. The mapping of stratigraphic units involves the evaluation of lithologies (rock types), bedding properties, thickness, geographic distribution, and other factors. Mappable geologic units may be described and named through a rigorously defined process that is standardized and codified by the professional geologic community (North American Commission on Stratigraphic Nomenclature 2021). In most instances, when a new geologic unit (such as a formation) is described and named in the scientific literature, a specific and well-exposed section or exposure area of the unit is designated as the stratotype (see “Definitions” below). The type section is an important reference exposure for a named geologic unit that presents a relatively complete and representative example for this unit. Geologic stratotypes are important both historically and scientifically, and should be available for other researchers to evaluate in the future.

The inventory of all geologic stratotypes throughout the 423 units of the NPS is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies. The focus adopted for completing the baseline inventories throughout the NPS was centered on the 32 inventory and monitoring (I&M) networks established during the late 1990s. The I&M networks are clusters of parks within a defined geographic area based on the ecoregions of North America (Fenneman 1946; Bailey 1976; Omernik 1987). These networks share similar physical resources (geology, hydrology, climate), biological resources (flora, fauna), and ecological characteristics. Specialists familiar with the resources and ecological parameters of the network, and associated parks, work with park staff to support network-level activities (inventory, monitoring, research, and data management).

Adopting a network-based approach to inventories worked well when the NPS undertook paleontological resource inventories for the 32 I&M networks. The planning team from the NPS Geologic Resources Division who proposed and designed this inventory selected the Greater Yellowstone Inventory and Monitoring Network (GRYN) as the pilot network for initiating this project. Through the research undertaken to identify the geologic stratotypes within the parks of the GRYN methodologies for data mining and reporting on these resources were established. Methodologies and reporting adopted for the GRYN have been used in the development of this report for the North Coast and Cascades Inventory & Monitoring Network (NCCN).

The goal of this project is to consolidate information pertaining to geologic type sections that occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic landmarks and geologic heritage resources. The review of stratotype occurrences for the NCCN shows there are currently no designated stratotypes for Fort Vancouver National Historic Site (FOVA), Lewis and Clark National Historical Park (LEWI), or San Juan Island National Historical Park (SAJH). Ebey's Landing National Historical Park (EBLA) has one type locality; Mount Rainier National Park (MORA) has two type sections and three type localities; North Cascades National Park Complex (NOCA) has one type locality, one type area, two principal reference localities, and one principal reference area; Olympic National Park (OLYM) has one type section; and Ross Lake National Recreation Area (ROLA) has one type section (Table 1).

This report ends with a recommendation section that addresses outstanding issues and future steps regarding park unit stratotypes. These recommendations will hopefully guide decision-making and help ensure that these geoheritage resources are properly protected and that proposed park activities or development will not adversely impact the stability and condition of these geologic exposures.



**Table 1.** List of NCCN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
EBLA	Partridge Gravel (Qgom(e))	Easterbrook 1968	Type locality: sea cliff between Partridge Point and West Beach on west side of Whidbey Island, Puget Sound, Island Co., WA	Pleistocene
MORA	Garda Drift	Crandell and Miller 1964	Type section: lateral and terminal moraines near Garda Falls, Pierce Co., WA	Holocene
MORA	Burroughs Mountain Drift	Crandell and Miller 1974	Type section: a moraine in the center of the West Fork valley 1 km (0.6 mi) southwest of Garda Falls and 2.5 km (1.6 mi) northwest of the summit of Burroughs Mountain, Pierce Co., WA	Holocene
MORA	McNeeley Drift	Crandell 1969	Type locality: moraine in north-facing cirque, 0.8 km (0.5 mi) south of McNeeley Peak, Pierce Co., WA	Pleistocene
MORA	Hayden Creek Drift	Crandell 1969	Type locality: till exposed in cuts along Mowich Lake Road near mouth of Hayden Creek in western MORA, Pierce Co., WA	Pleistocene
MORA	Stevens Ridge Formation (Ts)	Fiske et al. 1963	Type locality: Stevens Ridge, a prominent spur just north of Stevens Canyon, in the south-central part of MORA, Lewis Co., WA	Oligocene–Miocene
NOCA	Perry Creek phase of the Chilliwack Batholith [formerly Perry Creek Quartz Diorite] (MIOLcpc)	Grant 1969	Type area: Silver Creek, 3.2 km (2.0 mi) south of the Canadian border on west side of Ross Lake, in sec. 5, T. 40 N., R. 13 E., Whatcom Co., WA	Oligocene–Miocene
NOCA	Cascade River Schist (EKcs)	Tabor et al. 2002	Principal reference locality [composite]: main valley walls of the North, South, and Middle Forks of the Cascade River, surrounding lat. 48° 27' N., long. 121° 05' W., Cascade Pass 7.5' Quadrangle, Skagit Co., WA	Late Cretaceous–Eocene
NOCA	Magic Mountain Gneiss (EKmm)	Tabor et al. 2002	Principal reference locality: Magic Mountain, located south of Cascade Pass, in vicinity of lat. 48° 27' N., long. 121° 02' W., Cascade Pass 7.5' Quadrangle, Skagit Co., WA	Late Cretaceous–Eocene
NOCA	Eldorado Orthogneiss (Kog(e), Kog(ef))	Haugerud et al. 1991	Principal reference area: Eldorado, Klawatti, and Primus Peaks, and connecting ridges; from sec. 8, T. 35 N., R. 12 E., to sec. 27, T. 36 N., R. 13 E., Mount Baker 30' x 60' Quadrangle, northern WA	Cretaceous
NOCA	Shuksan Greenschist (Kes)	Misch 1966; Tabor et al. 1993	Type locality: on Mount Shuksan in the vicinity of lat. 48°50' N. long. 121°36' W., north of the Skykomish River 30' x 60' Quadrangle, WA	Early Cretaceous

**Table 1 (continued).** List of NCCN stratotype units sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
OLYM	Hoh Rock Assemblage (MIm(st))	Weaver 1937	Type section: exposures occurring between the mouth of the Hoh River and the northern point of Hoh Head, Clallam County, WA	Miocene
ROLA	Skagit Gneiss Complex (EKsbg, EKsbga)	Misch 1987; Haugerud et al. 1991	Type section: Skagit Gorge between Newhalem and Ross Dam, from sec. 21, T. 37 N., R. 12 E., to sec. 35, T. 38 N., R. 13 E., Mount Baker 30' x 60' Quadrangle, northern WA	Late Cretaceous–middle Eocene

## Acknowledgments

Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the North Coast and Cascades Inventory and Monitoring Network (NCCN). We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (U.S. Geological Survey) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Dave, and Nancy manage the National Geologic Map Database for the United States (NGMDB, [https://ngmdb.usgs.gov/ngm-bin/ngm\\_compsearch.pl?glx=1](https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl?glx=1)) and the U.S. Geologic Names Lexicon (“GEOLEX”, <https://ngmdb.usgs.gov/Geolex/search>), the national compilation of names and descriptions of geologic units for the United States, two critical sources of geologic information for science, industry, and the American public. We also extend our appreciation to Ralph Haugerud and Scott Bennett (USGS), as well as Rachel Teasdale (CSU, Chico) for their professional assistance in writing this report.

We thank our colleagues and partners in the Geological Society of America (GSA) and Stewards Individual Placement Program for their continued support to the NPS with the placement of geologic interns and other ventures. A special thanks to Susan Schnur (Washington Geological Survey, Department of Natural Resources) for the permission to use Figures 8, 42, and 43 in this publication. Additionally, we are grateful to Rory O’Connor-Walston and Alvin Sellmer from the NPS Technical Information Center in Denver for their assistance with locating hard-to-find publications.

Thanks to our NPS colleagues in the North Coast and Cascades Inventory and Monitoring Network and various network parks, including Rachel Mazur (NCCN), Scott Beason and Darin Swinney (MORA), Bradley Johnson and Sharon Sarrantonio (NOCA), and John Boetsch and Jerald Weaver (OLYM). Additional thanks to Denise Louie, Marsha Davis, and Jalyn Cummings for continued support for this and other important geology projects in the Department of Interior Regions 8, 9, 10, and 12 (previously the Pacific West Region of the NPS). We also want to extend our appreciation to Scott Beason (MORA) and Laura Walkup (USGS) for assisting with the review of this report.

This project is possible through the support from research associates and staff in the National Park Service Geologic Resources Division and we extend our thanks to Stephanie Gaswirth, Hal Pranger, Julia Brunner, Jason Kenworthy, and Jim Wood.





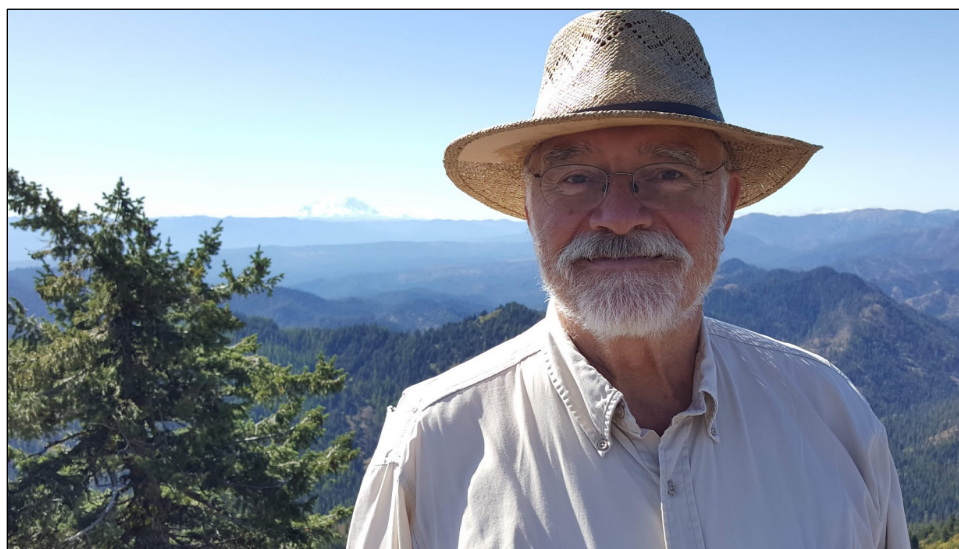
## Dedication

This North Coast and Cascades Inventory and Monitoring Network Geologic Type Section Inventory is dedicated to USGS Geologist Ralph Haugerud.

Ralph has worked at the USGS since 1985, first as a post-doc supported by the National Research Council. In the summer of 1980, he served as a temporary USGS employee working as a field assistant in the Glacier Peak Wilderness Area. During his 35+ year career with the USGS, Ralph has contributed greatly to the geology of the Pacific Northwest (PNW), a region he calls home. He appreciates the complexity and “youth” of PNW geology, as well as the notion that so much of the tectonics we infer from the rock record is reflected in the regional physiography. Ralph considers one of his greatest professional achievements to be the geologic map of the North Cascade Range (Haugerud and Tabor 2009; available at <https://pubs.usgs.gov/sim/2940/>).

Over the years Ralph has been inspired by his mentor, colleague, and friend Rowland Tabor (retired USGS), who set an example of broad interests, collegiality, and productivity he hopes to emulate. Ralph also acknowledges the work of Bailey Willis, who spent the summers of 1895–1900 in the Cascades, reflected on the overall topography of the range, and inferred the dimensions of crustal shortening that produced uplift (Willis 1903).

Thanks for your tremendous service, Ralph!



Ralph Haugerud (USGS)

# Introduction

The NPS Geologic Type Section Inventory Project (“Stratotype Inventory Project”) is a continuation of and complements the work performed by the Geologic Resources Inventory (GRI). The GRI is funded by the NPS Inventory & Monitoring Program and administered by the Geologic Resources Division (GRD). The GRI is designed to compile and present baseline geologic resource information available to park managers, and advance science-informed management of natural resources in the national parks. The goals of the GRI are to increase understanding and appreciation of the geologic features and processes in parks and provide robust geologic information for use in park planning, decision making, public education, and resource stewardship.

Documentation of stratotypes (i.e., type sections/type localities/type areas) that occur within national park boundaries represents a significant component of a geologic resource inventory, as these designations serve as the standard for defining and recognizing geologic units (North American Commission on Stratigraphic Nomenclature 2021). The importance of stratotypes lies in the fact that they represent important comparative sites where past investigations can be built upon or re-examined, and can serve as teaching sites for the next generation of students (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to libraries and museums in that they are natural repositories of Earth history and record the physical and biologic evolution of our planet.

The goals of this project are to (1) systematically report the assigned stratotypes that occur within national park boundaries, (2) provide detailed descriptions of the stratotype exposures and their locations, and (3) reference the stratotype assignments from published literature. It is important to note that this project cannot verify a stratotype for a geologic unit if one has not been formally assigned and/or published. Additionally, numerous stratotypes are located geographically outside of national park boundaries, but only those within 48 km (30 mi) of park boundaries are presented in this report.

This geologic type section inventory for the parks of the North Coast and Cascades Inventory & Monitoring Network (NCCN) follows standard practices, methodologies, and organization of information introduced in the Greater Yellowstone I&M Network type section inventory (Henderson et al. 2020). All network-specific reports are prepared, peer-reviewed, and submitted to the Natural Resources Stewardship and Science Publications Office for finalization. A small team of geologists and paleontologists from the NPS Geologic Resources Division and the NPS Paleontology Program have stepped up to undertake this important inventory for the NPS.

This inventory fills a void in basic geologic information compiled by the NPS at most parks. Instances where geologic stratotypes occurred within NPS areas were determined through research of published geologic literature and maps. Sometimes the lack of specific locality or other data limited determination of whether a particular stratotype was located within NPS administered boundaries. Below are the primary justifications that warrant this inventory of NPS geologic stratotypes.

- Geologic stratotypes are a part of our national geologic heritage and are a cornerstone of the scientific value used to define the societal significance of geoheritage sites (<https://www.nps.gov/articles/scientific-value.htm>);
- Geologic stratotypes are important geologic landmarks and reference locations that define important scientific information associated with geologic strata. Geologic formations are commonly named after topographic or geologic features and landmarks that are recognizable to park staff;
- Geologic stratotypes are both historically and scientifically important components of earth science investigations and mapping. Geologic stratotypes are similar in nature to type specimens in biology and paleontology, serving as the primary reference for defining distinctive characteristics and establishing accurate comparisons;
- Understanding and interpretation of the geologic record depends on the stratigraphic occurrences of mappable lithologic units (formations, members). These geologic units are the foundational attributes of geologic maps;
- Geologic maps are important tools for science, resource management, land use planning, and other areas and disciplines;
- Geologic stratotypes within NPS areas have not been previously inventoried and there is a general absence of baseline information for this geologic resource category;
- NPS staff may not be aware of the concept of geologic stratotypes and therefore would not understand the significance or occurrence of these natural references in the parks;
- Given the importance of geologic stratotypes as geologic references and geologic heritage resources, these locations should be afforded some level of preservation or protection when they occur within NPS areas;
- If NPS staff are unaware of geologic stratotypes within parks, the NPS cannot proactively monitor the stability, condition, or potential impacts to these locations during normal park operations or planning. This lack of information also prevents the protection of these localities from activities that may involve ground disturbance or construction;
- This inventory can inform important conversations on whether geologic stratotypes rise to the level of national register documentation. The NPS should consider if any other legal authorities (e.g., National Historic Preservation Act), policy, or other safeguards currently in place can help protect geologic stratotypes that are established on NPS administered lands. Through this inventory, the associated report, and close communication with park and I&M Network staff, we hope there will be an increased awareness about these important geologic landmarks in parks. In turn, the awareness of these resources and their significance may be recognized in park planning and operations, to ensure that geologic stratotypes are preserved and available for future study.

## Geology and Stratigraphy of the NCCN I&M Network Parks

The North Coast and Cascades Network (NCCN) is composed of nine park units in Oregon and Washington (Figure 1). These are Ebey's Landing National Historical Reserve (EBLA), Fort Vancouver National Historic Site (FOVA), Lake Chelan National Recreation Area (LACH), Lewis and Clark National Historical Park (LEWI), Mount Rainier National Park (MORA), North Cascades National Park (NOCA), Olympic National Park (OLYM), Ross Lake National Recreation Area (ROLA), and San Juan Island National Historical Park (SAJH); LACH, NOCA, and ROLA are managed together as North Cascades National Park Complex or National Park Service Complex (also NOCA) (Figure 1). The parks that comprise the North Coast and Cascades Network protect a combined 749,086 hectares (1,851,032 acres) and vary in size from 83 ha (207 acres) (FOVA) to 373,383 ha (922,650 acres) (OLYM). Elevations within the network range from sea level (EBLA, LEWI, OLYM, and SAJH) to 4,392 m (14,410 ft) above sea level (MORA).



**Figure 1.** Map of North Coast and Cascades I&M Network parks including: Ebey's Landing National Historical Reserve (EBLA), Fort Vancouver National Historic Site (FOVA), Lewis and Clark National Historical Park (LEWI), Mount Rainier National Park (MORA), North Cascades National Park Complex (NOCA), Olympic National Park (OLYM), and San Juan Island National Historical Park (SAJH) (NPS).

Rocks of the North Coast and Cascade Network consist of a geologic mosaic made of volcanic island arcs, deep ocean sediments, basaltic ocean floor, fragments of old continents, submarine fans, glacial debris, and pieces of deep sub-crustal mantle (Tabor and Haugerud 1999). In a broad sense, the geologic setting of the NCCN is well understood and records at least 400 million years of dynamic earth processes. Due to plate tectonics, dense oceanic crustal plates that comprise the Pacific Ocean Basin (e.g., the Juan de Fuca Plate, a remnant of the Farallon Plate) are converging with comparatively less-dense continental crust composing the North American Plate. Dense oceanic crust is effectively being driven beneath the more buoyant continental crustal rocks that comprise North America to be recycled deep within the Earth. This process, called subduction, has been heavily influencing the NCCN landscape since the Mesozoic Era.

Off the Pacific Northwest coast, subducting oceanic crust acted like a conveyor belt, transporting marine sediments and small landmasses (fragments of volcanic island arcs) closer to the continental margin as it descended beneath North America. At the subduction zone, where the oceanic crust plunged beneath the continental margin, marine sediments were scraped off the down-going slab, resulting in a jumbled and chaotic suite of marine rocks (referred to as “mélange”—a French word meaning “mixture”) that formed an accretionary prism (Fay et al. 2009). The Olympic Mountains (OLYM) represent such an accretionary prism that has been further uplifted, folded, and eroded into the rugged peaks seen today. Other diverse rock suites, called “terrane”, were also transported by the conveyor belt until they were compressed, uplifted, and welded to the continent in a process called accretion. Many terranes of the NCCN parks are geologically and temporally distinct from one another and were subsequently juxtaposed to form a mosaic of diverse rock assemblages. The San Juan Island Archipelago (SAJH), portions of the Olympic Peninsula (OLYM), and a large part of the North Cascade Range (NOCA) are underlain by terranes. Specific examples of accretionary terranes within NCCN include the Chelan Mountains Terrane and Little Jack Mountain Terrane of NOCA, the Turtleback Complex, Deadman Bay Terrane, and Decatur Terrane of SAJH, and the Crescent Terrane, Sooes Terrane, and Ozette Terrane of OLYM.

Deeper inside the earth, subducting rocks of the oceanic plate experience elevated temperature and pressure conditions. As these rocks heat up and lose moisture, the overlying rocks of the North American Plate begin to partially melt and generate magma. Molten rock generated by partial melting erupted at the surface to blanket older rocks with lava and pyroclastic flows while large masses of magma intruded from below and cooled to form hard crystalline basement rocks. The tall, steep-sided volcanoes of the Cascade Range, including Mount Rainier (MORA) are a part of an extensive active volcanic arc created by the subduction of oceanic crust beneath the western margin of Washington, Oregon, Northern California, and southern British Columbia.

In the more recent geologic past, Pleistocene-age continental ice sheets and alpine glaciers have eroded the regional landscape as it has continuously uplifted. The Cordilleran Ice Sheet deposited thick blankets of glacial till deposits during its initial advance and left behind glacial outwash deposits during its final retreat. Such deposits dominate the geologic landscape of SAJH and EBLA. Continental glaciation has contributed to the geology of OLYM and NOCA, but alpine glaciation is more dominant in those areas (Fay et al. 2009).

Intimate details of the geologic history of the NCCN remain somewhat elusive and problematic. Precise geologic reconstructions showing the evolution of the Pacific Northwest region are controversial in part due to the complex, regional geologic processes operating in this area, but also due to dense vegetation and rugged topography that limit access to exposures (Fay et al. 2009). Although the larger geologic framework is largely understood, some pieces of information are still not well understood. Some of the outstanding questions that still need addressed include the timing of certain glacial events, as well as the timing of certain structural and metamorphic events.

### **Precambrian**

Precambrian rocks are not exposed in any of the parks in NCCN (see Appendix B for a geologic time scale).

### **Paleozoic**

Some of the oldest Paleozoic rocks mapped in the North Coast and Cascades Network are found in the North Cascades National Park Complex (NOCA, ROLA, and LACH) and consist of ribbon chert, limestone, greenstones, volcanic breccias, tuffs, and pillow lavas of the Pennsylvanian–Triassic Hozomeen Group. These rocks are found within or near the Ross Lake Fault zone along eastern NOCA and northern ROLA.

San Juan Island National Historical Park contains isolated exposures of the Permian–Triassic Garrison Schist, a high-pressure metamorphic unit located at Garrison Bay near Bell Point.

### **Mesozoic**

Western NOCA contains rocks of the Late Jurassic–Cretaceous Bell Pass *mélange* that consist of sandstones, argillites (mudstones and shales), ribbon cherts, mafic rocks, and sheared blocks of other intensely metamorphosed units. Numerous Cretaceous-age metamorphic and igneous units form the crystalline core of NOCA, ROLA, and LACH, including the Early Cretaceous Eastern Metamorphic Suite (including the Darrington Phyllite and Shuksan Greenschist), Late Cretaceous–middle Eocene Chelan Mountains Terrane (including the Cascade River Schist, Napeequa Schist, and Magic Mountain Gneiss), Skymo Complex of Wallace (1976), Little Jack Mountain Terrane, Skagit Gneiss Complex, Eldorado Orthogneiss, and the Three Fools Sequence of Haugerud et al. (2002).

The only Mesozoic units mapped within OLYM are located along the coast and include Jurassic–Paleocene-age gabbro and diorite rocks associated with Portage Head/Point of the Arches block.

In SAJH there are numerous Mesozoic-age units that include the Triassic–Jurassic Deadman Bay Terrane and Orcas Chert. Crystalline rocks, volcanics, and metamorphosed marine sediments of the Jurassic–Cretaceous Decatur Terrane, Lopez Structural Complex, Lummi Formation, and Constitution Formation are also mapped within the historical park. The Lopez Structural Complex includes slices of Turtleback Terrane, Garrison Schist, and marine sedimentary rocks derived from the Lummi Formation of the Decatur Terrane.

## **Cenozoic**

The Cenozoic geology of the NCCN is a testament to volcanism associated with the subduction of oceanic crust beneath the western margin of North America (Cascade volcanism) combined with the more recent glacial history of the region.

Cenozoic formations form the entirety of bedrock at FOVA and include rocks of the Miocene Columbia River Basalt Group (Frenchman Springs Member of the Wanapum Formation), as well as Quaternary-age alluvium of the Columbia River Floodplain and deposits associated with the great Missoula floods (Waite 1985, 1987).

Dominant lithologies of southwestern Washington and northwestern Oregon in LEWI include the volcanic rocks of the Eocene Crescent Formation and sedimentary rocks composed primarily of the Oligocene Lincoln Creek Formation. Other geologic units mapped in LEWI include tuffaceous sedimentary rocks and volcanolithic sandstones of the Eocene Siltstone at Cliff Point and Siltstone at Shoalwater Bay, as well as tuffaceous sediments and sandstones of the Miocene Smuggler Cove formation and Sandstone at Megler. Younger surficial units in LEWI are Pleistocene–Holocene terrace deposits,olian dune sand, and Holocene alluvium and beach sand.

In MORA, the prominent Mount Rainier consists of late Pleistocene and Holocene lava flows and interbeds of volcanoclastic rocks. These younger igneous units partially bury older rocks mapped within the park such as the Eocene–Oligocene Ohanapecosh Formation, Oligocene–Miocene Stevens Ridge Formation, and the Fives Peak Formation. A number of Pleistocene and younger mudflows (lahar flows), landslides, and surficial deposits are found along the flanks of Mount Rainier.

The North Cascade National Park Complex contains younger Cenozoic igneous rocks of the Pliocene Hannegan Volcanics, Oligocene-age volcanic rocks of Mount Rahm, Pioneer Ridge, and Big Boson Buttes, as well as extensive Oligocene–Miocene-age intrusive rocks of the Cascade Pass, Snoqualmie, and Index families (including the Chilliwack composite batholith).

A major portion of bedrock at OLYM consists of rocks associated with the Eocene–Oligocene Olympic Subduction Complex, a suite of rock units which represent the accretionary prism of the Cascadia Subduction Zone. Within the boundaries of OLYM, the complex consists of the Crescent Terrane (including the Twin River Group, Aldwell Formation, Crescent Formation, Lyre Formation, and the Blue Mountain unit of Tabor and Cady 1978), Ozette Terrane, Sooes Terrane, and the Hoh rock assemblage.

Pleistocene-age glacial deposits are found with EBLA, NOCA, OLYM, and SAJH in the form of glacial till, drift, moraines, and outwash deposits.



# National Park Service Geologic Resources Inventory

The Geologic Resources Inventory (GRI) provides digital geologic map data and pertinent geologic information on park-specific features, issues, and processes to support resource management and science-informed decision-making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. The GRI team consists of a partnership between the GRD and the Colorado State University Department of Geosciences to produce GRI products.

## GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for non-geoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Scoping sessions were held on the following dates for the NCCN parks: LACH, MORA, NOCA, OLYM, ROLA, and SAJH on September 10–11, 2002; EBLA on September 11–12, 2002; LEWI on October 14, 2009; and FOVA on October 16, 2009.

Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. As of 2021, GRI reports have been completed for EBLA, FOVA, LEWI, MORA, and SAJH. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). Additional information regarding the GRI, including contact information, is available at <https://www.nps.gov/subjects/geology/gri.htm>.

## Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the NCCN parks follows the selected source maps and includes components such as: faults, mine area features, mine point features, geologic contacts, geologic units (bedrock, surficial, glacial), geologic line features, structure contours, and so forth. These are commonly acceptable geologic features to include in a geologic map.



Posters display the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: <https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm>.

### ***Geologic Maps***

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at, or beneath the land surface (Evans 2016). Color and sometimes symbols on geologic maps are used to distinguish geologic map units. The unit labels consist of an uppercase letter (or symbol for some ages) indicating the geologic age and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website (<https://www.americangeosciences.org/environment/publications/mapping>) and work by Bernknopf et al. (1993) provide more information about geologic maps and their uses.

Geologic maps are typically one of three types: surficial, bedrock, or a combination of both. Surficial geologic maps typically encompass deposits that are unconsolidated and which formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type, geologic processes, and/or depositional environment. GRI has produced various maps for the NCCN parks.

### ***Source Maps***

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources to produce the GRI GIS data sets for the NCCN parks can be found in Appendix A.

### ***GRI GIS Data***

The GRI team standardizes map deliverables by using a data model. The most recent GRI GIS data for MORA and OLYM was compiled using data model version 2.3, which is available at <https://www.nps.gov/articles/gri-geodatabase-model.htm>; the EBLA, FOVA, LACH, LEWI, NOCA, ROLA, and SAJH data are based on older data models and need to be upgraded to the most recent version. The data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI website (<https://www.nps.gov/subjects/geology/gri.htm>) provides more information about the program's products.

GRI GIS data are available on the GRI publications website (<https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm>) and through the NPS Integrated Resource Management Applications (IRMA) Data Store portal (<https://irma.nps.gov/DataStore/Search/Quick>). Enter “GRI” as the search text and select EBLA, FOVA, LEWI, MORA, NOCA, OLYM, or SAJH from the unit list.

The following components are part of the data set:

- A GIS readme file that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology;
- Federal Geographic Data Committee (FGDC)-compliant metadata;
- An ancillary map information document that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents that display the GRI GIS data; and
- A version of the data viewable in Google Earth (.kml / .kmz file).

### **GRI Map Posters**

Posters of the GRI GIS draped over shaded relief images of the park and surrounding area are included in GRI reports. Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

### **Use Constraints**

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the posters. Based on the source map scales (1:100,000, 1:62,500, and 1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 51 m (167 ft), 32 m (104 ft), and 12 m (40 ft), respectively, of their true locations.



## Methods

Described here are the methods employed and definitions adopted during this inventory of geologic type sections located within the administrative boundaries of the parks in the NCCN. This report is part of an inventory of geologic type sections throughout the National Park System. Therefore, the methods, definitions, and challenges identified here pertain not only to the parks of the NCCN, but also to other inventory and monitoring networks and parks.

There are several considerations for this inventory. The most up-to-date information available is necessary, either found online or in published articles and maps. Occasionally, there is a lack of specific information which limits the information contained within the final report. This inventory does not include any field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

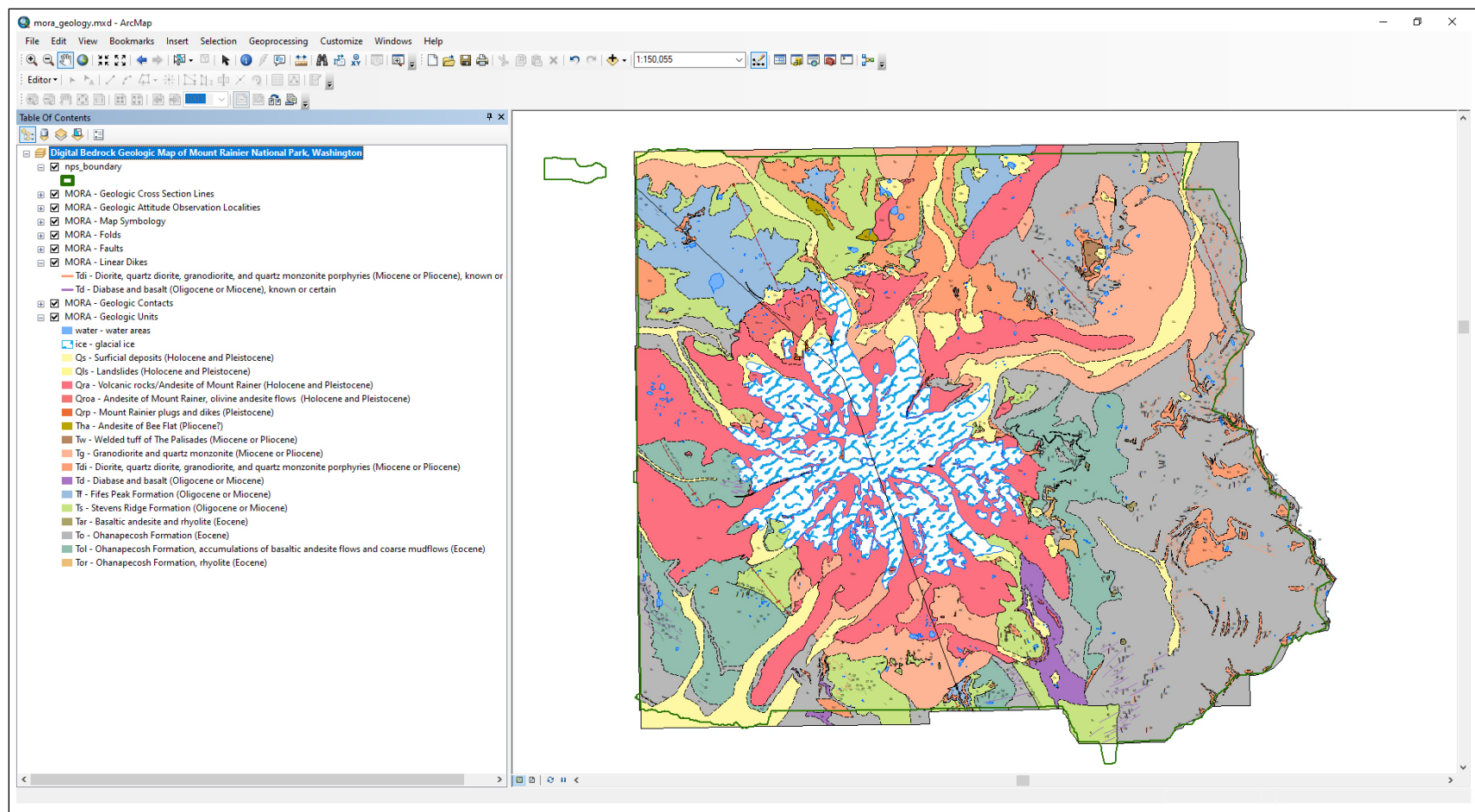
Stratigraphic nomenclature may change over time with refined stratigraphic field assessments and discovery of information through the expansion of stratigraphic mapping and measured sections. One important observation regarding stratigraphic nomenclature relates to differences in use of geologic names for units which transcend state boundaries. Geologic formations and other units which cross state boundaries may be referenced with different names in each of the states the units are mapped. An example would be the Triassic Chugwater Formation in Wyoming, which is equivalent to the Spearfish Formation in the Black Hills of South Dakota and Wyoming.

The lack of a designated and formal type section, or inadequate and vague geospatial information associated with a type section, limits the ability to capture precise information for this inventory. The available information related to the geologic type sections is included in this report.

Finally, this inventory report is intended for a wide audience, including NPS staff who may not have a background in geology. Therefore, this document is developed as a reference document that supports science, resource management, and a historic framework for geologic information associated with NPS areas.

## Methodology

The process of determining whether a specific stratotype occurs in an NPS area involves multiple steps. The process begins with an evaluation of the existing park-specific GRI map to prepare a full list of recognized map units (Figure 2).



**Figure 2.** Screenshot of digital geologic map of Mount Rainier National Park showing mapped units.

Each map unit name is then queried in the U.S. Geologic Names Lexicon online database (“GEOLEX”, a national compilation of names and descriptions of geologic units) at <https://ngmdb.usgs.gov/Geolex/search>. Information provided by GEOLEX includes unit name, stratigraphic nomenclature usage, geologic age, and published stratotype location descriptions, and the database provides a link to significant publications as well as the USGS Geologic Names Committee Archives (Wilmarth 1938; Keroher et al. 1966). Figure 3 below is taken from a search on the Skagit Gneiss Complex.

The screenshot shows the USGS GEOLEX website interface. At the top, there are logos for USGS (science for a changing world) and AASG (Association of American State Geologists). Navigation links include USGS HOME, CONTACT USGS, and SEARCH USGS. A secondary navigation bar contains Home, Catalog, Lexicon, MapView, New Mapping, Standards, and Comments. The main heading is "National Geologic Map Database" with a subheading "Geolex — Unit Summary".

The search results for the "Geologic Unit: Skagit" are displayed. On the right, there is a "Significant Publications" section with links to "Correlation charts", "GNC Archives", "N.A. Stratigraphic Code", and "More Resources".

**Usage:**

- Skagit Metamorphic Suite (WA)
- [?] Skagit Gneiss Complex (WA\*)
- [?] Skagit Gneiss (WA)

**Geologic age:**

Late Cretaceous to early Tertiary\* (metamorphic age)

**Type section, locality, area and/or origin of name:**

Type section: Skagit Gorge between Newhalem and Ross Dam, from sec. 21, T. 37 N., R. 12 E., to sec. 35, T. 38 N., R. 13 E., Mount Baker 30- x 60-min quadrangle, northern WA (Haugerud and others, 1991).

**AAPG geologic province:**

Cascades province\*

For more information, please contact [Nancy Stamm](#), Geologic Names Committee Secretary.  
 Asterisk (\*) indicates published by U.S. Geological Survey authors.  
 "No current usage" (†) implies that a name has been abandoned or has fallen into disuse. Former usage and, if known, replacement name given in parentheses ().  
 Slash (/) indicates name does not conform with nomenclatural guidelines (CSN, 1933; ACSN, 1961, 1970; NACSN, 1983, 2005). This may be explained within brackets ([ ]).

At the bottom, there is a footer with links for ACCESSIBILITY, FOIA, PRIVACY, and POLICIES AND NOTICES, social media icons, and a "usa.gov" logo. Text at the bottom left includes: "U.S. Department of the Interior | U.S. Geological Survey", "Supported by the National Cooperative Geologic Mapping Program", "Page Contact Information: [Personnel](#)", and "Page Last Modified: Thu 06 Aug 2020 08:45:04 PM MDT".

**Figure 3.** GEOLEX search result for Skagit Gneiss Complex unit.

Published GEOLEX stratotype spatial information is provided in three formats: (1) descriptive, using distance from nearby points of interest; (2) latitude and longitude coordinates; or (3) Township/Range/Section (TRS) coordinates. TRS coordinates are based upon subdivisions of a single 93.2 km<sup>2</sup> (36 mi<sup>2</sup>) township into 36 individual 2.59 km<sup>2</sup> (1 mi<sup>2</sup>) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (<https://www.earthpoint.us/TownshipsSearchByDescription.aspx>). They are typically presented in an abbreviated format such as “sec. [#], T. [#] [N. or S.], R. [#] [E. or W.]”. The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km<sup>2</sup> (0.0625 mi<sup>2</sup>). Once stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a “KML to Layer” conversion tool in ArcMap.

Upon accurately identifying the stratotypes, a Microsoft Excel spreadsheet is populated with information pertinent to the geologic unit and its stratotype attributes. Attribute data recorded in this way include: (1) whether a stratotype is officially designated; (2) whether the stratotype is on NPS land; (3) whether the stratotype location has undergone a quality control check in Google Earth; (4) reference of the publication citing the stratotype; (5) description of geospatial information; (6) coordinates of geospatial information; (7) geologic age (era, period, epoch, etc.); (8) hierarchy of nomenclature (supergroup, group, formation, member, bed, etc.); (9) whether the geologic unit was listed in GEOLEX; and (10) a generic notes field (Figure 4).

AutoSaveOff

NCCN Type Section Inventory

Search

Timothy Henderson

FileHomeInsertPage LayoutFormulasDataReviewViewHelp

PasteCutCopyFormat Painter

Clipboard

Calibri11

Font

Alignment

General

Number

Conditional Formatting

Format as Table

Cell Styles

Styles

Cells

AutoSum

Fill

Clear

Editing

Sort & Filter

Find & Select

Editing

Analyze Data

Analysis

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	A	B	C	D	E	F	G	H	I	J	K	L	M	
	Formation	Type Section Not Designated?	Type Section in NPS Boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc.	Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy	Geolox Map Symbol	
178	Little Jack terrane, phyllite and schist of Little Jack M	X								Cenozoic-Mesozo	Late Cretaceous to middle Eoce	NO	EKlp	
179	Plutons of the tonalitic group, orthogneiss of Marbl	X				Misch 1966				Cenozoic-Mesozo	Late Cretaceous to m Tonalitic g	YES	EKmo	
180	Skymo Complex of Wallace (1976)	X				Wallace 1976				Cenozoic-Mesozo	Late Cretaceous to m Skymo Coon	GNC	EKs	
181	Skymo Complex of Wallace (1976), fine-grained gran	X								Cenozoic-Mesozo	Late Cretaceous to m Skymo Co	NO	EKsf	
182	Skagit Gneiss Complex, banded gneiss, biotite gneiss		YES - NOCA			Misch 1987; Haugerud et al. 1991	Type section: Skagit Gorge			Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	YES	EKsbg	
183	Skagit Gneiss Complex, banded gneiss, amphibole g	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsbg	
184	Skagit Gneiss Complex, granite pegmatite	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsgp	
185	Skagit Gneiss Complex, marble and calcilicite rocks	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsm	
186	Skagit Gneiss Complex, orthogneiss of The Needle	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsn	
187	Skagit Gneiss Complex, orthogneiss	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKso	
188	Skagit Gneiss Complex, orthogneiss, mafic migmatit	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsoa	
189	Skagit Gneiss Complex, orthogneiss, mafic orthogne	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsom	
190	Skagit Gneiss Complex, ultramafic rocks	X								Cenozoic-Mesozo	Late Cretaceous to m Skagit Gni	NO	EKsu	
191	Trafton terrane of Whetten and others (1988)	X				Danner 1966, 1977; Whetten et al. 1988				Cenozoic-Mesozo	Late Cretaceous to m Trafton teon	GNC	EKt	
192	Trafton terrane of Whetten and others (1988), meta	X								Cenozoic-Mesozo	Late Cretaceous to m Trafton te	NO	EKtg	
193	Chelan Mountains terrane, Cascade River Schist, mica schist and amphi		YES - NOCA			Tabor et al. 2002			Principle reference locality	Cenozoic-Mesozo	Eocene and Late Cret	Chelan M	YES	EKcs
194	Chelan Mountains terrane, Cascade River Schist, mic	X								Cenozoic-Mesozo	Eocene and Late Cret	Chelan M	NO	EKcc
195	Chelan Mountains terrane, Marblemount pluton, meta-quartz diorite,		NO		Type area: near the town of M	Misch 1952; Laursen and Hammond 1974; White et al. 1988				Cenozoic-Mesozo	Eocene and Late Cret	Chelan M	YES	EKmd
196	Chelan Mountains terrane, Marblemount pluton, fla	X								Cenozoic-Mesozo	Eocene and Late Cret	Chelan M	NO	EKmf
197	Chelan Mountains terrane, Magic Mountain Gneiss		YES - NOCA			Tabor 1962; Tabor et al. 2002			Principle reference locality	Cenozoic-Mesozo	Eocene and Late Cret	Chelan M	YES	EKmm
198	Pipestone Canyon Formation		NO		Type section: Pipestone Canyc	Barksdale 1975				Cenozoic	Paleocene	YES	EPc(p)	
199	Oval Peak batholith, tonalite	X				Adams 1962; Libby 1964				Cenozoic	Paleocene	Oval Peak on GNC	EPit(o)	
200	Gneiss of Battle Mountain, orthogneiss	X				Miller and Bowring 1990				Cenozoic	Paleocene	on GNC	EPog(b)	
201	Skagit Gneiss, Lake Juanita leucogneiss, orthogneiss	X				Miller and Bowring 1990				Cenozoic	Paleocene	on GNC	EPog(j)	
202	Orthogneiss of Oval Peak batholith	X				Libby 1964				Cenozoic	Paleocene	on GNC	EPog(o)	
203	Gneiss of Tuckaway Lake, orthogneiss	X				Miller and Bowring 1990				Cenozoic	Paleocene	on GNC	EPog(t)	
204	Gneiss of War Creek, orthogneiss	X				Adams 1962				Cenozoic	Paleocene	on GNC	EPog(w)	
205	Orthogneiss of Mount Benzarino	X								Cenozoic-Mesozo	Paleocene and Cretaceous	NO	EPKog(b)	
206	Orthogneiss of Gabriel Peak	X				Adams 1964				Cenozoic-Mesozo	Paleocene and Cretaceous	YES	EPKog(g)	
207	Basaltic plugs and dikes of Chiwawa River	X								Cenozoic	Tertiary	NO	Tib(c)	

EBLAFOVALLEWIMORANOCAOLYMSAJH

Ready

Display Settings

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**Figure 4.** Stratotype inventory spreadsheet of the NCCN displaying attributes appropriate for geolocation assessment.



## Definitions

In order to clarify, standardize, and consistently reference stratigraphic concepts, principles, and definitions, the North American Stratigraphic Code is recognized and adopted for this inventory. This code describes explicit practices for classifying and naming all formally defined geologic units. An important designation for a geologic unit is known as a **stratotype**—the standard exposure (original or subsequently designated) for a named geologic unit or boundary that constitutes the basis for definition or recognition of that unit or boundary (North American Commission on Stratigraphic Nomenclature 2021). There are several varieties of stratotypes referred to in the literature and this report, and they are defined as follows:

- 1) **Unit stratotype:** the **type section** for a stratified deposit or the **type area** for a non-stratified body that serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2021). Once a unit stratotype is assigned, it is never changed (unless the unit is abandoned). The term “unit stratotype” is commonly referred to as “type section” and “type area” in this report.
- 2) **Type locality:** the specific geographic locality encompassing the unit stratotype of a formally recognized and defined unit. On a broader scale, a type area is the geographic territory encompassing the type locality. Before development of the stratotype concept, only type localities and type areas were designated for many geologic units that are now long- and well-established (North American Commission on Stratigraphic Nomenclature 2021).
- 3) **Reference sections:** for well-established geologic units for which a type section was never assigned, a reference section may serve as an invaluable standard in definitions or revisions. A principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2021). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2021).
- 4) **Lithodeme:** the term “lithodeme” is defined as a mappable unit of plutonic (igneous rock that solidified at great depth) or highly metamorphosed or pervasively deformed rock and is a term equivalent in rank to “formation” among stratified rocks (North American Commission on Stratigraphic Nomenclature 2021). The formal name of a lithodeme consists of a geographic name followed by a descriptive term that denotes the average modal composition of the rock (example: Cathedral Peak Granodiorite). Lithodemes are commonly assigned type localities, type areas, and reference localities.

## **Ebey's Landing National Historical Reserve (EBLA)**

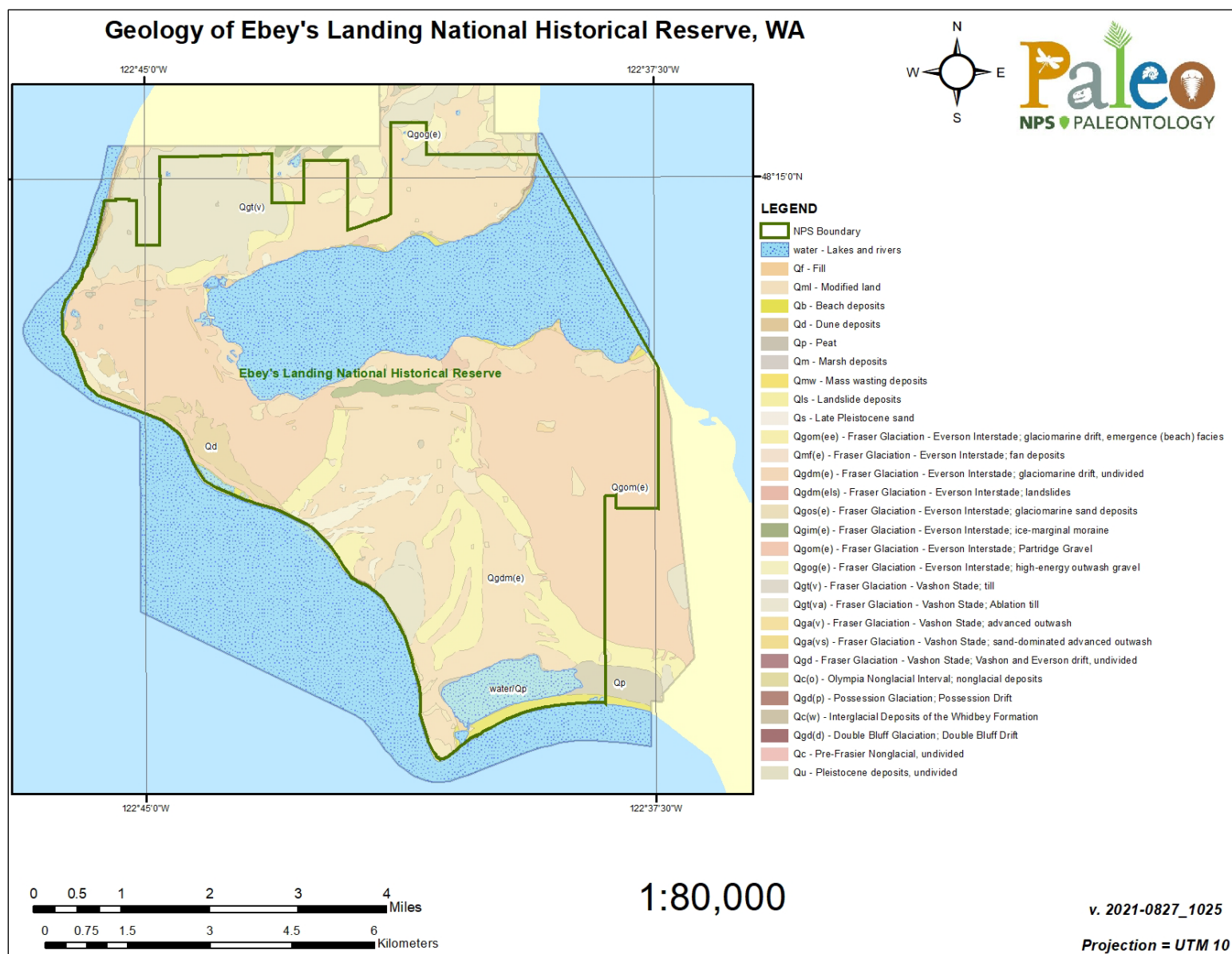
Ebey's Landing National Historical Reserve (EBLA) is located on Whidbey Island at the entrance of Puget Sound, approximately 80 km (50 mi) south of the Canadian border and 43 km (27 mi) north of Seattle in Island County, Washington (Figure 5). Authorized as the first national historical reserve of the NPS on November 10, 1978, EBLA encompasses about 7,824 hectares (19,333 acres) and preserves a rural community that provides an unbroken historical record of Puget Sound exploration and settlement from the 19<sup>th</sup> century to the present (National Park Service 2016). Within the boundaries of EBLA are areas that retain many characteristics of the mid-to-late 1800s, including architecture and historic farms with unchanged land-use patterns since westward-migrating settlers claimed the land in the 1850s under the Oregon Territory's Donation Land Claim Act (National Park Service 2018). The historic Victorian seaport community of Coupeville is also located within the reserve. Ebey's Landing National Historical Reserve is named after Isaac Ebey, one of the first permanent settlers on Whidbey Island.

Ebey's Landing National Historical Reserve is situated within the Puget Lowland physiographic province, a broad, low-lying region between the Cascade Range and Olympic Mountains that generally contains abundant glacial sediments and non-existent bedrock exposures (Graham 2011). Geologic units mapped within the reserve include Pleistocene and Holocene-age glacial and interglacial units of clay, silt, sand, and gravel. Geomorphic features at EBLA were shaped by continental glaciers that advanced over the Puget Lowland, with the most recent glaciation taking place approximately 18,000 and 14,000 years ago. Ebey's Landing National Historical Reserve is largely blanketed by a veneer of glacial deposits of the geologically recent Pleistocene Everson Interstade ("stade" is a substage of a glacial stage) that occurred about 14,000 years ago (Figure 6; Armstrong et al. 1965; Clark and Clague 2020). A significant portion of western and southeastern EBLA is covered by the Partridge Gravel of the Everson Interstade. The glacial history of the EBLA region has not only shaped the landscape but also provided the fertile soils for crops cultivated by American Indians and present-day farmers at Ebey's Prairie located in the central portion of the reserve (Graham 2011).

Ebey's Landing National Historical Reserve contains one identified stratotype that represents the Pleistocene Partridge Gravel (Table 2; Figure 7). In addition to the designated stratotype located within EBLA, stratotypes located within 48 km (30 mi) of the park boundaries include the Cambrian–Ordovician Turtleback Complex (type area); Devonian–Permian East Sound Group (type area); Permian–Triassic Deadman Bay Volcanics (type area); Jurassic–Cretaceous Constitution Formation (type area) and Lummi Formation (type area); Cretaceous James Island Formation (type area) and Obstruction Formation (type area); Eocene Chuckanut Formation (type section) and the type sections of the Bellingham Bay, Governors Point, and Padden Members of the Chuckanut Formation; and the Pleistocene Double Bluff Formation (type section, type locality), Whidbey Formation (type section, type locality), Everson Glaciomarine Drift (type locality), and Possession Drift (type locality).



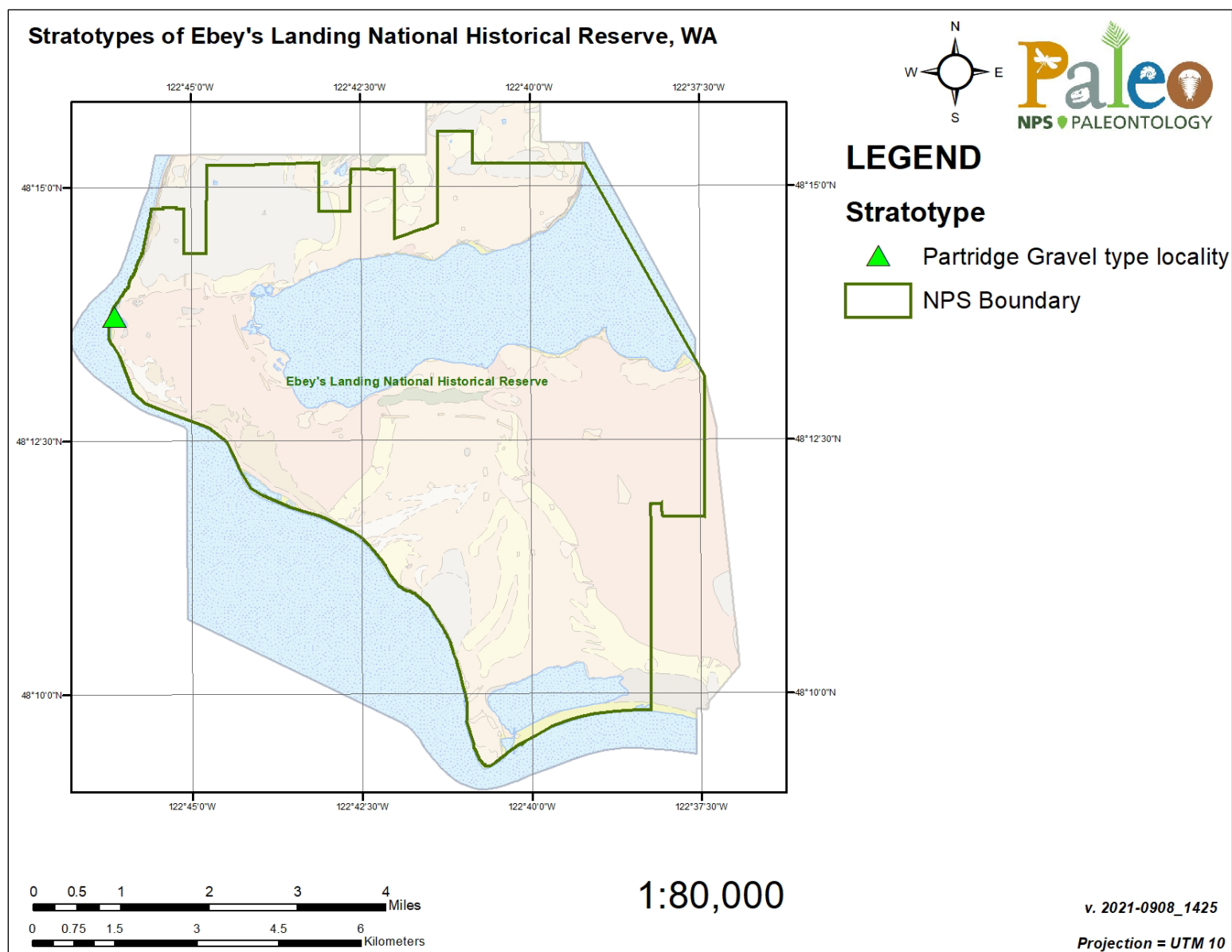
Figure 5. Park map of EBLA, Washington (NPS).



**Figure 6.** Geologic map of EBLA, Washington.

**Table 2.** List of EBLA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Partridge Gravel (Qgom(e))	Easterbrook 1968	Type locality: sea cliff between Partridge Point and West Beach on west side of Whidbey Island, Puget Sound, Island Co., WA	Pleistocene



**Figure 7.** Modified geologic map of EBLA showing stratotype locations. The transparency of the geologic units layer has been increased.

## Partridge Gravel

The Pleistocene Partridge Gravel was named by Easterbrook (1968) after its type locality exposures in the sea cliffs between Partridge Point and West Beach on the west side of Whidbey Island, Washington (Table 2; Figure 7). At the type locality the unit measures about 46 m (150 ft) thick and consists of moderately well-sorted and stratified pebble to cobble gravel and sand that underlie fossiliferous glaciomarine drift of Everson age (Figures 8 and 9; Easterbrook 1968). Cobbles range in size from 20–30 cm (8–12 in) in diameter and blanket the beach in places as a lag mantle (Easterbrook 1968). The Partridge Gravel is believed to overlie Vashon till but the contact is below sea level at the type locality (Easterbrook 1968).



**Figure 8.** Partridge Gravel at its type locality, Partridge Point, Whidbey Island. Figure 16 from Easterbrook (1968); image from the Washington Geological Survey (Washington Department of Natural Resources).





**Figure 9.** Gravel bluffs consisting of the Partridge Gravel at the type locality of Partridge Point. Photograph by user “Washington State Department of Ecology” available via Flickr <https://www.flickr.com/photos/ecologywa/13717889723> (Creative Commons Attribution-NonCommercial-NoDerivs 2.0 Generic [CC BY-NC-ND 2.0]; <https://creativecommons.org/licenses/by-nc-nd/2.0/>).





## Fort Vancouver National Historic Site (FOVA)

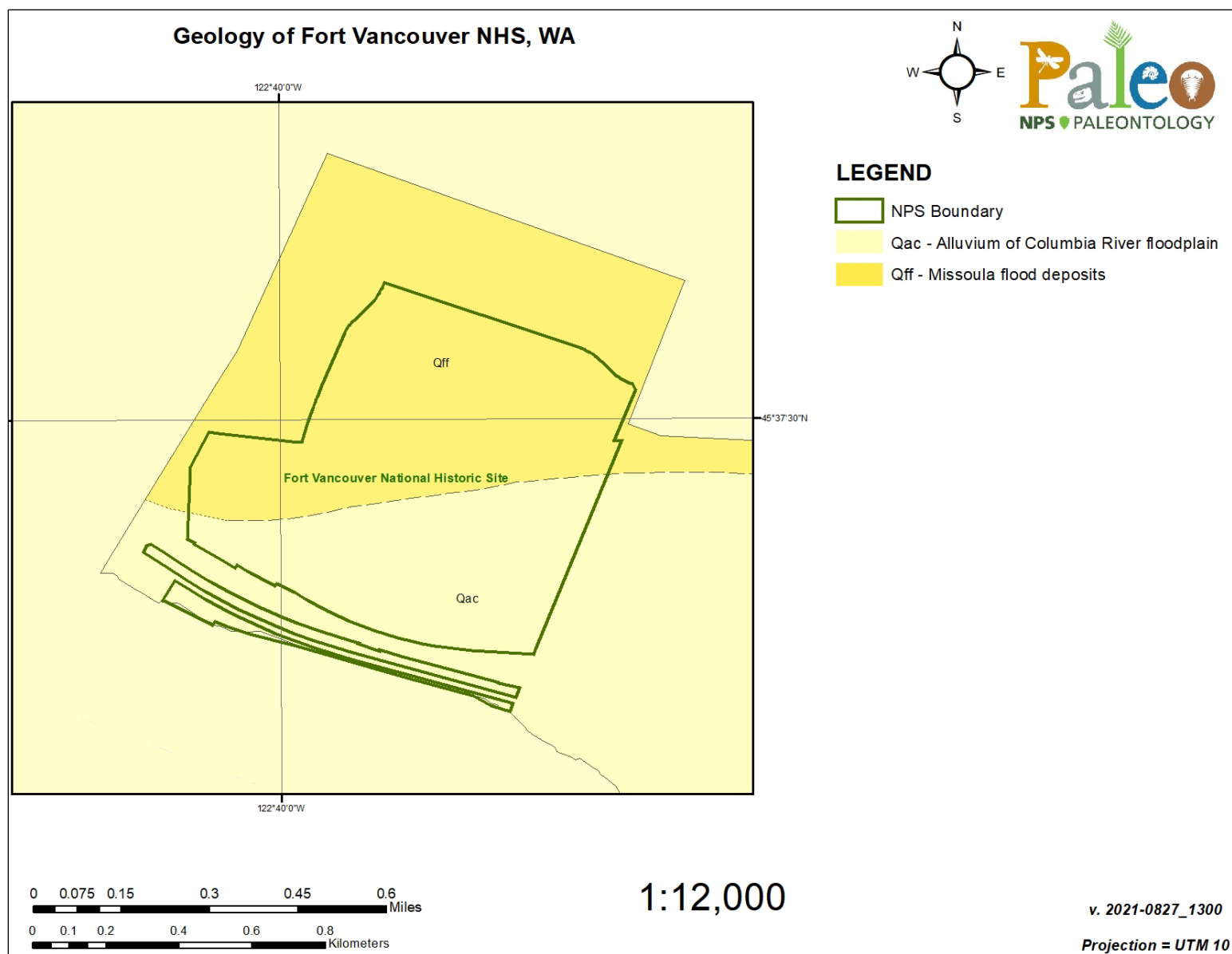
Fort Vancouver National Historical Site (FOVA) consists of two park units located on the north bank of the Columbia River (Fort Vancouver Unit) and along the Willamette River (McLoughlin House Unit) in Clackamas County, Oregon and Clark County, Washington (Figure 10). Originally authorized as a national monument on June 19, 1948, the park unit was re-designated a national historic site on June 30, 1961. Fort Vancouver National Historical Site encompasses approximately 84 hectares (207 acres) and preserves significant resources of American history related to emigration over the Oregon Trail, the military history at Vancouver Barracks, and the aviation history at Pearson Air Museum (National Park Service 2016). Fort Vancouver served as the western headquarters of the Hudson's Bay Company's fur trade empire and supply depot west of the Rocky Mountains. The McLoughlin house preserves the home of Dr. John McLoughlin, commonly referred to as "the Father of Oregon" because of the assistance he provided to migrating American homesteaders (Graham 2019a). The historical site protects historic structures and an extensive collection of American Indian, fur trade, and U.S. Army material which encompasses archeological artifacts, historic objects, and archival documents (National Park Service 2017a). These nationally significant resources directly contributed to the establishment of FOVA and showcase global trade networks, technological evolution, and cultural engagement over the past two centuries.

Fort Vancouver National Historic Site lies within the Portland Basin, a rhomboid-shaped depression that began forming during the Miocene ~20 Ma (mega-annum, million years ago) due to the subduction of the Juan de Fuca Plate beneath the North American Plate (Liberty et al. 2003). The geology of FOVA and the surrounding region reflects four main geologic episodes: (1) the development of the Portland Basin, (2) the eruption of vast quantities of Columbia River Basalt lavas, (3) the evolution of the Columbia River, and (4) the influence of catastrophic ice age floods on the current landscape (Swanson et al. 1979; Waitt 1985, 1987; Graham 2019a). The thick layers of rock and sediment that fill the Portland Basin record geologic processes that include voluminous flood basalts resulting from mantle upwelling, regionally and locally derived sediment and volcanic debris, earthquakes, subsidence, rivers and lake sediments, and catastrophic flood deposits (Figures 11 and 12; Graham 2019a). The bedrock geology of the McLoughlin House Unit consists solely of Miocene-age Wanapum Basalt of the Columbia River Basalt Group, while the Fort Vancouver Unit has underlying geology of younger Pleistocene-age Missoula flood deposits and Holocene alluvium of the Columbia River floodplain (Figures 11 and 12).

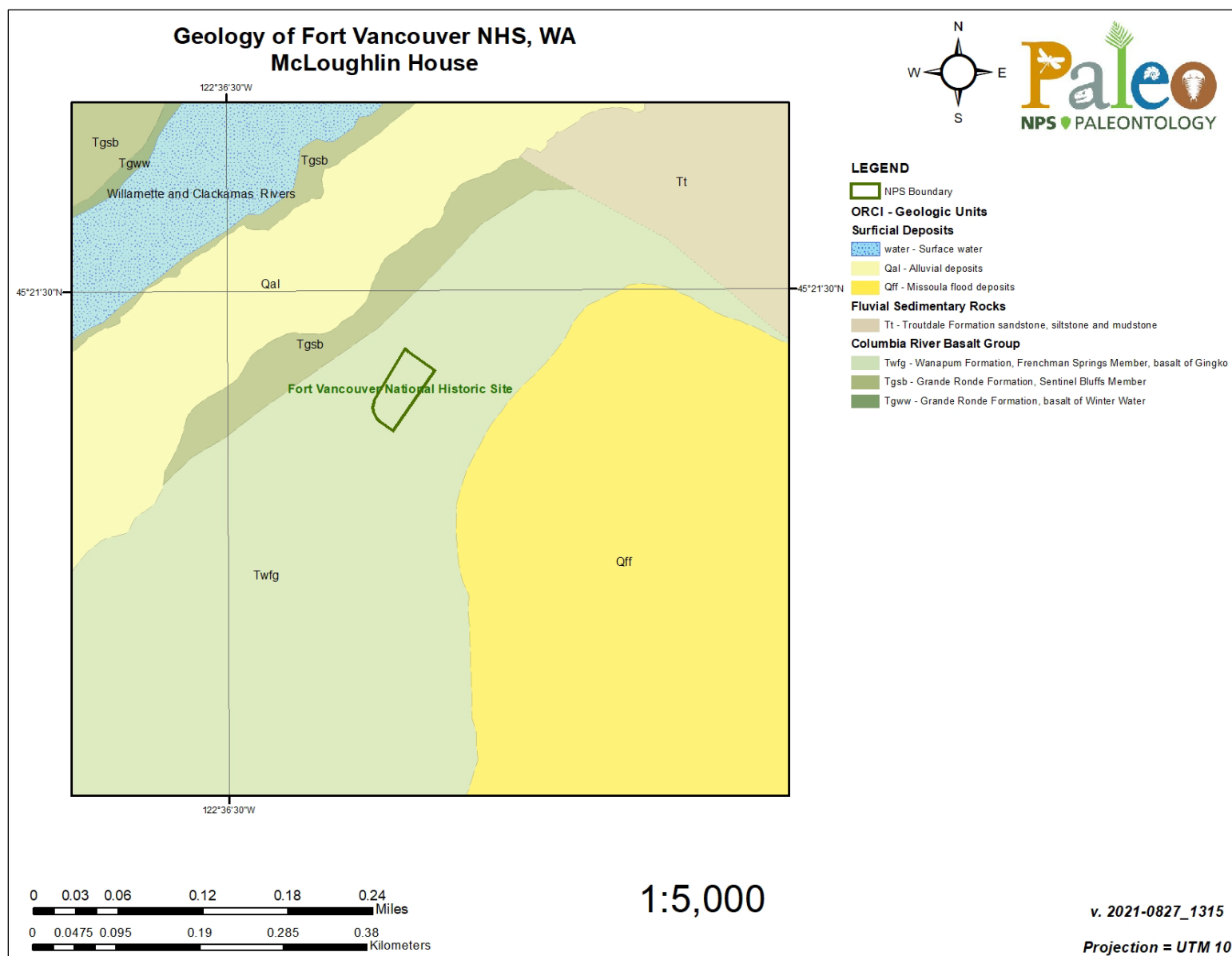
There are no designated stratotypes identified within the boundaries of FOVA. There are four identified stratotypes located within 48 km (30 mi) of FOVA boundaries, for the Miocene Sentinel Bluffs Member of the Grande Ronde Basalt (reference section); Miocene–Pliocene Troutdale Formation (type locality); Pliocene–Pleistocene Boring Lava (type locality); and the Pleistocene Amboy Drift (type area).



**Figure 10.** Regional map of FOVA, Oregon–Washington (NPS).



**Figure 11.** Geologic map of FOVA, Washington.



**Figure 12.** Geologic map of FOVA (McLoughlin House), Oregon.

## Lewis and Clark National Historical Park (LEWI)

Lewis and Clark National Historical Park (LEWI) consists of seven units that encircle the mouth of the Columbia River, extending some 64 km (40 mi) along the Pacific coast from Cannon Beach, Oregon (Clatsop County) to Long Beach, Washington (Pacific County). Established as Fort Clatsop National Memorial on May 29, 1958, the park unit was re-designated a national historical park on October 30, 2004. Lewis and Clark National Historical Park contains about 1,376 hectares (3,400 acres) and preserves, restores, and interprets key historical, cultural, scenic, and natural resources throughout the lower Columbia River area associated with the Lewis and Clark Expedition's arrival and exploration of the Pacific coast (Figure 13; National Park Service 2016). The historical park also commemorates the 1805–1806 winter encampment at Fort Clatsop following the successful crossing of the continent, where Meriwether Lewis, William Clark, and the Corps of Discovery provisioned, planned for the return journey, and compiled important scientific, cultural, and geographic information collected along their journey, including interactions with American Indian tribes (National Park Service 2015a). The area of LEWI encompasses ancestral homelands of the Chinook and Clatsop tribes, sites of the lower Columbia River where the expedition interacted with American Indian communities, and a reconstruction of the Corps' winter quarters at Fort Clatsop.

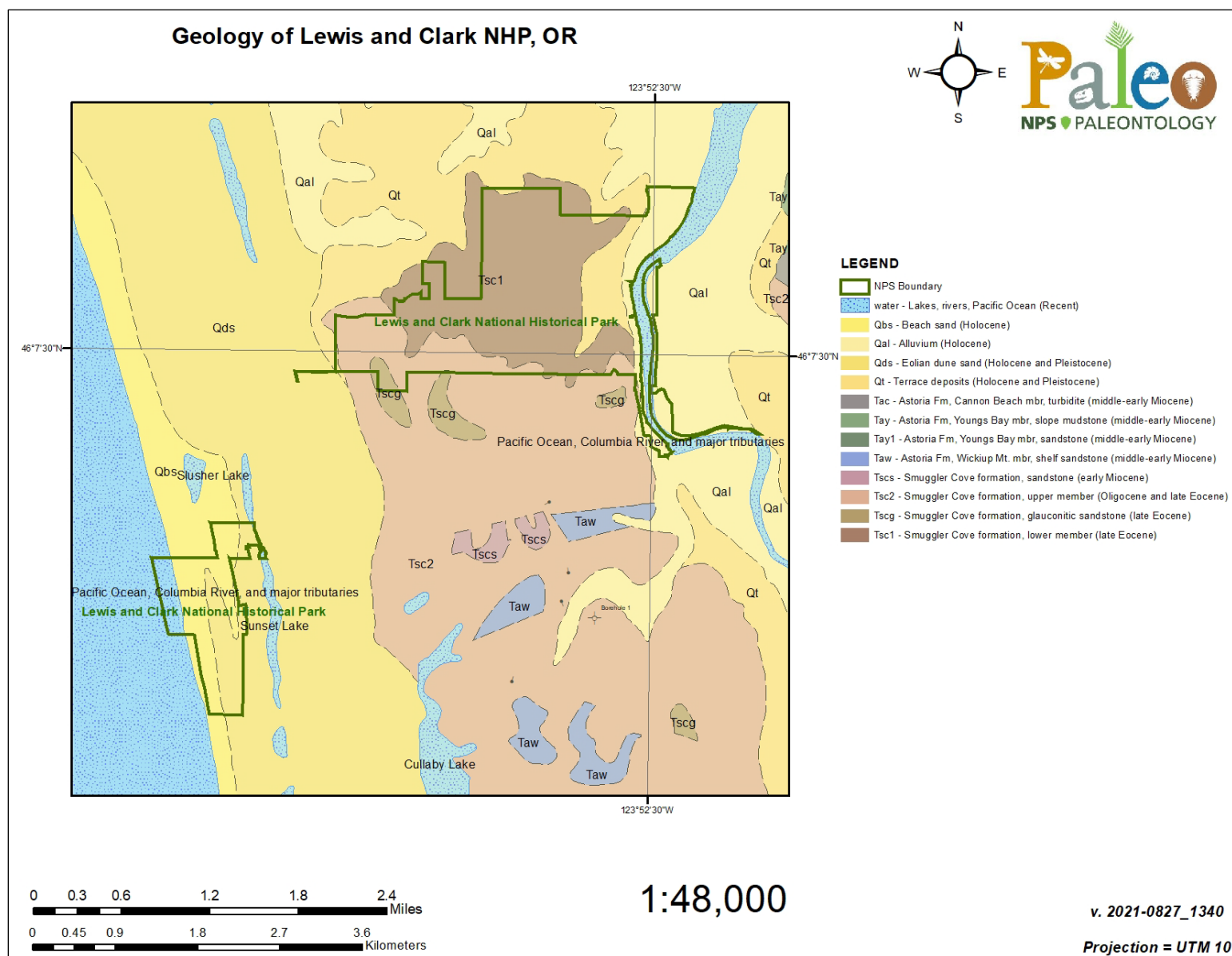
The geologic framework of the LEWI region records three major geologic events: (1) the formation of the Cascadia Subduction Zone (CSZ), (2) the extensive outpouring of Columbia River basalt, and (3) the Pleistocene ice ages and the colossal Glacial Lake Missoula floods (Swanson et al. 1979; Waitt 1985, 1987; Graham 2019b). An oblique collision between the North American and Juan de Fuca tectonic plates during the Eocene formed the CSZ off the Pacific Northwest coast. Geologic features in LEWI such as folds, faults, and inverted topography reflect tectonic processes associated with the CSZ that have been occurring for millions of years. During the Miocene (~16 Ma), extensive volcanism associated with the Columbia River Basalt Group covered roughly 164,000 km<sup>2</sup> (63,000 mi<sup>2</sup>) of the Pacific Northwest. Towering 1,000-m (3,000-ft) cliffs consisting of lava flows of the Columbia River Basalt Group were encountered by the Lewis and Clark Expedition as they traversed the Columbia River Gorge and explored the lower Columbia River (Graham 2019b). The failure of ice dams during the Pleistocene (~12 ka) produced the cataclysmic Missoula floods that scoured the landscape and shaped the Columbia River Gorge (Waitt 1985, 1987). Mapped units within the boundaries of LEWI include (from oldest to youngest): the Eocene Crescent Formation, basalt lapilli breccia and flows at Fort Columbia, sandstone at Megler, and siltstone at Shoalwater Bay; Eocene–Oligocene Lincoln Creek Formation and Smuggler Cove Formation; Pleistocene–Holocene terrace deposits; and Holocene fluvial, estuarine, and beach sand deposits (Figures 14 and 15).

There are no designated stratotypes identified within the boundaries of LEWI. There are two identified stratotypes located within 48 km (30 mi) of LEWI boundaries, for the Miocene Astoria Formation (type locality) and the Angora Peak Member of the Astoria Formation (type locality).



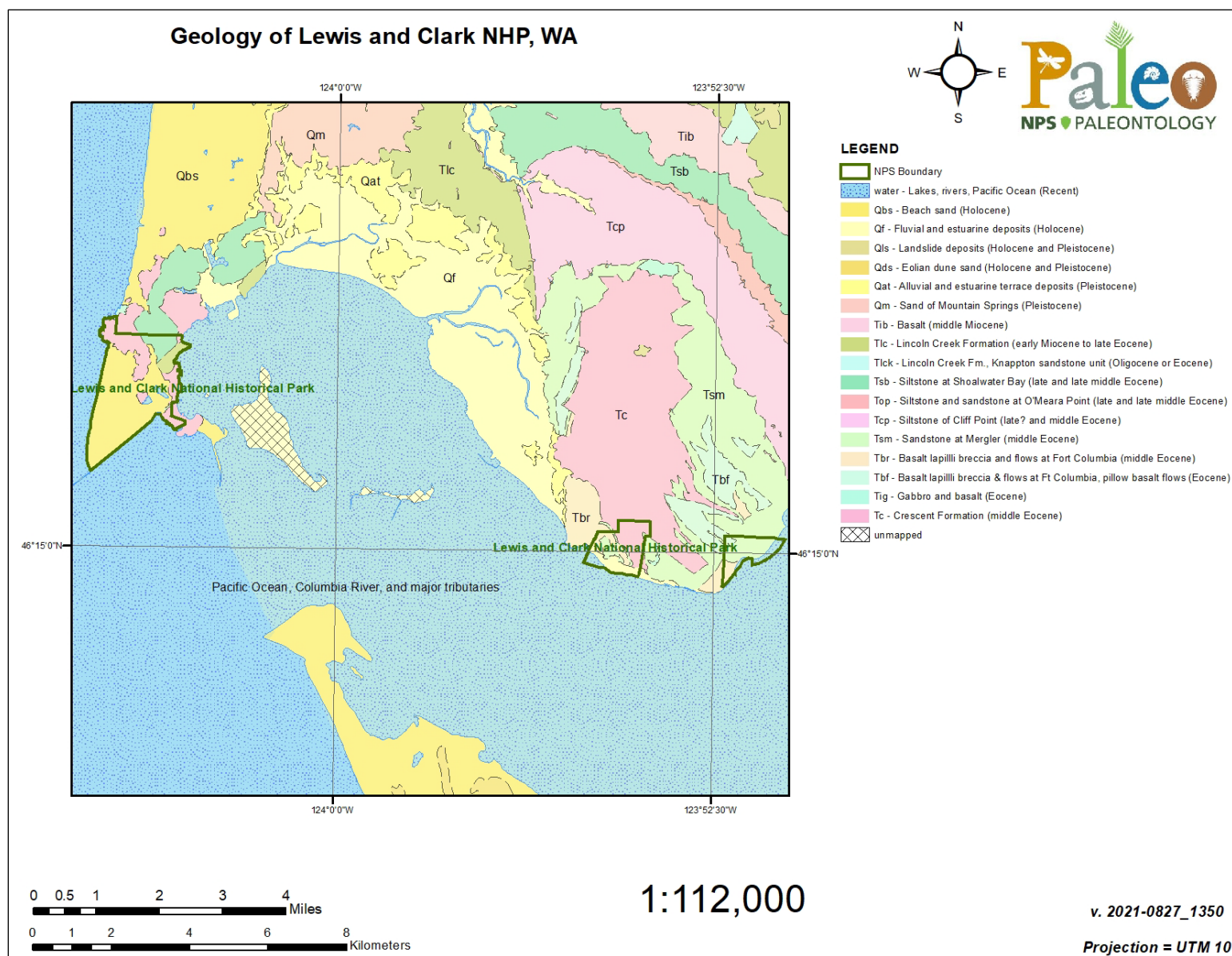
**Figure 13.** Regional map of LEWI, Oregon–Washington (NPS).





**Figure 14.** Geologic map of LEWI (Fort Clatsop and Sunset Beach units), Oregon.





**Figure 15.** Geologic map of LEWI (Cape Disappointment, Station Camp–Middle Village, and Clark’s Dismal Nitch units), Washington.

## Mount Rainier National Park (MORA)

Mount Rainier National Park (MORA) is located on the western slope of the Cascade Range approximately 75 km (47 mi) southeast of Seattle in Pierce and Lewis Counties, west-central Washington (Figure 16). Established on March 2, 1899, MORA encompasses 92,462 hectares (228,480 acres) of rugged topography that consists mainly of peaks and valleys (National Park Service 2016). The establishment of MORA is to protect and preserve Mount Rainier, a glaciated volcano, along with its natural and cultural resources, values, and dynamic processes (National Park Service 2015b). The base of the volcano covers an area of more than 259 km<sup>2</sup> (100 mi<sup>2</sup>) and the summit rises more than 2,745 m (9,000 ft) above the valley floor. Mount Rainier is a prominent landmark of the Pacific Northwest, containing more than 29 major glaciers constituting the greatest single-peak glacial system in the contiguous United States (Graham 2005; Beason 2017). Other significant park resources at MORA include 470 mapped rivers and streams, 382 mapped lakes and ponds, sub-alpine meadows, dense forests, and more than 1,214 hectares (3,000 acres) of wetland, waterfalls, and mineral springs. The national park is also home to more than 1,200 plant species and approximately 300 species of native birds, mammals, reptiles, amphibians, and fish.

The geology of MORA predominantly consists of rock that formed within the last 60 million years. As part of the Cascade Range, Mount Rainier is one of more than a dozen stratovolcanoes composed of successive eruptions of lava and pyroclastic flows. Mount Rainier is also the second most seismically active volcano in the Cascade Range and represents a regional hazard with a history of lava flows, lahars, mudflows, pyroclastic explosions, and ash falls mixed with glacial debris, glacial outwash floods, and rockfalls (Graham 2005; Ewert et al. 2018). The mountain first erupted during the Pleistocene (about 500,000 years ago) and has erupted as recently as 1894 (Sisson et al. 2006). The volcanic mountains of the Cascade Range began forming during the Eocene due to an oblique collision between the Juan de Fuca and North American tectonic plates (Graham 2005, 2019b). Mapped geologic units within the boundaries of MORA include the Eocene Ohanapecosh Formation, basaltic andesite (prominent rock type of the Cascade volcanoes) and rhyolite; Oligocene–Miocene Stevens Ridge Formation and Fifes Peak Formation; Miocene–Pliocene intrusive rocks and welded tuff of the Palisades; and Pleistocene–Holocene volcanic rocks and andesite flows of Mount Rainier (Figure 17).

Mount Rainier National Park contains five identified stratotypes that represents the Oligocene–Miocene Stevens Ridge Formation, Pleistocene Hayden Creek Drift and McNeeley Drift, and Holocene Burroughs Mountain Drift and Garda Drift (Table 3; Figure 18). Although the Eocene Ohanapecosh Formation is named from Ohanapecosh Hot Springs in MORA, there is currently no formal stratotype designated (see “Recommendations”). In addition to the designated stratotypes located within MORA, there are three stratotypes identified within 48 km (30 mi) of the park boundaries, for the Oligocene–Miocene Fifes Peak Formation (type section), Pleistocene Salmon Springs Drift, and Pleistocene Evans Creek Drift (type locality).



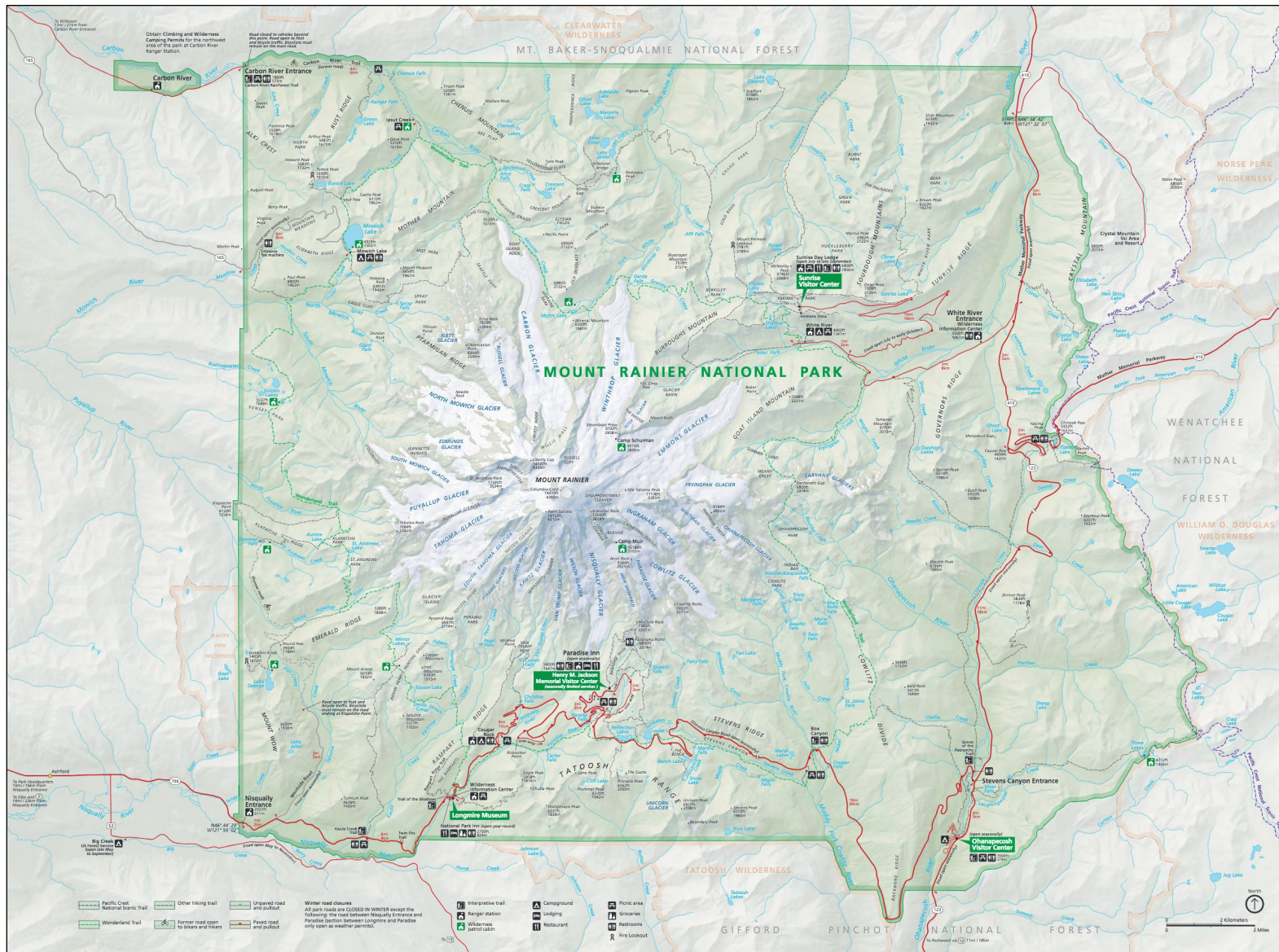
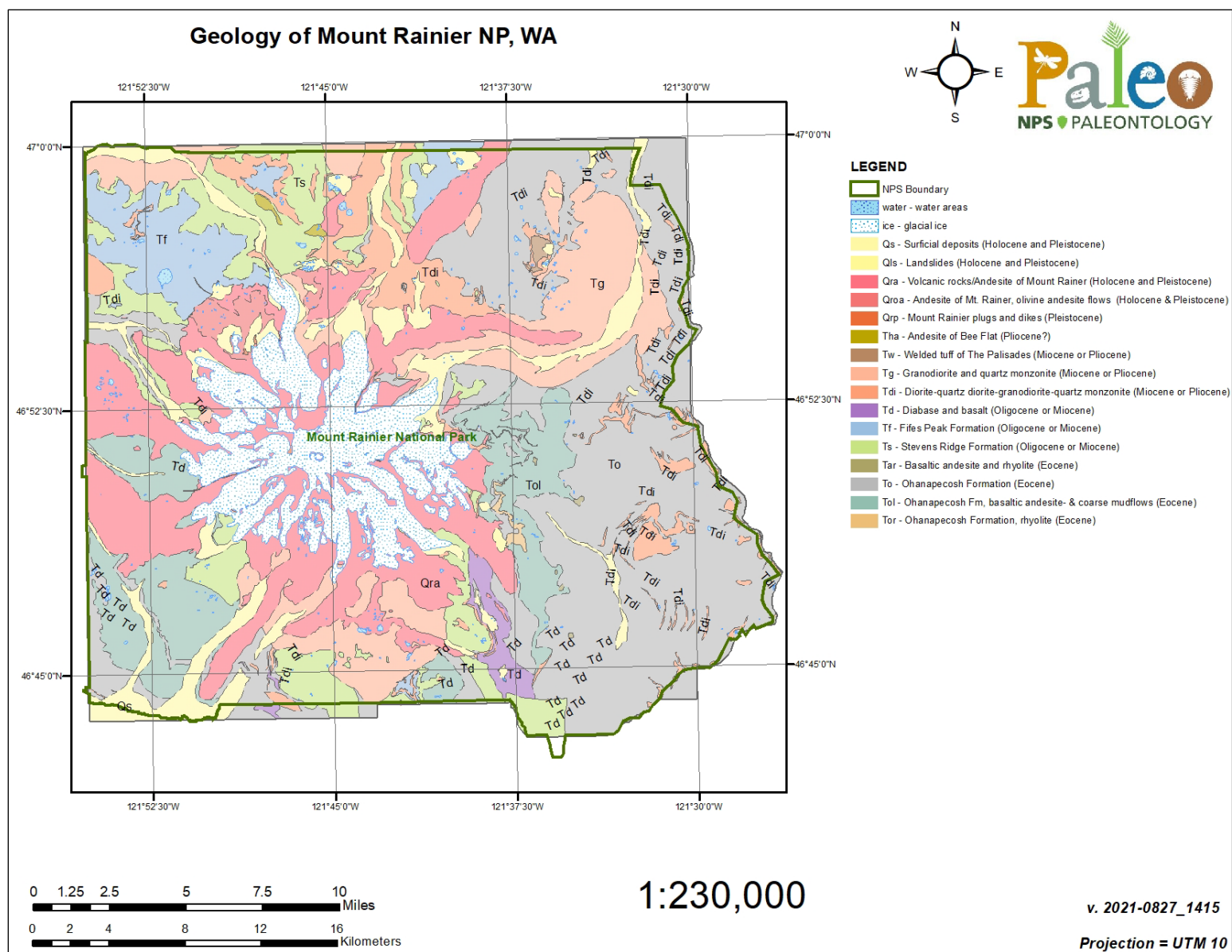


Figure 16. Park map of MORA, Washington (NPS).

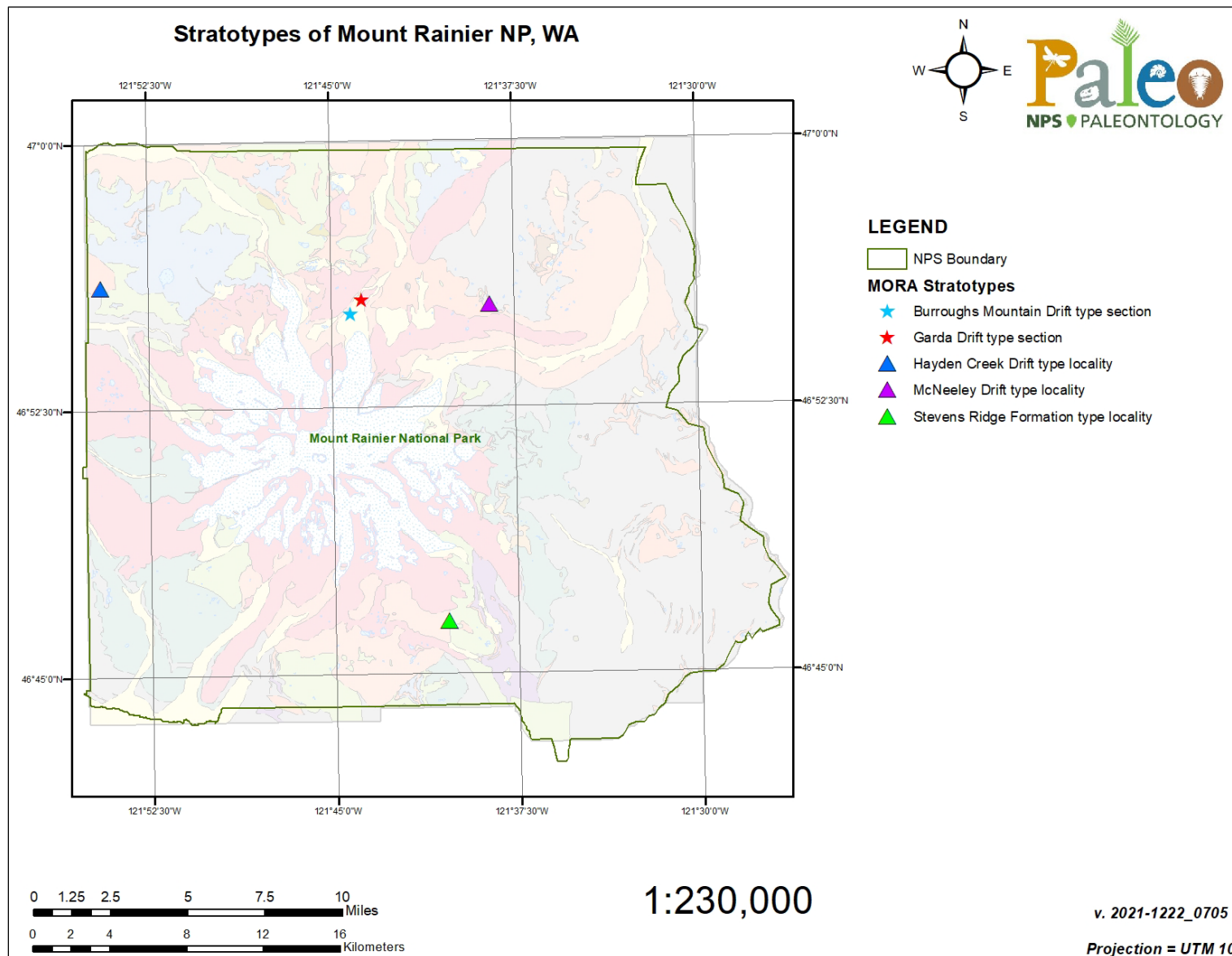


**Figure 17.** Geologic map of MORA, Washington.

**Table 3.** List of MORA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Garda Drift	Crandell and Miller 1964	Type section: lateral and terminal moraines near Garda Falls, Pierce Co., WA	Holocene
Burroughs Mountain Drift	Crandell and Miller 1974	Type section: a moraine in the center of the West Fork valley 1 km (0.6 mi) southwest of Garda Falls and 2.5 km (1.6 mi) northwest of the summit of Burroughs Mountain, Pierce Co., WA	Holocene
McNeeley Drift	Crandell 1969	Type locality: moraine in north-facing cirque, 0.8 km (0.5 mi) south of McNeeley Peak, Pierce Co., WA	Pleistocene
Hayden Creek Drift	Crandell 1969	Type locality: till exposed in cuts along Mowich Lake Road near mouth of Hayden Creek in western MORA, Pierce Co., WA	Pleistocene
Stevens Ridge Formation (Ts)	Fiske et al. 1963	Type locality: Stevens Ridge, a prominent spur just north of Stevens Canyon, in the south-central part of MORA, Lewis Co., WA	Oligocene–Miocene

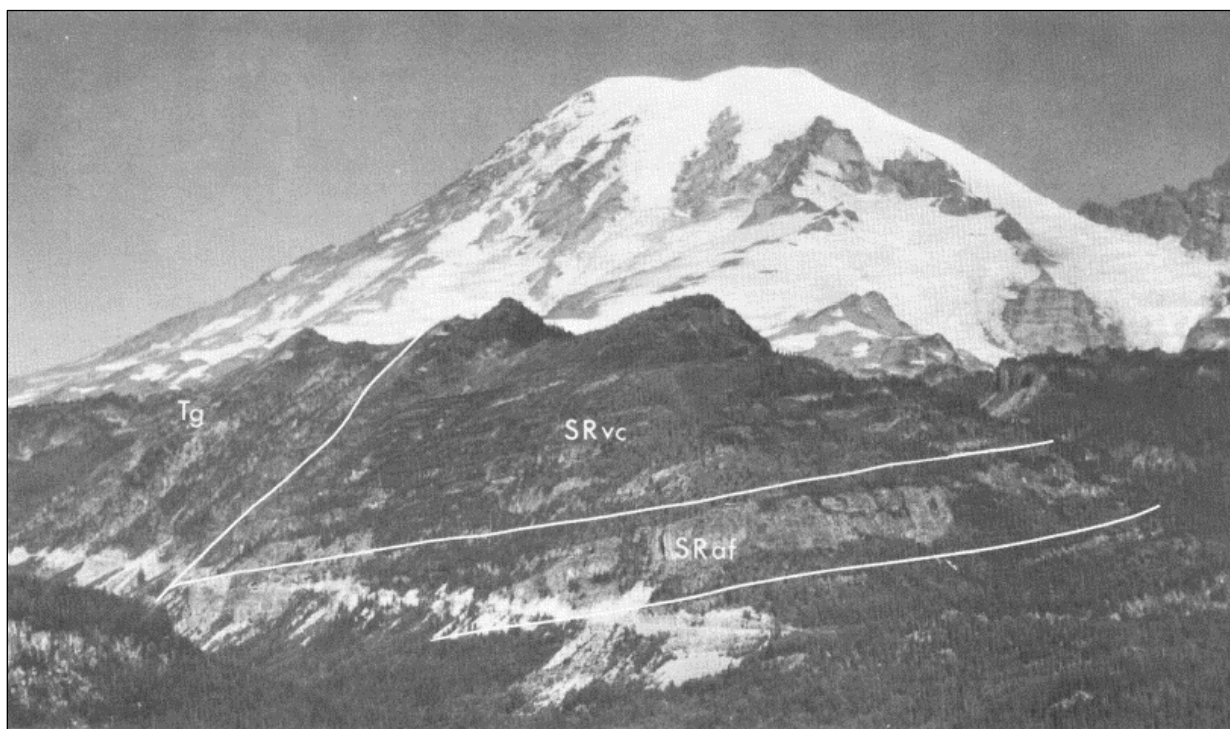




**Figure 18.** Modified geologic map of MORA showing stratotype locations. The transparency of the geologic units layer has been increased.

## Stevens Ridge Formation

The Oligocene–Miocene Stevens Ridge Formation was first mentioned by Waters (1961) and formally proposed by Fiske et al. (1963) after its type locality exposures along Stevens Ridge, a prominent spur just north of Stevens Canyon, Washington (Table 3; Figures 18 and 19). Type locality exposures measure approximately 457 m (1,500 ft) thick and consist of light colored volcaniclastic rocks and ash flows (Figure 20; Fiske et al. 1963). Ash flows are typically found in the lower part of the formation and contain an abundance of flattened pumice fragments that give a vague banding to some rocks (Fiske et al. 1963). Volcaniclastic rocks are most abundant in the upper part of the unit and are predominantly composed of finer-grained sand and silt that is well-bedded and shows cross-stratification and cut-and-fill structures (Fiske et al. 1963). The Stevens Ridge Formation unconformably overlies the Ohanapecosh Formation and conformably underlies the Fifes Peak Formation. At the type locality the upper contact with the Fifes Peak Formation is not preserved and the formation is crosscut by rocks related to the Tatoosh pluton (Fiske et al. 1963).



**Figure 19.** Type locality exposures of the Stevens Ridge Formation at Stevens Ridge. Ash flows and intercalated volcaniclastic rocks (SRaf) at the base are concordantly overlain by well-bedded volcaniclastic rocks (SRvc). Rocks of the Tatoosh pluton (Tg) sharply crosscut the bedded rocks of the Stevens Ridge Formation. Mount Rainier is seen looming above Stevens Ridge in the background. Figure 19 from Fiske et al. (1963).



**Figure 20.** Welded tuff of the Stevens Ridge Formation at the type locality along Stevens Ridge adjacent to Steven Canyon Road (NPS).

### Hayden Creek Drift

The Pleistocene Hayden Creek Drift was named by Crandell (1969) after its type locality exposures in cuts along Mowich Lake Road near the mouth of Hayden Creek in MORA, Pierce County, Washington (Table 3; Figures 18 and 21). Type locality exposures measure 7 m (23 ft) thick and consist of brownish-gray stony till that weathers to dark yellowish-brown to a depth of 1.8–2.4 m (6–8 ft) below the ground surface (Crandell 1969; Crandell and Miller 1974). Stones in the upper few feet of the till have weathered rinds or shells that exhibit large variations in thickness due in part to burial at some sites and erosion at others (Figure 22; Crandell 1969; Colman and Pierce 1981). Except for the till in the valleys of Hayden Creek and Meadow Creek, exposures of the Hayden Creek Drift are mapped on high ridges within MORA, including the summits of Iron Mountain, Copper Mountain, at the top of a flat-topped spur that extends eastward from Tyee Peak, and along a ridge northwest of The Palisades where the unit is at least 30 m (98 ft) thick (Figures 23 and 24; Crandell 1969; Crandell and Miller 1974). On the north valley wall of the White River ~3 km (2 mi) southeast of Yakima Park the Hayden Creek Drift is more than 15 m (50 ft) thick and underlies a pumice deposit containing wood fragments radiometrically dated as older than 38 ka (kilo-annum, thousand years ago) (Crandell 1969). The exact age of the Hayden Creek Drift remains unresolved but is probably 65 ka or 140 ka (Crandell and Miller 1974; Colman and Pierce 1981). At the type locality, the Hayden Creek Drift overlies rocks of older Cenozoic age.





**Figure 21.** Type locality exposures of the Hayden Creek Drift along the Mowich Lake Road in western MORA. The thick brown oxidized zone at the top of the till is typical of the Hayden Creek Drift. Bedrock at the right of the photo is much older than the Mount Rainier volcano. Figure 7 from Crandell (1969).



**Figure 22.** Weathered rinds on stones from the upper parts of the Hayden Creek Drift. Figure 10B from Crandell and Miller (1974).



**Figure 23.** Till of the Hayden Creek Drift located northwest of The Palisades in MORA. The till is at least 30 m (98 ft) thick and is at the crest of a ridge between adjacent cirques. Figure 13 from Crandell and Miller (1974).

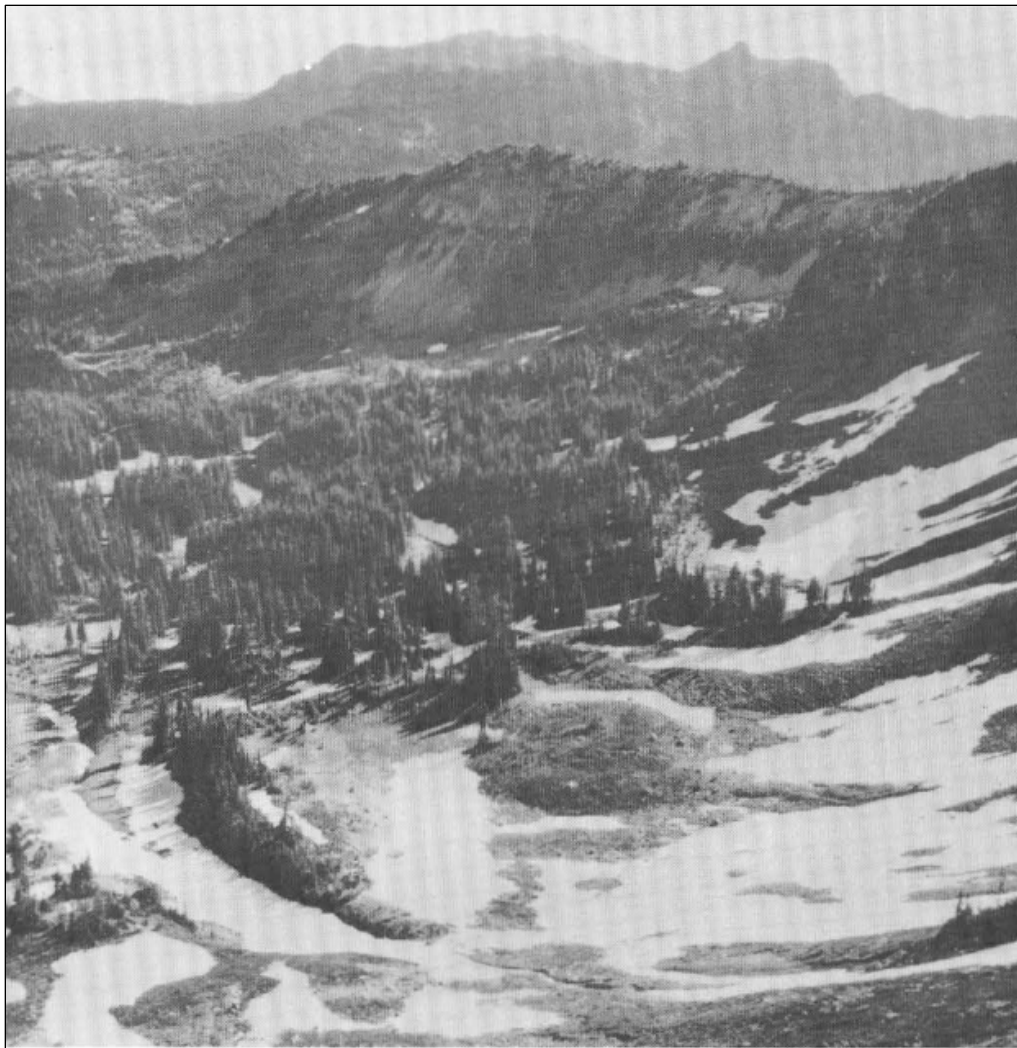


**Figure 24.** Exposures of the Hayden Creek Drift at the crest of a ridge east of Tye Peak. The slope to the left descends to the floor of the Chenuis Creek valley, which is nearly 600 m (1,969 ft) lower in altitude. Man (circled) at the top center of the photograph for scale. Figure 14 from Crandell and Miller (1974).

### **McNeeley Drift**

The Pleistocene McNeeley Drift was proposed by Crandell (1969) and named after its type locality exposures in a moraine that lies within a north-facing cirque 0.8 km (0.5 mi) south of McNeeley Peak in MORA, Pierce County, Washington (Table 3; Figures 18 and 25). The unit consists of till that forms sharp-crested moraines mapped adjacent to large active valley glaciers on Mount Rainier and in high altitude cirques between 1,676–2,042 m (5,500–6,700 ft) (Figure 26; Crandell 1969). The north fronts of the moraines are 6–20 m (20–66 ft) high and have a hummocky surface with closed depressions as much as 4.5 m (15 ft) deep (Crandell and Miller 1974). Moraines of the McNeeley Drift range from single, low, narrow ridges of till to accumulations as much as 305 m (1,000 ft) wide that are distinguished by multiple ridges (Crandell 1969). One of the largest moraines of the McNeeley Drift dams Mystic Lake on the northern side of MORA. Small moraines of the unit are located along the Wonderland Trail at the south end of Berkeley Park and along the highway between Tipsoo Lake and Chinook Pass (Crandell 1969; Crandell and Miller 1974). Deposits of the McNeeley Drift are mantled by pyroclastic deposits from ~8.75 ka and seem to date to the last major glaciation in MORA about 11 ka when cirque and valley glaciers expanded (Crandell 1969; Crandell and Miller 1974). The McNeeley Drift is underlain by ice-scoured bedrock or by featureless ground moraines of Evans Creek age.





**Figure 25.** Type locality exposures of the McNeeley Drift that form arcuate end moraines in a cirque on the north slope of the Sourdough Mountains 0.7 km (0.4 mi) south of McNeeley Peak in MORA. Figure 23 from Crandell and Miller (1974).



**Figure 26.** Forested McNeeley Drift (M) and bare Garda Drift (G) moraines at the north end of Old Desolate just north of Mount Rainier, MORA. Figure 24 from Crandell and Miller (1974).

### **Burroughs Mountain Drift**

The Holocene Burroughs Mountain Drift (and associated Burroughs Mountain Stade of the Winthrop Creek Glaciation) were proposed by Crandell and Miller (1964) and renamed by Crandell (1969). The original type section of the Burroughs Mountain Drift was designated by Crandell and Miller (1964) as a lateral moraine on the northwestern slope of Burroughs Mountain, MORA. However, a reexamination of the type section moraine determined that the deposits were older (probably McNeeley age) than the Burroughs Mountain Drift (Crandell and Miller 1974). Crandell and Miller (1974) revised the type section location, selecting a moraine in the center of the West Fork valley 1 km (0.6 mi) southwest of Garda Falls and 2.5 km (1.55 mi) northwest of the summit of Burroughs Mountain (Table 3; Figure 18). Moraines of the Burroughs Mountain Drift consist of gray, generally loose, and unweathered till, with some of the largest moraines located adjacent to Winthrop Glacier and between Winthrop and Carbon Glaciers (Crandell 1969). The age of the unit is bracketed by pyroclastic layers with a known age between  $3,500 \pm 200$  and  $2,340 \pm 200$  years ago (Crandell and

Miller 1974). The Burroughs Mountain Drift underlies a thin pumice layer (“Pyroclastic Layer C” of Crandell 1969; Crandell and Miller 1974) below the Garda Drift (Figure 27).



**Figure 27.** Moraine of the Garda Drift at Fryingpan Glacier at the left with a thin brown veneer of Pyroclastic Layer C in the center foreground above the Burroughs Mountain Drift. The large boulder in the middle foreground is about 2 m (6 ft) long. Figure 14 from Crandell (1969).

### **Garda Drift**

The Holocene Garda Drift (and associated Garda Stade of the Winthrop Creek Glaciation) were proposed by Crandell and Miller (1964) and redescribed by Crandell (1969). The Garda Drift is named after its type section exposure that forms the lateral and terminal moraines near Garda Falls, MORA (Table 3; Figure 18; Crandell and Miller 1964). Till of the Garda Drift consists of a gray unsorted mixture of pebbles, cobbles, and boulders in a matrix of silt and sand (Crandell 1969). Moraines of the unit border nearly every cirque and valley glacier on and near Mount Rainier and range in size from ridges only a few meters or feet high and a few meters or tens of feet wide to massive complex end moraines (Figure 28; Crandell 1969; Crandell and Miller 1974). One of the most accessible moraines of the Garda Drift in MORA is at the west end of the bridge across the Nisqually River, about 5.6 km (3.5 mi) northeast of Longmire (Crandell 1969). The age of the Garda

Drift is bracketed by pyroclastic layers with a known age between  $2,340 \pm 200$  and 450 years ago (Crandell and Miller 1974). The Garda Drift overlies a thin pumice layer (Pyroclastic Layer C) above the Burroughs Mountain Drift.



**Figure 28.** End moraine of the Garda Drift formed by Emmons Glacier, consisting of a hummocky accumulation of bare rock debris in the center of the White River valley, MORA. Figure 15 from Crandell (1969).



## North Cascades National Park Complex (NOCA, ROLA, and LACH)

North Cascades National Park Complex consists of North Cascades National Park (NOCA), Ross Lake National Recreation Area (ROLA), and Lake Chelan National Recreation Area (LACH). The park complex is located along and near the Canadian border approximately 160 km (100 mi) northeast of Seattle in Chelan, Skagit, and Whatcom Counties, Washington (Figure 29). Established on October 2, 1968, NOCA, ROLA, and LACH preserve about 276,928 hectares (684,305 acres) of wilderness decorated with alpine scenery, glaciated peaks, deep forested valleys, waterfalls, rivers, lakes, and a diverse array of plants and animals (National Park Service 2016). The area of NOCA represents the core of a vast mountainous ecosystem that encompasses extreme gradients of climate and topography. The national park consists of a north and south unit with ROLA situated between them along the upper Skagit River and LACH located south of the national park in Stehekin Valley. North Cascades National Park Complex preserves abundant evidence of more than 9,000 years of human habitation, revealing a range of cultural and technological adaptations to changing climates and environments at all elevations of the North Cascades (National Park Service 2012).

The steep mountains of the North Cascades National Park Complex are coupled with a diverse, complex assemblage of rocks that span from the Precambrian (>540 Ma) to the Holocene (<11.7 ka) (Figures 30 and 31). Situated within the North Cascade Range, the bedrock that forms the foundation of NOCA, ROLA, and LACH is still being uplifted due to geologic processes that began millions of years ago when the Juan de Fuca and North American tectonic plates collided (Graham 2005, 2019b). Mapped units within the parks represent a collage of geologically and temporally distinct terranes juxtaposed against one another and separated by faults. Fossils and paleomagnetic data indicate that different rock assemblages in the park complex formed thousands of kilometers or miles away and were slowly accreted (tectonically added) to the western edge of the North American continent (Haugerud et al. 1994; Haugerud and Tabor 2009). These masses of rock were thrust upwards and faulted into the jumbled array of mountains that are still rising today.

North Cascades National Park contains five identified stratotypes that represent the Cretaceous Shuksan Greenschist and Eldorado Orthogneiss, Cretaceous–Eocene Magic Mountain Gneiss and Cascade River Schist, and the Oligocene–Miocene Perry Creek phase of the Chilliwack Batholith (Table 4; Figure 32). Ross Lake National Recreation Area contains one identified stratotype for the Cretaceous–Eocene Skagit Gneiss Complex (Table 4; Figure 32). There are no designated stratotypes identified within the boundaries of LACH.

In addition to the designated stratotypes located within NOCA and ROLA, stratotypes located within 48 km (30 mi) of the park boundaries include: the Triassic–Jurassic Hozomeen Group (type area); Jurassic Wells Creek Volcanic Member of the Nooksack Formation (type area) and Twisp Formation (type area); Jurassic–Cretaceous Leecher Metamorphics (type locality and type area), Newby Group (type locality), and Nooksack Formation (type locality); Cretaceous Darrington Phyllite (type locality), Methow Gneiss (type locality), Chelan Complex (type area), Midnight Peak Formation (type section), Ventura Member of the Midnight Peak Formation (type section), Winthrop Sandstone

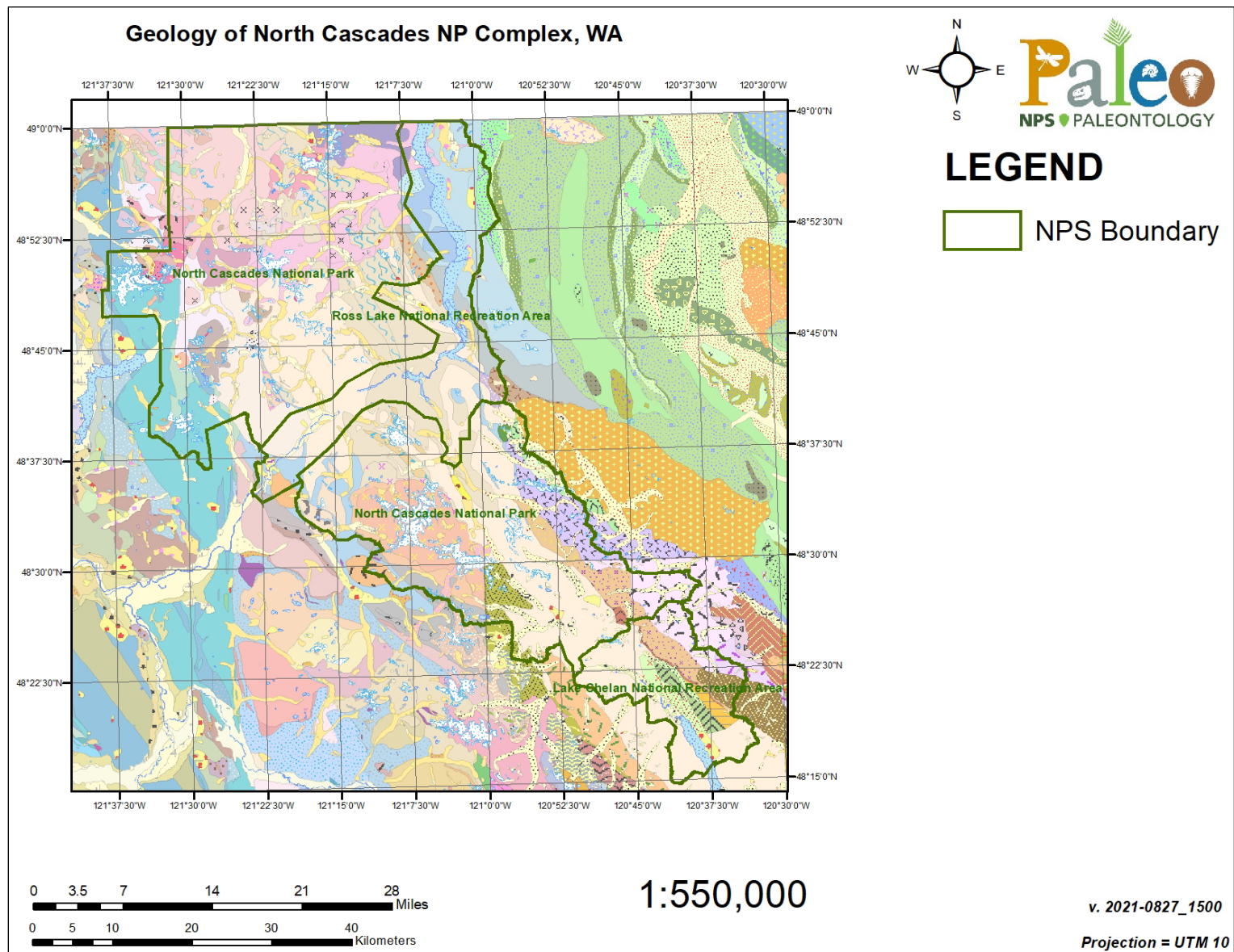


(type locality), Panther Creek Formation (type section), Buck Mountain Formation (type section), Virginian Ridge Formation (type section and type locality), Devil's Pass Member of the Virginian Ridge Formation (type section), Slate Peak Member of the Virginian Ridge Formation (type locality), Patterson Lake Member of the Virginian Ridge Formation (type locality), Harts Pass Formation (type area), and Goats Creek Formation (type section); Cretaceous–Eocene Napeequa Schist (type area) and Marblemount Quartz Diorite (type area); Paleocene Pipestone Canyon Formation (type section); Eocene Slide Member of the Chuckanut Formation (type section), Warnick Member of the Chuckanut Formation (type section), and Maple Falls Member of the Chuckanut Formation (type section); and the Pliocene Hannegan Volcanics (type area).



**Figure 29.** Park map of NOCA, ROLA, and LACH, Washington (NPS).





**Figure 30.** Geologic map of NOCA, ROLA, and LACH, Washington (see Figure 31 for legend).



**Figure 31.** Geologic map legend of NOCA, ROLA, and LACH, Washington.

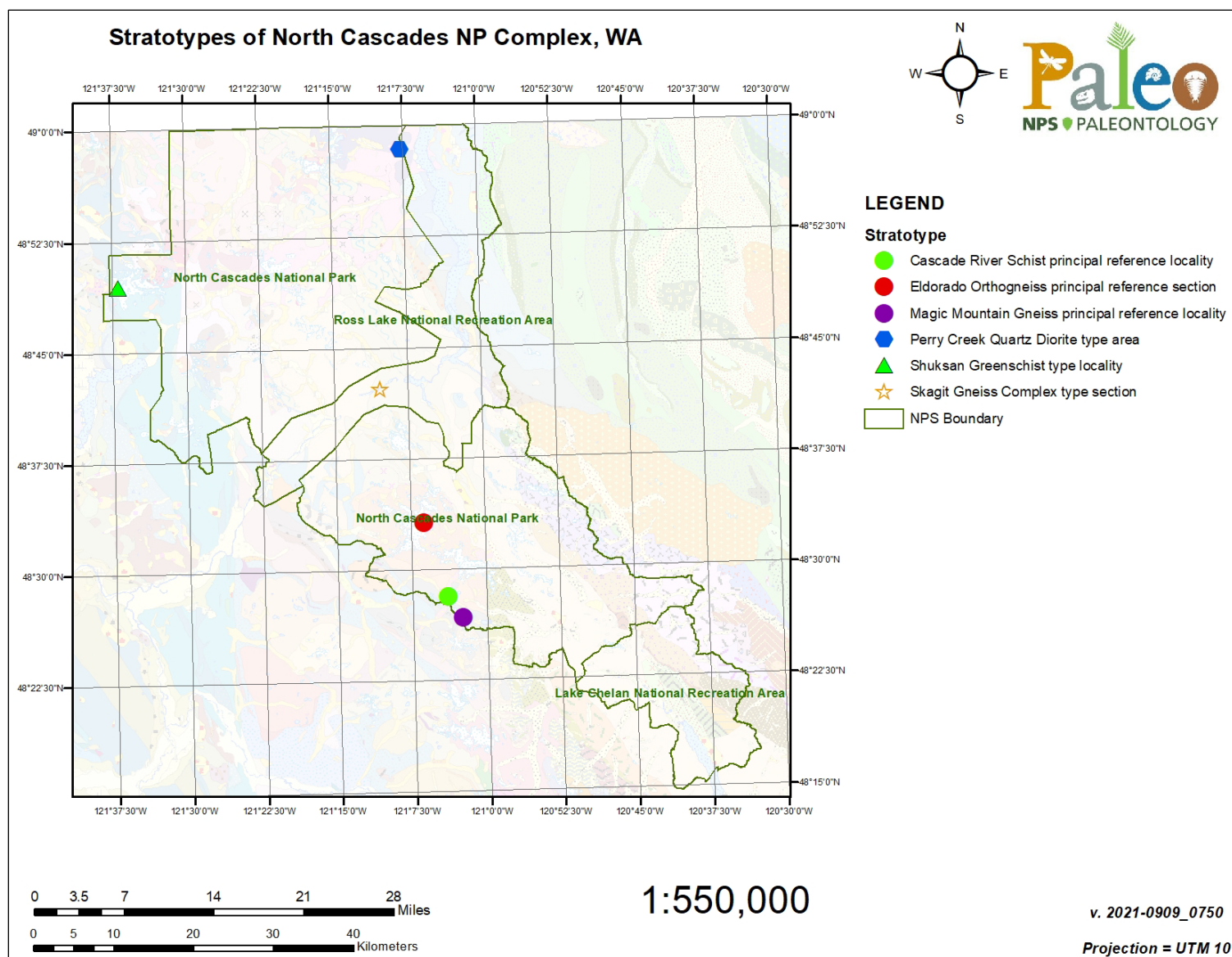




**Figure 31 (continued).** Geologic map legend of NOCA, ROLA, and LACH, Washington.

**Table 4.** List of NOCA and ROLA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Perry Creek phase of the Chilliwack Batholith [formerly Perry Creek Quartz Diorite] (MIOLcpc)	Grant 1969	Type area: Silver Creek, 3.2 km (2.0 mi) south of the Canadian border on west side of Ross Lake, in sec. 5, T. 40 N., R. 13 E., Whatcom Co., WA	Oligocene–Miocene
Skagit Gneiss Complex (EKsbg, EKsbga)	Misch 1987; Haugerud et al. 1991	Type section: Skagit Gorge between Newhalem and Ross Dam, from sec. 21, T. 37 N., R. 12 E., to sec. 35, T. 38 N., R. 13 E., Mount Baker 30' x 60' Quadrangle, northern WA	Late Cretaceous–middle Eocene
Cascade River Schist (EKcs)	Tabor et al. 2002	Principal reference locality [composite]: main valley walls of the North, South, and Middle Forks of the Cascade River, surrounding lat. 48° 27' N., long. 121° 05' W., Cascade Pass 7.5' Quadrangle, Skagit Co., WA	Late Cretaceous–Eocene
Magic Mountain Gneiss (EKmm)	Tabor et al. 2002	Principal reference locality: Magic Mountain, located south of Cascade Pass, in vicinity of lat. 48° 27' N., long. 121° 02' W., Cascade Pass 7.5' Quadrangle, Skagit Co., WA	Late Cretaceous–Eocene
Eldorado Orthogneiss (Kog(e), Kog(ef))	Haugerud et al. 1991	Principal reference area: Eldorado, Klawatti, and Primus Peaks, and connecting ridges; from sec. 8, T. 35 N., R. 12 E., to sec. 27, T. 36 N., R. 13 E., Mount Baker 30' x 60' Quadrangle, northern WA	Cretaceous
Shuksan Greenschist (Kes)	Misch 1966; Tabor et al. 1993	Type locality: on Mount Shuksan in the vicinity of lat. 48°50' N. long. 121°36' W., north of the Skykomish River 30' x 60' Quadrangle, WA	Early Cretaceous



**Figure 32.** Modified geologic map of NOCA, ROLA, and LACH showing stratotype locations. The transparency of the geologic units layer has been increased.



### Shuksan Greenschist

The Early Cretaceous Shuksan Greenschist of the Easton Metamorphic Suite was first defined by Misch (1966) to describe intercalated greenschist and blue-amphibole schist on the western side of the North Cascade Range, Washington. An earlier use of the name Shuksan (original spelling) Formation to describe fossiliferous Jurassic marine sandstone and shale by Weaver (1945) and Imlay (1952) has been abandoned due to vague descriptions (Tabor et al. 1993). The type locality of the formation is described by Misch (1966) and Tabor et al. (1993) on Mount Shuksan in the vicinity of latitude 48°50' N., longitude. 121°36' W., north-central Washington (Table 4; Figures 32 and 33). Type locality exposures consist of bright to dark olive-green greenschist and blue-amphibole schist with minor phyllite layers (Misch 1966; Staatz et al. 1972; Tabor et al. 1993). The Shuksan Greenschist underlies the Cretaceous Darrington Phyllite and overlies Late Jurassic-age barroisite schist (Brown et al. 1987).



**Figure 33.** Southeast-facing view of Mount Shuksan from Mount Baker–Snoqualmie National Forest (NPS/DEBY DIXON). Type locality exposures of the Shuksan Greenschist comprise portions of Mount Shuksan including the prominent Summit Pyramid.

### Eldorado Orthogneiss

The Cretaceous Eldorado Orthogneiss was originally named the Eldorado Gneiss by Tabor (1961) and subsequently re-described by Adams (1964) and Misch (1966). A principal reference area for the unit was designated by Haugerud et al. (1991) on Eldorado, Klawatti, and Primus peaks, and their connecting ridges (from section 8, T. 35 N., R. 12 E., to section 27, T. 36 N., R. 13 E., Mount Baker



30' x 60' Quadrangle, northern Washington) (Table 4; Figures 32 and 34). The Eldorado Orthogneiss consists of metamorphosed gneissic biotite–hornblende granodiorite and tonalite (Haugerud et al. 1991). Southwest of the principal reference area, the formation is strongly deformed and interlayered with rocks of the Chelan Mountains Terrane and is in conformable contact with banded gneiss of the Skagit Gneiss Complex to the northeast (Haugerud et al. 1991).

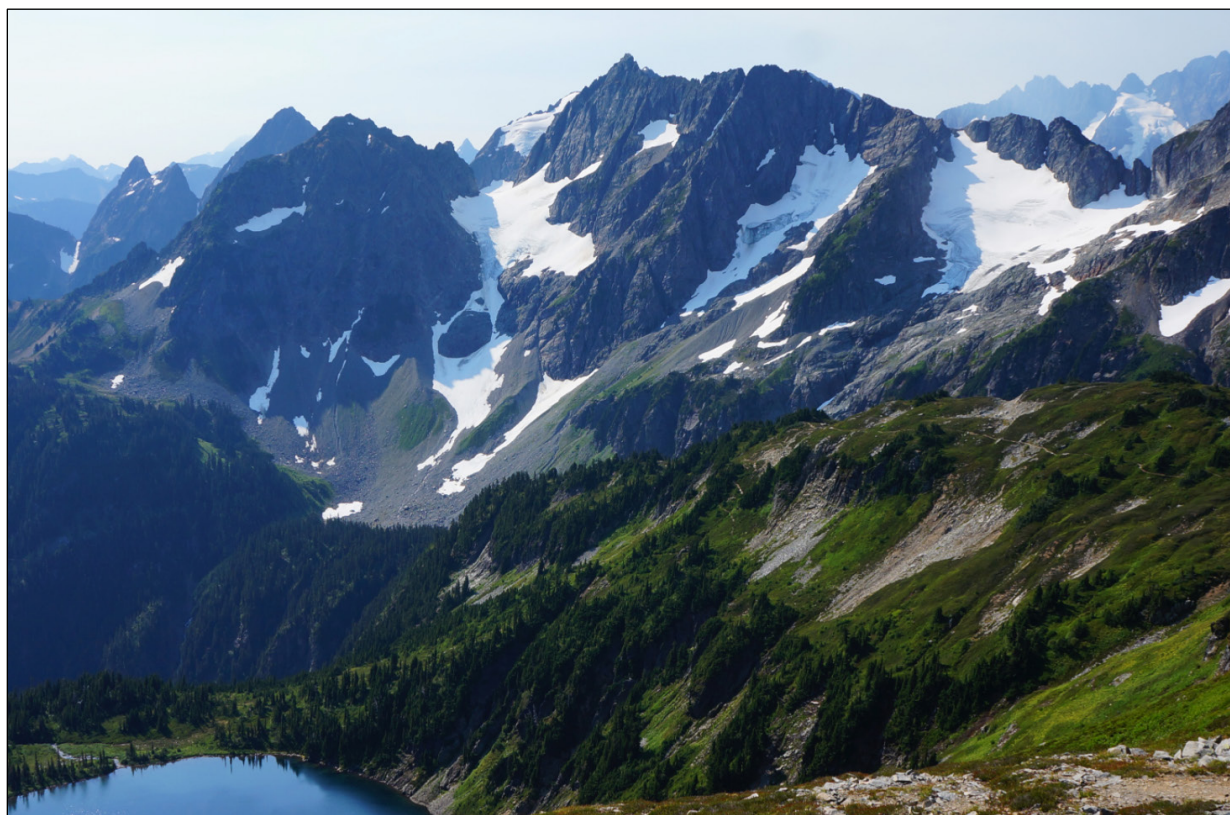


**Figure 34.** View looking south from the North Klawatti Glacier in the principal reference area of the Eldorado Orthogneiss (USGS). Rock in the foreground knob consists of the Eldorado Orthogneiss, which includes abundant dikes of light-colored pegmatite. Mount Buckner is seen in the left background, and Mount Forbidden is hidden in the clouds to the right.

### **Magic Mountain Gneiss**

The Late Cretaceous–Eocene Magic Mountain Gneiss was named by Tabor (1961) after exposures on Magic Mountain in the Cascade River 7.5' Quadrangle, Skagit County, Washington. A principal reference locality was designated by Tabor et al. (2002) on Magic Mountain, located just south of

Cascade Pass (near latitude 48° 27' N., longitude 121° 02' W., Cascade Pass 7.5' Quadrangle, Washington) (Table 4; Figures 32 and 35). The formation is a strongly layered unit consisting of light-colored chlorite–muscovite–epidote–quartz gneiss and flaser gneiss, mafic greenschist, and chlorite schist (Tabor et al. 2002). Thickness of the unit exceeds 60 m (200 ft) in areas where the unit is in contact with the Cascade River Schist (Tabor et al. 2002). The Magic Mountain Gneiss conformably overlies the Cascade River Schist and underlies the Spider Mountain Schist (Tabor 1961; Tabor et al. 2002).



**Figure 35.** Principal reference locality exposures of the Magic Mountain Gneiss at Magic Mountain. View is to the south across Doubtful Lake from Sahale Arm. Photograph by user “Martin Bravenboer” available via Wikimedia Commons [https://commons.wikimedia.org/wiki/File:Magic\\_Mountain\\_from\\_Sahale\\_Arm.jpg](https://commons.wikimedia.org/wiki/File:Magic_Mountain_from_Sahale_Arm.jpg) (Creative Commons Attribution 2.0 Generic [CC BY 2.0]; <https://creativecommons.org/licenses/by/2.0/deed.en>).

### **Cascade River Schist**

The Late Cretaceous–Eocene Cascade River Schist was first formally described by Tabor (1961) and named after exposures south of Cascade Pass, Washington. Tabor et al. (2002) designated a composite principal reference locality for the formation in the main valley walls of the North, South, and Middle Forks of the Cascade River, in the vicinity of latitude 48° 27' N., longitude 121° 05' W., Cascade Pass 7.5' Quadrangle, Skagit County, Washington (Table 4; Figures 32 and 36). The formation consists of plagioclase-rich mica schist, meta-conglomerate, and amphibolitic schist with minor constituents of silicic schists (meta-tuff), marble, and amphibolite (Tabor et al. 2002). The



Cascade River Schist is structurally overlain by the Magic Mountain Gneiss, shares an unconformable contact with the Marblemount pluton, and is in tectonic contact with the Eldorado Orthogneiss to the east of the principal reference area (Tabor et al. 2002).



**Figure 36.** View of Eldorado Peak looking northeast from the divide between Sibley and Marble Creeks. In the foreground, type locality exposures of the Cascade River Schist contain cobbles stretched to form streaks. Orthogneiss of the Eldorado pluton is visible in the background. Figure 17 from Haugerud and Tabor (2009).

### **Skagit Gneiss Complex**

The Late Cretaceous to middle Eocene Skagit Gneiss Complex was first described by Misch (1952, 1966) and named after exposures along Skagit River, northern Washington. The type section of the complex is located in ROLA along Skagit Gorge, between Newhalem and Ross Dam (from section 21, T. 37 N., R. 12 E. to section 35, T. 38 N. R. 13 E., Mount Baker 30' x 60' Quadrangle), northern Washington (Table 4; Figure 32; Misch 1987, Haugerud et al. 1991). The Skagit Gneiss Complex is composed of a heterogeneous suite of rock types, ranging from metamorphic granitoid plutons and related metamorphosed non-granitoid rocks, orthogneiss, banded gneiss, massive pegmatite, gabbro-troctolite-norite, amphibolite, marble, calc-silicate rocks, and ultramafic rocks (Haugerud et al. 1991; Haugerud and Tabor 2009). At the type section the unit is more than 50% orthogneiss and contains locally abundant deformed dikes and sills of lineated granite and pegmatitic tonalite (Figure 37; Misch 1987; Haugerud et al. 1991; Haugerud and Tabor 2009). Most mappable contacts of the Skagit

Gneiss Complex are either intrusive or faults; near the type section east and south of Mount Triumph the Skagit Gneiss Complex intrudes the Napeequa Schist (Haugerud et al. 1991).



**Figure 37.** View looking west across Skagit Gorge from Diablo Dam Road at type section exposures of the Skagit Gneiss Complex (NPS).

### **Perry Creek phase of the Chilliwack Batholith**

The Oligocene–Miocene Perry Creek phase of the Chilliwack Batholith (formerly Perry Creek Quartz Diorite) was first mentioned by Misch (1966) and named for exposures near Perry Creek, Whatcom County, northern Washington. The type area of the unit is located near Silver Creek, approximately 3.2 km (2 mi) south of the Canadian border on the west side of Ross Lake in section 5, T. 40 N., R. 13 E., Whatcom County, Washington (Table 4; Figure 32; Grant 1969). The Perry Creek phase predominantly consists of hornblende–biotite tonalite and granodiorite that have been dated between 25–22 Ma (Tabor et al. 2003). In the type area on the east side of lower Perry Creek, the Perry Creek phase intrudes biotite granodiorite of Little Beaver Creek (Tabor et al. 2003).



## Olympic National Park (OLYM)

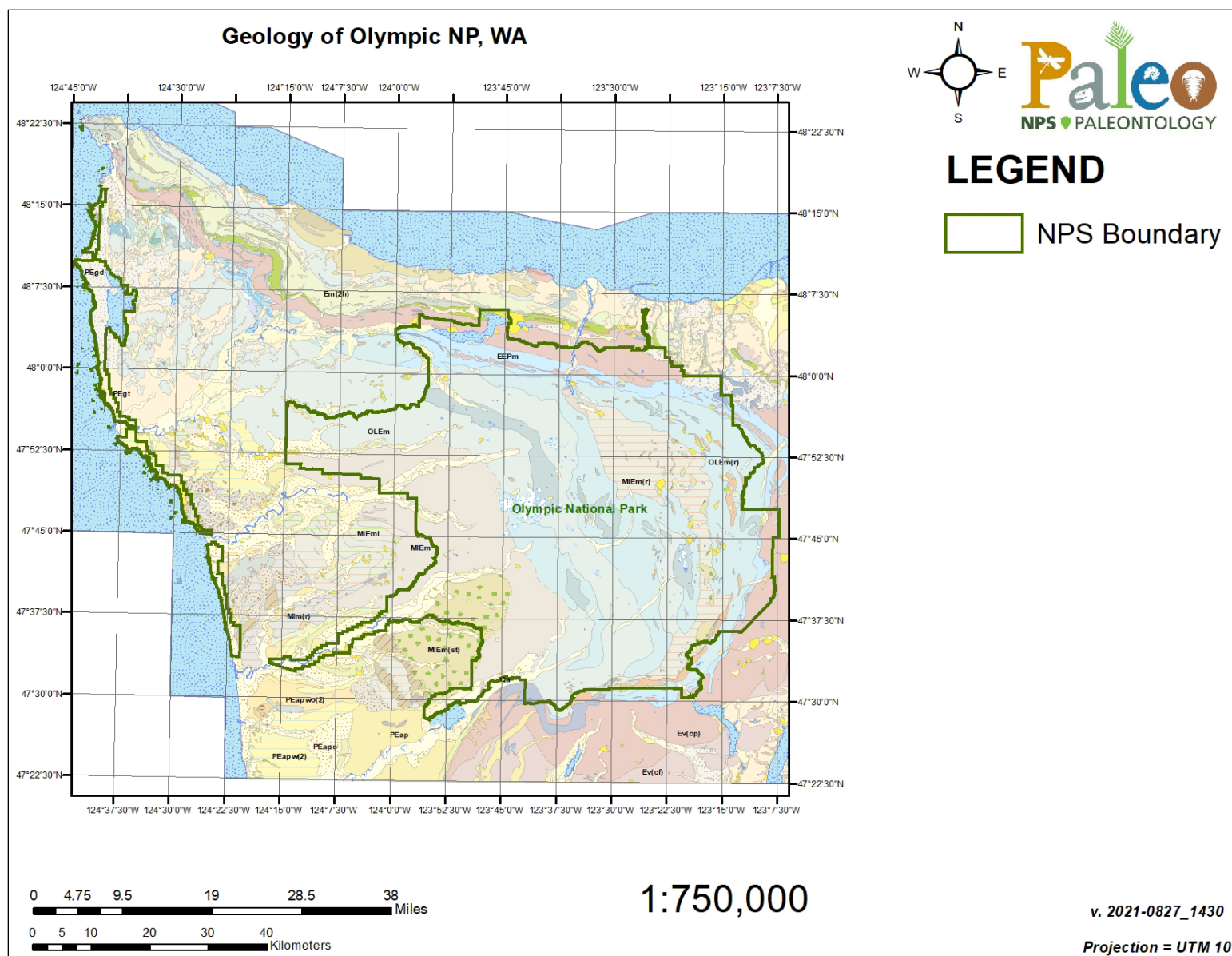
Olympic National Park (OLYM) is located along the Pacific coast approximately 72 km (45 mi) west of Seattle in Clallam, Grays Harbor, Jefferson, and Mason Counties, northwestern Washington (Figure 38). Originally authorized as Mount Olympus National Monument on March 2, 1909, the park unit was re-named and re-designated on June 29, 1938 (National Park Service 2016). The national park encompasses about 373,383 hectares (922,650 acres) containing glacier-capped mountains, deep valleys, meadows, lakes, old-growth forest, temperate rain forest, and more than 113 km (70 mi) of Pacific coastal beach (National Park Service 2017b). Olympic National Park hosts a rich biodiversity of more than 1,000 plant species, hundreds of bird species, and 70 species of mammals including the native Olympic marmot and herds of Roosevelt elk. Hundreds of archeological sites within OLYM record more than 12,000 years of human occupation, and historic sites reveal a 200-year history of exploration, homesteading, and community development in the Pacific Northwest (National Park Service 2017b). The significant natural resources of OLYM are internationally recognized, as the park was designated an International Biosphere Reserve in 1976 and World Heritage Site in 1981.

The geology of Olympic National Park predominantly consists of igneous and sedimentary rocks that were formed in the last 60 million years since the Paleocene (Figures 39 and 40). Many of the geologic formations within OLYM that form the prominent mountain peaks were originally deposited offshore as an accretionary prism and were then uplifted, folded, and eroded into the landscape seen today. Tectonic convergence between the Juan de Fuca and North American Plates during the Eocene (~34 Ma) has slowly accreted foreign masses of rock to the western coast of North America (Graham 2005, 2019b). As the denser Juan de Fuca Plate continues to subduct beneath the North American Plate, sedimentary packages on top of the Juan de Fuca Plate are scraped off and juxtaposed against the western margin of North America. Continuous subduction over millions of years have folded, thrust, and uplifted the rock assemblages into the mountain peaks of OLYM. Hurricane Ridge is a good example, consisting of ancient seafloor rocks that now stand approximately 1,830 m (6,000 ft) above sea level. Besides the continuously rising mountains, other notable geologic features in OLYM include the jagged sea stacks along the scenic coast (composed of the Hoh rock assemblage), coastal cliffs, glacially carved lakes such as Lake Crescent, and glacial features such as U-shaped valleys, erratics, and scree fields.

Olympic National Park contains one identified stratotype, for the Miocene Hoh Rock Assemblage (Table 5; Figure 41).







**Figure 39.** Geologic map of OLYM, Washington (see Figure 40 for legend).

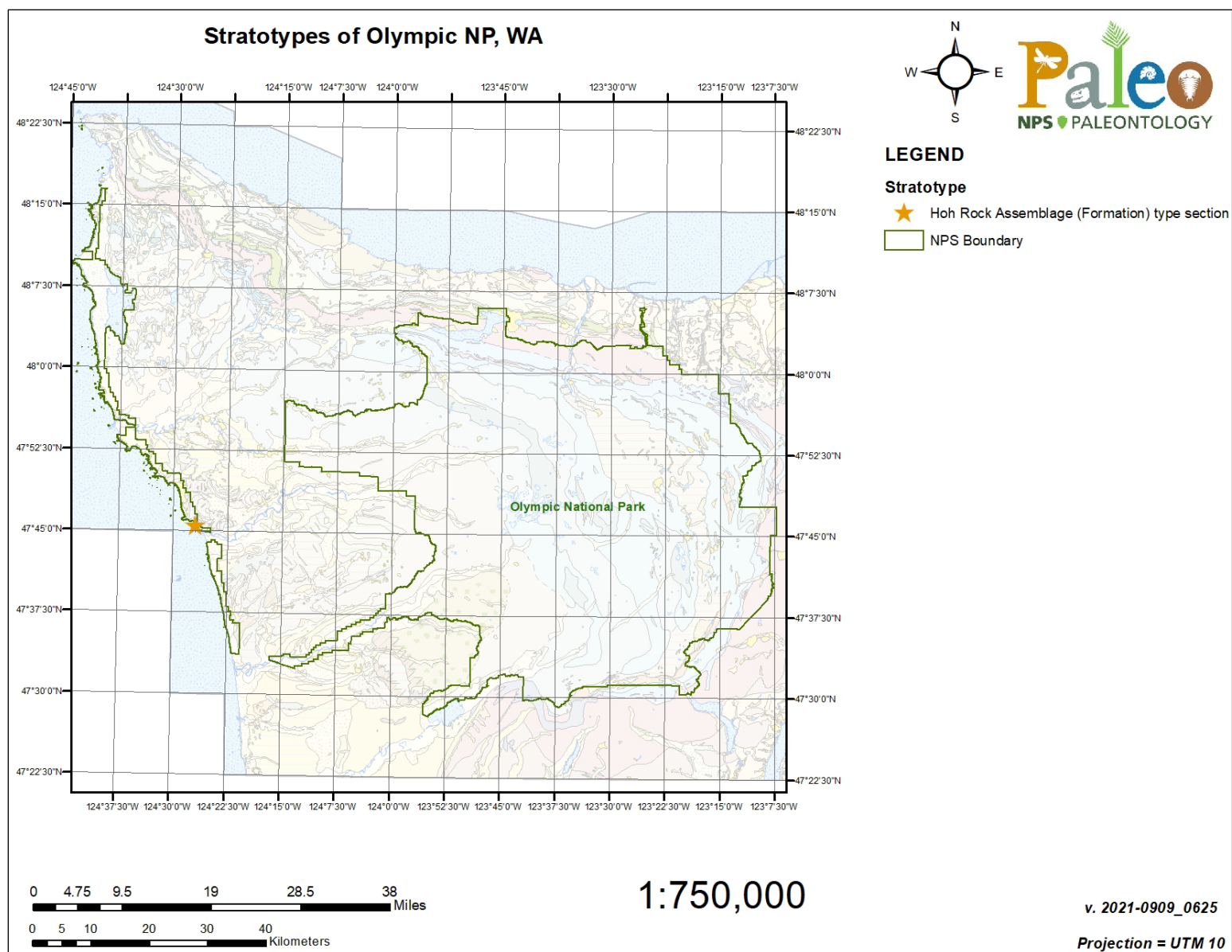




**Figure 40.** Geologic map legend of OLYM, Washington.

**Table 5.** List of OLYM stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Hoh Rock Assemblage (Mlm(st))	Weaver 1937	Type section: exposures occurring between the mouth of the Hoh River and the northern point of Hoh Head, Clallam County, WA	Miocene



**Figure 41.** Modified geologic map of OLYM showing stratotype locations. The transparency of the geologic units layer has been increased.



In addition to the designated stratotype located within OLYM, stratotypes located within 48 km (30 mi) of the park boundaries include: the Eocene–Miocene Twin River Group (type section); Eocene Hoko River Formation (type locality and two reference sections), Lyre Formation (type section and reference section), Crescent Formation (type locality), and Aldwell Formation (type section); Eocene–Oligocene Makah Formation (type section and two reference sections) and the type sections of the Baada Point, Carpenters Creek Tuff, Dtokoah Point, Jansen Creek, Klachopis Point, and Third Beach Members of the Makah Formation; Oligocene–Miocene Pysht Formation (type locality and reference section); Miocene Clallam Formation (type locality); and the Pleistocene Double Bluff Formation (type section and type locality) and Whidbey Formation (type section and type locality).

### **Hoh rock assemblage**

The Miocene Hoh rock assemblage was first described as the Hoh Formation by Weaver (1916; 1937) and named after its type section exposure occurring between the mouth of the Hoh River and the northern point of Hoh Head, Clallam County, Washington (Table 5; Figures 41–43). The type section consists of steeply tilted and overturned siltstones, sandstones, and conglomerates chaotically mixed with blocks of sandstone and pillow basalt in a claystone matrix (Rau 1980; Stewart and Brandon 2004). Many of the sandstone and siltstone strata within the Hoh rock assemblage represent turbidites, submarine gravity-driven sediment flows (Rau 1980; Stewart and Brandon 2004). In the type section area the Hoh rock assemblage underlies Pleistocene-age terrace gravels and sands, and the basal contact is not exposed (Weaver 1937).



**Figure 42.** Hoh Head, prominent headland along the Washington coast and type section location of the Hoh rock assemblage. Figure 31 from Rau (1980); image from the Washington Geological Survey (Washington Department of Natural Resources).



**Figure 43.** Exposures of the Hoh rock assemblage at Boulder Bay on the south side of Hoh Head. Figure 30 from Rau (1980); image from the Washington Geological Survey (Washington Department of Natural Resources).

## San Juan Island National Historical Park (SAJH)

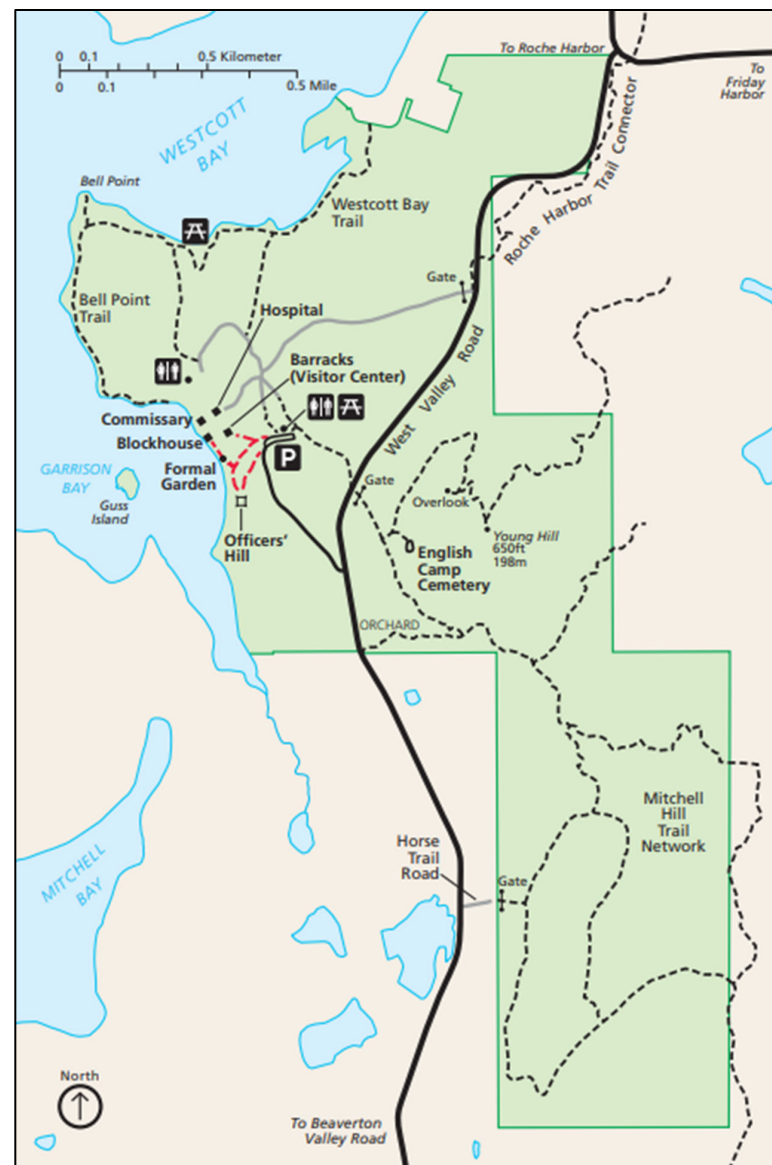
San Juan Island National Historical Park (SAJH) is located on San Juan Island, the second largest island in the San Juan Archipelago in San Juan County, Washington (Figure 44). Authorized as an NPS unit on September 9, 1966, SAJH preserves approximately 868 hectares (2,146 acres) that include more than 10 km (6 mi) of shoreline, trails, prairies, and military camps. It was established to protect and interpret the sites of the American and English Camps and to commemorate the peaceful settlement of the San Juan Boundary Dispute between Great Britain and the United States from 1853 to 1872, including the Pig War crisis of 1859 (National Park Service 2016; 2017c). The historical park is composed of two units, the American Camp (the larger of the two park units) located at the southern end of San Juan Island and the English Camp located at the northern end of the island. American Camp was the location of the U.S. Army camp during the 12-year joint occupation of the island, while English Camp was the location of a British Royal Marines camp. Both camps were established in 1859 in response to a border dispute triggered by the killing of a pig, an event that almost sparked a war between Britain and the United States (Neering 2011). In 1872, the boundary dispute was settled when Kaiser Wilhelm I of Germany awarded the San Juan Islands to the United States (Graham 2014). SAJH illustrates how war can be averted and peace maintained through positive action by individuals and governments.

The geology of SAJH has been dramatically influenced by dynamic earth processes that include plate tectonic collision, ice-age glaciation, and modern coastline processes. Within SAJH are Paleozoic and Mesozoic rock units (Garrison Schist, Decatur Terrane, and Deadman Bay Terrane) that record thrust faulting and metamorphism resulting from the tectonic collision between the North American and Farallon Plates during the Cretaceous approximately 84–100 Ma (Figures 45 and 46; Brandon et al. 1988). The convergence of these two plates deformed, juxtaposed, and transported masses of bedrock about 2,500 km (1,600 mi) north along the western coast of North America (Graham 2014). Pleistocene-age glaciers covered the landscape of San Juan Island approximately 17,000 years ago, carving and rounding the more resistant bedrock of the region. As the glaciers melted and receded, they left behind poorly-sorted, unconsolidated deposits of gravel, sand, and silt (Figures 45 and 46). With the tremendous weight of ice and snow removed, the landscape of SAJH began to slowly rise in a process known as isostasy, creating exceptionally well-developed terraces out of former beaches (Graham 2014). Since the end of the Pleistocene ice ages, coastal processes such as onshore winds, tides, rip currents, and longshore currents have continued to modify the shoreline of San Juan Island.

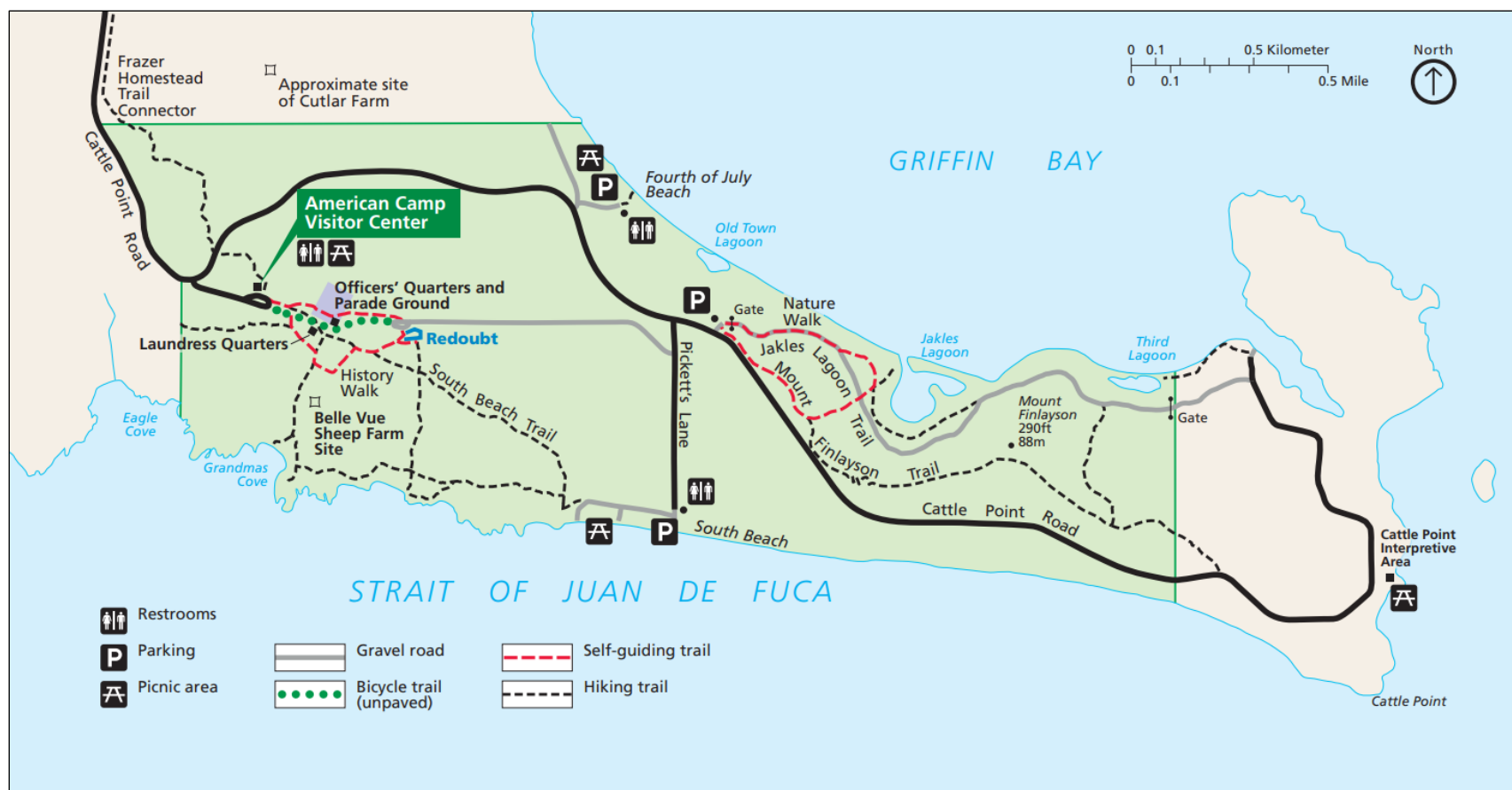
There are no designated stratotypes identified within the boundaries of SAJH. Although the Permian–Triassic Garrison Schist is named after exposures at Garrison Bay on northern San Juan Island, there is currently no formal stratotype designation (see “Recommendations”). There are 12 identified stratotypes located within 48 km (30 mi) of SAJH boundaries, for the Cambrian–Ordovician Turtleback Complex (type area); Devonian–Permian East Sound Group (type area); Permian–Triassic Deadman Bay Volcanics (type area); Jurassic–Cretaceous Constitution Formation (type area) and Lummi Formation (type area); Cretaceous James Island Formation (type area) and Obstruction Formation (type area); Eocene Chuckanut Formation (type section) and the type sections



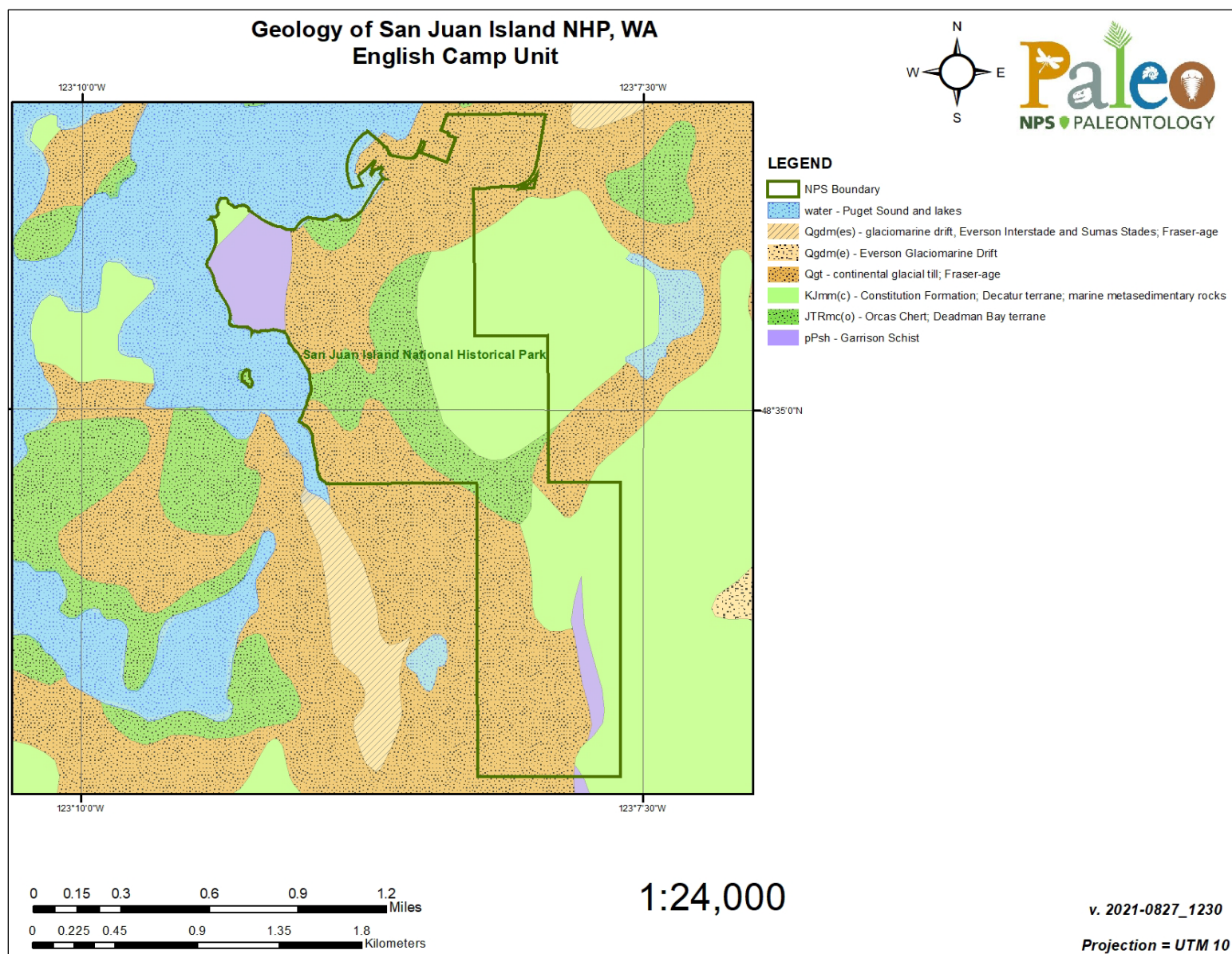
of the Bellingham Bay, Governors Point, and Padden Members of the Chuckanut Formation; and the Pleistocene Everson Glaciomarine Drift (type locality).



**Figure 44.** Park map of SAJH, Washington (NPS). Left: overview map of both the English Camp and American Camp units. Right: English Camp Unit.

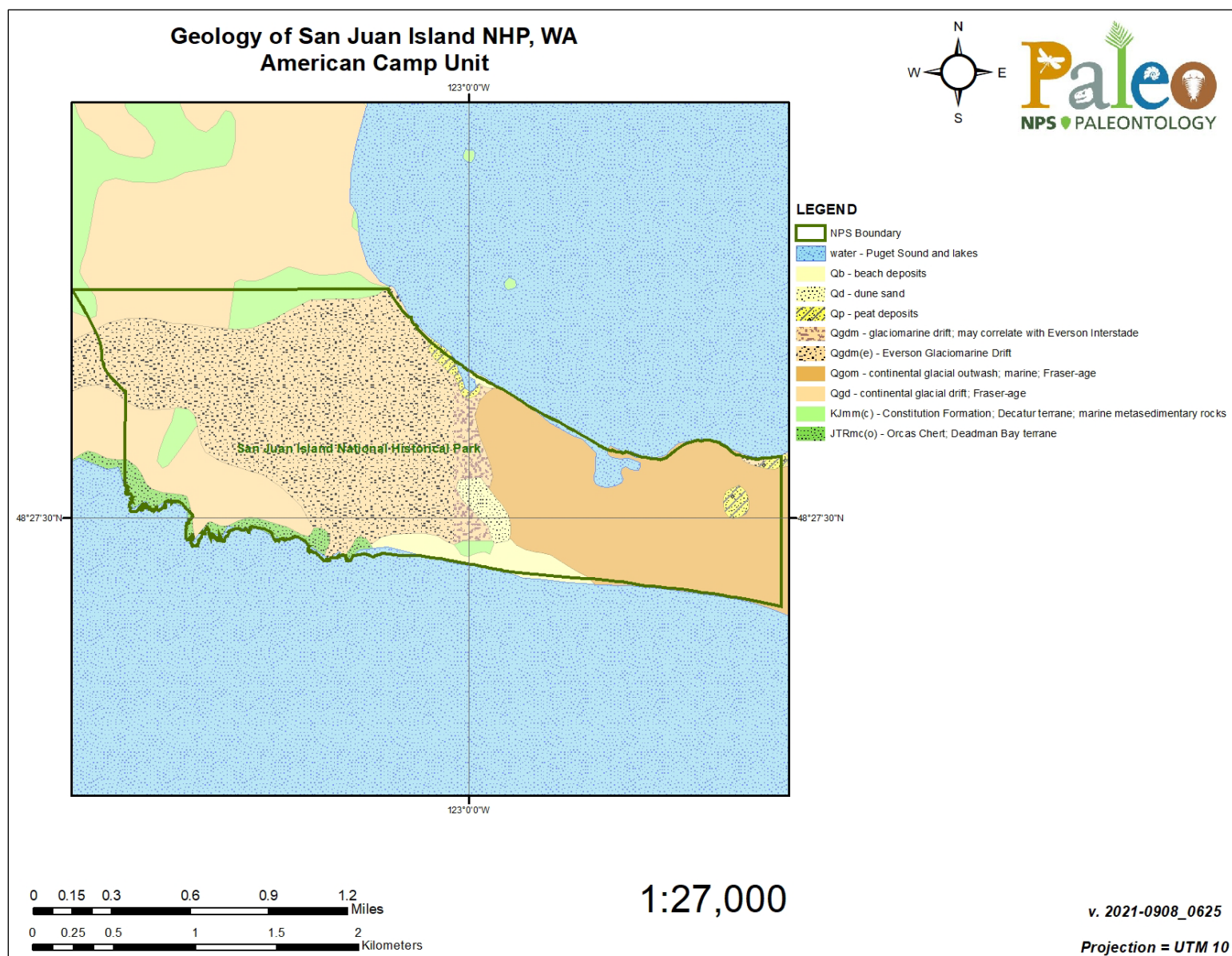


**Figure 44 (continued).** Park map of SAJH (American Camp Unit), Washington (NPS).



**Figure 45.** Geologic map of SAJH (English Camp Unit), Washington.





**Figure 46.** Geologic map of SAJH (American Camp Unit), Washington.



## Recommendations

- 1) The NPS Geologic Resources Division should work with park and network staff to increase their awareness and understanding about the scientific, historic and geologic heritage significance of geologic stratotypes (type sections/localities/areas, reference sections, lithodemes). *Stratotypes represent unique geologic exposures and should be considered extremely important to protect for the advancement of the scientific community for future generations.*
- 2) Once the NCCN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the NCCN and respective network parks.
- 3) The Eocene Ohanapecosh Formation is named from Ohanapecosh Hot Springs within the boundaries of MORA but currently lacks a formal stratotype designation (Fiske et al. 1963). Excellent exposures of the formation “...can best be illustrated by briefly describing a section that was measured in road cuts along the highway from Stevens Canyon to the Ohanapecosh River and then continued to the east along the White Pass highway [Washington State Highway 5] 6.4 km (4 mi) southeast of Ohanapecosh Hot Springs. More than 1,829 m (6,000 ft) of volcanic clastic rocks are exposed in this composite section” (Fiske et al. 1963). It is recommended that a stratotype designation of the unit be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of this unit; and C) help safeguard these exposures.
- 4) The Permian–Triassic Garrison Schist is named after exposures at Garrison Bay near Bell Point in SAJH but currently lacks a formal stratotype designation (Danner 1966). It is recommended that a stratotype designation of the unit be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of this unit; and C) help safeguard these exposures.
- 5) The NPS Geologic Resources Division should work with park and network staff to ensure they are aware of the location of stratotypes in park areas. This information would be important to ensure that proposed park activities or development would not adversely impact the stability and condition of these geologic exposures. Preservation of stratotypes should not limit availability for future scientific research but help safeguard these exposures from infrastructure development.
- 6) The NPS Geologic Resources Division should work with park and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or statewide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature.
- 7) From the assessment in (6), NPS staff should focus on registering new stratotypes at state and local government levels where current legislation allows, followed by a focus on registering at federal and state levels where current legislation allows.

- 8) The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations.
- 9) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.
- 10) The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.
- 11) The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of photogrammetry may be considered for monitoring of geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.
- 12) The NPS Geologic Resources Division should work with park and network staff to consider the collection and curation of geologic samples from type sections within respective NPS areas. Samples collected from type section exposures can be useful as reference specimens to support future studies, especially where stratotypes may be lost through natural processes or human activities.
- 13) The NPS Geologic Resources Division should work with park and network staff to utilize selected robust internationally and nationally significant type sections as formal teaching/education sites and for geotourism so that the importance of the national- and international-level assets are more widely (and publicly) known, using information boards and walkways.
- 14) The NPS Geologic Resources Division should work with park and network staff in developing conservation protocols of significant type sections, either by appropriate fencing, walkways, and information boards or other means (e.g., phone apps).

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## Appendix A: Source Information for GRI Maps of NCCN Parks

### EBLA

- GMAP 7061: Polenz, M., S. L. Slaughter, J. D. Dragovich, and G. W. Thorsen. 2005. Geologic map of the Ebey's Landing National Historical Reserve, Island County, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2005-2. Scale 1:24,000.

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### LEWI

- GMAP 15326: Wells, R. E. 1989. Geologic map of the Cape Disappointment-Naselle River area, Pacific and Wahkiakum Counties, Washington, U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series 1832. Scale 1:62,500. Available at: <https://pubs.er.usgs.gov/publication/i1832> (accessed December 28, 2021).
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- GMAP 75206: Ma, L., L. P. Madin, K. V. Olson, R. J. Watzig, R. E. Wells, A. R. Niem, and G. R. Priest. 2009. Oregon Geologic Data Compilation [OGDC], Release 5 (statewide), Oregon Department of Geology and Mineral Industries, Portland, Oregon. Scale 1:100,000.
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### MORA

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## NOCA

- GMAP 3118: Stoffel, K. L., and M. F. McGroder. 1990. Geologic map of the Robinson Mountain 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 90-5. Scale 1:100,000.
- GMAP 3205: Bunning, B. B. 1992. Geologic map of the east half of the Twisp 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 90-9. Scale 1:100,000.
- GMAP 3207: Dragovich, J. D., and D. K. Norman. 1995. Geologic map of the west half of the Twisp 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 95-3. Scale 1:100,000.
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- GMAP 74830: Tabor, R. W., R. A. Haugerud, W. Hildreth, and W. H. Brown. 2006. Database for the geologic map of the Mount Baker 30-minute by 60-minute Quadrangle, Washington (I-2660). U.S. Geological Survey, Reston, Virginia. Data Series 205. Scale 1:100,000. Available at: <https://pubs.usgs.gov/ds/2006/205/> (accessed December 28, 2021).
- GMAP 74832: Washington Division of Geology and Earth Resources staff. 2008. Digital geology of Washington State at 1:100,000 Scale; On-line GIS data, version 2.0. Washington Department of Natural Resources, Olympia, Washington.

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- GMAP 1525: Gerstel, W. J., and W. S. Lingley, Jr. 2000. Geologic map of The Forks 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2000-4. Scale 1:100,000.
- GMAP 7433: Schasse, H. W. 2003. Geologic map of the Washington Portion of the Port Angeles 1:100,000 Quadrangle. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-6. Scale 1:100,000.
- GMAP 7434: Schasse, H. W. 2003. Geologic map of the Washington portion of the Cape Flattery 1:100,000 Quadrangle. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-5. Scale 1:100,000.
- GMAP 7435: Gerstel, W. J., and W. S. Lingley, Jr. 2003. Geologic map of the Mount Olympus 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-4. Scale 1:100,000.
- GMAP 7436: Logan, R. L. 2003. Geologic map of the Shelton 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-15. Scale 1:100,000.

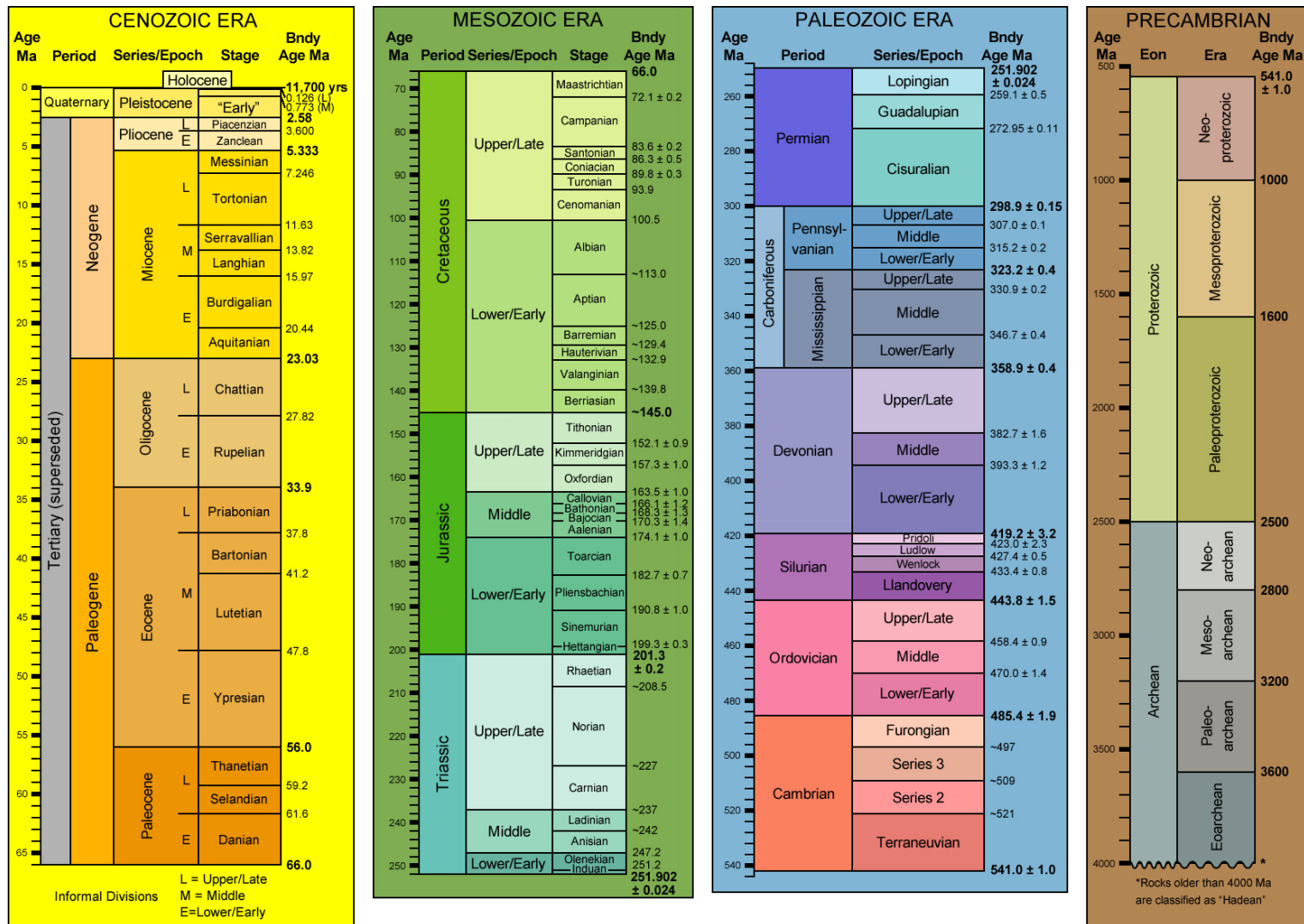
- GMAP 7437: Logan, R. L. 2003. Geologic map of the Copalis Beach 1:100,000 Quadrangle, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-16. Scale 1:100,000.
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- GMAP 3068: Whetten, J. T., P. I. Carroll, H. D. Gower, E. H. Brown, and F. Pessl. 1988. Bedrock geologic map of the Port Townsend 30- by 60-minute Quadrangle, Puget Sound region, Washington, U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series Map I-1198-G. Scale 1:100,000. Available at: [https://ngmdb.usgs.gov/Prodesc/proddesc\\_9030.htm](https://ngmdb.usgs.gov/Prodesc/proddesc_9030.htm) (accessed December 28, 2021).
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- GMAP 7432: Logan, R. L. 2003. Geologic map of the Washington portion of the Roche Harbor 1:100,000 Quadrangle. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 2003-17. Scale 1:100,000.
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- GMAP 74870: Dethier, D. P., D. P. White, and C. M. Brookfield. 1996. Plate 2, Maps of surficial geology and depth to bedrock of the False Bay, Friday Harbor, Richardson, and Shaw Island 7.5-minute Quadrangles, San Juan County, Washington. Washington Division of Geology and Earth Resources, Olympia, Washington. Open File Report 96-7. Scale 1:24,000.



## Appendix B: Geologic Time Scale



**Figure B1.** Geologic Time Scale. **Ma**=Millions of years old. **Bndy Age**=Boundary Age. Layout after 1999 Geological Society of America Time Scale (<https://www.geosociety.org/documents/gsa/timescale/timescl-1999.pdf>). Dates after Gradstein et al. (2020).



The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 963/179723, March 2022

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