



North Cascades National Park Service Complex

Geologic and Soil Resources Inventory Summary



On this page: Historic 1963 photograph of Ross Lake facing north towards Tenmile Island (foreground), Desolation Peak (right), and Hozomeen Mountain (right background) in Ross Lake National Recreation Area. NPS photograph.

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Abstract

This document summarizes the status of National Park Service (NPS) Geologic Resources Inventory (GRI) and Soil Resources Inventory (SRI) deliverables for North Cascades National Park Service Complex. It also provides information on current geology and soil resources management concerns, with a focus on identified inventory needs related to geologic heritage, geohazards, and related soil features and processes. This document is intended to assist park staff with prioritizing technical assistance or new inventory and assessment funding requests in the near term (roughly 1–5 years).

The GRI hosted a baseline scoping meeting for North Cascades National Park Service Complex in 2002. Baseline bedrock and surficial geologic maps were delivered to the parks in 2010 and updated in 2023. SRI delivered a legacy soil database and map to the park in 2008 (updated in 2013) and published an “enhanced report” in 2012. The most up-to-date soil data for the park is available through [Web Soil Survey](#).

North Cascade National Park Service Complex’s geologic heritage is engrained in its diverse stratigraphic, tectonic, and paleontological records; stratotypes; Indigenous connections; geologic exploration and mining history; and its intimate connections to hydroelectric power. The geologic and soil resources inventory needs for the park include various data and/or GIS information related to the inventory and monitoring of abandoned mineral lands, geohazards, geoscience research, glaciers, fossils, and mapping.

Geologic hazards identified in the park include climate change, disturbed lands (e.g., abandoned mineral lands), dust storms, flooding, mass wasting (e.g., rockfalls, debris or ice avalanches, slumping or creep), permafrost, radon, swelling clays, seismicity, toxicological soils, and volcanic activity. Inventory needs related to geohazards address monitoring strategies to help quantify and mitigate the damage these processes pose to the park’s geologic and soil resources.

Additional guidance for park staff regarding proposal processes and timeframes for the new Inventories and Assessment (I&A) program is available on the [GSRI](#) and [I&A](#) SharePoint sites.

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Background of the GSRI

The Geologic and Soil Resources Inventory (GSRI) facilitates the collection of new data, or derives new information from existing data, regarding the presence, absence, abundance, distribution, and significance of geologic or soil features or processes to inform park management decisions and planning.

In the 1990s, the NPS Geologic Resources Inventory (GRI) and Soil Resource Inventory (SRI) programs were established as two of the original 12 baseline inventories in the Inventory and Monitoring (I&M) program. These baseline inventories compiled existing information, acquired new information, and helped establish a minimum level of data across more than 270 parks, which served as a common starting point for natural resource monitoring. For both the GRI and SRI, the primary deliverable was a digital (GIS) map. Between the 1990s and early 2020s, GRI scoping summaries, geologic map posters, and GRI reports were also produced for most of the 270 parks. As of 2024, the I&M program is transitioning from a baseline inventory strategy to a park-proposed inventory strategy.

The GRI and SRI are now unified as one inventory program, the Geologic and Soil Resources Inventory (GSRI), and will be integrated into the new Inventories & Assessment (I&A) Program, in which parks will submit geology- and soil-related project requests in PMIS during the Servicewide Comprehensive Call (SCC). This transition will begin in FY25, with new guidance enacted for GSRI. During this transition period, 13 “priority” parks, including North Cascades National Park Service Complex (“NCCO,” also referred to as the “park complex” herein), were identified as missing a baseline GRI report.

This GSRI summary serves as a substitute for a baseline GRI report and is intended to support the park complex’s participation in the new inventories program. As such, it summarizes the status of GRI and SRI deliverables for NCCO and provides information on current geology and soil resources management concerns with a focus on identified inventory needs. Information in this summary was compiled from existing reports, meetings with park staff, and the best professional judgment from GRI and WASO Geologic Resources Division (GRD) geoscientists.

Baseline GSRI Products

Geology

The digital geologic map for NCCO is available on the NPS DataStore accessed through the Integrated Resource Management Applications (IRMA) portal (see <https://irma.nps.gov/DataStore/Reference/Profile/2297144>) and is adapted from multiple source maps created by the USGS and the Washington Division of Geology and Earth Resources. Additional GSRI documents include the NPS Scoping Report (Graham 2002).

GSRI source maps:

- 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, Open-File Report 90-9, scale 1:100,000. http://www.dnr.wa.gov/Publications/ger_ofr90-9_geol_map_twisp_e_100k.zip (accessed November 2024)

- 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, Open-File Report 95-3, scale 1:100,000. http://www.dnr.wa.gov/Publications/ger_ofr95-3_geol_map_twisp_w_100k.zip (accessed November 2024)
- Stoffel, K. L., and M. F. McGroder. 1990. Geologic map of the Robinson Mtn. 1:100,000 Quadrangle, Washington: Washington Division of Geology and Earth Resources, Open-File Report 90-5, scale 1:100,000. http://www.dnr.wa.gov/Publications/ger_ofr90-5_geol_map_robinsonmtn_100k.zip (accessed November 2024)
- Tabor, R. W., D. B. Booth, J. A. Vance, and A. B. Ford. 2006. Database for the geologic map of the Sauk River 30-minute by 60-minute Quadrangle, Washington (I-2592). US Geological Survey Data Series 188, scale 1:100,000. <https://pubs.usgs.gov/ds/2006/188/> (accessed November 2024)
- Tabor, R. W., R. A. Haugerud, W. Hildreth, and E. H. Brown. 2006. Database for the geologic map of the Mount Baker 30-minute by 60-minute Quadrangle, Washington (I-2660). US Geological Survey Data Series 205, scale 1:100,000. <https://pubs.usgs.gov/ds/2006/205/> (accessed November 2024)
- Washington Division of Geology and Earth Resources. 2008. Digital geology of Washington State At 1:100,000 Scale: Washington Division of Geology and Earth Resources, Online GIS data, version 2.0 [updated 2010; cited 28 September 2010]. <https://www.dnr.wa.gov/programs-and-services/geology/publications-and-data/gis-data-and-databases> (accessed November 2024)

GSRI scoping report:

- Graham, J. 2002 [updated 2006]. Geologic resource evaluation scoping summary: North Cascades National Park, Ross Lake National Recreation Area, and Lake Chelan National Recreation Area. <https://irma.nps.gov/DataStore/Reference/Profile/2250387>

Soils

Soil maps provide information on soil types, including scores of different characteristics and management considerations including linear extensibility (“shrink-swell”) potential, erosion potential, soil stability, suitability for site development, suitability for recreation development (e.g., trails), and many other topics. [Perrone \(2023\)](#) provides an overview of the use of soil data at the NPS WASO level and lists soil data currently available in the Natural Resources Conservation Service (NRCS) [Web Soil Survey website](#) along with NPS-specific uses for the data. The NRCS plans to complete all soil survey areas in the US by 2026 (Thompson et al. 2020).

Soil mapping by the NPS Soil Resources Inventory (SRI) was updated for NCCO in 2013 and is available on IRMA (<https://irma.nps.gov/DataStore/Reference/Profile/2170715>; accessed November 2024). Additionally, in 2012 the SRI published a detailed soil survey report in cooperation with the NRCS (United States Department of Agriculture, Natural Resources Conservation Service and United States Department of Interior, National Park Service 2012). Additional soil data and maps for Chelan, Skagit, and Whatcom counties, Washington, are provided by the National Cooperative Soil Survey Geographic Database (SSURGO; <https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx>; accessed November 2024). Currently, small areas of the park complex on the western side adjacent to Mount Baker-Snoqualmie National Forest do not yet have soil data but are anticipated to have some coverage by 2026.

The most up-to-date soils data for NCCO is available via Web Soil Survey, which is updated and maintained regularly. Management-focused maps for the park or potential project areas can be developed on-demand on the website. The Web Soil Survey homepage gives instructions for how to view and download soil data. The Web Soil Survey data are broken down into county-level soil survey areas. Each soil survey area is assigned a code and a name. The park complex boundary currently extends across five soil survey areas, four of which have been completed and posted to Web Soil Survey:

- WA774 North Cascades National Park Complex, Washington (complete)
- WA608 Cashmere Mountain Area, Washington, Parts of Chelan and Okanogan Counties (complete)
- WA657 Skagit County Area, Washington (complete)
- WA749 Okanogan National Forest Area, Washington (complete)
- WA762 Mount Baker-Snoqualmie National Forest, Washington (not yet complete)

To view the soil data for NCCO on the [Web Soil Survey website](#), use the navigation pane on the left side of the main webpage to select the soil survey area and set it as the “area of interest” using the “AOI” icon along the top of the map. Use the “Soil Map” tab at the top to view the soil map and the “Soil Data Explorer” tab to view additional soil data including linear extensibility and suitability for development. See additional Web Soil Survey [guidance](#) and [FAQs](#) or contact the [NRCS state soil scientist](#) for technical assistance.

Possible Future GSRI Products

As the GSRI becomes integrated into the I&A, future GSRI products will be determined by the project proposals submitted by the parks. Moving forward, the GSRI program will fund inventory projects that include the following:

- Collect new data or derive new information from existing data regarding the presence, absence, abundance, distribution, and significance of geologic heritage, soil features or processes, or geohazards.
- Include features or processes on an individual feature- or landscape-scale.
- Include groups of features or maps of multiple features in a defined area of management needs.
- Are a snapshot in time and may set a baseline for monitoring or assessment.
- Typically include a geospatial (GIS) component.

GSRI project examples:

- Features and processes eligible for funding through the GSRI program include cave/karst, geothermal, paleontological (fossils), landslides and rockfall, other geohazards (e.g., avalanche, permafrost, volcanoes, earthquakes, tsunamis, sinkholes), eolian, erosion, soil suitability and limitations for use, soil properties and qualities, ecological site descriptions, and other geologic or soil features or processes of management interest.
- Features and processes covered by other sources of funding and *not* eligible for GSRI funding are abandoned mineral lands (AML), orphaned oil and gas wells, coastal processes, coastal storm

response, sea-level change projections or mitigation, coastal engineering structures, or shoreline sediment movement.

The GSRI will accept proposals for new baseline map products, such as funding a traditional geologic (bedrock or surficial) or soil mapping effort, especially at new or expanded parks outside the original 270 I&M parks. Parks requesting these products will need to indicate a management need the baseline data will support.

Geologic Setting and History

Park Establishment and Setting

North Cascades National Park Service Complex (“NCCO”) is located along the US–Canada border, approximately 160 km (100 mi) northeast of Seattle, in portions of Whatcom, Skagit, and Chelan counties, Washington. Established in 1968, the park complex is comprised of North Cascades National Park (“NOCA”), Ross Lake National Recreation Area (“ROLA”), and Lake Chelan National Recreation Area (“LACH”), a complementary suite of protected lands encompassing nearly 275,655 ha (681,158 ac). Together, NCCO preserves the core of the greater North Cascades, a vast alpine landscape featuring rugged mountain peaks, more than 300 glaciers, deep canyons, myriad creeks and river systems, and vast expanses of wilderness (National Park Service 2012). In fact, about 93% of the park complex is part of the legislatively designated Stephen Mather Wilderness, named after the first director of the National Park Service, Stephen T. Mather. Beginning in the 1920s, the Skagit and Stehekin Rivers were dammed to create four large reservoirs (Ross Lake, Diablo Lake, Gorge Lake, and Lake Chelan) responsible for generating hydroelectricity—today the Seattle City Light project at ROLA forms the hydroelectric centerpiece of the park complex (see “Hydroelectric Power”). Prior to NCCO’s establishment, the North Cascades region was inhabited by Indigenous cultures dating back roughly 10,000 years; cultural resources and sites found throughout NCCO include stone tools, pictographs, quarries, and rock shelters (see “Indigenous Connections”; Mierendorf and Reid 1986; Mierendorf 1998, 2004; Mierendorf and Baldwin 2015). During the 19th and 20th centuries, prospectors and miners scoured the Skagit River Valley for placer gold before venturing into the remote mountains to mine other metals such as silver, lead, and galena (see “Mining”; Luxenberg 1986).

Geologic History

The geology of the North Cascades is perhaps the most complex and least understood in North America, as the region has undergone multiple tectonic collisions that sutured new territory to the state of Washington and the greater Pacific Northwest. The rocks underlying NCCO record at least 400 million years of geologic history and represent a jumbled collection of volcanic island arcs, deep marine sediments, basaltic ocean floor, fragments of ancient continents, submarine fans, and mantle-derived rocks (Tabor and Haugerud 1999; Haugerud and Tabor 2009). Additionally, the alpine landscape of the park complex is a premier laboratory for glacial studies, as the last Ice Age sculpted vast areas, including its valuable watersheds. The diverse suite of rocks, landforms, faults, and folds is a testament to these collisional and erosional events—many of which continue to shape the park complex today.

According to Haugerud and Tabor (2009), the major geologic events recorded in the North Cascades include the following (from oldest to youngest): (1) pre-mid-Cretaceous assembly of Mesozoic and Paleozoic terranes (large, exotic landmasses or bodies of rock that are bounded by faults) of different origin, lithology (rock types), and structural or metamorphic history; (2) middle to Late Cretaceous crustal thickening by thrusting and plutonism (the process of magma intrusion and crystallization) accompanied by regional metamorphism; (3) Eocene strike-slip faulting, extensional faulting, rapid exhumation (erosion and uplift) of deeply buried metamorphic rocks, basin development, and local metamorphism and plutonism; (4) growth of the Cascade Magmatic Arc from the Oligocene to the Holocene; and (5) Quaternary glacial erosion, drainage development, and deposition of glacial sediments. These five events are broken down by geologic era and discussed in more detail below.

Mesozoic Era (251.9 million to 66.0 million years ago): Chaos in the Cordillera

The bedrock underlying NCCO is a series of accreted terranes that originated thousands of miles away and were added to ancestral North America throughout the Jurassic–Cretaceous Periods, approximately 200 million to 90 million years ago (Haugerud and Tabor 2009; Riedel et al. 2012a, b, c, d, e). During the Cretaceous–Eocene (approximately 66.0 million to 33.9 million years ago), the Pacific Northwest was a convergent margin (a boundary between colliding plates) defined by the Coast Mountains Magmatic Arc, a large volcanic system fueled by the subduction of dense oceanic crust (Farallon and Juan de Fuca Plates) below the more buoyant continental crust of the North American Plate (Miller et al. 2023). As oceanic crust subducted below western North America, the accompanying terranes merged with the margin of the continent to produce thrust faults, folds, and mountains that predate the modern Cascade Range. The combination of subduction-driven magmatism and tectonic deformation thickened, metamorphosed, and uplifted the continental crust underlying the park complex (Haugerud and Tabor 2009).

Several lines of evidence, including lithology, paleontology, radiometric dating, and paleomagnetism, indicate the North Cascades consist of at least 10 distinct Paleozoic–Mesozoic terranes. Aptly referred to as a “mountain mosaic” by Haugerud and Tabor (1999), these unique terranes are juxtaposed against each other along a regional network of faults. Terranes that comprise the mosaic have been grouped together into three separate domains, or regions that have similar geologic histories (Figures 1–2). In the westernmost portion of the park complex, metamorphosed oceanic rocks of the Bell Pass Mélange and Easton terrane underlie NOCA and form the Western Domain. Rocks of the Western Domain comprise a regional, thrust-faulted stack of terranes—the Northwest Cascade System—that are separated from higher-grade metamorphic rocks along the Straight Creek Fault. A significant portion of NCCO is underlain by crystalline metamorphic and plutonic rocks of the Nason, Swakane, Chelan Mountains, and Little Jack terranes; together, these form the Metamorphic Core Domain. East of the Metamorphic Core Domain, the high-grade metamorphic core of the North Cascades is separated from unmetamorphosed oceanic rocks along the Ross Lake Fault Zone. In the easternmost portions of NOCA and ROLA, these oceanic rocks form the Hozomeen and Methow terranes that comprise the Methow Domain.

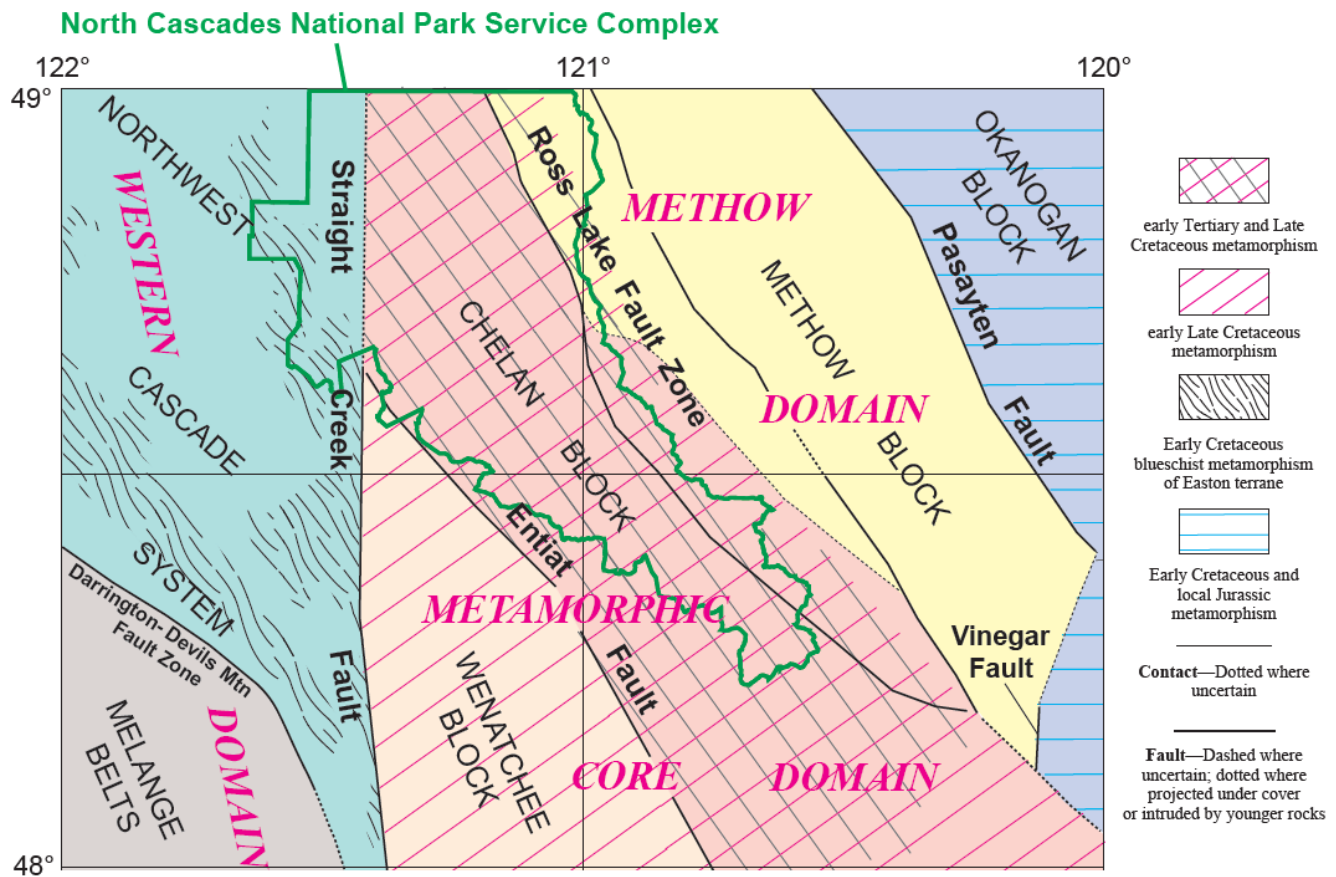


Figure 1. Map showing major geologic structures, domains, and metamorphic episodes of the North Cascades. The bedrock underlying the park complex is a mosaic of different crustal blocks chaotically juxtaposed along regional strike-slip faults. Figure 4 from Haugerud and Tabor (2009), modified by Timothy C. Henderson (Colorado State University).

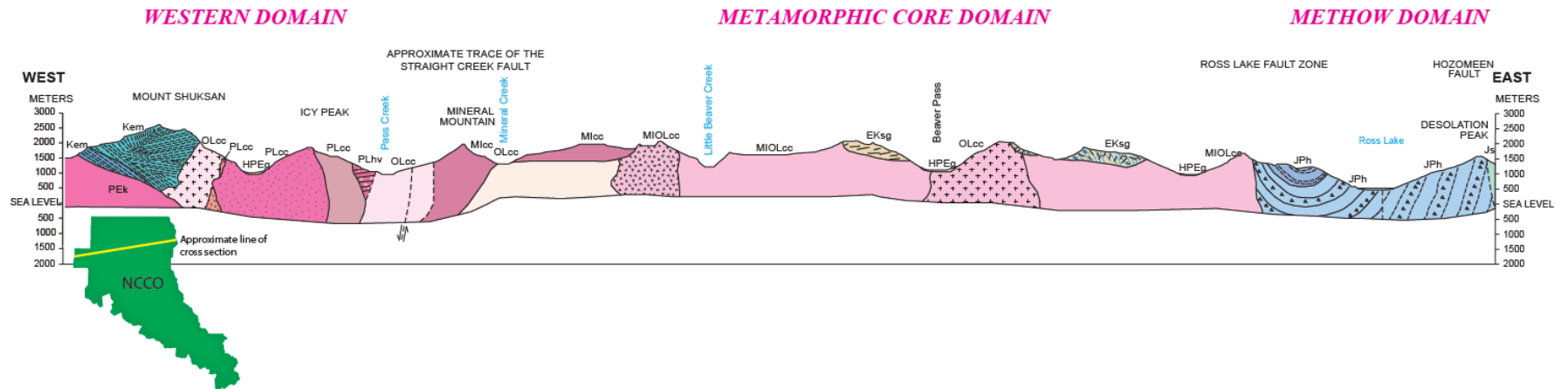


Figure 2. Geologic cross section across northern NOCA and ROLA. The bedrock underlying the park complex can be subdivided into three distinct domains that are separated by the Straight Creek Fault and the Ross Lake Fault Zone. Inset map of NCCO shows the approximate line of cross section. Cross section B-B' of Haugerud and Tabor (2009) modified by Timothy C. Henderson (Colorado State University).

Cenozoic Era (66.0 million years ago to present): A Land of Fire and Ice

One of the final major landmass additions to what is now Washington state was the Siletzia terrane, a large crustal block approximately 645 km (400 mi) long that merged with North America during the Eocene Epoch, about 50 million years ago (Miller et al. 2023). The arrival of Siletzia generated several large strike-slip faults—notably the Straight Creek Fault, Entiat Fault, and the Ross Lake Fault Zone—that transported rocks significant distances along the Pacific Northwest coast. These large fault offsets accounted for nearly 325 km (200 mi) of displacement, effectively jumbling or rearranging the geology of the North Cascades (Miller et al. 2023). Additionally, these faults fractured, weakened, and extended the crust to produce numerous plutons that intruded and metamorphosed rocks of the Metamorphic Core Domain.

Following terrane assembly about 50 million to 40 million years ago, the North American Plate boundary shifted west of Siletzia, resulting in the establishment of a new subduction zone (the modern Cascadia subduction zone) off the coast of Washington. The development of the Cascadia subduction zone marked the final stages of the Coast Mountains Magmatic Arc and heralded the initial stages of a new arc system—the Cascade Magmatic Arc (Haugerud and Tabor 2009; Miller et al. 2023). Several magmatic flare-ups within and surrounding the park complex record the final stages of the Coast Mountains Magmatic Arc, including the following (from oldest to youngest): the Lost Peak stock (a small igneous intrusion; 49.6 million years ago), Cooper Mountain batholith (a large igneous intrusion; 49.3 million to 47.9 million years ago), Golden Horn batholith (48.5 million to 47.7 million years ago), Duncan Hill pluton (46.5 million years ago), and Railroad Creek pluton (45.5 million years ago; Miller et al. 2023). Arc magmatism is responsible for intruding but also metamorphosing the Metamorphic Core Domain, especially the Skagit Gneiss Complex, before ceasing around 45 million years ago (Miller et al. 2023). The initiation of the Cascade Magmatic Arc uplifted the modern North Cascades and exhumed the ancient crystalline core of the pre-North Cascades mountain range, which predominantly consists of the Chelan Mountains terrane (e.g., Napeequa Schist, Cascade River Schist, metaplutonic rocks of the Marblemount-Dumbell belt) and Skagit Gneiss Complex (Tabor et al. 2003; Riedel et al. 2012a, b, c, d, e). Plutonic rocks associated with the Cascade Magmatic Arc are subdivided into three age groups or families: (1) the Index family (35 million to 29 million years ago); (2) the Snoqualmie family (28 million to 22 million years ago); and (3) the Cascade Pass family (younger than 20 million years ago; Haugerud et al. 2009). Today, the magmatic arc continues to influence the Pacific Northwest and is responsible for ongoing volcanic and seismic activity (see “Geologic Hazards”).

The last major geologic events to impact the park complex were several continental and alpine glacial pulses that scoured the landscape and altered the fluvial morphology of the North Cascades. Many glacial features found throughout NCCO include U-shaped valleys, hanging valleys, cirques (semicircular basins or valleys), horns (sharp, pyramid-shaped peaks), eskers (long ridges of stratified sand and gravel), and moraines (thick, unconsolidated deposits of till; Riedel et al. 2012a, b, c, d, e). During the Quaternary Period (2.58 million to 11,700 years ago), the North Cascades were repeatedly inundated by a thick sheet of ice referred to as the Cordilleran Ice Sheet. Although evidence of previous glacial events is commonly obscured or destroyed by subsequent advances, the surficial geology of the park complex records at least three major phases (“stades”) of the Pleistocene Fraser Glaciation (from oldest to youngest): (1) Evans Creek Stade, approximately 30,000 years ago; (2) Vashon Stade, about 17,000 years ago; and (3) Sumas Stade, roughly 14,000 to 11,000 years ago (Tabor et al. 2002, 2003; Haugerud et al. 2009; Riedel et al. 2012a, b, e). Following the Ice Age, small alpine glaciers continued to advance and retreat multiple times during the Holocene Epoch; the most extensive of these is the “Little Ice Age” that took place circa 1350–1900 A.D. (Riedel et al. 2012a, b, c, d,

e). Alpine glaciers are still present today but are rapidly shrinking (see “Geologic Resource Protection”). These critical resources continue to modify the physical expression of the park complex but also provide valuable drinking water, sustain ecosystems, and generate hydroelectric power.

Geologic Heritage

Geologic heritage (also called “geoheritage”) evokes the idea that the geology of a place is an integral part of its history and cultural identity. In 2015, the NPS GRD, in cooperation with the American Geosciences Institute, published a booklet introducing the American experience of geoheritage, geodiversity, and geoconservation: *America's Geologic Heritage: An Invitation to Leadership*. This publication introduces key principles and concepts of America's geoheritage, which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States. That booklet introduced the American experience of geologic heritage and outlined key principles and concepts, including the following five big ideas:

- America’s geologic landscape is an integral part of its history and cultural identity, and Americans have a proud tradition of exploring and preserving geologic heritage.
- America’s geologic heritage, as shaped by geologic processes over billions of years, is diverse and extensive.
- America’s geologic heritage holds abundant values—aesthetic, artistic, cultural, ecological, economic, educational, recreational, and scientific—for all Americans.
- America’s geologic heritage benefits from established conservation methods developed around the world and within the United States.
- America’s geologic heritage engages many communities, and involvement by individuals will ensure its conservation for future generations.

Additional information about the geology of Washington state, including its geoheritage connections, can be found at the Washington State Department of Natural Resources “Washington 100” website:

<https://wa100.dnr.wa.gov/> (accessed November 2024).

Stratotypes

Stratotypes are important geologic reference exposures that help identify, define, and correlate geologic units from one location to another. When geologists propose or describe a new layer or body of rock, a stratotype is assigned to exposures containing all (or most) of the unique diagnostic criteria. Stratotypes have significant scientific value and are often easily accessible, world-class locations to study outcrops of rock. Akin to natural libraries of Earth history, stratotypes preserve meaningful clues to the past and serve as geologic classrooms (Henderson et al. 2023). The stratotype concept is ingrained in the modern system of geologic nomenclature, as many formal geologic unit names are derived from geologic or geographic features found near stratotype locations. Some particularly recognizable examples from within the National Park System (and their stratotype assignments) include the Permian De Chelly Sandstone (Canyon de Chelly National Monument, Arizona), the Cretaceous Mesaverde Group (Mesa Verde National Park, Colorado), and the Pleistocene Valles Rhyolite (Valles Caldera National Preserve, New Mexico). More information about the various kinds of stratotypes (i.e., lithostratigraphic versus chronostratigraphic) and how to propose or modify them can be found in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 2021) as well as Stamm (2023).

NCCO contains six stratotypes that represent Triassic, Cretaceous, and Tertiary metamorphic or igneous units. Stratotypes include the oldest units within the park complex (Triassic Magic Mountain Gneiss and

Cascade River Schist) and help comprise the crystalline Metamorphic Core Domain underlying NCCO (see Figure 1 and “Geologic History”). Many of these stratotype assignments reflect the dedicated careers of geologists Peter Misch (University of Washington), Rowland Tabor, and Ralph Haugerud (both USGS; Henderson et al. 2021). The following geologic time scale (Table 1) puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. Likewise, geologic units (rocks and unconsolidated deposits) are listed stratigraphically, with stratotype designations mentioned in parentheses. Information in the following geologic time scale, including timing of geologic events, is primarily from Tabor and Haugerud (1999), Tabor et al. (2002, 2003), Haugerud and Tabor (2009), and Miller et al. (2023).

Table 1. Geologic units mapped within the park complex.

GSRI map abbreviations for each time division and GSRI map unit symbols are in parentheses. Units with stratotype designations within the park complex are mentioned in parentheses. Only geologic units mapped within NCCO are included. Boundary ages follow the International Commission on Stratigraphy (2023).

Geologic Time Unit	Age	Geologic Units (GSRI map symbol)	Geologic Events
Quaternary Period: Holocene (H) Pleistocene (PE)	2.58 million years ago to present	Alluvium and alluvial fan deposits (HPEa) Bog deposits (Hb) Mass wasting deposits (HPEmw) Talus deposits (HPEta) Sedimentary deposits or rocks, undivided (HPEs) Glacial deposits and drift (HPEg)	Continued growth and development of the Cascade Magmatic Arc. During the Quaternary Period, the park complex was inundated by multiple advances of the Cordilleran Ice Sheet. Tephra found in soil and other surficial deposits record multiple volcanic eruptions dating back over 13,000 years. Following the last Ice Age, rivers and streams incise deep canyons and become dominant drivers of landscape change.
Pliocene (PL)	5.33 million to 2.58 million years ago	Hannegan Volcanics (PLhv) Chilliwack Composite Batholith (PLcc) Intrusive rocks of the Cascade Pass Family	Continued growth and development of the Cascade Magmatic Arc. Rocks that form the North Cascades continue to be uplifted, eroded, and buried.
Miocene (MI)	23.03 million to 5.33 million years ago	Chilliwack Composite Batholith (MIcc) Intrusive rocks of the Cascade Pass Family Cascade Pass Dike (MIc) Cloudy Pass batholith (MIcp) Chilliwack Composite Batholith (MIOLcc) Intrusive rocks of the Snoqualmie Family Perry Creek phase (STRATOTYPE)	Continued growth and development of the Cascade Magmatic Arc. Rocks that form the North Cascades continue to be uplifted, eroded, and buried.
Oligocene (OL)	33.9 million to 23.03 million years ago	Volcanic rocks of Mount Rahm (OLvr) Volcanic rocks of Bis Bosom Buttes (OLbb) Volcanic rocks of Pioneer Ridge (OLpr) Chilliwack Composite Batholith (OLcc) Intrusive rocks of the Snoqualmie Family Intrusive rocks of the Index Family	Continued growth and development of the Cascade Magmatic Arc. Rocks that form the North Cascades continue to be uplifted, eroded, and buried.

Geologic Time Unit	Age	Geologic Units (GSRI map symbol)	Geologic Events
Eocene (E) Paleocene (EP) Cretaceous (K)	145 million to 33.9 million years ago	Golden Horn batholith (Eig[g]) Granodiorite (Eg) Orthogneiss (EPo) Orthogneiss of Gabriel Peak and Mount Benzarino (EPKgb) Tonalite (Tkt) Older sandstone and conglomerate (Tos) Ultrabasic (ultramafic) rocks (pTu) Skagit Gneiss Complex (EKsg; STRATOTYPE) Plutons of the tonalitic group (EKho, EKmo, TKto) Plutons of the granodioritic group (EKhl, EKao) Eldorado Orthogneiss (Keo; STRATOTYPE) Virginia Ridge Formation (Kvr) Harts Pass Group (Khp) Black Peak batholith (Kbp) Metavolcanic rocks (Kmv) Rocks in the Ross Lake Fault Zone Ruby Creek Heterogeneous Plutonic Belt (EKrc) Skymo Complex (EKsc) Little Jack terrane Phyllite and schist of Little Jack Mountain (EKj) Chelan Mountains terrane Marblemount pluton (Kmp) Easton terrane (Shuksan nappe) Eastern Metamorphic Suite (Kem) Darrington Phyllite Shuksan Greenschist (STRATOTYPE) Welker Peak and Excelsior nappes Bell Pass mélangé (KJbp)	During the Cretaceous Period, the Pacific Northwest was a convergent margin defined by the Coast Mountains Magmatic Arc, a large volcanic system fueled by the subduction of oceanic crust below ancestral North America. Multiple terranes that underlie NCCO and constitute western Washington were added to the continental margin from about 200 million to 50 million years ago. The arrival of the Siletzia terrane during the Eocene Epoch activated regional strike-slip faulting that reorganized the geology of the North Cascades and marked the beginning stages of the Cascade Magmatic Arc.
Jurassic (J) Triassic (TR) Permian (P) Pennsylvanian (PN)	323.2 million to 145 million years ago	Ladner Group (Jm[l]) Methow terrane Sand and argillite (Js) Hozomeen terrane Hozomeen Group (JPh) Chelan Mountains terrane Napeequa Schist (TRn) Cascade River Schist (TRcr; STRATOTYPE) Magic Mountain Gneiss (TRmm; STRATOTYPE)	Deposition of rocks constituting various terranes within or surrounding the park complex, including the Chelan Mountains, Chilliwack River, Hozomeen, and Methow terranes.

Paleontology

Paleontological resources (fossils) preserved within the park complex provide glimpses of ancient marine and terrestrial environments dating back to the Paleozoic–Mesozoic Eras, as well as the shifting climate and environment of the most recent tens of thousands of years, such as the influence of glaciers and glacial lakes (Riedel 2007; Spooner 2007, 2008; Fay et al. 2009). Fossils documented within NCCO are associated with several geologic formations, cultural sites, and museum collections (Table 2). Although many of the Holocene cultural deposits lack a robust geologic context, they contain bone fragments approximately 2,700 years old or younger, in addition to charred wood dating back nearly 9,000 years (Justin Tweet, NPS GRD, written communication 22 January 2025).

The geology holdings at NCCO include two major collections: the Rowland W. Tabor and Peter Misch collections. The Tabor collection contains over 3,000 geologic specimens collected during USGS field campaigns in the North Cascades region during the 1970s, 1980s, and 1990s. Many rock specimens of the collection can be viewed at the following website: [NPS Museum Collections - NCCO](#). According to Fay et al. (2009), less than one-third of the Tabor collection has been cataloged. Similarly, geologic specimens and thin sections collected by Peter Misch between 1948 and 1984 have not been inventoried or assessed for their paleontological merit. It is possible that both the Tabor and Misch collections could yield additional fossils of interest to the park complex (Fay et al. 2009).

Table 2. Paleontological resources by geologic unit.

The following table shows paleontological resources associated with geologic units or cultural deposits within NCCO.

Information for the table was sourced from Mierendorf (1998), Tabor et al. (2003), Riedel (2007), Spooner et al. (2007, 2008), Fay et al. (2009), Mierendorf and Baldwin (2015), and Riedel (2017).

Geologic age	Geologic unit name	Paleontological resources reported within the park complex
Holocene	Cultural deposits	Charred animal bone fragments (including mountain goat [<i>Oreamnos americanus</i>], deer [<i>Odocoileus spp.</i>], bear [<i>Ursus spp.</i>], beaver [<i>Castor canadensis</i>], elk [<i>Cervus elaphus</i>], Canid, and unidentified fish and bird), carbonized wood, seeds, beetle fragments (<i>Dyslobus decorates</i>), and mollusk shells (<i>Detalium</i>)
Quaternary	Mass wasting deposits	Bivalves (<i>Buchia</i> sp.) and gastropods
Quaternary	Glacial and lacustrine deposits	Plant macrofossils, pollen, charcoal, and a diverse suite of flora including fir (<i>Abies amabilis/gradis</i> , <i>Abies lasiocarpa</i> , <i>Abies procera</i> , <i>Alnus sinuata</i> , <i>Pseudotsuga menziesii</i>), alder (<i>Alnus rubra</i>), Asteraceae-family (daisies), birch (<i>Betula</i>), cypress (<i>Chaemacyparis nootkatensis</i> , <i>Thuja plicata</i>), heath (<i>Ericaceae</i>), ash (<i>Fraxinus</i>), spruce (<i>Picea engelmannii</i>), pine (<i>Pinus albicaulis</i> , <i>P. contorta</i> , <i>P. monticola</i>), willow (<i>Salix</i>), and hemlock (<i>Tsuga heterophylla</i> and <i>T. mertensiana</i>)
Late Cretaceous–Eocene (Tertiary?)	Chuckanut Formation and “other Tertiary sandstones”	Fossil logs
Pennsylvanian–Triassic	Hozomeen Group	Radiolaria

Indigenous Connections

Scattered across the park complex are hundreds of archeological sites that record evidence of early human occupation spanning nearly 10,000 years (National Park Service 2012; Mierendorf and Baldwin 2015). For millennia, Indigenous inhabitants have used the geologic resources of the North Cascades for various

utilitarian purposes, including stone tools (e.g., bifaces, blades, drills, hammerstones, knives, manos, pestles, projectile points, scrapers, soapstone pipe bowls, soapstone effigies), bedrock mortars, quarries, pictographs (rock paintings), rock shelters, and rock structures (e.g., hunting blind pits, circular rock piles) (Mierendorf and Reid 1986; Mierendorf 1998, 2004; Mierendorf and Baldwin 2015).

Stone Tools

The diverse geology of the park complex provided Indigenous peoples with a rich assortment of raw materials, namely rocks and minerals for making tools and for trading. According to Mierendorf and Baldwin (2015), there are five main categories of bedrock that were locally sourced for most North Cascades toolstone: (1) extrusive volcanic rocks of the Pliocene Hannegan Volcanics in northern NOCA; (2) rocks of the Paleozoic–Mesozoic Hozomeen Group in the northeast corner of NOCA and ROLA; (3) a body of Easton terrane metamorphic rocks along the western margin of NOCA; (4) crystalline igneous and metamorphic rocks of the North Cascades core; and (5) local dikes and other areas of secondary hydrothermal alteration. In some cases, unconsolidated glacial deposits provided secondary, non-local sources of toolstone. Altogether, roughly two dozen toolstone lithologies have been recognized in the North Cascades, which reflect the dynamic, complex geologic processes that shaped the landscape over millions of years (Mierendorf and Baldwin 2015). An exhibit displaying various Indigenous stone tools is located in the NCCO visitor center in Newhalem. Additional items from the NCCO museum collections can be viewed at the following website: [National Park Service Museum Collections - North Cascades National Park Service Complex](#) (accessed November 2024).

Quarries

One of the oldest cultural sites in the park complex is a chert quarry (Desolation Chert Quarry) located near the eastern shore of Ross Lake in ROLA. The quarry has been radiocarbon dated to about 7,600 years ago and is one of several stone procurement sites (a “chert quarry complex”) now recognized along the upper Skagit River Valley (Mierendorf 1993, 1998, 2004; Mierendorf and Baldwin 2015). It is important to acknowledge that radiocarbon dates are not equivalent to calendar dates and that radiocarbon years require calibration to yield calendar years. Often referred to as the “Hozomeen chert,” the local source of the abundant chert deposits is the Paleozoic–Mesozoic Hozomeen Group that underlies the northeastern portion of NCCO (Mierendorf 1993; Mierendorf and Baldwin 2015). Near Ross Lake, outcrops of chert commonly form cliffs, rock buttresses, ridges, summits, and steep slopes. Samples of chert are commonly dark gray or black but can also appear light gray or bluish-gray, medium gray, pink, red, pale green, white, and waxy gray. In thin section, the chert contains distinctive recrystallized radiolarian fossils (see “Paleontology”; Mierendorf 1993). As a raw material for making tools, Hozomeen chert varies in quality and required judicious selection to remove undesired impurities or waste rock—characteristics that help explain the vast lithic scatter deposits at or near the quarry sites (Mierendorf and Baldwin 2015). A compilation of 70 radiocarbon age estimates indicates that Hozomeen chert was quarried for thousands of years, with ages clustering in four time periods (in radiocarbon years before present): (1) 8,000–6,100; (2) 5,400–3,600; (3) 2,800–1,000; and (4) 600–150 (see table 6-1 of Mierendorf and Baldwin 2015). According to Mierendorf (1993), the word “Hozomeen” is of Indigenous origin and alludes to the tool-making quality of the rock; accordingly, “hozo-” means “sharp” and “-meen” denotes “an instrument out of it.”

In the northern portion of NOCA, another quarry complex has been identified in proximity to the Hannegan caldera near the headwaters of the Chilliwack, Nooksack, and Silesia watersheds. Unlike the quarries

situated adjacent to Ross Lake, these sites procured vitrophyre (igneous glass) from exposed dikes (vertical or near vertical intrusions of igneous rock) consisting of the Pliocene Hannegan Volcanics (Mierendorf 2004; Mierendorf and Baldwin 2015). In addition to dikes, other sources of vitrophyre included reworked deposits, isolated gravels or cobbles, and talus (Mierendorf and Baldwin 2015). A collection of 10 radiocarbon age estimates suggests that the Hannegan Volcanics vitrophyre was procured from roughly 4,470 to 1,460 radiocarbon years ago (see table 6-4 of Mierendorf and Baldwin 2015).

Pictographs

Pictographs are forms of artistic or spiritual expression that consist of painted motifs, shapes, figures, symbols, designs, and scenes applied to rock surfaces. Currently, only one pictograph site has been confirmed within NCCO, but others are likely to exist (Mierendorf and Reid 1986). In the southern portion of the park complex, pictographs are located on smooth granitic cliffs on Lake Chelan in LACH (Figure 3). The vertical pictograph escarpment runs directly into the lake, suggesting that the original artist must have worked from a canoe or raft (Cain 1946). Referred to as the “Stehekin Pictographs,” these pictographs consist of stylized human and animal figures (including mountain goats, sheep, and fish) painted with red ocher, a natural pigment made of iron oxide minerals (see plate 14 of Cain 1946; Mierendorf and Reid 1986). Following the construction of the Lake Chelan Dam in the 1920s, the Stehekin Pictographs have been partially inundated by Lake Chelan and vandalized with commercial paint. According to Mierendorf and Reid (1986), these pictographs form the basis for Indigenous interpretation and need to be adequately documented (e.g., photographed, sketched, historically referenced) or considered for restorative techniques to remove evidence of vandalism. A replicated panel of the pictographs is on display in the NCCO visitor center in Newhalem.

Although not located within the park complex, another notable pictograph site is located along the west bank of the Columbia River approximately 65 km (40 mi) southeast of LACH. Pictographs at the site are well preserved beneath a natural overhang of large boulders and depict various human- or animal-like figures (see plate 16 of Cain 1946).

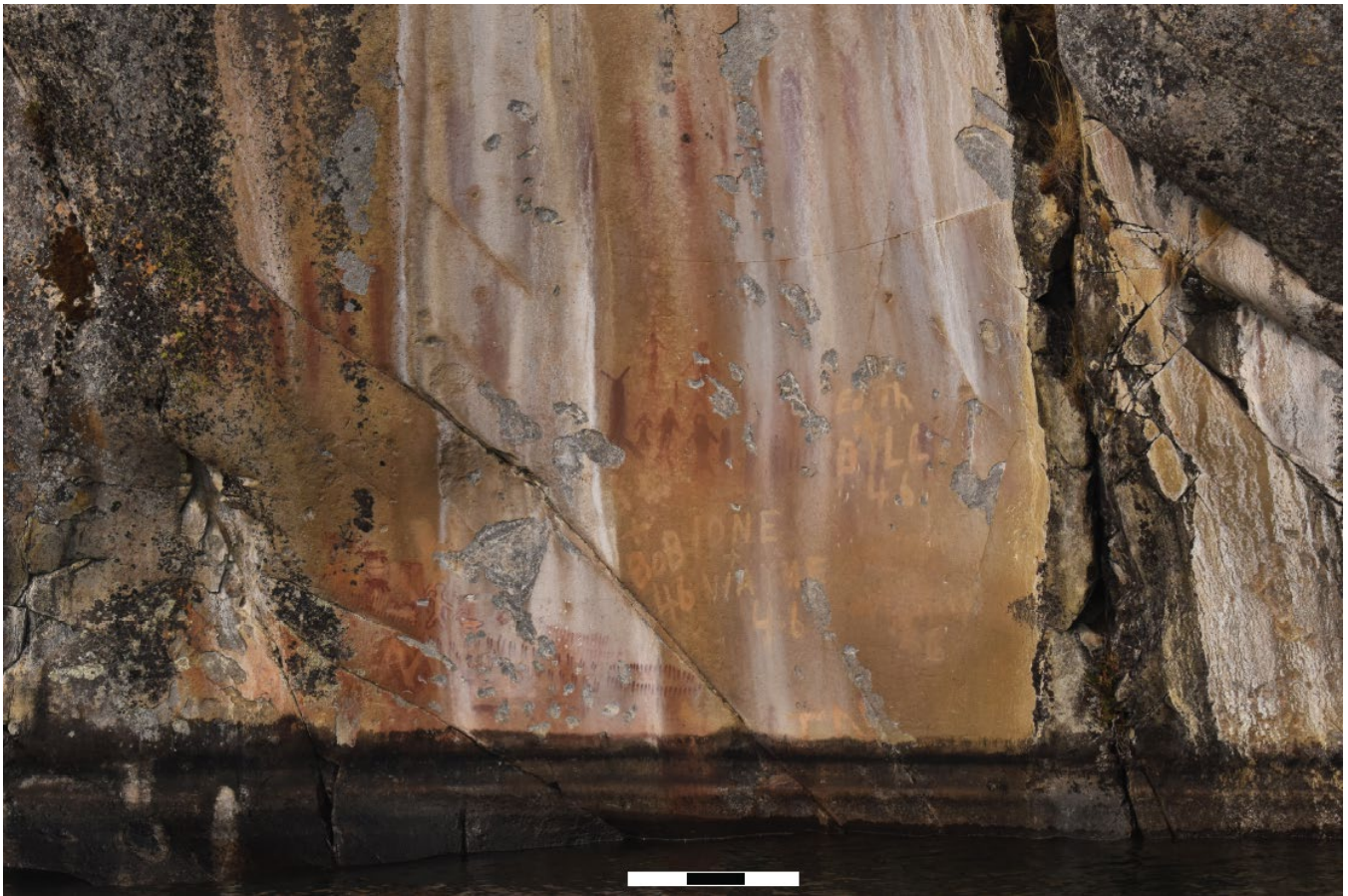


Figure 3. Photograph of Indigenous pictographs in LACH. The cliffs contain several animal- and human-like depictions painted in red ocher. The scale bar at the bottom represents 1 m (3 ft). See plate 14 of Cain (1946) for additional information about figure interpretation. Over many years these valuable rock paintings have been vandalized (tan paint) and partially inundated by the lake. NPS photograph.

Tephrochronology

Soils within the park complex are classified by the presence of tephra (airborne volcanic debris of various sizes) that was ejected from multiple volcanic eruptions, the most recent of which date back to and are preserved amongst cultural deposits throughout NCCO. The tephrochronology (volcanic ash dating) of the Pacific Northwest has revealed that Indigenous cultures possibly coped with frequent volcanic eruptions associated with the Cascade Magmatic Arc. Currently, at least seven chemically distinct ash horizons have been identified within NCCO soils and lake sediments that include the following (from oldest to youngest): (1) Glacier Peak, 13,155 years ago; (2) Mount St. Helens J horizon, about 12,000 years ago; (3) the cataclysmic eruption of Mount Mazama that formed Crater Lake roughly 7,700 years ago; (4) Glacier Peak Dusty Creek, 5,830 years ago; (5) Mount St. Helens Y horizon, 3,761 years ago; (6) an unidentified horizon of Mount St. Helens affinity, about 2,500 years ago; and (7) Mount St. Helens W horizon, 500 years ago (Mierendorf 1998; Spooner et al. 2007, 2008). Some of these ash beds are prominent within cultural sites or the deposits above or below them.

Early Geologic Exploration

Both historically and today, the geologic exploration of the North Cascades is a slow, difficult process hindered by extreme topography, dangerous climatic conditions, and an extremely complex geologic history.

During the latter half of the 19th century, George Gibbs (1874) explored the Pacific Northwest and parts of the Skagit River to begin one of the earliest geologic and geographic studies of the North Cascades region (Tabor et al. 2003). At the turn of the century in 1898, USGS geologist Israel Russell visited Cascade Pass and later published a preliminary geologic map and report of the Cascade Range in northern Washington (Tabor et al. 2002). Reconnaissance mapping by Russell (1900) included areas of the park complex along the Skagit River and Ruby Creek. In the early 1900s, the US and Canada sent geologists to resurvey areas along the international border. The American side of the 49th parallel was mapped by USGS geologists George Smith and Frank Calkins, while the Canadian side was surveyed by a Boston geology professor named Reginald Daly. Although Smith and Calkins (1904) made significant contributions to the geologic framework of the North Cascades, Daly's (1912) highly detailed report later surpassed their work (Tabor and Haugerud 1999; Tabor et al. 2003). According to Tabor et al. (2003), Daly's publication was the first to attempt to synthesize what has become an extremely complicated geologic story. To aid in his geologic investigations, Daly exploited lumberjack trails that cleared large, nearly 30 m (100 ft)-wide swaths of forest; these corridors allowed premiere access to areas never seen before by geologists (Tabor and Haugerud 1999).

The modern era of North Cascades geology began in 1948, when University of Washington professor Peter Misch initiated a dedicated career of investigation that would span the next four decades (Misch 1952, 1966, 1977a, b). Two of Misch's protégés include USGS geologists Rowland Tabor and Ralph Haugerud, who have both published several detailed geologic reports, field guides, and maps covering the area of the park complex (Tabor et al. 1989, 2002, 2003; Haugerud 1995; Tabor and Haugerud 1999; Haugerud and Tabor 2009).

Mining

The mining history of the park complex is a colorful story involving dreams of mineral wealth and riches, boom-and-bust operations, and shattered dreams. Throughout the Cascade Range, precious mineral or metallic ore occurrences are associated with granitic intrusions such as the Chilliwack composite batholith that hydrothermally altered the surrounding bedrock. The emplacement of molten material created superheated fluids concentrated in dissolved metal ions that later precipitated to form ore deposits (Staatz et al. 1972). As early as the 1850s, prospectors ventured into the North Cascades seeking gold, scouring the banks of the Skagit River. Although these early efforts were rather unsuccessful, seemingly large deposits of placer gold were discovered along Ruby Creek in the late 1870s, kicking off the first official gold rush in the North Cascades (Staatz et al. 1972; Luxenberg 1986). Interestingly, it is rumored that Ruby Creek received its name during this time, as one of the prospectors found a sizable ruby while panning for gold. Although hundreds of inspired prospectors and miners flocked to the region, the lack of appreciable discovery ended the gold rush by 1880. The 1890s brought a new wave of prospectors who abandoned searching the river valleys for placer gold in favor of other minerals (e.g., silver, copper, lead, galena, talc) found in the remote high country of the Cascade Range (Figure 4; Luxenberg 1986). By the end of the 19th century, hundreds of mineral claims were filed throughout the park complex across various drainages, including Thunder, Bridge, Bacon, Silver, and Marble creeks.

At the turn of the 20th century, a new era of mining unfolded where large companies bought out or replaced individual prospectors or miners. Despite their attempts to substantially develop mining claims—including the construction of trails, log cabin housing, sawmills, and water pipelines—many of these mining companies were unsuccessful or were discouraged as metal values dropped (Luxenberg 1986). Some of the

last mining attempts in the North Cascades region were driven by an increased demand for metal during World War I and in the years following World War II. During the summers of 1966 and 1967, the USGS surveyed all possible mineral resources in the northern portion of NCCO and determined only two mineral occurrences were of any economic value (Staatz et al. 1972). These occurrences include copper- and molybdenum-bearing sulfide minerals in the valley of Silver Creek (NOCA–ROLA) and molybdenum-bearing quartz veins in the Sulphide Creek basin (NOCA; Staatz et al. 1972).



Figure 4. The Black Warrior Mine in NOCA. Prospectors dreamed of building a 6.4 km (4 mi) tunnel under Horseshoe Basin, but their optimism was ruined by poor ore recovery, dangerous weather conditions, and landslides. The mine tunnels into intrusive rocks of the Cretaceous–Eocene Eldorado Orthogneiss. The mine is listed on the National Register of Historic Places. NPS photograph.

Hydroelectric Power

The four reservoirs of ROLA (Gorge, Diablo, and Ross lakes) and LACH (Lake Chelan) are all impounded by dams constructed to provide recreational opportunities and transportation routes, but also harness the power of the Skagit and Stehekin Rivers to provide hydroelectricity. Prior to the construction of these dams, 19th and early 20th century settlers, prospectors, and mining companies utilized the glacial streams emanating from the North Cascades to power homesteads, mines, mills, and other endeavors (Luxenberg 1986). The hydroelectric centerpiece of the park complex—Seattle City Light’s Skagit River Hydroelectric Project—successively dammed the Skagit River starting in the 1920s to create Gorge, Diablo, and Ross lakes in ROLA (1924, 1930, and 1949, respectively; Luxenberg 1986). Today, Ross Lake (and by extension ROLA) bears the name of Seattle City Light superintendent J. D. Ross. From the 1940s to the 1960s, Ross Dam was raised in height twice, and the original Gorge Dam (constructed out of rocks and logs) was replaced, updated, and expanded (National Park Service 2019). The continuous expansion of Ross Lake Dam (sometimes

referred to as the “High Ross project”) developed into a volatile issue by the late 1960s, as the project would have progressively raised the lake level by 38 m (125 ft) and inundated miles of shoreline within ROLA (Louter 1998; National Park Service 2012). The High Ross project never came to fruition and was settled out of court by the early 1980s.

In LACH, Lake Chelan was dammed in the 1920s to help regulate reservoir levels for hydroelectric power (Hoffman et al. 2015). Although the construction of the Lake Chelan Dam provided a valuable source of electricity, it raised the level of the reservoir nearly 6 m (20 ft) and introduced several management issues associated with resource inundation and erosion (see “Cultural Resource Protection”; Hoffman et al. 2015).

Geologic Resource Management Issues and Inventory Needs

This section briefly summarizes the geologic resource management issues, inventory needs, and geologic hazards that have been identified by discussions with NCCO staff. Geologic resource management issues refer to problems related to geologic resources. Inventory needs are highlighted to summarize what is currently known and what is needed to ensure good management of the park complex. Geologic hazards refer to notable hazards stemming from geologic features or processes that may require active management. Refer to the [Guidance for Resource Management SharePoint](#) for more information regarding geologic resource management.

Summary of Geologic and Soil Hazards

Park resources are not only visitor attractions but may also be potentially hazardous. The mountainous North Cascades landscape presents a variety of geologic hazards, or “geohazards”—naturally occurring, dynamic geologic processes that have the potential to cause damage, loss of property, and/or injury and loss of life. The Addressing Climate Change and Natural Hazards Handbook (NPS 2015, 2023), grounded in NPS Policy Memorandum 15-01 (Jarvis 2015), provides a process and information to help teams and decision-makers identify, avoid, and mitigate risks associated with environmental change hazards and effects on proposed and planned facility investments. The handbook supports NPS planning guidance, policy directives, and executive orders and does not supersede existing mandated compliance processes and policies. Additional guidance for facility management (e.g., [Climate-Smart Planning Principles](#) and [Recommended Practices](#)) has been developed to support effective decision-making.

According to PM 15-01, managers should apply the handbook guidance to identify options to manage natural hazard and climate change risks throughout all levels of facility planning and design. Project teams are required to submit the completed Natural Hazards Checklist (Table 3) as part of Regional and Bureau Investment Review Board submissions. This information can also be used as part of the updated (2024) Automated Investment Review Board (AIRB) submittal process at the Investment Concept (IC) stage. Table 3 includes selected geologic and soil hazards listed in Part 1 of NPS (2023). The GSRI team has added additional hazards where appropriate for the park. If needed, Part 2 of the handbook could inform the completion of the checklist, such as whether a hazard is applicable. Contact the NPS Geologic Resources Division with any questions.

Table 3. Geologic hazards checklist.

This summary table is a synthesis of existing GSRI-compiled map data and information, as well as published US Geological Survey and other government agency information. It is suitable for use at park-scale discussions and assessments. It is not a substitute for site-specific investigations or NEPA analysis. Ground-disturbing activities should neither be approved nor denied based on the information here. This table is modeled after the Natural Hazard Checklist (see National Park Service 2015 and Jarvis 2015). It is meant to provide general information to identify the full range of natural hazard-based risks for the national park.

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Earthquake	Falling objects Collapsing structures Inoperability of major building systems (e.g., power, sewer, water) Trigger to other hazards (e.g., landslides, volcanic activity) Human injury or casualty	Chance of a damaging earthquake in the next 100 years is: <u>NOCA and ROLA</u> Known hazard (very high; DOI SHIRA) <u>LACH</u> Known hazard (moderate; DOI SHIRA)	Czajkowski and Bowman (2014) Pacific Northwest Seismic Network Rogers et al. (1996) Silva et al. (1998) US Department of Interior (DOI) Strategic Hazard Identification and Risk Assessment (SHIRA) Risk Mapper Report United State Geological Survey (USGS) Earthquake Hazard Probability Map (Petersen et al. 2023) WA DNR - Earthquakes and Faults Washington Geological Survey (2017)
Slope movements (also called “mass wasting”)	Landslides (e.g., debris flows, debris avalanches, rockfalls, slumping or creep) Debris flows often mobilize large masses of woody debris Damage or destruction of park infrastructure Damage to or loss of natural or cultural resource sites or features Human injury or casualty	Known hazard (susceptible to landslides and avalanches; DOI SHIRA)	DOI SHIRA Risk Mapper Report GSRI GIS hazard layers or slope movement deposits (e.g., “mass wasting deposits,” “incipient blockslides,” “talus deposits”) Haugerud and Tabor (2009) Hoffman et al. (2015) Riedel et al. (2012a, b, c, d, e) Tabor et al. (2002, 2003)
Permafrost	Thawing can lead to enhanced erosion, destabilized building or road foundations, and surface collapse Increased mass wasting susceptibility Thermokarst development	Potential hazard (isolated <10% permafrost coverage; DOI SHIRA)	DOI SHIRA Risk Mapper Report Gonzalez (2017)
Cave/karst	Not applicable	Not applicable	Not applicable
Shrink/swell soils	Damage to infrastructure “Heaving” of ground beneath roads, trails, or structures Increased susceptibility to slope movements	Potential hazard (low; USDA Web Soil Survey)	USDA Web Soil Survey USDA, NRCS and US DOI, NPS (2012)

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Coastal storm surge/ sea or lake level change/shoreline erosion	Not applicable	Not applicable	Not applicable
Tsunami	Not applicable	Not applicable	Not applicable
Riverine Flood	Flooding (driven by storms, prolonged rainfall or snowmelt) capable of generating mass wasting events Rising water levels within park complex reservoirs (Lake Chelan and Ross, Diablo, and Gorge Lakes) resulting in shoreline flooding Enhanced flow regimes capable of carrying large rock and woody debris The Stehekin River Valley is prone to flooding that often results in widespread damage to private and public property Destruction of infrastructure Stream channel migration Stream bank erosion Destruction of cultural or paleontological sites Human injury or casualty	Known hazard (extreme; DOI SHIRA)	DOI SHIRA Risk Mapper Report Federal Emergency Management Agency (FEMA) Map Service Center Louter (1998) Mierendorf and Reid (1986) Riedel et al. (2012a, b, c, d, e) Strauch et al. (2018)
Flash Flood	Sudden rising water (i.e., dry wash or tributary valley) capable of generating mass wasting events Enhanced flow regimes capable of carrying large rock and woody debris Destruction of infrastructure Stream channel migration Stream bank erosion Destruction of cultural or paleontological sites Human injury or casualty	Known hazard (extreme; DOI SHIRA)	Riedel et al. (2012c, d)

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Volcanic eruption	Lava Flows Pyroclastic flows Ash fall Toxic gas or steam releases Fire Seismicity Volcanic landslides Damage to HVAC and other mechanical systems (ash) Damage or destruction to park infrastructure Volcanic ash health hazards if inhaled Human injury or casualty	<u>NOCA only</u> Known hazard (very high; DOI SHIRA)	DOI SHIRA Risk Mapper Report Gardner et al. (1995) Mastin and Waitt (2000) Mierendorf (1998) Schilling (1996) Scott et al. (2000) Spooner et al. (2007, 2008) USGS Volcano Hazard Assessments WA DNR - Volcanoes and Lahars Waitt et al. (1995)
Hydrothermal activity	Not applicable	Not applicable	Not applicable
Radon	Health hazard	Potential hazard (moderate – zone 2) defined by average indoor radon levels that may be between 2 and 4 pCi/L (US EPA).	US Environmental Protection Agency (EPA) Map of Radon Zones

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Toxicological soil (arsenic, asbestos or erionite, <i>Bacillus anthracis</i> [causes anthrax], cadmium, lead, and selenium)	Health hazard	<u>NOCA and ROLA</u> Arsenic – Potential hazard (very high) Asbestos or erionite – Potential hazard (high) Bacillus anthracis – Potential hazard (high) Cadmium – Potential hazard (high) Lead – Potential hazard (high) Selenium – Potential hazard (low) <u>LACH</u> Arsenic – Potential hazard (very high) Asbestos or erionite – not considered likely Bacillus anthracis – Potential hazard (high) Cadmium – Potential hazard (high) Lead – Potential hazard (low) Selenium – Potential hazard (low)	DOI SHIRA Risk Mapper Report
Dust storms	Health hazard	Known hazard	Graham (2002)

Climate Change

Although climate change planning is beyond the scope of this GSRI summary, a discussion of climate change is included because of the potential disruption it may cause to the national park's resources, including geologic resources. In the North Cascades, climate change and water availability are two major concerns for NCCO (Hoffman et al. 2015; Riedel and Larrabee 2016, 2017; National Park Service 2019). In 2011, the multi-agency North Cascadia Adaptation Partnership was established to increase the awareness of climate change, assess vulnerabilities of cultural and natural resources, and incorporate climate change adaptation ideas into NPS and US Forest Service planning documents (Strauch et al. 2018; see <https://adaptationpartners.org/ncap/>; accessed November 2024). The partnership provides science-based management strategies aimed at protecting roughly 2.4 million ha (6 million ac) of land, including the park complex, Mount Rainier National Park, Mount Baker-Snoqualmie National Forest, and Okanogan-Wenatchee National Forest.

The climate at NCCO is already changing; all future climate model projections include temperatures above the recent historical average (1979–2012), and average annual precipitation is anticipated to be highly variable (Climate Change Response Program 2024). Alpine glaciers and snowpacks—critical reservoirs that sustain NCCO's rivers, ecosystems, recreational opportunities, and hydroelectric power generation—are receding and will likely impact the availability of water (Riedel et al. 2008; Hoffman et al. 2015; Riedel and Larrabee 2016, 2017; National Park Service 2019). Projected increases in several variables (air temperatures, evaporation rates, droughts, and precipitation) may negatively affect wildfire occurrence, aquifer recharge, as well as watershed quality and flow. These modifications to water availability are likely to impact additional geologic processes (e.g., floods, landslides, erosion), in addition to ecological processes (e.g., invasive species, phenology), visitation, and park management procedures (Climate Change Response Program 2024).

Climate change manifestations that may intensify geologic hazards include the following:

- Increased average temperatures
- More frequent and intense storms
- Increased frequency and magnitude of fires
- Increased susceptibility to mass wasting events
- Increased extreme weather scenarios, including drought and flooding
- Decreased water availability as alpine glaciers and snowpacks dissipate

Disturbed Lands

Disturbed lands are those areas where the natural conditions and processes have been directly impacted by development, including facilities, mining, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; and overuse or inappropriate use. Restoration aims to restore a site, watershed, or landscape to a previous condition, typically a desirable historic baseline. Human activity often disturbs lands, leading to unintended and long-lasting issues that affect other resources. Many of these disturbances obliterate soil profiles, exacerbate the invasion of exotic plants, result in contamination of water and soil, and/or cause erosion and sedimentation. These damages, in turn, frequently impair the quality of habitats, disrupt ecosystem functions, and cause problems for parks

managing areas as wildlands. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities.

Abandoned Mineral Lands

Historic gold mining and other mineral resource development during the late 19th and 20th centuries left behind several abandoned mineral lands (AML) features that are vestiges of the past. These remnants of mining activity, and the mines themselves, are still visible throughout the North Cascades and present several safety issues, including sharp wooden or metallic debris, rockfalls, and mine collapse. According to Burghardt et al. (2014), there are over 150 AML sites or features distributed across the park complex in NOCA (111), ROLA (32), and LACH (16). Sixteen of these are ranked “high” regarding priority mitigation needs, meaning there is a risk of serious injury or severe natural or cultural resource damage (Burghardt et al. 2014). Some mine sites are now protected bat roosts that have been restricted to the public.

According to Graham (2002), the park complex is concerned that AML sites may be leaching contaminants or pollutants into the environment that are negatively impacting water quality conditions in NCCO. West of and adjacent to Lake Chelan is the Holden mine, an inactive underground copper mine and Superfund site located on the eastern slopes of the Cascade Mountains. Between 1938 and 1957, the mining of copper, gold, silver, and zinc from the Holden mine produced roughly 229,000 m³ (8,100,000 ft³) of waste rock and about 8.5 million tons of mine tailings (US Department of Agriculture, Forest Service 2018). Since abandonment, the tailings piles have leached reactive minerals and toxic metals into the surrounding environment, and the mine has partially filled with water contaminated with hazardous substances, including iron and aluminum compounds, arsenic, cadmium, copper, zinc, and lead (see <https://www.epa.gov/enforcement/case-summary-epa-and-forest-service-issue-uao-holden-mine-site#site>; accessed November 2024). Contaminated water, soil, and wind-blown dust have already impacted the nearby Railroad Creek that feeds into Lake Chelan at Lucerne (US Department of Agriculture, Forest Service 2018). Since remediation began in 2013, several measures have been completed to contain, reshape, and stabilize mine tailings, as well as treat contaminated groundwater at on-site treatment plants. The US Environmental Protection Agency (EPA) continues to remediate and monitor the site.

Dust Storms

Dust storms, also referred to as sandstorms, are meteorological phenomena that arise when strong wind gusts blow loose fine particles of sand, silt, clay, or dirt from dry, exposed surfaces. In the park complex, dust storms are known to occur after periods of spring snowmelt when there is an approximate six-week period where reservoir levels are drawn down and lake beds are exposed (Graham 2002). Although dust storms are common throughout the western US, the frequency and distribution of these events are changing in response to water diversions and climate change (Barringer 2024). Any variables that contribute to lowering reservoir levels in the park complex (e.g., increased average annual temperatures, enhanced evaporation rates, and shrinking glacial or snowpack extent) will likely increase the susceptibility of additional dust storms at the park complex (see “Climate Change”). Dust storms present several hazards, as these events can negatively impact air quality, causing health issues or visibility concerns, and can also lead to premature snowmelt if deposited on snowpacks (Abbott et al. 2023). An increase in dust storm frequency may accelerate glacier or snowpack loss in the park complex, which could impact ecological communities but also present additional geohazards related to flooding, drought, and mass wasting.

Flooding

Hydrologic processes such as flooding help govern landform development in the North Cascades but also present several hazards, including inundation, infrastructure damage, riverbank erosion, washouts, and mobilization of woody debris (Mierendorf and Reid 1986; Louter 1998; Riedel et al. 2012a, b, c, d, e). Flooding within NCCO is driven by large storms (including cyclones and atmospheric rivers) and seasonal fluxes in rainwater or snowmelt that occur during the spring and late fall. During the fall, rivers and creeks typically reach flood stage between late October and December and are associated with large rain-on-snow events. Fall floods generally produce short-duration, high-magnitude flows that dominate lower elevations further west (Riedel et al. 2012a, b, c, d, e). Spring snowmelt floods occur between May and June and have durations that can span weeks (Riedel et al. 2012a, b, c, d, e). These spring floods are more predominant at higher elevations and typically occur further east, especially if their headwaters are located east of the Skagit and Pacific Crests (Riedel et al. 2012c). As a critical source of water throughout the North Cascades, the future and longevity of alpine glaciers will impact the frequency and magnitude of floods within the park complex (see “Climate Change”).

The frequency and size of floods affect the supply of water, sediment, and debris to stream channels, which in turn modifies flow and reshapes channel dimensions. Throughout the park complex, flooding often leads to slope instability and is intimately associated with mass wasting events such as debris flows. Large landslides are capable of obstructing rivers or streams, which temporarily allows water to backfill and flood upstream segments; subsequent dam failures can lead to downstream flooding (Fay et al. 2009; Riedel et al. 2012d). According to Strauch et al. (2018), culvert systems that divert water under roads or trails will be at an increased risk of flooding and failure as hydrologic regimes respond to climate change. These culverts are a critical component in maintaining the longevity of the transportation infrastructure within NCCO, especially the North Cascades Scenic Highway (Washington State Route 20; Strauch et al. 2018). The Stehekin River Valley is especially prone to flooding due to its climate, steep topography, and watershed sources (e.g., snowfields, glaciers); some of the largest floods on record for the park complex have caused widespread damage to public and private property along the river corridor (Mierendorf and Reid 1986; Louter 1998; Riedel et al. 2012d).

Mass Wasting

The term “mass wasting” is used to describe downhill movements of rock, soil, or ice and includes several types of landslide phenomena, including debris (or snow) avalanches, debris flows, slumping or slope creep, and rockfalls. Throughout the park complex, mass wasting events are generally influenced by erosional or freeze-thaw processes related to seasonal fluxes in temperature, rainwater, and snowmelt (Riedel et al. 2012b). However, several other factors, including lithology, fault proximity, slope angle, and aspect (slope direction), help control the development of landslide events. These naturally occurring geologic disturbances not only reorganize the physical context and dynamics of the North Cascades but also pose a considerable hazard to visitors, NCCO staff, infrastructure, ecosystems, and other natural resources. Mass wasting events can vary from minor inconvenience to life-threatening disaster and have the potential to impair roads and trails, damage buildings, disrupt utilities (e.g., electricity, internet), wipe out forested hillsides, engulf vehicles, and bury sensitive geologic features (Figures 5–9). According to Graham (2002), park development activities along the Thunder Lake fault at Sourdough Creek destabilized the base of a slope, leading to a recurrence of debris avalanches. Road maintenance activities performed by Washington DOT along the North Cascades Scenic Highway (WA State Route 20) encountered similar slope instability issues with

subsequent rockfalls impacting the travel corridor (Graham 2002). Several landslides documented in the park complex have blocked or obstructed rivers and streams to form temporary lakes and wetlands; subsequent dam failures likely resulted in catastrophic downstream flooding (Fay et al. 2009; Riedel et al. 2012d).

According to Riedel et al. (2012a, b, c, d, e), there are over 1,000 mass wasting landforms inventoried across five of NCCO's major watersheds (Table 4). A significant portion (almost 95%) of these landforms include rockfalls, debris flow deposits, and debris avalanches. One particularly large landslide landform, or sackung, was identified by Riedel et al. (2012a) along the Upper Skagit watershed on the west side of Ross Lake. Sackung typically form when unstable valley slopes gravitationally spread out and away from an adjacent ridge top (Riedel et al. 2012a). Other notable mass wasting landforms in NCCO are snow avalanche impact landforms (SAILS) located in the Stehekin River, Thunder Creek, and Upper Skagit watersheds. These SAILS are depressions or ridge-like deposits formed when a snow avalanche impacts saturated and unconsolidated sediments (Riedel et al. 2012a, c, d).



Figure 5. Photograph of a March 2010 landslide that occurred in ROLA. The 60 m (200 ft)-wide landslide consisted of large boulders and woody debris that buried a section of the Ross Lake Haul Road and destroyed Seattle City Light's barge dock. NPS photograph.



Figure 6. Photograph of a September 2013 debris flow that engulfed several vehicles in LACH. The debris flow damaged or destroyed homes, businesses, roadways, and cars in Stehekin following heavy rains. NPS photograph.



Figure 7. Photograph of debris from a snow avalanche obstructing the North Cascades Highway in ROLA. Consisting of a chaotic mix of snow, rock, and woody debris, this 2011 avalanche originated from Ruby Mountain and blocked the highway near Lillian Creek. A roadway worker stands atop the avalanche for scale. NPS photograph.



Figure 8. Photograph of roadway and culvert damage following a landslide in 2003. The landslide event occurred near Pyramid Creek in ROLA and has wiped out sections of the North Cascades Highway. NPS photograph.



Figure 9. Photograph of a large logjam and muddy floodwaters along Boston Creek in NOCA. Floods such as this one in August 2013 generate large masses of jagged, woody debris that can obstruct rivers or streams and pose a considerable hazard. NPS photograph.

Table 4. Landslide landform inventory along five major watersheds within NCCO.

The following table shows different landslide landforms recorded across the Bacon Creek, Chilliwack River, Stehekin River, Thunder Creek, and Upper Skagit watersheds in NCCO. Information for the table was sourced from Riedel et al. (2012a, b, c, d, e).

--	Bacon Creek	Chilliwack River	Stehekin River	Thunder Creek	Upper Skagit	NCCO Total
Rockfall or topple	64	66	312	57	258	757
Debris flow or torrent	10	10	41	23	32	116
Debris avalanche	7	58	13	24	59	161
Slump/creep	3	9	14	10	16	52
Snow avalanche impact landform (SAIL)	0	0	2	1	2	5
Sackung	0	0	0	0	1	1
Watershed total	84	143	382	115	368	1,092

Permafrost

Permafrost is ground that remains frozen throughout the year due to cold climate conditions. Over the last century, permafrost throughout the Arctic regions of Alaska has thawed in response to warming climate, leading to a slew of consequences including drying or emerging ponds, soil erosion, mass wasting events, destabilized building or road foundations, thermokarst (karst resulting from the selective thawing of ground ice), increased sediment loads of streams and lakes, enhanced greenhouse gas emissions, altered soil profiles,

and impacted nutrient cycling (Gonzalez 2017). Although no incidents of permafrost thaw have been reported within NCCO, it may be important for park management to remain aware of its effects.

Because permafrost is in the subsurface, it is often difficult to observe or map without sufficient soil, environmental, and climate data. According to the DOI SHIRA risk mapper report, only NOCA is identified as having isolated permafrost probability, meaning that <10% of NOCA's land area is underlain by permafrost. Permafrost data provided to DOI SHIRA were produced by the Central Institute for Meteorology and Geodynamics in Austria based on remotely sensed land surface temperatures, climate reanalysis, and land cover classification data.

Radon

Radon is a naturally occurring gas created by the decay of radioactive elements present in many rocks. Although radon is almost always present in small amounts in soil and rocks, some types of rock (e.g., volcanic rocks, granites, dark shales, phosphate-rich rocks, and metamorphic rocks) have the potential to produce above-average amounts of radon gas that can pose a known health risk (Otton 1992). According to the EPA map of radon zones, Whatcom, Skagit, and Chelan counties are identified as zones of moderate potential (zone 2) for elevated indoor radon levels between 2 and 4 pCi/L (see <https://www.epa.gov/radon/epa-maps-radon-zones-and-supporting-documents-state>; accessed November 2024).

Seismicity

Washington state is ranked second in terms of seismic risk in the United States, with at least 15 major damaging earthquakes recorded since 1872 (Washington Geological Survey 2017). According to the national seismic hazard model of Petersen et al. (2023), NCCO occupies a zone of intermediate seismic probability compared to the rest of the country. The park complex is surrounded by multiple seismic stations within a radius of 32 km (20 mi) that are part of the Pacific Northwest Seismic Network (see <https://pnsn.org/seismograms/map>; accessed November 2024). A recent 2024 research permit was submitted to install a USGS ShakeAlert earthquake early warning system in Stehekin (see "Prior NRSS-based Work").

For millions of years, earthquakes accompanied the geologic assembly and restructuring of the North Cascades (see "Geologic History"). Today, seismic activity continues to influence the landscape of NCCO and is known for triggering or accompanying other geohazards, including landslides and volcanism. Low magnitude (a measure of seismic energy at its source) seismic events regularly occur within or adjacent to the park complex. However, many faults throughout the Pacific Northwest can generate earthquakes larger than magnitude M6.5 at shallow depths (Walsh 1996; Silva et al. 1998). Additional tsunami evidence suggests that the Cascadia subduction zone can generate earthquakes greater than magnitude M9.0, the impact of which has been estimated at roughly \$49 billion in damage (Hyndman 1995; Atwater et al. 2015; Washington Geological Survey 2017). According to Rogers et al. (1996), a particularly large historic earthquake occurred near Lake Chelan on 14 December 1872 that had a registered modified Mercalli intensity rating of 9 (a measure of observable seismic damage). Events of this intensity are characterized by "violent" shaking capable of damaging or destroying buildings and other structures (<https://www.usgs.gov/programs/earthquake-hazards/modified-mercalli-intensity-scale>; accessed November 2024).

Swelling Clays

Swelling clays, or shrink-swell clays, include minerals such as smectites that are physically altered by the presence of water and tend to swell when wet and shrink when dry. As swelling clays expand or contract, the change in volume can undermine the integrity of the substrate, increase the susceptibility of slope failure, and cause infrastructural problems along roadways or trails. According to the USDA NRCS Web Soil Survey, all soils mapped within the park complex are rated “low” in linear extensibility (a determination of shrink-swell potential of soils).

In addition to swelling clays, several soil land management ratings are included in the enhanced soil survey report by the USDA, NRCS and DOI, NPS (2012) that address several hazards including soil erosion and road suitability, site restoration, and soil rutting. These ratings can help guide management decision-making regarding erosion-control measures (e.g., revegetation), maintenance, and roadway or trail construction.

Toxicological Soil

According to the DOI SHIRA risk mapper report, soils within the park complex have potentially high amounts of arsenic, asbestos or erionite (fibrous silicate minerals), cadmium, lead, selenium, and *Bacillus anthracis*—a naturally occurring soil pathogen known to cause anthrax. Naturally occurring asbestos or erionite occurs in certain geologic settings (e.g., those containing ultramafic or mafic rocks [rocks with low silica content] and fibrous minerals) and can introduce health issues if disturbed by natural erosion or human activities. Inhalation of fine airborne particles of asbestos or erionite can cause various respiratory illnesses, including mesothelioma and other types of cancer. Soil maps show that potentially hazardous concentrations of arsenic, cadmium, lead, and selenium occur within the top 5 cm (2 in) of soil based on 2010 sampling (DOI SHIRA). For more information on naturally occurring arsenic, cadmium, lead, selenium, and their potential health impacts, visit the US Department of Health and Human Services Agency for Toxic Substances and Disease Registry (see <https://www.atsdr.cdc.gov/>; accessed September 2024).

The bacteria *Bacillus anthracis* causes the rare, naturally occurring disease anthrax, which can cause severe illness in both humans and livestock exposed to spores. For more information on the public health risks associated with anthrax, visit the US Centers for Disease Control and Prevention's anthrax website (see <https://www.cdc.gov/anthrax/about/index.html>; accessed September 2024).

Volcanic Activity

Volcanism has shaped the North Cascades for millions of years and continues to do so today. Washington state has five volcanoes listed as having high or very high threat potential: Glacier Peak, Mount Adams, Mount Baker, Mount Rainier, and Mount St. Helens. Of these, Mount Baker and Glacier Peak have the potential to impact the NCCO region. According to USGS assessments, NOCA is located adjacent to and just outside of Mount Baker's “near-volcano” hazard zone, an area defined by lava and pyroclastic flows (fast-moving avalanches of hot ash, rock fragments, and gas), thick tephra, lahars (volcanic mudslides), ballistic ejecta, and rockfalls (Schilling et al. 1996; Scott et al. 2000; see also <https://www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/volcanoes-and-lahars#volcano-hazard-information-map>; accessed November 2024). Additional hazard studies by Gardner et al. (1995) include the westernmost portion of NOCA within Mount Baker's hypothetical lateral blast (volcanic eruption in which energy is directed horizontally) zone. Future volcanic activity of Mount Baker or Glacier Peak could severely impact several major watersheds (e.g., Nooksack, Sauk, Skagit, Stillaguamish, Suiattle, Sumas, and White Chuck rivers) that ultimately flow west into Puget Sound (Gardner et al. 1995; Waitt et al.

1995; Scott et al. 2000). No other volcanoes present any near-volcano threats to the park complex. Fine-grained tephra deposits preserved within NCCO soils and surficial deposits record multiple eruptions dating back over 13,000 years ago (see “Tephrochronology”; Mierendorf 1998; Spooner et al. 2007, 2008). Following an eruption, airborne tephra or ash can present several safety hazards through fine particulate inhalation and utility or mechanical system damage.

Geologic Resource Protection

Legislatively Required Geologic Inventories

The NPS GRD has developed an article series (<https://www.nps.gov/articles/series.htm?id=FA0A8F89-CD67-1CCE-5A6608B444E8A7C0>; accessed December 2024) that summarizes the laws, regulations, and policies that specifically apply to geologic and soil resources or processes. These protection measures were established to maintain the integrity of these resources or processes while minimizing the impacts of natural or human activity.

The core responsibility of the NPS is to preserve and protect park resources, processes, systems, and values unimpaired for present and future generations. According to National Park Service (2006), the NPS will preserve and protect geologic resources, features, and processes as integral components of park natural systems. The goals of the NPS are to assess the impacts of natural processes and human activities on geologic resources; maintain and restore the integrity of existing geologic resources; integrate geologic resources management into NPS operations and planning; and interpret geologic resources for the benefit and enjoyment of park visitors (National Park Service 2006). Various management protection policies applicable to geologic resources, features, and processes are included in National Park Service (2006) and are also organized at the following website: <https://home.nps.gov/subjects/geology/geoheritage-nps-management-policies.htm> (accessed 26 June 2024).

Paleontological and Cultural Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism’s activity such as nests, burrows, tracks, or feces). Fossils may occur in rocks or unconsolidated deposits, in museum collections, or in cultural contexts, such as building stone.

The paleontological and cultural resources of NCCO are invaluable and provide a unique window into the geologic and historical past. Often discovered in the same context, these resources are susceptible to damage or loss resulting from several natural processes. Indigenous pictographs located in LACH are susceptible to inundation and degradation as Lake Chelan water levels fluctuate in response to seasonal rainfall or snowmelt, flooding, and controlled releases at the Lake Chelan Dam (Mierendorf 1993). In addition to Lake Chelan, the waters of Ross Lake have encroached upon and inundated the Desolation Chert Quarry site in most years (Mierendorf 1993). Several catastrophic floods have destroyed or buried cultural sites along the floodplains throughout the North Cascades; modern communities continue to be impacted along major river valleys (see “Flooding”). There is no way of knowing at present how many sites have been impacted by floods, but the number is likely to be high (Mierendorf and Reid 1986). In addition to flooding, many cultural sites in the park complex are susceptible to disturbance from tree rip-ups, mass wasting events, freeze-thaw, and plant root activity (Mierendorf 1993).

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (PRPA). For additional information regarding paleontological resource laws, regulations, and policies, the NPS GRD developed the following summary article: <https://www.nps.gov/articles/paleontology-legal-instruments.htm> (accessed 26 June 2024).

Hydrological Resources

The park complex contains a vast and diverse network of hydrological features, including snowfields, over 310 alpine glaciers (representing the highest concentration [about 25%] of all glaciers in the lower 48 states), approximately 530 lakes or ponds, roughly 835 ha (2,065 ac) of wetlands, and about 10,000 km (6,200 mi) of rivers and streams (National Park Service 2012, 2019; Hoffman et al. 2015). Together, these hydrological resources are a valuable component of the region’s ecological and geological systems while also serving as sensitive indicators of climate change. It is worth emphasizing that NOCA, ROLA, and LACH were all established to protect the wilderness landscape of the North Cascades—with an emphasis on its glaciated peaks, the upper Skagit River Valley, and the lower Stehekin River Valley (National Park Service 2012).

Over the last century, glaciers within the park complex have diminished considerably in extent and volume; it is estimated that NCCO glaciers have declined about 50% since 1900 (Hoffman et al. 2015). Beginning in 1993, the NPS began long-term monitoring of glacier mass balance within the park complex. These mass balance investigations include direct field measurements of seasonal volume or extent change at four glaciers (Noisy Creek, North Klawatti, Sandalee, and Silver Creek glaciers) in NOCA and LACH (Riedel et al. 2008; Riedel and Larrabee 2017). Glaciers represent critical reservoirs of water that sustain and buffer the supply, flow, temperature, water quality, and geochemistry of lakes, ponds, rivers, streams, and Puget Sound (Riedel and Larrabee 2016). As climate change continues to impact glaciers throughout the North Cascades, their disappearance may have considerable ramifications for aquatic and terrestrial ecosystems (including endangered species such as salmon, bull trout, and western cutthroat trout), recreational opportunities (e.g., lake access, recreational climbing), hydroelectric power generation, and municipal or agricultural water supplies (Hoffman et al. 2015; Riedel and Larrabee 2016, 2017).

Inventory Needs

The following table (Table 5) presents geologic and soil resources inventory needs that were identified during the 2024 follow-up meeting, in NPS planning documents, or through literature review.

Table 5. List of identified geologic and soil resources inventory needs for the national park.

Subject	Inventory Need(s)	Reference(s)
Abandoned mineral lands	Create an inventory of AML sites within the park complex. During the 1990s, the Washington Department of Geology and Earth Resources began an AML program to map these sites but did not investigate AML sites in national parks. AML sites are known to exist in the North Cascades, but they have not been mapped for their biological, cultural, and hazards significance.	Graham (2002)
Geohazards	The park complex should consider using the Unstable Slope Management Program to help communicate hazardous areas and mitigate risk.	2024 follow-up call

Subject	Inventory Need(s)	Reference(s)
Geoscience Research	Although many of the larger plutons have been dated by K-Ar or U-Pb methods, many smaller plutons have not been dated.	Haugerud and Tabor (2009)
Geoscience Research	NCCO could work with the GRD to assist culvert replacement projects that require sediment and/or geomorphological analyses.	2024 follow-up call
Geoscience Research	Perform sedimentological studies along the Stehekin River near the head of Lake Chelan. Hydrologic modeling of Lake Chelan shows a back water effect extending about 0.8 km (0.5 mi) up the Stehekin River at the head of the lake. The impact on sedimentation is not known, but over the years, segments of the lower part of the river are being channelized and hardened.	Graham (2002)
Glacial monitoring	Continued monitoring of all aspects of glacial change is highly recommended, including, but not limited to, glacial area and extent, and cumulative and net mass balance. Supporting research and monitoring of the distribution and diversity of glacier biota such as ice worms and near-glacier biota such as the stonefly (<i>L. borealis</i>). Research link should be pursued between the effects of seasonal glacier melting and long-term glacier recession on stream temperature.	Hoffman et al. (2015)
Glacial monitoring	Monitoring the duration and extent of annual snowpack would provide valuable information to supplement temperature and precipitation data for understanding alpine and subalpine responses to climate change.	Hoffman et al. (2015)
Mapping	Park could benefit from producing an updated, complete map of wetlands for the entire park complex.	Hoffman et al. 2015)
Mapping	NCCO could work with GRD to digitize the USGS geologic map of Haugerud and Tabor (2009), which provides seamless geologic coverage of the park complex.	Tim Henderson (Colorado State University, written communication, November 2024)
Mapping	Some landform maps need to be updated with new LiDAR data. New LiDAR for the park complex is forthcoming, and the last missing pieces were flown a year or two ago. Ongoing landform mapping supports the park complex's ecological long-term monitoring with demonstrated applications to identifying and tracking geological disturbances, fire history, and cultural resource sites. Analysis of geologic and landform maps provides information and understanding on vegetation patterns and paleoecology, hydrological response of watersheds, derivative maps for fire regimes, geologic hazards, information for cultural resource surveys, and natural history information for interpreters.	Graham (2002); 2024 follow-up call
Paleontology	Most of the large landslides at NCCO have been inventoried, and lake deposits upstream of landslide dams likely contain records of floral and faunal change at NCCO in the Holocene. However, many of these features have not been studied in detail.	Fay et al. (2009)
Paleontology	Less than one-third of the Rowland W. Tabor collection at NCCO has been cataloged thus far. It is possible that other specimens within the Tabor collection will also be of paleontological interest.	Fay et al. (2009)
Paleontology	Field samples collected by Peter Misch between 1948 and 1984 are accessioned at NOCA but not cataloged. The collection consists of hand specimens and thin sections. It is not clear which, if any, of the specimens are paleontological.	Fay et al. (2009)

Subject	Inventory Need(s)	Reference(s)
Paleontology	NCCO could work with the GRD to identify fossil plant specimens in the park collections. Collections managers should be aware that the accessioning and cataloging of other “geological” specimens, particularly from the Rowland Tabor geology collection, may reveal additional paleontological specimens.	Fay et al. (2009)
Paleontology	The park should consider future field inventories for paleontological resources to more fully document in situ occurrences of fossils. The park may consider a formal site documentation and condition assessment for significant fossil localities. Monitoring of significant sites should be undertaken at least once a year in the future.	Fay et al. (2009)

Prior NRSS-based Work

Geologic or Soil Research Permits

The following table (Table 6) is a list of completed research projects related to the geology or soils of NCCO. These items are located on the NPS Research Permit and Reporting System of IRMA (see <https://irma.nps.gov/RPRS/Search>; accessed May 2024) but may require government access or assistance. Since 2000, there have been numerous (>75) geoscience research permits issued that include geologic and soil mapping; cultural resource surveys; seismic monitoring; geochemical sampling; stratigraphic, volcanogenic, tectonic, and glacial investigations; AML research; and ecological studies.

Table 6. Research permits related to the geology or soils of NCCO since 2000.

Year(s)	Title
2000	Emplacement and deformation of the Black Peak batholith
2001, 2002, 2003	Geology and petrology of the Hannegan caldera
2001, 2002, 2004, 2005, 2007, 2008	Tectonic significance of the Magic Mountain Gneiss, North Cascades Washington
2001, 2002	Goodell Creek gravel mine restoration research
2002	GIS-based mapping of soil distribution in the Thunder Creek watershed, North Cascades National Park, Washington
2002, 2003	Effects of soil treatments (and bulk density) of germination rates of subalpine plant species: implications for restoration
2002, 2003	Geomorphic Stream Studies Woody dominance, and the frequency of bankfull discharge
2003	The Skagit talc mine: a cultural landscape report
2004, 2005	Soil moisture effects on host plant phenology and larval survival of a checkerspot butterfly, <i>Euphydryas anicia</i> , in the North Cascades National Park Complex
2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2017, 2018, 2019	Structural and thermochronological history of the Skagit Gneiss Complex, North Cascades
2004	USGS national geochemical sample project
2005	Recreational impacts on soil processes and mycorrhizae
2005, 2007, 2008, 2009, 2010	Soil survey of North Cascades National Park Complex
2005	The ecological function of cryptobiotic crusts in subalpine and alpine plant communities
2007	GIS soil mapping: development of the remote area soil proxy model, North Cascades National Park, Washington
2007, 2008	Refinement of a digital soil modeling tool: the remote areas soil proxy model
2007	Distribution of Mount Baker volcanic ash and assessment of volcanic hazard in North Cascades National Park
2007	Glacial rearrangement of drainage in the northern North Cascades Range, Washington: U-Th/He dating of the Skagit River gorge
2010	Linking delta and submarine sedimentary systems: a bathymetric and sub-bottom survey of northern Lake Chelan, Washington

Year(s)	Title
2011	Tree-ring based reconstructions of historic glacier mass balance at South Cascade Glacier, Washington State, USA
2012, 2013, 2014	Assessing the effects of nitrogen deposition on high-elevation plant and soil communities
2012	Low temperature thermochronology of the North Cascades, Washington State, USA
2013	An examination of Froude-supercritical flows and cyclic steps on a subaqueous lacustrine delta, Lake Chelan, WA, USA
2018	Archeological data recovery at two sites within the draw down of Ross Lake, 2018
2018	The role of soil in the evolution of genus <i>Penstemon</i>
2020, 2021, 2022, 2024	Effects of a flare-up on continental magmatic arcs: insights from the structure and metamorphism of the Skagit Gneiss Complex
2020	Archeological testing at 45WH698 rockshelter, Seattle City Light (Applicant)
2021, 2022	Sediment deposition in reservoirs affecting resource areas of concern, Skagit River hydroelectric project, FERC No. 553; Seattle City Light (Applicant)
2021, 2022	CR-03 Gorge Bypass Reach cultural resources survey, Seattle City Light (Applicant)
2021	Transboundary monitoring of water and sediment quality and ecological health in the Skagit River and Ross Lake, Washington State
2021, 2022, 2023	GE-04 Skagit River geomorphology between Gorge Dam and Sauk River study (floodplain level loggers), Seattle City Light (Applicant)
2021, 2022	CR-02 Cultural resources survey, Seattle City Light (Applicant)
2022	GE-03 Erosion and deposition mapping in the Ross Lake drawdown zone, Skagit hydroelectric project, FERC No. 553
2023, 2024	Relating talus characteristics to habitat use by vulnerable alpine mammals in a changing climate
2024	Install ShakeAlert earthquake early warning system in Stehekin, WA

Previous or Ongoing Technical Assistance Requests

The following table (Table 7) provides previous or ongoing technical assistance requests submitted to the GRD related to the geology or soils of the national park. These items are located on the NPS Solution for Technical Assistance Requests (STAR) of IRMA (see <https://irma.nps.gov/STAR/>; accessed May 2024) but may require government access or assistance.

Table 7. Previous or ongoing technical assistance requests related to the geology and soils of the national park.

Year(s)	Title	Program Area
2011	Provide draft report review of nine surficial geology reports for NOCA, MORA, and OLYM	Geologic Features, Processes, and Hazards
2014	Geomorphology of North Cascades National Park: Landform Mapping at North Cascades National Park, Washington	Active Geologic Processes and Hazards

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