National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

# San Juan Island National Historical Park

*Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2014/835

**ON THE COVER**
View of American Camp shoreline looking east. National Park Service photograph.

**THIS PAGE**
Wildflowers blooming in a field in American Camp. The glacial history of San Juan Island deposited large amounts of gravel. Later inhabitants of the island piled large rocks at the edges of fields. National Park Service photograph.

# San Juan Island National Historical Park

## *Geologic Resources Inventory Report*

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August 2014

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

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Please cite this publication as:

Graham, J. P. 2014. San Juan Island National Historical Park: geologic resources inventory report. Natural resource report NPS/NRSS/GRD/NRR—2014/835. National Park Service, Fort Collins, Colorado.

NPS 438/125611, August 2014

# Contents

# List of Figures



# List of Tables

# Executive Summary

*The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for San Juan Island National Historical Park in Washington State on 10–12 September 2002 and a follow-up conference call on 29 November 2012, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.*

San Juan Island National Historical Park commemorates the peaceful resolution of the boundary dispute between Great Britain and the United States that occurred between 1853 and 1872. It is the only national park in the United States that commemorates a British military site. When the park was designated in 1966, the British and American garrisons became two distinct management units. American Camp, at the southern end of San Juan Island, borders the Strait of Juan de Fuca and Griffin Bay. English Camp is sheltered by islands located off San Juan Island's northwestern coast. Its historic buildings border Garrison Bay.

San Juan Island is the second largest island in the San Juan Archipelago, a collection of more than 100 islands approximately 105 km (65 mi) northwest of Seattle and 25 km (15 mi) north of Ebey's Landing National Historical Reserve on Whidbey Island. The islands are part of the Puget Lowland physiographic province, a broad region between the Cascade Range and the Olympic Mountains.

Three radically different geologic processes are responsible for the landscape of the San Juan Islands: plate tectonic collision, ice-age glaciation, and modern coastline processes. These processes have created a diverse collection of geologic features in the park, which include:

- Tectonic features. San Juan Island National Historical Park contains outstanding examples of thrust faulting and metamorphism that resulted from the collision of the North American Plate with the Farallon Plate. Over a relatively short geologic period of 16 million years, from approximately 100 million to 84 million years ago, this tectonic collision also transported the deformed bedrock approximately 2,500 km (1,600 mi) north along the western margin of North America.
- Glacial features. Pleistocene ice-age glaciers carved the bedrock into the current landscape of San Juan Island. Glaciers flowing over the island scratched and gouged the bedrock, resulting in erosional features that are now exposed in English and American camps. High-velocity streams emerging from the glaciers produced outwash plains of well-sorted sediment. Meltwater also cut some of the channels of Puget Sound. As the glaciers receded, they left behind poorly-sorted, unconsolidated deposits of gravel, sand, and silt. The plain at American Camp is a recessional moraine that formed as the glaciers melted. Boulders that had been transported by the ice from origins in the north, referred to as glacial erratics, are now scattered on this plain.
- Raised beaches. During the ice ages, glaciers on San Juan Island were more than 1 km (0.6 mi) thick, and the land was compressed beneath the weight of the ice. Following glaciation, the land began to rise. Former beaches became the exceptional, "world-class" terraces that are now part of the landscape of American Camp.
- Aeolian features. Strong onshore winds have shaped some of the glacial deposits into dunes adjacent to South Beach and Grandma's Cove at American Camp.
- Beaches, headlands, and other coastal features. Modern processes have shaped San Juan Island's coastline to form American Camp's South Beach, which is the longest public beach on the island, as well as the headland of Bell Point at English Camp.
- Estuaries and wetlands. Three temperate marine lagoons, which are rare along the northwestern Pacific coast, border the quiet waters of Griffin Bay along the northern shore of American Camp. Freshwater wetlands occur in both camps and provide some of the few sources of surface water on the island.
- Paleontological resources. Invertebrate fossil assemblages discovered in the park and beyond its borders provide the opportunity to study past environments, climates, and geography of the San Juan Archipelago.

Participants at a 2002 GRI scoping meeting and a 2012 follow-up conference call identified the following geologic issues of particular significance for resource management at San Juan Island National Historical Park.

- Coastal erosion. Coastal wind and wave action erode the glacial outwash deposits that form the bluff supporting the Cattle Point Road in American Camp. The preferred management alternative will realign the road to protect it from further coastal erosion.

- Earthquakes and tsunamis. Located at the juncture of two colliding tectonic plates, the San Juan Islands experience earthquakes that may reach magnitudes of 8 or 9 on the Richter scale. Tsunamis triggered by submarine earthquakes pose a potential hazard to Cattle Point. Some low-lying areas of American and English camps may also be vulnerable to tsunamis.
- Volcanic hazards. San Juan Island National Historical Park lies in the shadow of the Cascade Range. Although volcanic eruptions pose a relatively minor hazard for the park, potential ash-fall and ground shaking from the active Glacier Peak Volcano may occur.
- Global climate change. Rising sea level and increased intensity and frequency of storms will exacerbate bluff erosion at American Camp, impact the historic structures along the coast at English Camp, inundate low-lying areas, change the salinity of semi-enclosed bays and estuarine wetlands, and potentially increase saltwater intrusion into local groundwater aquifers. As part of the NPS Climate Friendly Parks program, San Juan Island National Historical Park developed a Climate Action Plan to reduce its carbon footprint.
- Groundwater issues. Groundwater aquifers provide potable water to the residents of San Juan Island. Increased groundwater pumping to satisfy a growing residential community, along with rising sea level, may cause saltwater to intrude into the aquifers. Excessive groundwater pumping also may decrease the flow of fresh water to the park's lagoons, resulting in a loss of ecological integrity.
- Oil and fuel spills. Every day, thousands of barrels of oil travel through Haro Strait and the Strait of Juan de Fuca. Oil and fuel spills have occurred in Puget Sound in recent years, and future spills may impact the shoreline of San Juan Island. Coastal circulation patterns suggest that oil spills will particularly impact the shores of American Camp, and the entrapment of oil in Westcott and Garrison bays will result in longer residence time along the shores of English Camp.
- Driftwood impacts to coastline features. Logs and woody debris that accumulate along South Beach and estuarine wetlands may change sedimentation patterns and smother vegetation.

The bedrock in San Juan Island National Historical Park records a geologic history extending back millions of years. The older Paleozoic bedrock documents events leading up to the formation of the supercontinent Pangaea. Mesozoic rocks record the collision between the North American and Farallon plates and the accretion of one of at least four individual land masses to the western margin of North America.

Linear striations cut into the bedrock of San Juan Island reflect the erosive power of Pleistocene ice sheets. The glaciers that flowed into the Puget Lowland not only formed the current landscape of the islands, but also gouged deep troughs that became Haro Strait and the San Juan Channel. The unconsolidated deposits of gravel, sand, silt, and mud that blanket most of American Camp document a variety of glacial depositional settings. When the glaciers melted and the extraordinary weight of glacial ice was removed, the San Juan Islands rebounded faster than sea level rose. Former beaches became the terraces that are now exposed at American Camp.

Since the last glacier disappeared from the San Juan Islands approximately 13,600 calendar years before present, the islands have been exposed to coastline processes. Dunes have formed and relentless wave action, tides, and storms continue to erode headlands. Nearshore circulation patterns deposit sediment in sheltered coves and along South Beach.

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in science-based decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report. The report discusses geologic issues facing resource managers at the park, distinctive geologic features and processes within the park, the geologic history leading to the park's present-day landscape, and provides information about the GRI geologic map data produced for the park. Map posters illustrate the geologic data. The Map Unit Properties Table summarizes report content for each geologic map unit. This report also contains a glossary and a geologic time scale.

# Products and Acknowledgements

*The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section describes those products and acknowledges contributors to this report.*

### GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" section and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

### Acknowledgements

Special thanks to Marsha Davis and Jon Reidel for providing excellent photographs and reviews of the GRI report. Jerald Weaver (San Juan Island National Historical Park) provided updated park boundary files. Trista Thornberry-Ehrlich (Colorado State University) drafted many of the graphics used in this report.

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# Geologic Setting and Significance

*This section describes the regional geologic setting of San Juan Island National Historical Park, as well as summarizes connections between geologic resources and other park resources and stories.*

#### Park Location and Designation

San Juan Island National Historical Park preserves approximately 840 ha (2,070 ac) on San Juan Island and is subdivided into two discrete management units: American Camp and English Camp (fig. 1). Both camps were established in 1859 in response to a border dispute triggered by the killing of a pig (NPS 2012a). The 1871 Treaty of Washington demilitarized the United States–Canada border, and the dispute was referred to Kaiser Wilhelm I of Germany for settlement. In 1872, the Kaiser awarded the San Juan Islands to the United States. The British Royal Marines abandoned their garrison in November, 1872, and the US soldiers left in July 1874. The US Congress designated San Juan Island National Historical Park on 9 September 1966 to commemorate the boundary dispute between Great Britain and the United States and its peaceful resolution. San Juan Island National Historical Park is the only national park in the United States that commemorates a British military site and flies the British Union Flag.

American Camp, the larger of the two park units is located at the southern end of San Juan Island. Griffin Bay borders American Camp to the north, and a sand beach extends approximately 10 km (6 mi) along the camp's southern border, which abuts the Strait of Juan de Fuca. The highest point in American Camp is Mt. Finlayson, which rises 90 m (295 ft) above sea level.

English Camp is located at the northern end of the island (fig. 1). Sheltered by islands to the northwest, English Camp borders Garrison and Westcott bays of Haro Strait. At 198 m (650 ft) above sea level, the summit of Young Hill at English Camp is the highest point in the park.

San Juan Island is the second largest island in the San Juan Islands, an archipelago of 175 named islands north of the Strait of Juan de Fuca (fig. 2). The San Juan Channel borders San Juan Island to the east and the Haro Strait lies to the west (fig. 1). Ebey's Landing National Historical Reserve is located on Whidbey Island, approximately 25 km (15 mi) south of the archipelago (see GRI report by Graham 2011). The open waters of the Strait of Georgia lie to the north. Friday Harbor on San Juan Island is the largest town in the archipelago and serves as the San Juan County seat.

The San Juan Islands lie within the Puget Lowland physiographic province, a broad, low-lying region between the Cascade Range and the Olympic Mountains (Easterbrook 1994; Dragovich et al. 2002). Their position relative to the Olympic Peninsula results in an unusually dry climate compared with the rest of western Washington. The mountains on the Olympic Peninsula and Vancouver Island block the warm, moisture-laden air blowing in from the Pacific Ocean, creating a rain-shadow effect in the San Juan Islands. Average annual rainfall is 381 cm (150 in) on the western slopes of these mountain barriers, but only 64 cm (25 in) at English Camp and 48 cm (19 in) at American Camp (Avery 2004; NPS 2012b).

#### Geologic Setting

Eroded headlands, dunes, beaches, terraces, exposures of metamorphosed sedimentary and volcanic rock units, and unconsolidated glacial deposits record three distinct episodes in the evolution of San Juan Island. The older Paleozoic and Mesozoic rock units document the tectonic suturing of a variety of terranes (regionally extensive, fault-bounded blocks of rock) to the North American continent during the Mesozoic, while the more prevalent glacial and interglacial deposits record the influence of the Pleistocene ice ages (figs. 3–5). Since the Pleistocene, modern erosional and depositional processes have modified the island's coastline and contoured the unconsolidated glacial sediments into the beaches and dunes found in American Camp and the Bell Point headland at English Camp.

The San Juan Islands consist of a 10-km- (6-mi-)- thick sequence of nappes, which are sheetlike bodies of rock that have been displaced from their original locations along predominantly horizontal surfaces. These nappes have been stacked onto each other by thrust faults and are collectively referred to as the San Juan Thrust System (Brandon et al. 1988). The nappes and San Juan Islands also form part of the Insular Superterrane, one of four major terranes accreted to the western margin of North America during the Cretaceous (fig. 3). Wrangellia, which is also part of the Insular Superterrane, lies to the west of the San Juan Thrust System and forms Vancouver Island.

The west coast of North America has been part of a convergent continental margin for hundreds of millions of years. During the Cretaceous (fig. 4), the North American Plate collided with the Farallon Plate to produce a linear, 1,200-km- (750 mi-) long region of folded and deformed rocks that extends from northwestern Washington and southwestern British Columbia to southeastern Alaska (Rubin et al. 1990; Cowan and Brandon 1994). When Wrangellia was driven eastward beneath the North American continent, the San Juan Island nappes were thrust approximately 55 km (34 mi) westward onto the Wrangellia terrane (Brandon and Cowan 1987; Brandon et al. 1988). The Mesozoic and Paleozoic rock units in San Juan Island National

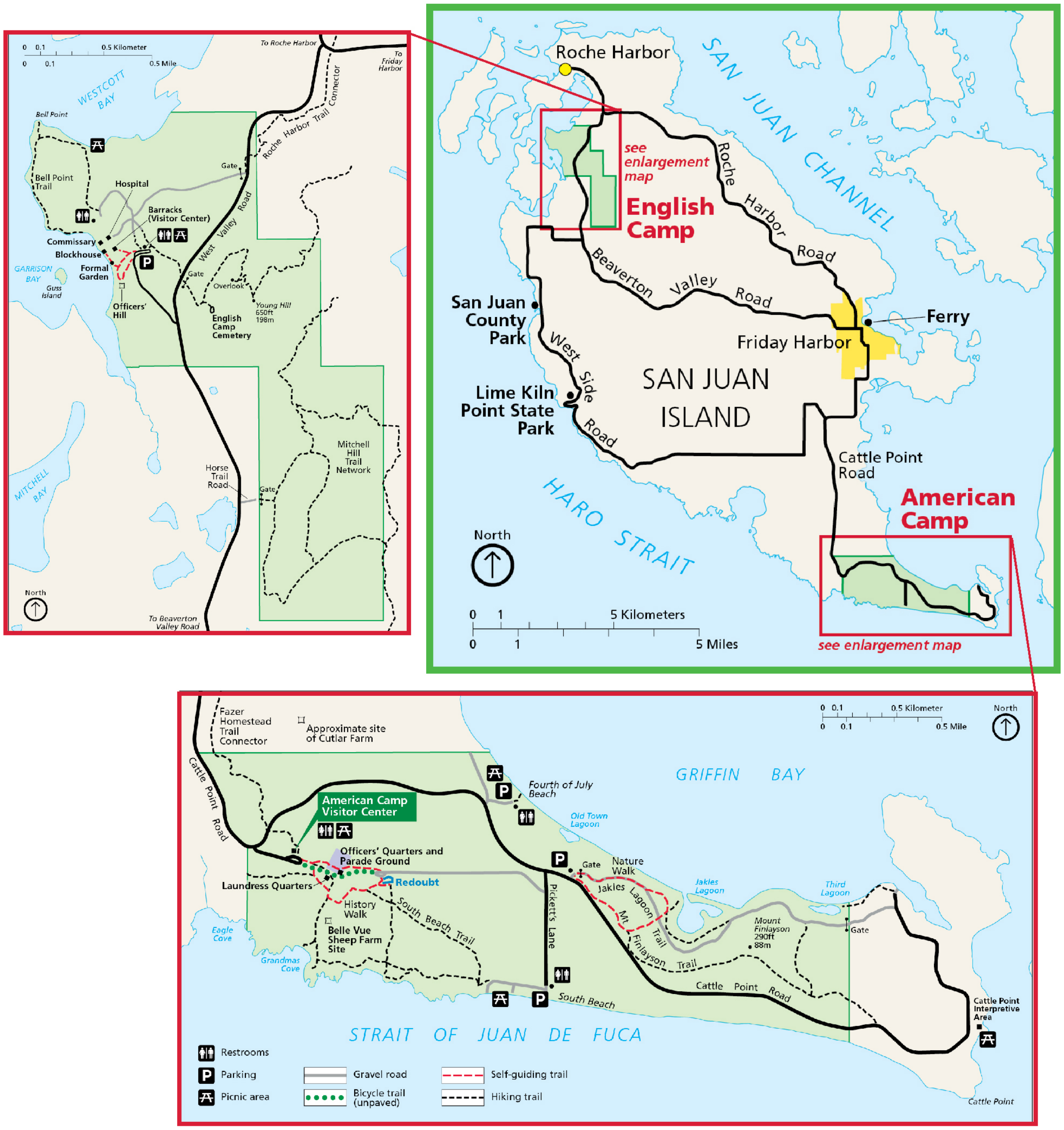



**Figure 1. Park maps. San Juan Island National Historical Park consists of two units—English Camp and American Camp—on San Juan Island in Washington. National Park Service maps, available at: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=SAJH (accessed 22 July 2014).**

Historical Park (fig. 5) provide evidence of this dynamic tectonism that shaped the western margin of North America between 100 million and 84 million years ago.

Massive continental ice sheets shaped the current landscape of San Juan Island and ultimately supplied material for the soil that supported the garden that attracted the pig that almost started a war between two great nations in 1859. The most recent glacial advances to inundate San Juan Island climaxed approximately 17,000 years before present (BP; Dethier et al. 1996; Porter and Swanson 1998; Booth et al. 2004; Washington State Department of Natural Resources 2010). The Puget Lobe of the Cordilleran Ice Sheet likely covered the island for 2,000 years, and the San Juan Islands were covered with approximately 1.2–1.5 km (0.7–0.9 mi) of glacial ice during the glacial maximum (Booth 1986). The powerful eroding force of the glaciers smoothed and rounded the more resistant bedrock of the islands. The combined effects of the thick, fast-moving ice and its surging meltwaters carved deep channels, such as Haro and Rosario straits.

Sea level began to rise 21,000 years ago as the Puget Lobe moved south. This rise, however, was offset by isostatic depression resulting from the weight of glacial ice. By 17,000 years ago, the ice sheet in the Puget Lowland and isostatic depression were both at maxima.

Unconsolidated glacial deposits cover much of San Juan Island, especially at American Camp. As the glaciers advanced, braided streams left outwash deposits of well-sorted gravel and sand [geologic map units Qvrmo and Qgom(e)] in front of the advancing ice front. As the


**Figure 2. The San Juan Archipelago. San Juan Island is the second largest island in the archipelago, following Orcas Island. NHP: National Historical Park; NHR: National Historical Reserve. Map compiled by Jason Kenworthy (NPS Geologic Resources Division) using ESRI World Imagery basemap layer.**

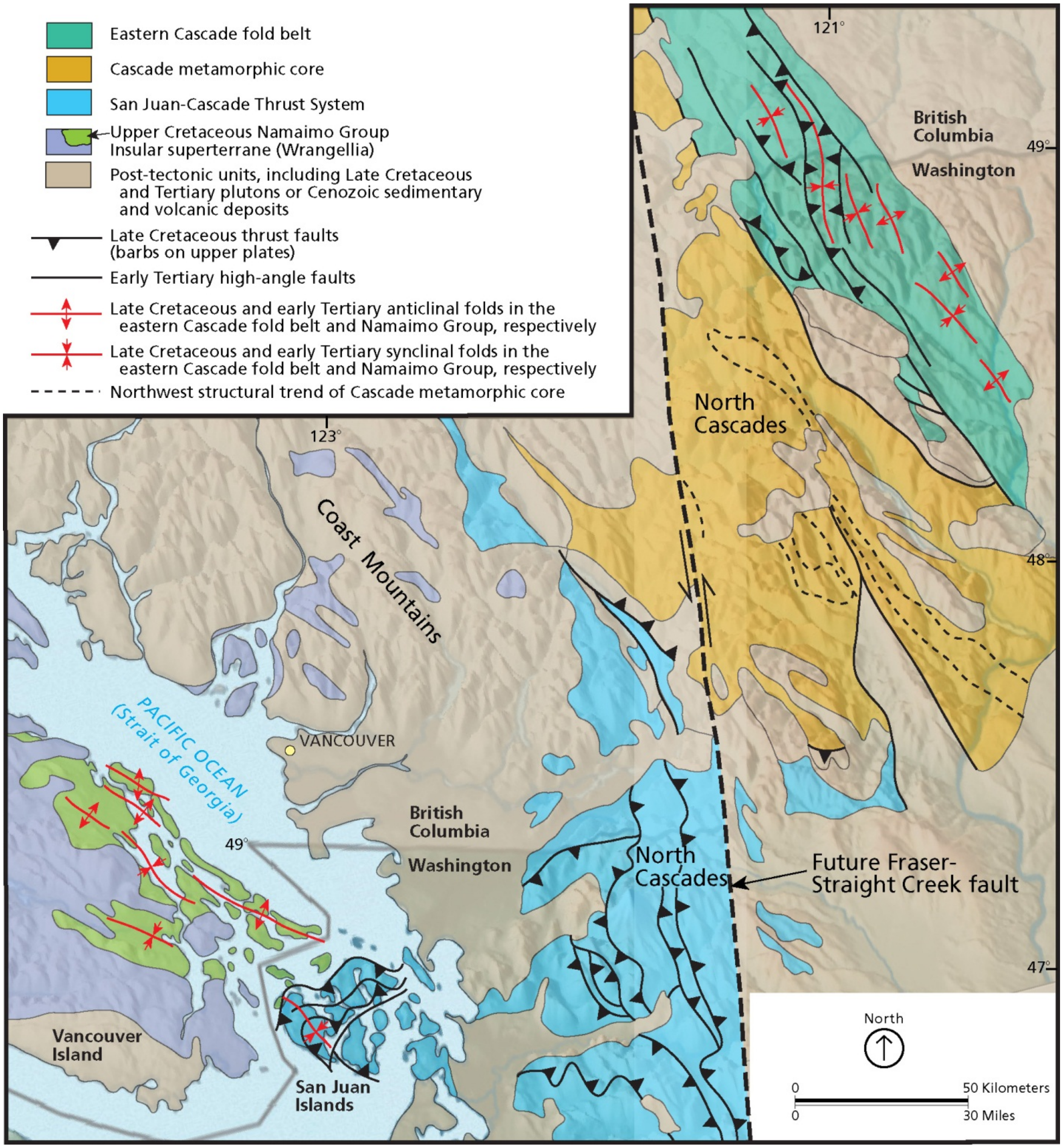



**Figure 3. Simplified regional geologic map. This map shows modern geographic features and the four major tectonic terranes that accreted to Washington's western margin during the Cretaceous: (1) Wrangellia, (2) San Juan–Cascade Thrust System (San Juan Thrust System), (3) Cascade metamorphic core, and (4) eastern Cascade fold belt. Wrangellia, a large terrane that is part of the larger Insular Superterrane, lies west of the San Juan Archipelago and composes most of Vancouver Island. The northwest–southeast-trending San Juan Thrust System includes the San Juan Islands and the Cascade Mountains of northwestern Washington. The other two tectonic zones lie east of the San Juan Thrust System. Graphic by Trista Thornberry-Ehrlich (Colorado State University), redrafted after Cowan and Brandon (1994, fig. 2) using basemap by Tom Patterson (http://www.shadedrelief.com/physical/pages/download.html; accessed 4 April 2014).**

glaciers receded from the San Juan Islands region beginning about 13,600 calendar years BP (Porter and Swanson 1998), a poorly sorted mixture of pebbly silts [(diamicton); Qvrdm and Qgdm(e)] was deposited over much of San Juan Island and American Camp.

A rapid, worldwide rise in sea level occurred following the retreat of the continental ice sheets. Sea level was approximately 100 m (300 ft) higher than it is today (Clark and Steig 2008). Some of this sea-level rise, however, was relative to a land surface that had been compressed beneath the immense weight of the glaciers. When the tremendous weight melted away, the land began to slowly rebound (rise) in a process known as isostacy. Because the land rebounded at a rate faster than the sea level rose, areas that were once below sea level became exposed. For example, sediments deposited in marine environments (Qvrmd and Qvrmo) now form

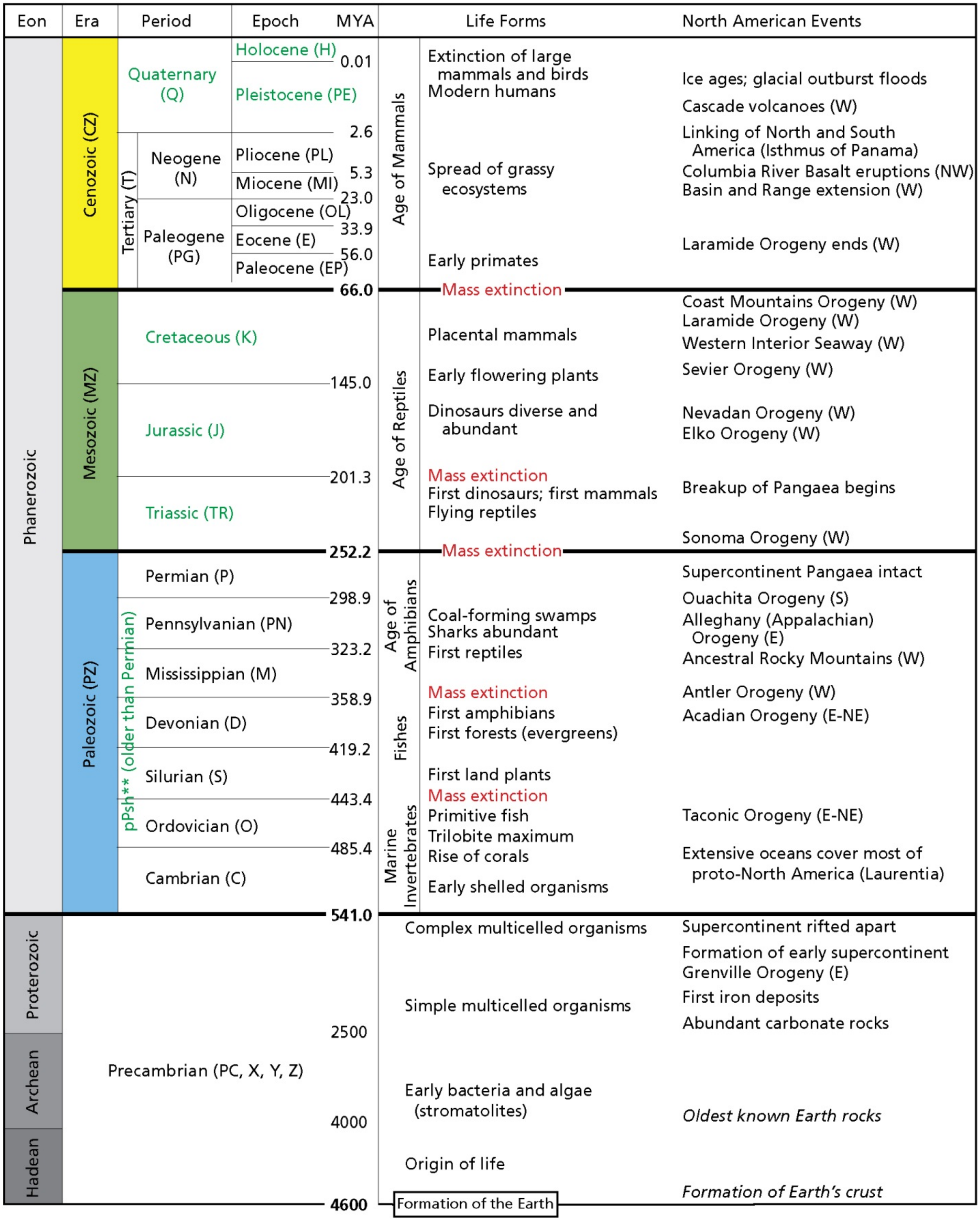



**Figure 4. Geologic time scale. The rock units in San Juan National Historical Park record the collision between the North American and Farallon tectonic plates during the Mesozoic and the influence of the Pleistocene ice ages. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Green text indicates time periods mapped within San Juan Island National Historical Park. **= The age of map unit pPsh is unclear, but is older than Permian. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014).**

| Era | Period (Epoch) | American Camp/southern San Juan Island: Formation/Unit (map symbol) | | American Camp/southern San Juan Island: Description | English Camp/northern San Juan Island: Formation/Unit (map symbol) | | English Camp/northern San Juan Island: Description |
|---|---|---|---|---|---|---|---|
| CENOZOIC | Quaternary (Holocene) | | Fill (Qf) | Artificial material | | Fill (Qf) | Artificial material |
| | | | Dune deposits (Qd) | Well-sorted sand | | Dune sand (Qd) | Well-sorted sand |
| | | | Beach deposits (Qb) | Sand and gravel | | Beach deposits (Qb) | Sand and gravel |
| | | | Marsh, bog, or swamp (Qm) | Fine sand, silt, and peat | | Alluvium (Qa) | Cobbles, gravel, sand, silt, and clay |
| | | | Tidal-flat deposits (Qtf) | Sand and silt | | Peat deposits (Qp) | Peat, silt, clay, and organic matter |
| | | | Landslide deposits (Ql) | Dislocated strata | | | |
| | Quaternary (Pleistocene) | Everson Interstade | Recessional-marine deposits (Qvrm) | Pebbly silt, sand, and gravel | Everson Interstade | Glaciomarine drift (Qgdm) | Poorly compacted pebbly silt and clay |
| | | | Recessional-marine: emergence deposits (Qvrme) | Moderately to well-sorted gravel and sand | | | |
| | | | Recessional-marine: subtidal deposits (Qvrms) | Moderately to well-sorted sand and silt | | Recessional-marine: subtidal deposits [Qgdm(es)] | Well- to moderately-sorted sand, silty sand, and silt |
| | | | Recessional-marine: marine diamicton (Qvrmd) | Pebbly silt and diamicton | | Recessional-marine: marine diamicton [Qgdm(e)] | Well- to moderately-sorted pebbly silt and diamicton |
| | | | | | | Glaciomarine drift [Qgom(e)] | Gravelly sand, sandy gravel, and sand |
| | | Vashon Stade | Recessional-marine: marine outwash (Qvrmo) | Moderately to well-sorted gravel and sand | Vashon Stade | Glacial outwash, marine (Qgom) | Sand, gravel, and silt in ice-contact, outwash, and alluvial-fan deposits |
| | | | Diamicton (Qvd) | Nonstratified till | | Glacial drift (Qgd) | Mixture of till, sand, gravel, silt, and clay |
| | | | Till (Qvt) | Poorly sorted sand, silt, clay, and pebbles | | Glacial till (Qgt) | Clay, silt, sand, gravel, and boulders |
| | Tertiary | No Tertiary rocks are mapped on the island. | | | | | |
| MESOZOIC | Cretaceous | | Lopez Structural Complex [pTbr, KJm(ll)] | Bedrock mantled with <3 m (<10 ft) of surficial deposits | | Lopez Structural Complex [KJm(ll)] | Argillite with minor chert, greenstone, and conglomerate |
| | Jurassic | | Constitution Formation [pTbr, KJmm(c)] | | | Constitution Formation [KJmm(c)] | Sandstone, cherty sandstone, mudstone, and conglomerate with tuff, pillow lava and rare limestone |
| | Jurassic–Triassic | | Orcas Chert; Deadman Bay Terrane [pTbr, JTRmc(o)] | | | Orcas Chert; Deadman Bay Terrane [JTRmc(o)] | Chert with basalt, tuff, limestone, and mudstone |
| | Triassic | | | | | Haro Formation (TRn) | Nearshore sedimentary rocks |
| | | | | | | Volcanics of Deadman Bay (TRPv) | Metamorphosed volcanic rocks |
| PALEOZOIC | Permian | | | | East Sound Group (PDmt) | | PDmt (Perm.–Dev.): metamorphosed sedimentary and volcanic rocks |
| | Pennsylvanian; Mississippian; Devonian | | | | | Garrison Schist (pPsh) ? | pPsh (pre-Perm.): metamorphosed sedimentary rocks |
| | pre-Devonian | | | | Turtleback Complex (pDi, pDitt) | | pDi (pre-Dev.): metamorphosed igneous rocks |

**Figure 5. Stratigraphic column for San Juan Island. Colored units have been mapped in San Juan Island National Historical Park. Perm. = Permian; Dev. = Devonian. See the Map Unit Properties Table for further detail.**


**Figure 6. Mount Finlayson from the Bluff Walks in American Camp, San Juan Island National Historical Park. Now part of the terrestrial landscape, Mount Finlayson consists of marine sediments deposited during the Pleistocene glaciation. Tides and ocean currents have eroded the coastline, exposing pre-Tertiary bedrock. National Park Service photograph by Mike Vouri, available at http://www.nps.gov/sajh/photosmultimedia/The-American-Camp-Prairie.htm (accessed 1 November 2012).**

much of the landscape of American Camp, including Mt. Finlayson, which reaches 90 m (295 ft) above sea level (fig. 6). The exceptionally well-developed terraces above South Beach are remnants of former beaches that were elevated by this isostatic rebound.

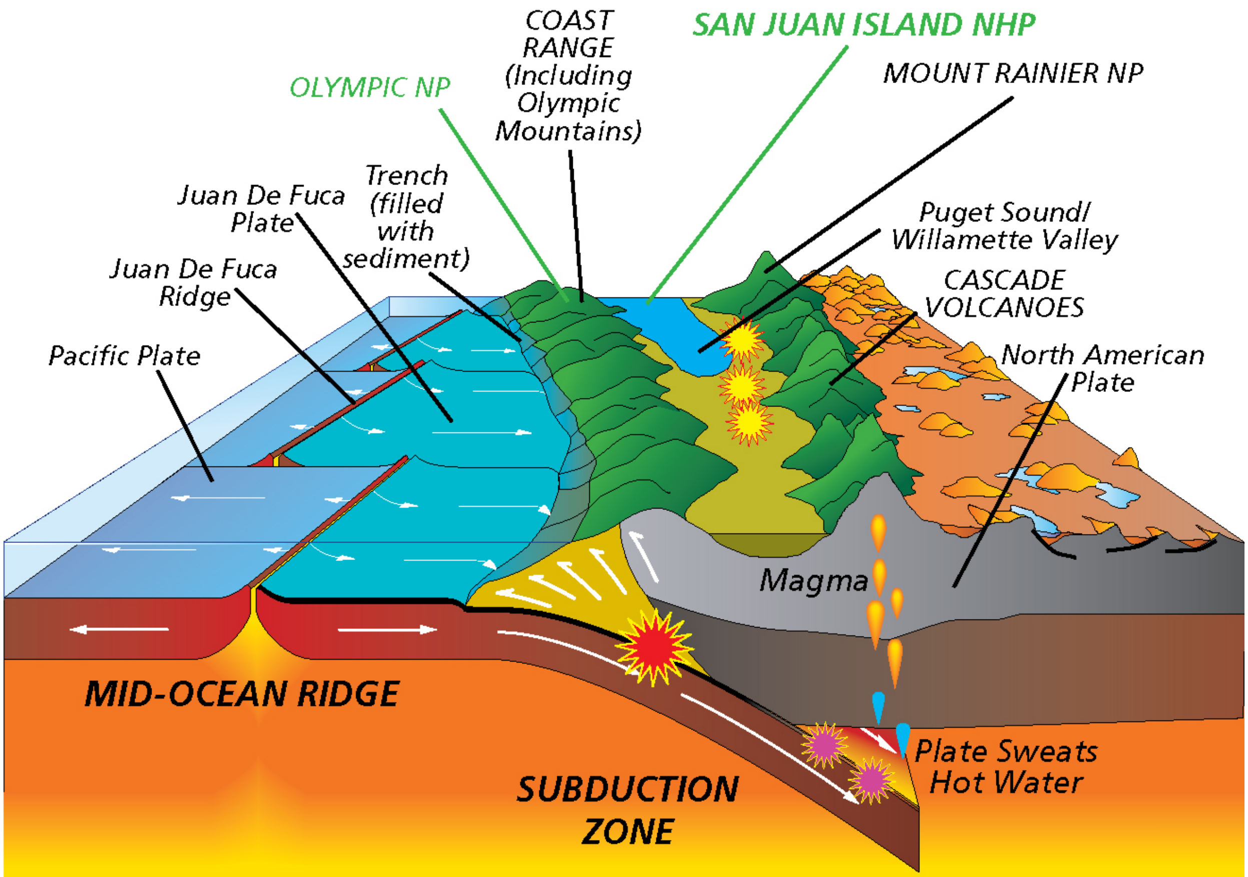
Since the end of the Pleistocene ice ages, strong onshore winds have molded dune deposits (Qd) landward of the beach deposits (Qb) at South Beach. Tides, rip currents, surf, and long-shore currents continuously modify the coastline of San Juan Island (fig. 7). Tidal ranges vary throughout the San Juan Islands, but average 1.3–2.2 m (4.2–7.3 ft). The average diurnal tidal range is 1.6–2.6 m (5.2–8.6 ft). Intertidal exchange between the Strait of Juan de Fuca and the Strait of Georgia results in the passage of an enormous volume of water through the Salish Sea (NPS 2012c). Currents have eroded less-resistant, unconsolidated material from San Juan Island headlands, such as Cattle Point at the southern end of the island and Bell Point at English Camp, and deposited well-sorted, rounded sand and gravel in quieter waters, such as those at South Beach and along the shoreline of Griffin Bay.

The San Juan Islands currently lie above the Cascadia Subduction Zone, where the North American and Juan de Fuca plates are converging at a rate of approximately 3–4 cm (1–2 in) per year (fig. 8). The subduction zone

**Figure 7. Headlands and beaches at American Camp, San Juan Island National Historical Park. The sea continues to modify the coastline of San Juan Island, eroding headlands and less-resistant rocks and depositing sand and silt in protected beaches and coves. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

extends about 1,000 km (600 mi) from northern Vancouver Island to Cape Mendocino in California. The release of strain built up by the collision of the two plates generates earthquakes, some of which are felt on San Juan Island.

San Juan Island National Historical Park preserves a landscape that has been shaped by the ancient activity of glacial ice and the modern processes of wind and water. Windswept prairies, sandy beaches, woodlands, and panoramic views across the Strait of Juan de Fuca and Haro Strait characterize American Camp. On the northern end of the island, Garrison and Westcott bays shelter the meadow, formal gardens, and surrounding forests of English Camp. San Juan Island contains one of the last remaining native prairies in the Puget Sound/Northern Straits region. The maritime climate, sheltered harbors, open prairie, secluded woodlands, and abundant food sources drew people to the area soon after the glaciers melted. Hunters and gatherers arrived between 6,000 and 8,000 years ago, and the first Europeans to enter the area encountered a vibrant marine culture about 2,500 years ago (NPS 2012d). More than preserving a small piece of American history, San Juan Island Historical Park preserves a rich and diverse environment constructed over hundreds of millions of years that has been home to humans for thousands of years.




## Cascadia earthquake sources

| *Source* | *Affected area* | *Max. size* | *Recurrence* |
|---|---|---|---|
| Subduction Zone | West. WA, OR, CA | M 9 | 500–600 years (1700) |
| Deep Juan De Fuca Plate | West. WA, OR | M 7+ | 30–50 years (1949, 1965, 2001) |
| Crustal faults | WA, OR, CA | M 7+ | hundreds of years? (CE 900, 1872) |

**Figure 8. Cascadia Subduction Zone. At the convergent boundary, the denser Juan de Fuca Plate is subducted beneath the North American Plate, causing three kinds of earthquakes. Rocks melt to form magma, which rises to the surface to form volcanoes. Max. size refers to Richter magnitude (M). West.: Western; NHP: National Historical Park; NP: National Park; CE: Common Era (preferred to "AD"). Diagram by Robert J. Lillie (Oregon State University), modified by Jason Kenworthy (NPS Geologic Resources Division). Cascadia earthquake sources information from the US Geological Survey and Pacific Northwest Seismic Network (http://www.pnsn.org/outreach/earthquakesources; accessed 10 November 2012).**

# Geologic Features and Processes

*This section describes noteworthy geologic features and processes in San Juan Island National Historical Park.*

Geologic features in San Juan Island National Historical Park resulted from three vastly different processes: (1) plate tectonic collision that deformed the bedrock; (2) ice-age glaciation that shaped the island's landscape; and (3) recent processes that modified, and continue to modify, the coastline. These processes generated a diverse collection of geologic features in the park, which include:

- Tectonic features
- Glacial features
- Raised beaches
- Aeolian features
- Beaches, headlands, and other coastal features
- Estuaries and wetlands
- Paleontological resources

The first six features are listed in chronological order, beginning with features resulting from Mesozoic tectonics. Paleontological resources include fossils from Quaternary deposits and Mesozoic rocks and are discussed at the end of the section.

### Tectonic Features

San Juan Island National Historical Park contains some outstanding examples of Late Cretaceous thrust faults (fig. 9), metamorphism, and uplift that produced the extensive Cascade Orogeny (Brandon et al. 1988; Cowan and Brandon 1994). Subduction of the Farallon Plate's oceanic crust beneath the less-dense continental crust of the North American Plate resulted in a complex array of faults and folds in the San Juan Archipelago and within the borders of the park (fig. 3; see geologic map posters). Convergence of the two plates produced the San Juan Thrust System, one of four major north–south-trending tectonic terranes that compose the 1,200-km- (750-mi-) long belt of rocks in the Cascade Orogen (fig. 3; Cowan and Brandon 1994). Furthermore, deformation associated with the San Juan Thrust System occurred over a period of 16 million years, from 100 million to 84 million years ago, a surprisingly short geologic period of time for such a remarkable display of tectonic elements (Brandon et al. 1988; Cowan and Brandon 1994).

#### Late Cretaceous Thrust Faults

Four major thrust fault zones have been recognized in the San Juan Thrust System: Haro, Orcas, Rosario, and Lopez (Brandon et al. 1988; Cowan and Brandon 1994). These thrust faults have transported sheetlike bodies of rock on relatively horizontal surfaces and stacked them atop one another (fig. 10). Each thrust unit is internally faulted and deformed, creating a complex zone of imbricate (overlapping) thrust slices. In general, the lower halves of the thrust systems consist of Paleozoic and lower Mesozoic units, and the upper halves consist of upper Mesozoic units.

The Rosario Thrust, the dominant thrust on San Juan Island, is exceptionally well-exposed along the southwestern coast of the island, including part of American Camp (Cowan and Brandon 1994). The thrust has transported the Constitution Formation [geologic map unit KJmm(c)] at least 30 km (19 mi) and placed it over the Deadman Bay terrane [JTRmc(o) and TRPv; fig. 11]. At South Beach, the Rosario Thrust trends offshore and terminates against the north–south-trending Buck Bay Fault, which branches from the Lopez Thrust and is buried by glacial deposits in American Camp (Brandon et al. 1988; Cowan and Brandon 1994).

In English Camp, the Rosario thrust fault separates the Constitution Formation [KJmm(c)] from the underlying Orcas Chert of the Deadman Bay terrane [JTRmc(o)]. The Commissary, Blockhouse, Formal Garden, and Officers' Hill were constructed adjacent to one of the imbricated thrust slices in the Rosario Fault Zone that has juxtaposed the Orcas Chert of the Deadman Bay terrane above the Garrison Schist (pPsh). The 198-m- (650-ft) high crest of Young Hill, in eastern English Camp, is composed of the Constitution Formation [KJmm(c)], which has been thrust over Orcas Chert [JTRmc(o)].

Slices of Garrison Schist (pPsh) have been caught up in the upper 100–200 m (330–660 ft) of the thrust zone (fig. 11). Garrison Schist clasts are exceptionally large, with diameters ranging from 1 to 10 m (3–30 ft). Excellent exposures of the Rosario Thrust at Eagle Point and along the southwestern coast of San Juan Island display fault slices of Garrison Schist surrounded by Orcas Chert [JTRmc(o); Brandon et al. 1988]. Because they have no relationship with the rocks in the footwall and hanging wall (fig. 9) of the Rosario Thrust, these slices are considered to be "exotic" components of the fault zone (Brandon et al. 1988; Cowan and Brandon 1994).

The Lopez Fault Zone intersects the southernmost end of San Juan Island. Imbricate thrust slices within this zone cut the southern hook of San Juan Island and the southeastern corner of American Camp (Brandon et al. 1988). On the Cattle Point headland, the Lopez Structural Complex [KJm(ll)] is juxtaposed with the Constitution Formation [KJmm(c)].

The Haro Fault Zone intersects only the far northern portion of San Juan Island, near Davidson Head north of English Camp. Orcas Chert [JTRmc(o)] in the hanging wall of the east–west-trending Haro thrust fault lies

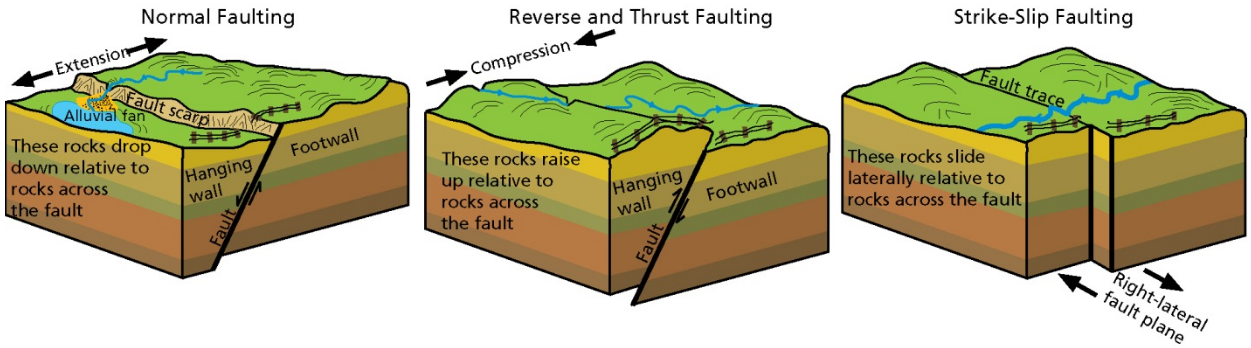



**Figure 9. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).**

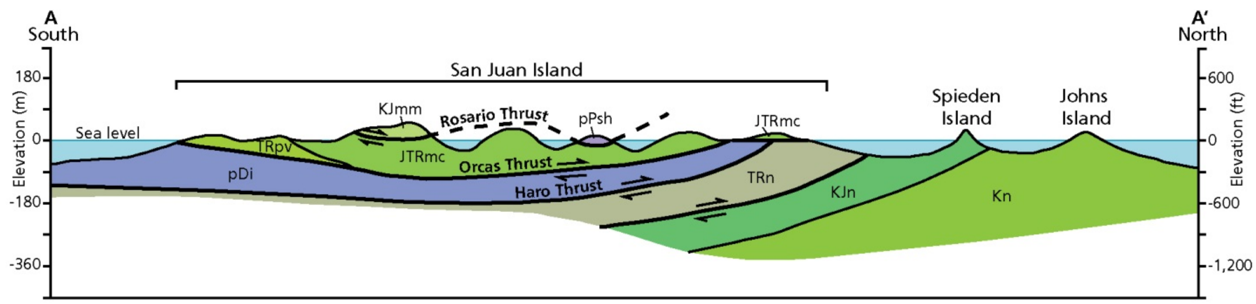
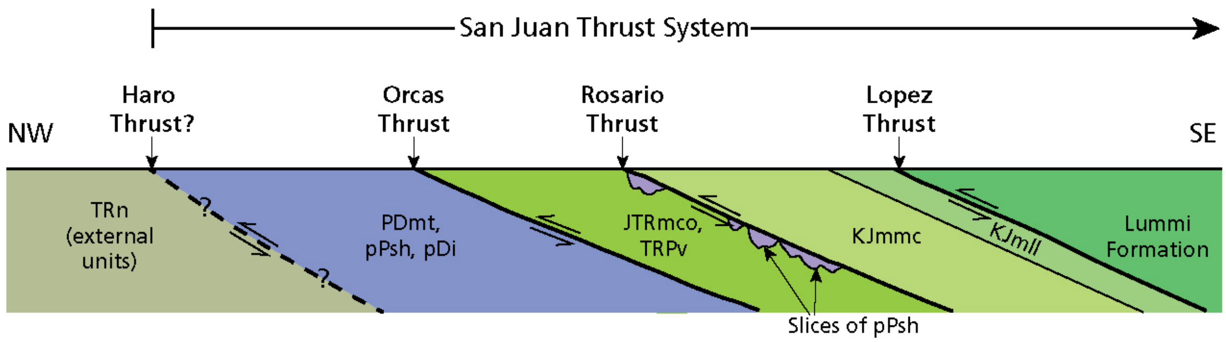



**Figure 10. South–north geologic cross section (A–A′) showing the subsurface structure of San Juan Island. The cross section suggests that the following deformation events occurred: (1) a thrust transported older Triassic rocks of the Haro Formation (TRn) over Jurassic and Cretaceous units (KJn, Kn), (2) the Haro Thrust transported the pre-Devonian Turtleback Complex (pDi) over the Haro Formation, (3) the Orcas Thrust juxtaposed the Deadman Bay terrane (TRPv, JTRmc) above the Turtleback Complex, (4) the Rosario Thrust transported the Constitution Formation (KJmm) over the Deadman Bay terrane, and (5) the sequence was then folded into a broad syncline. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Logan (2003).**




**Map Units**

| | | | |
|---|---|---|---|
| KJmll | Lopez Structural Complex | TRPv | Volcanics of Deadman Bay terrane |
| KJmmc | Constitution Formation | PDmt | East Sound Group |
| JTRmco | Orcas Chert, Deadman Bay terrane | pPsh | Garrison Schist |
| TRn | Haro Formation | pDi | Turtleback Complex |

**Figure 11. Schematic cross section of the San Juan Thrust System. The Rosario Thrust, which is the dominant thrust on San Juan Island and in San Juan Island National Historical Park, separates the Paleozoic and lower Mesozoic units in the lower part of the San Juan Thrust System from the younger, upper Mesozoic units in the upper part of the system. Arrows indicate direction of movement. Diagram modified from Brandon et al. (1988, fig. 4) by Trista Thornberry-Ehrlich (Colorado State University).**

immediately south of the steeply-dipping Haro Formation (TRn; Cowan and Brandon 1994).
The Orcas Fault Zone is not represented on San Juan Island. The west–east-trending Orcas Thrust has been mapped north and east of the island (Brandon et al. 1988).

### Metamorphism

The rocks in the San Juan Archipelago record two primary episodes of metamorphism. The Turtleback Complex [pDi, pDit(t)], Garrison Schist (pPsh), and Deadman Bay Volcanics (TRPv), which are thrust sheets in the lower half of the San Juan Thrust System, document high-grade metamorphism that occurred in the Permian and Triassic, prior to Late Cretaceous thrust faulting and deformation. A second episode of very low-grade, high-pressure metamorphism then occurred in the Late Cretaceous and is characterized by the formation of the metamorphic minerals lawsonite, prehnite, and aragonite (Vance 1968; Brandon 1982; Brandon et al. 1988). Prehnite- and lawsonite-bearing assemblages are best developed in Jurassic and Cretaceous volcaniclastic sandstones, such as the Constitution Formation [KJmm(c)] on San Juan Island, but they are found in all rocks in the San Juan Thrust System. Many limestone units were recrystallized into coarse-grained marble, and veins of aragonite cut other rock types. The widespread distribution of metamorphic mineral assemblages post-dates the emplacement of the San Juan thrusts and helps constrain the timing of thrusting, metamorphism, and subsequent uplift (Brandon et al. 1988).

The Paleozoic and Triassic rocks of the Turtleback Complex, Garrison Schist, and Deadman Bay Volcanics contain minerals and rock types that developed from the initial metamorphic event. The mudstone, siltstone, and sandstone in the Garrison Schist and Deadman Bay terrane have been metamorphosed to slate, phyllite, schist, and quartzite (fig. 12). Well-developed schistosity (parallel alignment of fine-grained minerals) in the Garrison rocks distinguishes them from adjacent less-metamorphosed rocks of the Orcas [JTRmc(o)] and Constitution [KJmm(c)] formations (fig. 13). In the upper 100–200 m (330–660 ft) of the Rosario Fault Zone, the metamorphic minerals prehnite, epidote, and actinolite occur in slices of the Garrison Schist (Brandon et al. 1988; Cowan and Brandon 1994).

| Parent rock | | | |
|---|---|---|---|
| **Shale** | **Sandstone** | **Limestone** | **Basalt** |
| Slate | | | |
| Phyllite | | | |
| Schist | | | |
| Gneiss | Quartzite | Marble | Eclogite |
| Rock melts, forming magma | | | |

**Figure 12. Classification of metamorphic rocks and metamorphic rock types present in San Juan Island National Historical Park. The grade of metamorphism increases with temperature and pressure down the columns until the rock ultimately melts. Classification diagram after Lillie (2005, Table 2.5).**

**Figure 13. Orcas Chert [JTRmc(o)] and Constitution Formation [KJmm(c)]. The Orcas Chert (upper image) forms in "ribbons" and is composed of accumulations of silica-bearing skeletons of radiolaria, siliceous sponges, and diatoms. Originally, the ribbons of chert were relatively horizontal, but deformation events have mangled the chert, resulting in its present appearance. Photograph from Dan McShane (http://washingtonlandscape.blogspot.com/; accessed 15 July 2013). The Constitution Formation (lower image) forms the slopes of Young Hill in English Camp. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

Orcas Chert [JTRmc(o)] also contains limestone that has been metamorphosed to marble. Early in the twentieth century, limestone quarries at Roche Harbor, north of English Camp, were the principal lime producers in the state of Washington (Landes 1914; McLellan 1927). The layers of marble at Roche Harbor are separated by interbeds of chert and argillite. Although not especially thick, the layers have been folded and the folds have been overturned so that each limestone layer is repeated at least three times (McLellan 1927). Lime kilns also existed at Friday Harbor and on the west coast of San Juan Island. On the west side of San Juan Island, Lime Kiln Point, the only state park on the island, offers tours of the old kiln and the opportunity to view Orca whales.

Thrust sheets associated with the Rosario Fault Zone on San Juan Island document a high-pressure metamorphic event that occurred after the initiation of Late Cretaceous thrust faulting about 100 million years ago, but prior to 84 million years ago (Cowan and Brandon 1994). Compared with the older rock units, these rocks have been only slightly metamorphosed. The Constitution Formation, for example, contains the metamorphic minerals lawsonite, prehnite, and pumpellyite, indicative of low-grade, high-pressure metamorphism. The unit also contains sandstone that has not been metamorphosed to quartzite and mudstone that has been compacted to form argillite, representing a lower metamorphic grade than slate. In addition, Mesozoic radiolarians, microscopic marine organisms with siliceous skeletons, escaped destruction by metamorphism. Metamorphic minerals and rock types associated with the Rosario Fault Zone suggest that peak metamorphism occurred at temperatures of 150°C–200°C (300–390°F) and about 500 Mpa (5 kb) pressure (Cowan and Brandon 1994).

### The San Juan Thrust System and Metamorphism

Commonly, metamorphism in subduction zones records increased pressure and temperatures resulting from plate convergence. However, Late Cretaceous metamorphism of the rocks in San Juan Island National Historical Park resulted from burial, rather than long-term subduction, thrusting, and accretion of exotic terranes to North America (Brandon et al. 1988). By the Late Jurassic, the thrust-bounded rock units in the San Juan Thrust System had been attached to continental America (Brandon et al. 1988). The diversity of clastic units (ranging from volcaniclastics to metamorphic rocks and chert) on San Juan Island and their lithologic and metamorphic similarity to pre-Late Jurassic terranes in northern California and southern Oregon suggest that they were part of a larger, continent-like land mass. Late Cretaceous thrusting thus involved tectonic reworking of older assemblages that had previously been accreted to the North American continental margin.

As the thrust sheets of the San Juan Thrust System were stacked atop one another, increased pressure from burial caused metamorphism. The maximum depth of burial was about 20 km (12 mi), corresponding to peak temperatures and pressures calculated for these units (Brandon et al. 1988). With uplift and erosion, these metamorphosed thrust slices were exposed at the surface.

### Uplift

Although the Late Cretaceous Nanaimo Formation is not exposed on San Juan Island, Nanaimo conglomerates on Sucia Island contain clasts derived from the Deadman Bay terrane. Erosion of the Deadman Bay rocks indicates that they were uplifted, most likely above sea level. Deadman Bay clasts in younger rock units indicate that the units in San Juan Island National Historical Park were uplifted and eroded following thrusting and metamorphism during the Late Cretaceous (Brandon et al. 1988).

### Folding

In the Tertiary, the thrust sheets were folded into broad folds. Some fold limbs dip as steeply as 45° to 60° (Brandon et al. 1988). A northwest–southeast-trending syncline (concave fold) bisects the northern part of San Juan Island from Westcott Bay to northern Griffin Bay. The axis of the fold tilts gently to the southeast. English Camp is located on the southwestern limb of the fold.

## Glacial Features

Glacial features (fig. 14) in San Juan Island National Historical Park resulted from the last major ice age, known locally as the Fraser Glaciation. This event included inundation of the Puget Lowland by ice that was more than 1 km (0.6 mi) thick for 2,000 years.

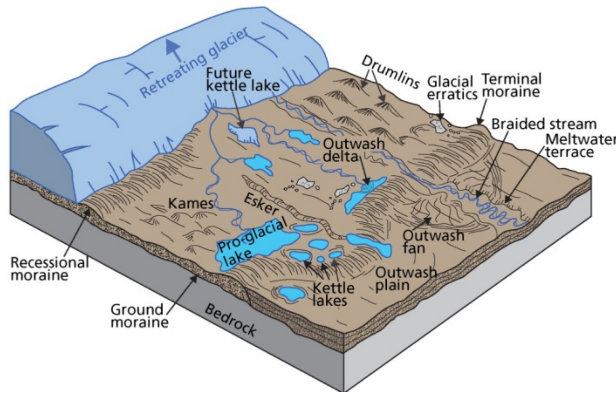



**Figure 14. Schematic illustration of various alpine and continental glacial features. Not all features on the illustration are found in all glacial landscapes. Glacial features in San Juan Island National Historical Park include moraines, outwash plains, and glacial erratics. Graphic by Trista Thornberry-Ehrlich (Colorado State University).**

As the glaciers flowed over the islands, they elongated, smoothed, and rounded the landscape by plucking and abrading the bedrock. Young Hill at English Camp was scoured into a series of nearly flat bedrock benches. Coarse rock fragments frozen into the base of the ice scraped and ground against bedrock, leaving grooves and scratches known as glacial striations (fig. 15). Such striations, which formed parallel to the direction of ice-flow are visible on exposed bedrock at English and American camps. Striations on Young Hill at English Camp and in pre-Tertiary bedrock [pTbr, KJmm(c), and JRTmc(o)] bordering American Camp indicate that the last glacier flowed from the northeast to the southwest (Dethier et al. 1996).

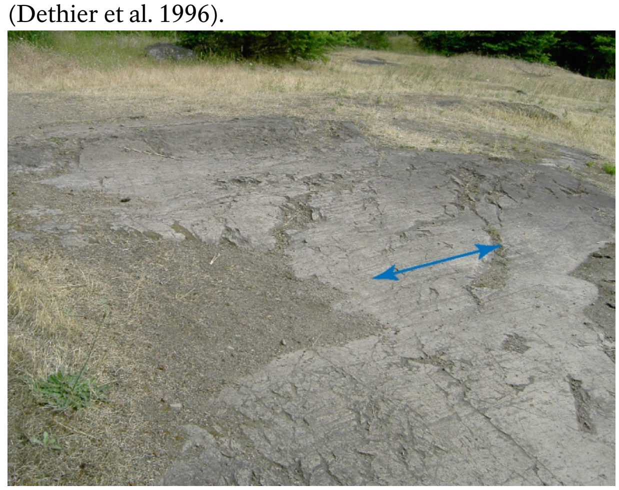


**Figure 15. Glacial striations and glacial polish at English Camp. The striations form parallel to the movement of the glacier (arrows). National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

Glacial deposits left behind after the last glacier melted dominate the geologic units in English Camp and American Camp. At English Camp, continental glacial till (Qgt) consists of an unstratified, highly compacted mixture of poorly sorted clay, silt, sand, pebbles, and boulders. This unit is called a "lodgment till" because it was deposited and compacted directly beneath the base of a glacier. At its maximum during the last ice age, glacial thickness was more than 1.2 km (0.7 mi).

On the peninsula south of Friday Harbor, lodgment till is overlain by outwash deposits [Qgom(e)] consisting of stratified medium- to well-sorted cobbles, pebbles, and coarse- to medium-grained sand. Outwash deposits formed as high-velocity braided streams, choked with sediment, emerged from the glacier front and transported, sorted, and rounded the cobbles, pebbles, and sand (fig. 14).

At American Camp, outwash deposits (Qvrmo and Qgom) overlie glacial till or bedrock and have been radiocarbon dated to approximately 13,200 years old (16,300 calendar years BP; Dethier et al. 1996). The cross-bedded, well-sorted beds of gravel and sand are generally 0.3–2.1 m (1–7 ft) thick and are overlain by marine diamicton, a general term for poorly to moderately sorted mixtures of pebbles, sand, and silt [Qvd, Qvrmd, and Qgdm(e)]. Thick deposits of glacial till are visible east of Pickett's Lane and from the Cattle Point Road observation pullouts.

The expansive prairie at American Camp, one of the few remaining undeveloped prairies in western Washington, formed on top of an end moraine left by the retreating ice sheet. The moraine is composed of 3–15 m (10–15 ft) of glaciomarine diamicton [Qgdm(e) and Qvrmd; fig. 16], with the greatest thickness occurring near Cattle Point. Fossil shells collected in growth position from this fossiliferous unit yielded ages of 13,100 and 12,800 years (15,900 and 15,100 calendar years BP; Dethier et al. 1996).

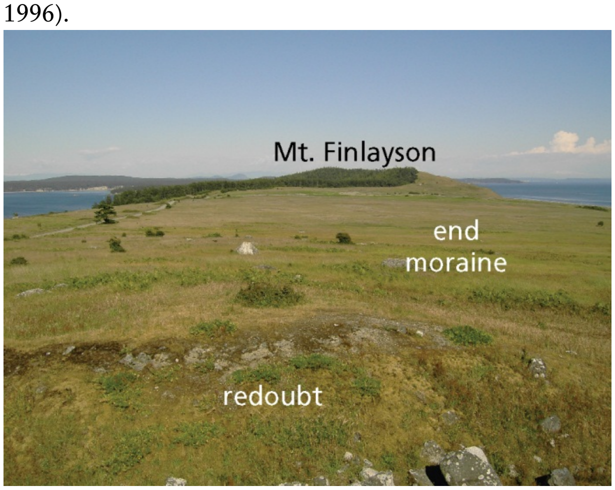



**Figure 16. American Camp prairie. The vast prairie at American Camp formed in glacial diamicton. The view in this photograph is to the southeast, toward Mt. Finlayson, with the redoubt (temporary fortification) in the foreground and the Strait of Juan de Fuca to the right. The diamicton forms an end moraine that developed beneath the most recent glacier. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

Emergent terrestrial (Qvrme) and marine subtidal (Qvrms) deposits form the youngest glacial deposits on San Juan Island and overlie the marine diamicton (fig. 5). Radiometric ages of the cross-stratified to massively bedded sands and silts of the marine subtidal deposits range from 12,900 to 12,500 years (15,200–14,800 calendar years BP), and those of shell fragments collected from the locally cross-stratified sand and gravel beds of the emergent deposits range from 12,800 to 12,300 years (15,100–14,100 calendar years BP; table 1). The emergent deposits unconformably overlie glacial till or marine deposits and are overlain by aeolian sand.

When glacial melting began about 15,000 years ago, eroded sediment formed fan-shaped deposits at the ice-contact margin at the southern end of San Juan Island. The gravel (and some sand) built up into a delta at sea level, which was 90 m (300 ft) higher than it is today. The thick gravel and sand became Mt. Finlayson, a glacial moraine composed of ice-contact marine fans (Qgom, Qvrmo). It is the only feature of its kind in the northern Puget Lowland (Fay et al. 2009).

The melting glacier also left behind glacial erratics, boulders and rocks that had been plucked from their northern bedrock source and transported to San Juan Island. Glacial erratics provide widespread evidence of glaciation. The open prairie at American Camp is studded with these erratics, some of which traveled approximately 300–480 km (200–300 mi) from their source outcrops in the north.

### Raised Beaches

San Juan Island National Historical Park contains "world-class" marine terraces on the southern side of Mt. Finlayson. Each terrace represents a beach that formed at sea level. Following glaciation, two corresponding events with contrasting effects significantly impacted San Juan Island. Melting glaciers caused sea level to rise, while the land, which had been depressed by the tremendous weight of glacial ice, began to rise in a process known as isostatic rebound. A rapid sea level fall (land uplift) occurred approximately 12,000 years ago (James et al. 2000). The rate of isostatic rebound exceeded that of sea-level rise, and beaches, which had been beveled into gently sloping platforms by wave action, became raised and terrace-like. The spectacular series of terraces above South Beach record episodes of relatively rapid isostatic rebound coupled with periods of slower rebound, which formed wave-cut terraces (fig. 17).

Raised beaches also occur in the forests around English Camp, at the northern end of Bell Point, and on the northwestern side of Young Hill. They are flat and range from 3 m (10 ft) to more than 60 m (200 ft) above modern sea level (Jon Riedel, NPS North Cascades National Park, geologist, written communication, 18 January 2014).

The widespread Mazama ash—erupted from Mt. Mazama within what is now Crater Lake National Park (see GRI report by KellerLynn 2013)—in the Puget

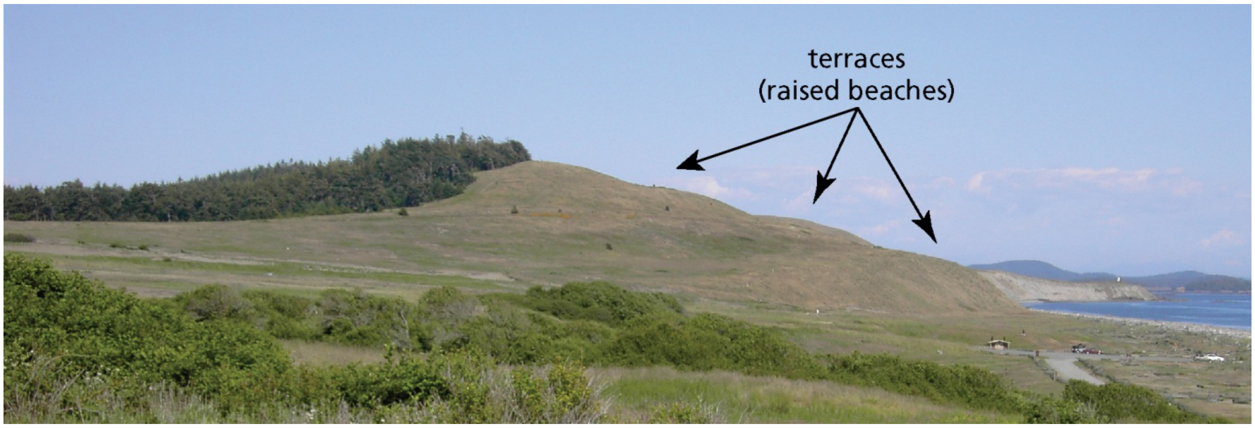



**Figure 17. Terraces (raised beaches) on the southern side of Mt. Finlayson. These former beaches were elevated during isostatic rebound following glaciation. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

Lowland was deposited approximately 7,700 years ago. It is overlain by brackish-water and terrestrial peats, suggesting that isostatic uplift was mostly complete by this time (Thorson 1981). Present-day postglacial rebound uplift rates are estimated to be less than 0.1 mm (0.004 in) per year (James et al. 2000).

### Aeolian Features

Strong onshore winds coming off the Strait of Juan de Fuca have eroded beaches on the southern side of American Camp and deposited a field of sand dunes [Od; generally 2–5 m (7–16 ft) thick] adjacent to South Beach and Grandma's Cove. Active and sparsely vegetated dunes are most extensive near South Beach. The well-sorted, cross-stratified, medium- to coarse-grained dune sand contains layers of silt and may include one or more buried ancient soil intervals (paleosols).

### Beaches, Headlands, and Other Coastal Features

American Camp's South Beach is the longest public beach on San Juan Island. The moderately well- to well-sorted gravel and coarse sand (Qb) that blanket the shoreline above the high tide line have been deposited over bedrock in most areas. Numerous smaller pocket beaches, such as that at Grandma's Cove (fig. 7), also occur along the coast. During extreme low tide, extensive tidal mud flats (Qt) are exposed in Garrison Bay at English Camp.

Relentless wave action, tidal ranges of 1.3–2.2 m (4.2–7.3 ft), and storms continue to modify the coastal landscape of San Juan Island. Unconsolidated glacial deposits have been eroded from the headlands and unprotected stretches of shoreline, exposing bedrock. The Lopez Structural Complex [KJm(ll)] forms Cattle Point at the southern end of the island, and surf pounds the Orcas Chert [JTRmc(o)] along the southwestern coast (fig. 7). The headland at Bell Point in English Camp is composed of erosion-resistant Garrison Schist (pPsh). Battering by waves and surf has carved tide pools in the exposed bedrock, generating habitats for a variety of marine organisms (fig. 18).

**Figure 18. Tide pools. Tide pools carved into bedrock by persistent wave action become habitats for a variety of marine organisms. National Park Service photograph courtesy of Julia Vouri, available at http://www.nps.gov/sajh/naturescience/oceans.htm (accessed 19 November 2012).**

### Estuaries and Wetlands

Transport of sand and gravel eroded from glacial deposits on bluffs has formed gravel barriers that created lagoons on the northern shore of Cattle Point. Jakles, Old Town, and Third lagoons are the only estuarine wetlands (Qm and Qp) on San Juan Island. Jakles Lagoon is the largest of these three temperate marine lagoons, which are rare along the northwestern Pacific coast (fig. 19). Fluctuations in salinity result from the interaction of salt water and subsurface fresh water inflow. No surface creek flows into the lagoon (National Park Service 2012e). Together, these tidal lagoons contain 4.05 ha (10.1 ac) of subtidal unconsolidated bottom deposits, 3.93 ha (9.72 ac) of emergent intertidal deposits, and 1.2 ha (2.9 ac) of intertidal shoreline.

Wetlands, which are transitional areas between terrestrial and aquatic systems, cover approximately 5% of San Juan Island National Historical Park. American Camp contains 26 wetland units covering a total of 32.1 ha (79.2 ac), and English Camp contains nine wetlands covering 5.14 ha (12.7 ac). The largest freshwater wetland in American Camp covering about 0.13 ha (0.33

**Figure 19. Jakles Lagoon. The lagoon, located along the northern shore of American Camp, is the largest of three estuarine wetlands in San Juan National Historical Park and a valuable ecological resource. Climate change may impact estuarine wetlands. Rising sea level may change the lagoon's hydrology and ecological integrity. Groundwater pumping may also decrease the amount of fresh water entering the lagoon. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

ac), occurs along a hiking trail between Jakles and Third lagoons. In 1860, the Royal Marines at English Camp used discarded shells from an immense shell midden (see the "Paleontological Resources" section) to fill in wetlands and create parade grounds.

### Paleontological Resources

Fossils in San Juan Island National Historical Park and the Puget Lowland provide the opportunity to study past environments, climates, and geography. Most fossils in the park are contained in unconsolidated Quaternary deposits, but invertebrate marine fossils have been discovered in older bedrock exposures outside of the park and may eventually be found within the park boundaries (Fay et al. 2009). Some Quaternary fossils from San Juan Island National Historical Park are associated with archaeological sites, providing an example of fossils found in cultural resource contexts. The paleontological resources in San Juan Island National Historical Park have been summarized in Fay et al. (2009).

#### Quaternary Fossils (Pleistocene and Holocene)

Pleistocene fossil assemblages from San Juan Island document the transition from marine to non-marine environments on San Juan Island during the Vashon Stade (a period of glacial advance) and Everson Interstade (a period of glacial retreat) of the Fraser Glaciation. The assemblages also provide a framework for the timing of Pleistocene glacial events, although radiocarbon ages have not been calibrated to calendar years or corrected for marine reservoir effects (Fay et al. 2009). In the park, invertebrate fossils (primarily mollusks) are known from marine outwash (Qvrmo), diamicton (Qvrmd), subtidal (Qvrms), and emergent (Qvrme) deposits (table 1). Genera and species are listed on the Map Unit Properties Table.

Analyses of pollen assemblages from bog or lake beds on San Juan and neighboring islands may aid the understanding of the region's ecological history. Ancient pollen has been collected from fir, alder, spruce, lodgepole pine, poplar, Douglas fir, willow, buffaloberry shrub, and mountain and western hemlocks. Fay et al. (2009) summarized and provided references to these fossil studies.

In addition to invertebrates and pollen, Quaternary megafauna have been identified from sites in the San Juan Archipelago (Fay et al. 2009; Wilson et al. 2009). A jawbone belonging to the bear *Arctodus simus* was discovered on private land on San Juan Island, between Friday Harbor and Cattle Point. The site also contained bison vertebrae and associated shell material. All known Quaternary megafauna from the islands have been recovered from wetlands. Because calcium carbonate from shells tends to neutralize the acidic conditions of wetlands, preservation of bones and other faunal remains is greater in wetlands that also contain abundant shell material.

#### Mesozoic and Paleozoic Fossils

Although no Mesozoic or Paleozoic fossil has been documented from formations within San Juan Island National Historical Park, several units in the footwall of the Rosario thrust fault contain fossils (table 2). For example, Late Triassic conodonts, which have helped to establish an age for the Orcas Chert, have been recovered from small limestone pods incorporated into the Orcas Chert mudstone along the eastern edge of Eagle Cove and the western boundary of American Camp (Brandon et al. 1988).

#### Cultural Resource Contexts

The arrangement, breakage, and proportion of bison fossils uncovered at the pre-Clovis site on Orcas Island suggest butchering by humans (Wilson et al. 2007, 2009). If this hypothesis is correct, it will document earlier human occupation of the islands than previously thought.

Prior to excavation by the British to build a parade ground in 1860, discarded shells along the shore at English Camp formed an immense mound nearly 3 m (10 ft) high and 370 m (1,200 ft) long. Such features containing stratified artifacts and faunal remains have helped to establish the chronology of human occupation in the region, as well as the ecological and anthropological history of the San Juan Islands. The English Camp site was excavated before San Juan Island National Historical Park was established, but a site at American Camp has held archaeological interest before and after the park's establishment. This site contains material dating to approximately 600 calendar years BP (Stein 2000; Fay et al. 2009). Future field investigations may lead to the discovery of additional fossils and artifacts, which may contribute further insight into the past.

**Table 1. Pleistocene fossil genera and radiocarbon ages from glacial deposits, San Juan Archipelago, Washington. Yellow rows signify locations on San Juan Island.**

| Stratigraphic Unit (symbol) | Sample Location | Most Abundant Genera | 14C Age | Cal BP | Depositional Environment |
|---|---|---|---|---|---|
| Emergence deposits (Qvrme) | Shaw Island Quadrangle | Beetles: *Chlamys*<br>Bivalve fragments: *Saxidomus* | 12.32 | 14.16 | Shallow marine subtidal to intertidal |
| | Davis Bay, Lopez Island | Bivalves: *Clinocardium*, *Mya* | 13.07 | 15.64 | Nonspecific marine |
| Questionable Qvrme deposits | Shaw Island Quadrangle | Bivalves: *Macoma, Mytilus*, *Saxidomus*, *Clinocardium, Protothaca*<br>Gastropods: *Heliosoma*, *Physa* | 12.62 | 15.01 | Shallow marine subtidal to intertidal |
| | Davis Bay, Lopez Island | Gastropods: *Heliosoma*, *Physa*, *Limnophysa* | 12.88 | 15.20 | Lagoons or coastal wetlands |
| Subtidal deposits (Qvrms) | False Bay Quadrangle | Bivalves: *Mytilus, Macoma, Mya, Saxidomus, Hiatella* | | | Shallow marine subtidal to intertidal |
| | Friday Harbor Quadrangle | Bivalves: *Macoma, Mytilus, Mya, Clinocardium*<br>Barnacles: *Balanus*<br>Urchins: *Strongylocentrotus* | 12.64 | 15.03 | Marine subtidal |
| | South Beach, San Juan Island | Bivalves: *Macoma*, *Mya*, *Saxidomus*<br>Gastropods: *Trichotropis*<br>Polychaete worms: *Serpula*<br>Barnacles: *Balanus* | 12.6 | 15.0 | Shallow marine subtidal to intertidal |
| Questionable Qvrms deposits | False Bay, San Juan Island | Bivalves: *Macoma, Mytilus, Mya, Clinocardium, Serripes, Hiatella*<br>Limpets: *Puncturella*<br>Gastropods: *Trichotropis, Spirobis*<br>Polychaete worms: *Serpula*<br>Barnacles: *Balanus* | | | Moderately deep marine to subtidal? |
| | | Bivalves: *Saxidomus* | 12.65 | 15.04 | Shallow marine subtidal to intertidal |
| | Shaw Island Quadrangle | Bivalves: *Mytilus*, *Macoma*, *Mya*, *Clinocardium, Saxidomus*, *Protothaca,*<br>Polychaete worms: *Serpula*<br>Periwinkles: *Littorina* | | | |
| | | Bivalves: *Hiatella* | 12.60 | 14.99 | Nonspecific marine |
| Marine diamicton (Qvrmd) | False Bay, San Juan Island | Bivalves: *Nuculana, Clinocardium,*<br>Barnacles: *Balanus* | | | Moderately deep marine to subtidal |
| | Friday Harbor, San Juan Island | Bivalves: *Macoma, Mytilus, Mya, Nuculana, Clinocardium, Hiatella,*<br>Barnacles: *Balanus* | 13.05 | 15.60 | |
| | Griffin Bay, San Juan Island | Bivalves: *Macoma, Mytilus, Mya, Clinocardium, Serripes, Hiatella*<br>Polychaete worms: *Serpula*<br>Barnacles: *Balanus*<br>Urchins: *Strongylocentrotus* | 13.00 | 15.53 | |
| | Davis Bay, Lopez Island | Bivalves: *Clinocardium*, *Mya* | 13.07 | 15.64 | |
| | Richardson Quadrangle | Bivalves: *Hiatella* | 12.80 | 15.14 | |
| Questionable Qvrmd deposits | False Bay, San Juan Island | Bivalves: *Clinocardium*, *Hiatella, Nuculana* | 12.77 | 15.13 | |
| | False Bay Quadrangle | Bivalves: *Hiatella*, *Mya*, *Nuculana*, *Serripes* | | | |
| Marine outwash (Qvrmo) | Friday Harbor, San Juan Island | Bivalves: *Macoma*, *Mytilus*, *Hiatella*<br>Barnacles: *Balanus* | 13.24 | 16.40 | Nonspecific marine |

***Note: Compiled and modified from Dethier et al. (1996, table 1), which is available in the Ancillary Map Information Document (in GRI GIS data). Ages in thousands of years; Cal BP: radiocarbon (14C) age calibrated to calendar years before present using the table available at http://c14.arch.ox.ac.uk/intcal09.14c (accessed 5 February 2014). Fossils collected in San Juan National Historical Park are documented in the Map Unit Properties Table.***

**Table 2. Paleozoic and Mesozoic fossils and isotopic ages from San Juan Island.**

| Geologic Unit (map symbol) | Sample Location | Age-Diagnostic Fossils or Dating Method | Age |
|---|---|---|---|
| Constitution Formation (KJmmc) | Mulno Cove, Griffin Bay | Radiolaria | Late Jurassic to Early Cretaceous |
| | Dinner Island, Griffin Bay | Radiolaria | Late Jurassic to Early Cretaceous |
| | Eagle Cove | Conodonts | Late Triassic |
| Orcas Chert (JTRmco) | Northeastern San Juan Island (7 localities) | Radiolaria<br>Conodonts | Middle or Late Triassic to Early Jurassic |
| | Northwestern San Juan Island (11 localities) | Radiolaria<br>Conodonts | Late Triassic to Early Jurassic |
| | Southwest San Juan Island (6 localities) | Radiolaria<br>Conodonts | Late Triassic |
| Haro Formation (TRn) | Davison Head (3 localities) | *Halobia* cf. (clam)<br>*H. inortissima*<br>Radiolaria | Late Triassic |
| | Davison Head | K/Ar whole rock | 141 million years ago (Early Cretaceous) |
| Deadman Bay Volcanics (TRPv) | Deadman Bay | Algae<br>Conodonts | Early Permian |
| | Cowell Quarry | Fusulinids (Tethyan) | Late Permian |
| | Mitchell Bay | Fusulinids (Tethyan) | Late Permian |
| Garrison Schist (pPsh) | Mt. Dallas | K/Ar hornblende | 256–228 million years ago (Permian–Triassic) |
| Turtleback Complex (pDitt) | Cape San Juan (southeastern promontory) | U/Pb zircon | 398 million years ago (Devonian) |
| | | Fission-track zircon | 265–294 million years ago (Permian) |

***Note: Compiled and modified from Brandon et al. (1988, tables A-3–A-5, A-9, T-6). Isotopic ages are based on the ratio of potassium (K) to argon (Ar) in the mineral hornblende and uranium (U) to lead (Pb) in zircon.***

# Geologic Resource Management Issues

*This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in San Juan Island National Historical Park. The NPS Geologic Resources Division provides technical and policy assistance for these issues.*

During the 2002 scoping meeting and 2012 conference call, the following geologic resource management issues of significance for San Juan National Historical Park were identified:

- Coastal erosion
- Earthquakes and tsunamis
- Volcanic hazards
- Global climate change
- Groundwater issues
- Oil and fuel spills
- Driftwood impacts to coastline features

**Figure 20. Shoreline erosion at English Camp. High tides extend to the base of the historic blockhouse (show here), and the Formal Garden (adjacent to the blockhouse) lies near the water's edge. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

### Coastal Erosion

Unrelenting wave action, tidal exchange, onshore winds, and global climate change affect the coastlines at English and American camps. At English Camp, the formal gardens and Blockhouse border Garrison Bay and rest on bedrock composed of the Garrison Schist (geologic map unit pPsh). By comparison, the coastline at American Camp consists primarily of unconsolidated glacial outwash (Qvrmo and Qgom) and beach deposits (Qb). On southern San Juan Island, wave action frequently generates landslides by undercutting bluffs composed of glacial sediments. Climate change (see "Global Climate Change" section) is expected to exacerbate coastal erosion by increasing the rate of sea-level rise, precipitation, wave energy from storms, and storm frequency (MacLennan et al. 2010; MacLennan and Williams 2012).

Although rising sea level will affect the structures at English Camp (fig. 20), the more significant and immediate coastal erosion issue concerns American Camp, where wave action has been undercutting the bluff that supports Cattle Point Road, the only thoroughfare to the east end of the Cattle Point peninsula (fig. 21). Wave-cutting processes, which are most intense in winter, when large storm waves and high tides coincide, cut steep scarps in the toe of the bluff, initiating slope failure, especially near Milepost 8.3. Human foot traffic has also contributed to slope instability at the top of the bluff [Western Federal Lands Highway Division and San Juan Island National Historical Park (WFLHD-SAJH) 2012].

Although rates of bluff erosion vary in the area in which the road is located closest to the bluff, they average 0.4 m (1.3 ft) per year (WFLHD-SAJH 2012). The rate of bluff retreat was fairly steady from 2004 to 2012, but major storm events may cause larger portions of the bluff to fail rapidly in the future. In 2012, erosion brought the bluff scarp as close as 9.4 m (31 ft) from the roadway. Some estimates place the bluff scarp 0.6 m (2 ft) from the outside face of the guardrail by about 2026 if the road is not moved (WFLHD-SAJH 2012).

In 2010, a draft Environmental Impact Statement proposed realignment of the Cattle Point Road. The preferred alternative, presented in the Final Environmental Impact Statement for the Cattle Point Road Realignment Project (WFLHD-SAJH 2012), involves realignment of about 1,510 m (4,950 ft) of the road to the north. The new alignment would follow the highest terrace on Mt. Finlayson for approximately 300 m (1,000 ft) and will place the road about 90 m (300 ft) from its current location. This realignment will protect the Cattle Point Road from coastal erosion for an estimated 105 years (WFLHD-SAJH 2012).

Under the preferred alternative, construction of the new roadway, road cuts and fills, and equipment storage areas, as well as removal of the old road, will disturb approximately 6.9 ha (17 ac). About 5.3 ha (13 ac) will be restored and revegetated and 1.2 ha (3.0 ac) of pavement from the abandoned road will be removed, leaving a net increase of approximately 0.4 ha (1 ac) of impermeable pavement surface. Sites may be required to dispose of excess soil and rock material, but no new disposal site will be created in the park, where such activity is prohibited (WFLHD-SAJH 2012).

**Figure 21. Erosion of the bluff near Cattle Point Road at American Camp, San Juan Island National Historical Park. The bluff is composed of recessional-marine outwash deposits (geologic map units Qvrmo and Qgom). Note the steepness of the bluff. As waves undercut its base, mass wasting potential increases and the bluff will eventually collapse. Also note the relatively horizontal layering of deposits. National Park Service photograph by David Steensen (NPS Geologic Resources Division).**

The marine terraces on Mt. Finlayson represent former beaches that were uplifted following the last glaciation of San Juan Island. Covered by open grassland and showing minimal disturbance by human activity, these terraces are excellent examples of the process of isostatic rebound following glaciation. They represent significant geologic features in San Juan Island National Historical Park, and are among the more outstanding remaining terraces in the Puget Lowlands. The new roadway will make visitors' observation of these terraced benches more difficult, but it will allow access to Cattle Point (WFLHD-SAJH 2012).

### Coastal Erosion and Sediment Supply

The approximately 29 km (18 mi) of coastline surrounding San Juan Island can be divided into 28 drift cells (MacLennan et al. 2010). These drift cells transport sediment from sources (feeder bluffs) that comprise approximately 18% [5.1 km (3.2 mi)] of the coastline. Most of the feeder bluffs border American Camp and occur along southern Griffin Bay and South Beach, as well as in False Bay. An especially long drift cell begins 0.8 km (0.5 mi) east of Eagle Cove and transports sediment east along South Beach to a point 0.5 km (0.3 mi) west of the Cattle Point lighthouse (Johannessen 1992; Klinger et al. 2006). Smaller, less frequently occurring segments of feeder bluffs occur in rocky embayments on the northern part of the island. Several drift cells have been identified in Westcott Bay, and a drift cell in Garrison Bay moves 1 km (0.6 mi) southwestward from Bell Point along the English Camp shoreline (Johannessen 1992; Klinger et al. 2006; MacLennan et al. 2010).

The drift cells associated with Westcott Bay and South Beach originate outside the boundaries of San Juan Island National Historical Park. As a result, any shoreline development that restricts the natural erosion of the feeder bluffs associated with these drift cells will alter the sediment supply to shorelines in the park (Klinger et al. 2006). Within the park, the realignment of the Cattle Point Road is not expected to affect the feeder bluffs upon which it will be located, and thus will not alter sediment transport dynamics along South Beach.

## Earthquakes and Tsunamis

The San Juan Archipelago lies within a complex region of deformation with a long history of earthquakes. The subduction of the Juan de Fuca Plate beneath North America generates three types of earthquakes, all of which pose potential hazards to San Juan Island National Historical Park: subduction zone, deep, and shallow crustal earthquakes (fig. 8). Earthquakes occurring along the Cascadia Subduction Zone also may generate tsunamis that may inundate low-lying areas of Puget Sound. A variety of earthquake monitoring techniques are in place throughout the Pacific Northwest.

At the southern tip of San Juan Island, a northwest–southeast-trending thrust fault juxtaposed the Lopez Structural Complex [KJm(ll)] over the Constitution Formation [KJmm(c)]. Several northwest-trending faults have been mapped in the Strait of Juan de Fuca, near the island's coastline (Balfour et al. 2012). Branching faults extend northward from this fault zone and disappear into Mitchell Bay, south of English Camp.

### Subduction Zone Earthquakes

Subduction zone earthquakes occur at the interface of the North American and Juan de Fuca plates. These plates are converging at a rate of approximately 4.5 cm (1.8 in) per year, and the collision causes strain to build up (Balfour et al. 2012). The seismic strain is complicated by oblique strain, as the northward-moving Pacific Plate is pushing the Juan de Fuca Plate to the northeast. Earthquakes occur when accumulated stain is released suddenly.

Subduction zone earthquakes can be enormous, with magnitudes of 8 to more than 9 on the Richter scale (Walsh et al. 2012). On average, these earthquakes occur every 550 years, but the recurrence interval has been irregular, ranging from 100 years to about 1,100 years. The last subduction zone earthquake in Washington occurred on 26 January 1700 and had an estimated magnitude of 8.7 to 9.2 (Atwater et al. 2005).

### Deep Earthquakes

Deep earthquakes occur in the subducting Juan de Fuca Plate at depths of 25–100 km (16–62 mi). Since 1870, six deep earthquakes with measured or estimated magnitudes of at least 6.0 have occurred in the Puget Sound Basin. The deep Nisqually earthquake of 2001 had a measured magnitude of 6.8 and ground shaking lasted about 40 seconds. Deep earthquakes occur at an average interval of 30–50 years and are generated by mineral changes in response to increased pressure and temperature. Minerals in the subsiding Juan de Fuca Plate alter to denser forms that are more stable at depth; as they do, the plate shrinks and stresses build up that pull it apart (Walsh et al. 2012).

### Shallow Earthquakes

Shallow earthquakes occur on faults in the overlying crust of the North American Plate and have recurrence intervals of hundreds of years (fig. 8). Although shallow earthquakes are influenced by strain from the Cascadia Subduction Zone, they are generated primarily by the shearing motion of the Pacific Plate as California grinds along the western edge of the North American Plate (Pacific Northwest Seismic Network 2012).
These earthquakes occur within approximately 35 km (20 mi) of the surface and have recorded magnitudes of up to 7.3; they thus pose significant hazards to major population centers, such as Seattle, Victoria, and Vancouver, as well as to San Juan Island National Historical Park (Balfour et al. 2012). In 1946, a magnitude-7.3 crustal earthquake occurred near Courtney on Vancouver Island, causing the collapse of chimneys and building fronts, slumping, and landslides (Rogers and Hasegawa 1978; Balfour et al. 2012). Recent examples in Washington include magnitude-5 to -5.5 earthquakes near Bremerton in 1997, near Duvall in 1996, off Maury Island in 1995, near Deming in 1990, near North Bend in 1945, and in the St. Helens Seismic Zone in 1981 (Walsh et al. 2012).

### Earthquake Risk, Monitoring, and Tsunami Potential

The Puget Lowland is classified as a Seismic Risk Zone 3 on a scale of 0 to 4, with 4 representing the highest risk (Washington State Department of Natural Resources 2010). In 1949 and 2001, the epicenters of damaging earthquakes with Richter-scale magnitudes of 7.1 and 6.8, respectively, were located under Olympia, and the 1965 magnitude-6.5 earthquake was centered under Seattle/Tacoma. Magnitude-6 to -7 earthquakes occur in the Puget Lowland, and future earthquakes may impact San Juan Island.

Although magnitude-6 to -7 earthquakes occur in this region, determination of when and on which fault the next earthquake will occur is difficult. The US Geological Survey maintains an online application to estimate the probability of a particular magnitude earthquake occurring over a specified time period. The tool is available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 23 July 2014). According to that tool, there is between a 0.20 and 0.25 probability (between 20% and 25%) of a magnitude 6.5 earthquake occurring near Friday Harbor, Washington during the next 50 years (fig. 22).

Damage from earthquakes is caused principally by strong ground shaking, ground failures (surface rupture, ground cracking, landslides, liquefaction, subsidence), and/or tsunamis (Walsh et al. 2012). Infrastructure in San Juan Island National Historical Park that may sustain damage from future earthquakes includes buildings near surface faults and areas associated with water-saturated sands, silts, or gravel, which are prone to liquefaction.

Earthquake data from many seismographs are sent automatically to centralized locations for routine analysis. The US Geological Survey maintains an earthquake website (http://earthquake.usgs.gov, accessed 23 July 2014) that contains historical and near-real-time data, as well as links to regional information. The Pacific Northwest Seismic Network (http://www.pnsn.org/, accessed 23 July 2014) provides information on Pacific Northwest earthquake activity and hazards and operates seismographs in Washington and Oregon. These websites can provide up-to-date information on seismic activity affecting San Juan Island National Historical Park and the archipelago.

Braile (2009) described the following methods and vital signs useful for understanding earthquakes and monitoring seismic activity: (1) earthquake monitoring, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. This chapter on

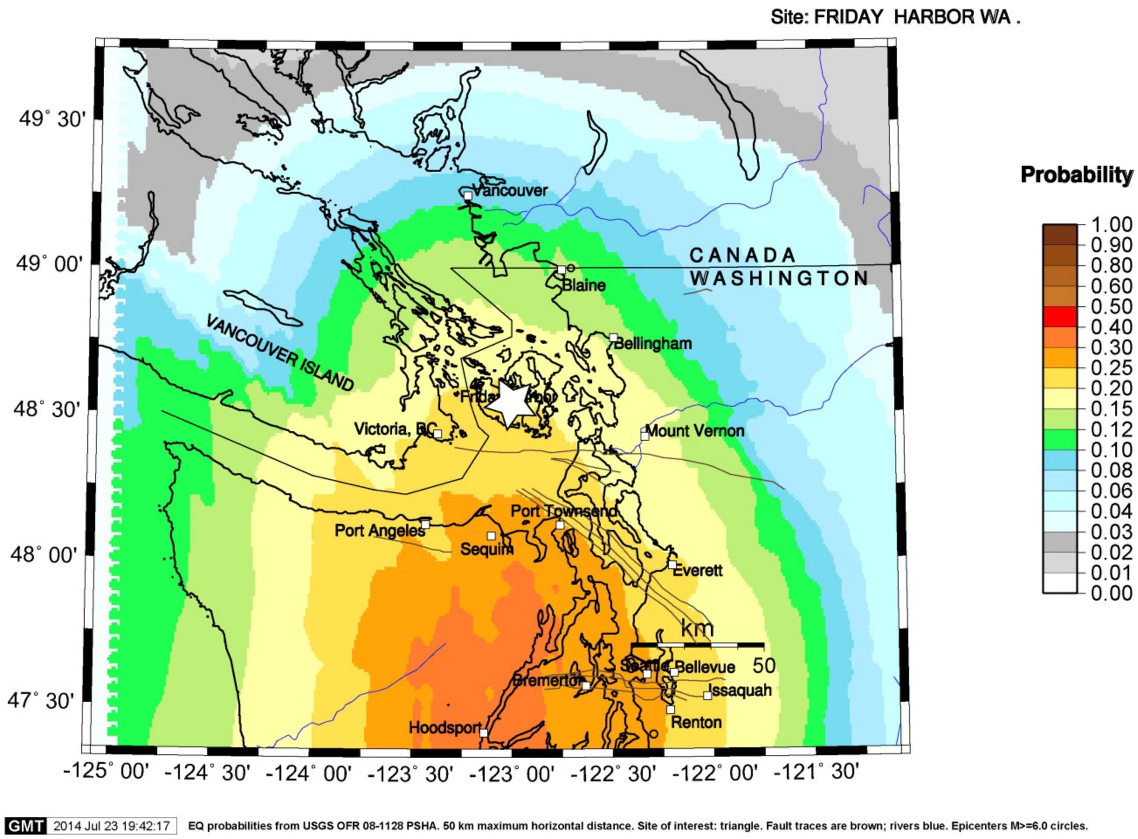



**Figure 22. Probability of magnitude 6.5 or greater earthquake within 50 years at Friday Harbor, Washington. The white star indicates the location of Friday Harbor. Map created by the US Geological Survey 2009 Earthquake Probability Mapping tool, available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 23 July 2014).**

seismic monitoring includes case studies from Joshua Tree and Yellowstone national parks.

Large magnitude earthquakes generated by the Cascadia Subduction Zone may trigger tsunamis capable of inundating the coasts of British Columbia, Washington, Oregon, and northern California (detailed information and maps are available through the Pacific Northwest Seismic Network: http://www.pnsn.org/outreach/earthquakehazards/tsunami, accessed 23 July 2014). A study conducted in 2004 concluded that most of San Juan County has a relatively low risk of tsunami inundation due to the "high-bank waterfront" (bluffs along the coast) that characterizes the islands (San Juan County 2004; Klinger et al. 2006). However, Cattle Point was identified as a potentially high-risk area because of a funneling effect that would increase the height and force of waves.

### Volcanic Hazards

Earthquakes associated with Cascade volcanoes provide clues about potential volcanic eruptions. The Pacific Northwest Seismic Network includes seismic stations on Mt. Baker and Glacier Peak, two active volcanoes in the northern Cascade Range of northwestern Washington. Both of these volcanoes are considered "High" to "Very High" threat potential according to the US Geological Survey Cascades Volcano Observatory; view the observatory's website at: http://volcanoes.usgs.gov/observatories/cvo/ (accessed 23 July 2014).

From the redoubt in American Camp, visitors can view Mt. Baker, which lies approximately 97 km (60 mi) northeast of San Juan Island (fig. 23). Mt. Baker last erupted in the mid-1800s. Although active, it does not pose a threat to San Juan Island National Historical Park. No record of a highly explosive eruption, like those of Mount St. Helens and Glacier Peak, exists for this 3,285-m- (10,778-ft-) tall volcano, and it does not erupt frequently (Gardner et al. 1995). According to the Pacific Northwest Seismic Network, recent earthquakes associated with Mt. Baker have had magnitudes of less than 2 (http://www.pnsn.org/volcanoes/mount-baker#recent-seismicity, accessed 23 July 2014).

Debris flows and debris avalanches, which will affect only the area immediately surrounding Mt. Baker, are the main hazards associated with the volcano. Mt. Baker has not produced voluminous amounts of volcanic ash in the past and probably will not in the future.

Glacier Peak, on the other hand, poses a potentially greater hazard. Glacier Peak is located approximately 160 km (100 mi) southeast of San Juan Island and 110 km (70 mi) northeast of downtown Seattle. Since the retreat of the ice-age glaciers, Glacier Peak has produced more explosive eruptions with voluminous volcanic ash

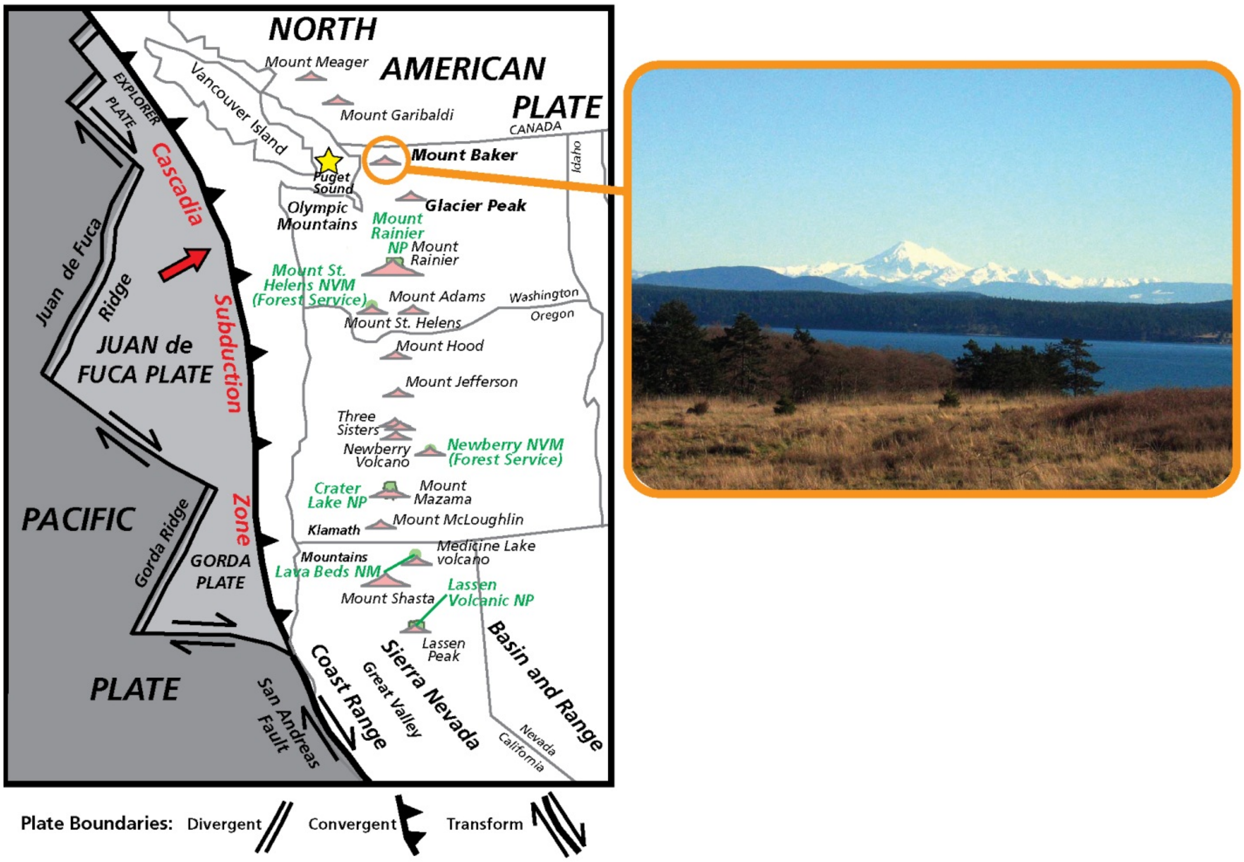



**Figure 23. Cascade volcanoes. Mt. Baker is an active volcano in the Cascade Range, but it does not pose a hazard to San Juan Island National Historical Park. National Park Service photograph courtesy of Mike Vouri, available at http://www.nps.gov/sajh/photosmultimedia/The-American-Camp-Prairie.htm (accessed 7 November 2012). The map shows the location of Mt. Baker and other Cascade volcanoes in relation to San Juan National Historical Park (yellow star). National Park Service graphic by Jason Kenworthy (NPS Geologic Resources Division) after Lillie (2005, fig. 5.5). NP: National Park; NVM: National Volcanic Monument; NM: National Monument.**

content than any other Washington volcano except Mount St. Helens (Waitt et al. 1995; US Geological Survey 2008). The volcanic hazards of Glacier Peak tend to be overlooked. The volcano is not visible from any major population center, and its summit of only 3,213 m (10,541 ft) does not draw many hikers. However, Glacier Peak and Mount St. Helens are the only Washington volcanoes to produce large, explosive ash eruptions. For example, the Whidbey Formation exposed in Ebey's Landing National Historical Reserve contains pebbles from a lahar (volcanic mudflow) generated by the Glacier Peak Volcano (Polenz et al. 2005; see GRI report by Graham 2011).

Since the retreat of glacial ice, Glacier Peak has produced two major eruptions: one between 13,100 and 12,500 years ago and another between 6,300 and 5,900 years ago. Smaller eruptions producing small amounts of ash and lahars of limited areal extent have occurred more frequently than these larger eruptions. In the past 2,000 years, Glacier Peak has generated at least seven smaller eruptions (US Geological Survey 2008).

Should Glacier Peak produce another large eruption, lahars would present the greatest danger to nearby communities (Waitt et al. 1995; US Geological Survey 2008). The San Juan Channel eliminates the potential lahar hazard for the San Juan Islands. Airborne ash, the second greatest hazard from a large Glacier Peak eruption, might impact San Juan Island, but most ash would be carried eastward by the prevailing wind (Waitt et al. 1995). Earthquakes would accompany a Glacier Peak eruption, but the potential extent of ground shaking is difficult to determine.

The US Geological Survey Cascades Volcano Observatory website (http://volcanoes.usgs.gov/observatories/cvo/, accessed 23 July 2014) contains detailed information on volcanoes in the Cascade Range, including Glacier Peak. The website contains information on potential volcanic hazards and related publications, photographs, and current news releases. It also provides links to other relevant websites.

### Global Climate Change

Climate change is expected to cause significant changes in the Puget Sound region, such as long-term sea-level rise, inundation of low-lying coastal areas, increased landsliding due to increased winter rainfall, and growing frequency and magnitude of coastal erosion, shoreline retreat, and storm surge (Canning 2002; Klinger et al. 2006; Mote et al. 2014). Changes in the timing of snowmelt will cause impact water supply throughout the northwest leading to major ecological and sociological consequences (Mote et al. 2014). By 2100, sea level in the Eastern Pacific may exceed the global average by more than 20 cm (8 in), and sea level in the Puget Sound Basin may rise 33 cm (13 in) or more, depending on the rate of ice melt from Greenland and Antarctica (Klinger et al. 2006; Karl et al. 2009). Mote et al. (2014) report sea level rise projections for latitude 45°N (Newport, Oregon) between 15 and 145 cm (6 and 57 in) by 2100.

The Puget Lowlands are located in a tectonically active area, and vertical land movements vary among sites, affecting apparent sea-level changes. Currently, postglacial rebound rates for the northern Puget Lowlands are less than 0.1 mm (0.004 in) per year (James et al. 2000). The net vertical movement of San Juan Island is expected to be close to zero, which suggests that the relative sea-level rise for San Juan Island National Historical Park will be similar to that predicted for the Eastern Pacific (Klinger et al. 2006).

The combined effects of sea-level rise, heavier winter rainfall, and increased intensity and frequency of winter storms may dramatically impact the 9.8 km (6.1 mi) of shoreline in San Juan Island National Historical Park. Exposed bluffs facing Haro Strait and the Strait of Juan de Fuca may retreat at an accelerated rate, especially along the narrow beaches at American Camp (fig. 21; Klinger et al. 2006).

Rising sea level will also inundate low-lying coastal areas and change the salinity of semi-enclosed bays and estuarine wetlands, such as Jakles Lagoon (fig. 19). Jakles, Old Town, and Third lagoons are the only estuarine wetlands on San Juan Island, and they are all located along the northern shore of American Camp. Rarely found along the northwestern Pacific coast, these lagoons are valuable ecological resources. Jakles Lagoon, the largest and most hydrologically and biologically productive of the three lagoons, has been the focus of extensive biological studies of marine organisms by the University of Washington Friday Harbor Labs (National Park Service 2012e). The lagoons will eventually disappear as sea level continues to rise (fig. 19; Klinger et al. 2006). English Camp currently lies 0.9–1.8 m (3–6 ft) above sea level, and high tides already reach the base of the historical blockhouse (fig. 20; National Park Service 2012f).

Changing precipitation patterns will produce warmer, wetter winters and warmer summers, resulting in more freshwater flow in fall and winter and less flow in summer, when demand for water resources is higher. Rising sea level may increase saltwater intrusion into coastal aquifers (see the "Groundwater Issues" section). Combined with land-use changes and increased population, these factors may reduce the availability of freshwater on the island (Orr et al. 2002; Klinger et al. 2006; Mote et al. 2014).

The NPS Climate Change Response Program coordinates science, adaptation, mitigation, and communication regarding climate change throughout the National Park System. For NPS climate change resources, refer to http://www.nps.gov/subjects/climatechange/resources.htm (accessed 23 July 2014). San Juan Island National Historical Park is a "Climate Friendly Park" with additional information available online: http://www.nps.gov/climatefriendlyparks/parks/SAJH.html (accessed 23 July 2014).

#### Groundwater Issues

Because large sources of surface water are scarce, groundwater is the primary water source for the San Juan Island ecosystem. Seeps and springs replenish wetlands and tidal lagoons with freshwater, and aquifers (geologic zones where groundwater is found and extracted) provide potable water for the residents of San Juan Island. Wells completed on San Juan Island produce from two major aquifer types: fractured bedrock aquifers and glacial aquifers (fig. 24). In general, thick, saturated glacial deposits yield large quantities of groundwater. Bedrock aquifers, on the other hand, yield limited quantities of groundwater that are usually sufficient only for single-family domestic use. However, because sufficient thicknesses of glacial deposits are lacking, most wells in the San Juan Islands produce water from bedrock aquifers (Orr et al. 2002).

Most bedrock on San Juan Island is exposed at the surface or covered by a thin veneer [generally less than 9 m (30 ft) thick] of unconsolidated glacial debris (Orr et al. 2002). Within San Juan Island National Historical Park, bedrock aquifers are located primarily in English Camp. Groundwater is limited because the bedrock is neither porous nor permeable. However, the bedrock does contain a network of water-yielding fractures and joints.

Wells drilled into bedrock aquifers are generally deep; more than 80% of bedrock wells in the San Juan Islands have been drilled to depths below sea level (San Juan County Water Resources Management Plan 2004). The wells are drilled deeply with the anticipation of intercepting many water-yielding fractures, although the number of such fractures tends to decrease with depth (fig. 24). Because water-bearing zones in fractured rock are susceptible to dewatering from pumping, added depth provides increased groundwater storage capacity (San Juan County Water Resources Management Plan 2004).

Glacial aquifers exist in the southern part of San Juan Island, where unconsolidated deposits are up to 30 m (100 ft) thick. At American Camp, fresh groundwater fills the spaces between porous glacial outwash sand and gravel (Qgom and Qvrmo).

Bedrock and glacial aquifers in the San Juan Islands are directly recharged solely by water from local precipitation. Infiltration of precipitation into the island's aquifers depends on surface and subsurface geology, soil type, topography, vegetation, and aquifer type. Overall, aquifers on San Juan Island are recharged at an annual rate of approximately 5.05 cm (1.99 in) per year (Orr et al. 2002). Fractures in shallow or exposed bedrock are recharged at a slower rate of less than 3.8 cm

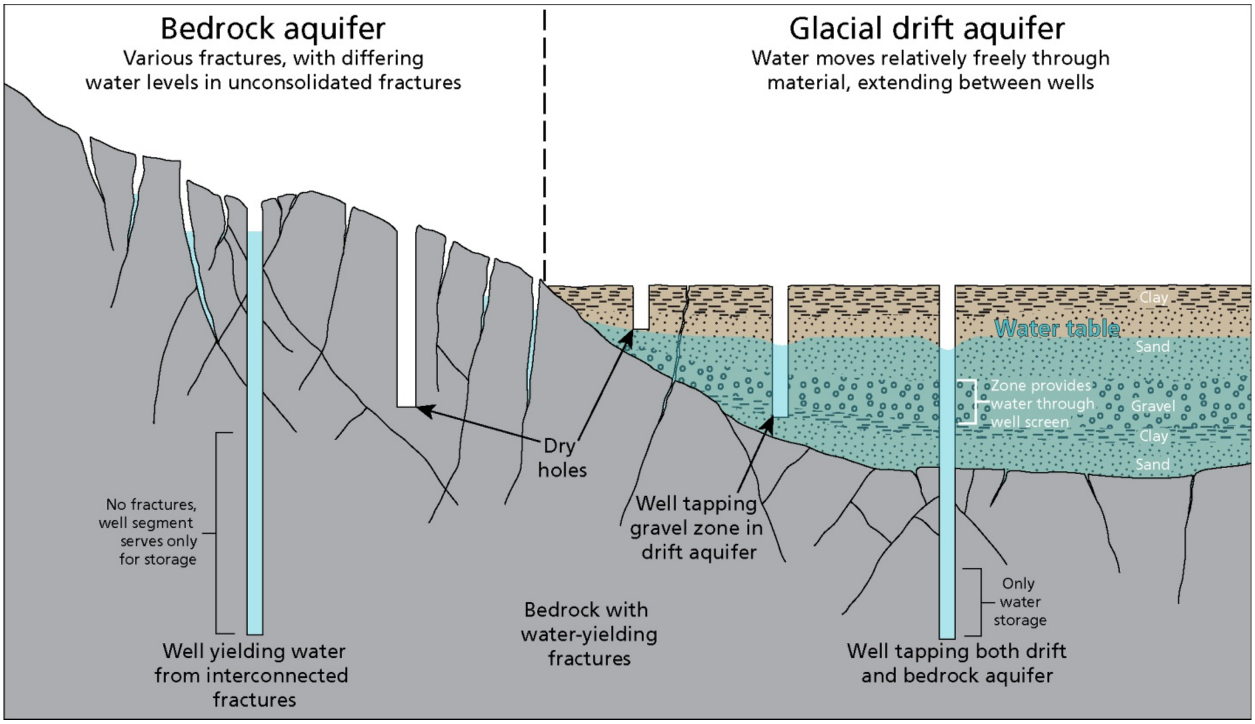



**Figure 24. Two types of aquifer on San Juan Island are bedrock and glacial aquifers. Both aquifer types are connected to the surface and recharged by precipitation. Bedrock wells rely on interception of a fracture network. Glacial wells are drilled into saturated unconsolidated sands and gravels. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Whiteman et al. (1983).**

(1.5 in) per year. In contrast, areas of well-sorted, highly permeable glacial outwash sand may recharge at a rate of 23 cm (9 in) per year (Orr et al. 2002).

Recharge is affected by evapotranspiration. When soil and plant roots have the capacity to hold large quantities of groundwater, recharge to aquifers can be nearly zero. In some areas of the Puget Lowland, annual advective evaporation of intercepted precipitation may be as much as 25–46 cm (10–18 in) and daily evaporation may exceed the daily potential for evapotranspiration; potential recharge may thus be less than estimated (Orr et al. 2002).

Recharge does not equate to groundwater availability. Subsurface flow to the ocean, shallow groundwater uptake by roots, and groundwater contributions to streams, springs, and wetlands balance recharge under natural conditions. The pumping of groundwater from wells diminishes outflow to one or more of these discharge areas.

Typical of most island aquifers, the fresh groundwater on San Juan Island floats on top of denser saltwater. If freshwater is pumped faster than it is recharged, saltwater intrudes into the aquifer in its place. Saltwater intrusion is the primary hazard that degrades groundwater quality on the island. Moreover, the recovery of an aquifer that has been contaminated with saltwater is slow. Some wells on the island have been degraded by saltwater intrusion. Since 1981, water from the American Camp well has exceeded the chloride standard for drinking water, indicating the influence of saltwater (Klinger et al. 2006; National Park Service 2012g). Analysis of water samples collected from five park locations between 1999 and 2000 showed that the overall quality of groundwater and surface water was good, but that the American Camp well contained elevated specific conductance and chloride concentrations and an ammonia-to-nitrate ratio indicating increased saltwater intrusion (National Park Service 2012h).

Currently, aquifer recharge occurs primarily from October through April, when the rate of precipitation is high and that of evapotranspiration is low. During the dry season, diminished groundwater flow may transform wetlands into drier environments. During a drought, groundwater may be withdrawn faster than it is replenished, with disastrous effects on the ecosystem and drinking water supplies. For example, the extended drought of 1994 drew the American Camp well that supplies drinking water down to a critical level. The well was shut down for 2 months during the height of the visitor season to allow it to recharge (National Park Service 2012g).

Climate change may further influence recharge rates as the frequency, intensity, and duration of precipitation change (see the "Global Climate Change" section; Klinger et al. 2006). Changes in one part of the ecosystem are likely to result in changes to the whole system. For example, changes in precipitation patterns may affect root growth and soil moisture-holding capacity, which in turn affect recharge rates.

Excessive groundwater pumping to satisfy neighboring residential communities may decrease the inflow of freshwater into the park's lagoons, resulting in a loss of ecological integrity. In general, increased groundwater withdrawals may:

- Lower water tables
- Increase saltwater intrusion
- Alter freshwater inputs to springs, seeps, ponds, and wetlands
- Alter salinity regimes in tidal lagoons
- Alter existing habitats.

Because the aquifers in San Juan Island National Historical Park are connected hydrologically to the surface, they are exposed to potential contamination. Fractures in bedrock provide no filtering mechanism and can be direct conduits for contamination or saltwater intrusion. During the rainy season, surface water may convey bacteria and organic material directly to near-surface fractures. In addition, bedrock wells may contain natural contaminants, such as barium, arsenic, fluoride, and sodium, which pose risks to human health, and minerals such as iron and manganese that have cosmetic and functional impacts, such as odors, staining, and mineral deposits (San Juan County Water Resources Management Plan 2004). The unconsolidated material in glacial aquifers offers some filtering benefit to reduce contamination from septic systems and other sources, but wells drilled near the shoreline are susceptible to saltwater intrusion.

Water quality data and additional information regarding groundwater and surface water in San Juan Island National Historical Park are available from the Water Resources Division of the National Park Service, located in Fort Collins, Colorado (http://www.nature.nps.gov/water/horizon.cfm, accessed 23 July 2014).

#### Oil and Fuel Spills

The southern and western shores of San Juan Island border major shipping channels. Ships carrying thousands of barrels of unrefined oil travel daily through Haro Strait and the Strait of Juan de Fuca on their way to major refineries at Ferndale, Cherry Point, and March Point in northern Puget Sound. In addition, tanker traffic to Vancouver crosses the Rosario Strait, east of Orcas and Lopez islands, and a proposal to transport tar sands via supertankers to Vancouver is being considered (Jon Riedel, NPS North Cascades National Park, geologist, written communication, 18 January 2014). Oil and fuel spills pose potential hazards, particularly to the shores of American Camp, for the following reasons (Klinger et al. 2006):

- The shores are located at the confluence of three major traffic lanes
- Floating material accumulates on South Beach due to local ocean circulation patterns
- Buoyant materials in San Juan Channel are trapped by eddies in southern Griffin Bay
- The soft-sediment beaches retain oil longer and are more difficult to clean than rocky substrates
- Oil spill response is logistically difficult due to prevailing wind, current, and wave conditions.

Circulation patterns would tend to trap oil spills in Westcott and Garrison bays, resulting in potentially longer residence time along the shores of English Camp (Klinger et al. 2006; MacLennan et al. 2010).

In response to a 1985 spill near Westcott Bay, San Juan Island residents formed the Islands Oil Spill Association (IOSA), the only non-profit, community-based and -supported oil spill response organization in the San Juan Islands (http://iosaonline.org, accessed 23 July 2014). Its mission is to provide prompt and effective local spill response and prevention. From 1988 to 2005, IOSA responded to 397 spill reports in the San Juan Islands (Klinger et al. 2006).

In addition, the National Oceanic and Atmospheric Administration (NOAA) has developed the General NOAA Oil Modeling Environment (GNOME) computer program, which can be used to predict the path of an oil spill based on wind, currents, and other forces (NOAA 2014). The model is most useful when an actual spill has just occurred. It is available on the NOAA website (http://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome.html, accessed 23 July 2014).

#### Driftwood Impact to Coastline Features

Driftwood, a natural feature along the shorelines of Puget Sound, serves many important ecological functions. At some localities, driftwood has been emplaced to slow beach and bluff erosion and restore original ecological functions (Jon Riedel, NPS North Cascades National Park, geologist, written communication, 10 April 2013). The impact of large woody debris (driftwood) on the shoreline of San Juan Island National Historical Park has not been studied, but research in the Puget Sound region suggests that it changes sedimentation patterns and negatively impacts vegetation (MacLennan 2005). Logs and woody debris that accumulate on the shoreline, as along South Beach, may smother vegetation and benthic invertebrates. In the Puget Sound area, large woody debris has also been found in peat deposits and at the bases of large dunes and spits. Beale (1990) found that the weight of driftlogs may even compact marsh sediments and cause site-specific relative sea-level rise.

# Geologic History

*This section describes the chronology of geologic events that formed the present landscape of San Juan Island National Historical Park.*

Three main events capture the geologic history of San Juan Island National Historical Park: (1) the assembly of the west coast of North America, (2) the shaping of the landscape by ice-age glaciers, and (3) modern shaping of the landscape by waves and wind.

### Assembling the West Coast of North America

By the Late Jurassic (fig. 25), all units in the San Juan Thrust System appear to have been attached or adjacent to continental North America. Rather than being associated with long-lived subduction throughout the Mesozoic, as previously thought, the thrust-bounded terranes in the San Juan Thrust System record tectonic accretion over a geologically brief period of time in the Late Cretaceous, approximately 100 million to 84 million years ago (Brandon et al. 1988).

Although attached to the North American continent by the Cretaceous, the rock units were far removed from their present-day locations adjacent to the Canadian border. Paleomagnetic data suggest that most of British Columbia and western Washington, including Wrangellia, the Coast Plutonic Complex, and the San Juan–Cascades Thrust System, were located at the latitude of Baja California about 85 million years ago. San Juan Island National Historical Park is the only park on the Pacific Coast that preserves a deformation episode in which these terranes may have been displaced northward about 2,500 km (1,600 mi) and rotated about 65° clockwise during the latest Cretaceous and Early Tertiary (Irving et al. 1985; Brandon et al. 1988).

#### Lower Half of the San Juan Thrust System

Some terranes of the San Juan Thrust System on San Juan Island, such as the Turtleback and Deadman Bay terranes, were foreign, or exotic, to North America prior to tectonic collision (Brandon et al. 1988). Along with fault slices of the Garrison Schist, these terranes compose the lower part of the San Juan Island Thrust System.

The Turtleback Complex (geologic map unit pDi) consists of Paleozoic plutonic and volcanic igneous rocks. The intrusive history and age of this complex are difficult to determine because a Permian metamorphic event "reset" the isotopic dates. One sample of tonalite from the Turtleback Complex [pDit(t)] exposed on the promontory at the southern end of San Juan Island records this Late Paleozoic thermal event (table 2). However, other samples from the islands suggest that the Turtleback Complex originated during an Early Devonian or Late Proterozoic intrusion event (Brandon et al. 1988). The plutonic and volcanic rocks of this complex represent a volcanic-arc tectonic setting, but whether the original volcanoes were attached to a continent or formed as oceanic islands is not known.

The Orcas Thrust separates the Turtleback terrane from the Deadman Bay terrane, a deformed sequence of Lower Permian to Lower Jurassic chert, basalt, and limestone. The terrane consists of two stratigraphically related units: the Deadman Bay Volcanics (TRPv) and the Orcas Chert [JTRmc(o)]. Both units contain pillow basalts of similar mineralogy, and their ages overlap. The type locality (the site of a formation's official designation) for the Deadman Bay Volcanics is on the western side of San Juan Island, between English and American camps (Brandon et al. 1988).

The presence of fusulinids, conodonts, and radiolarians indicates that the Deadman Bay Volcanics are Early Permian to Late Triassic in age. The presence of conodonts, which became extinct in the Triassic, and radiolaria indicates that the Orcas Chert is Triassic to Early Jurassic in age (table 2). The age of the Deadman Bay terrane correlates with the breakup of the supercontinent Pangaea (fig. 26). All major land masses had sutured together at the end of the Paleozoic to form Pangaea, which then began to break apart during the Triassic.

Rifting of Pangaea created the narrow Tethys Sea between present-day North Africa and Asia, which is the origin of Permian fusulinids and calcareous algae found in laminated limestones draped over pillow basalts in the Deadman Bay Volcanics (Johnson and Danner 1966; Danner 1977; Whetten et al. 1978; Brandon et al. 1988). This unit is the only one in the San Juan Islands that contains Tethyan fusulinids (table 2). The presence of Tethyan fauna indicates that the Deadman Bay terrane traveled some distance before accreting to North America. The presence of pillow basalts, which form at submarine spreading centers, fusulinids, and calcareous algae, and the lack of continent-derived sediment, suggest that the Deadman Bay terrane originated as oceanic islands or large seamounts near the paleo-Pacific equator (Saleeby 1983; Brandon et al. 1988).

The Garrison Schist (pPsh) is characterized by Permian to Triassic high-pressure metamorphic rocks. In the San Juan Islands, this unit occurs only as a discontinuous sheet of fault slices in the Rosario Fault Zone. Metamorphism occurred approximately 286 million or 242 million years ago, during the Permian and/or Early Triassic (Brandon et al. 1988).

The relationships of the Garrison Schist to the Orcas Chert [JTRmc(o)] and overlying Constitution Formation [KJmm(c)] remain unclear, although Garrison Schist metamorphism is older than both of these units

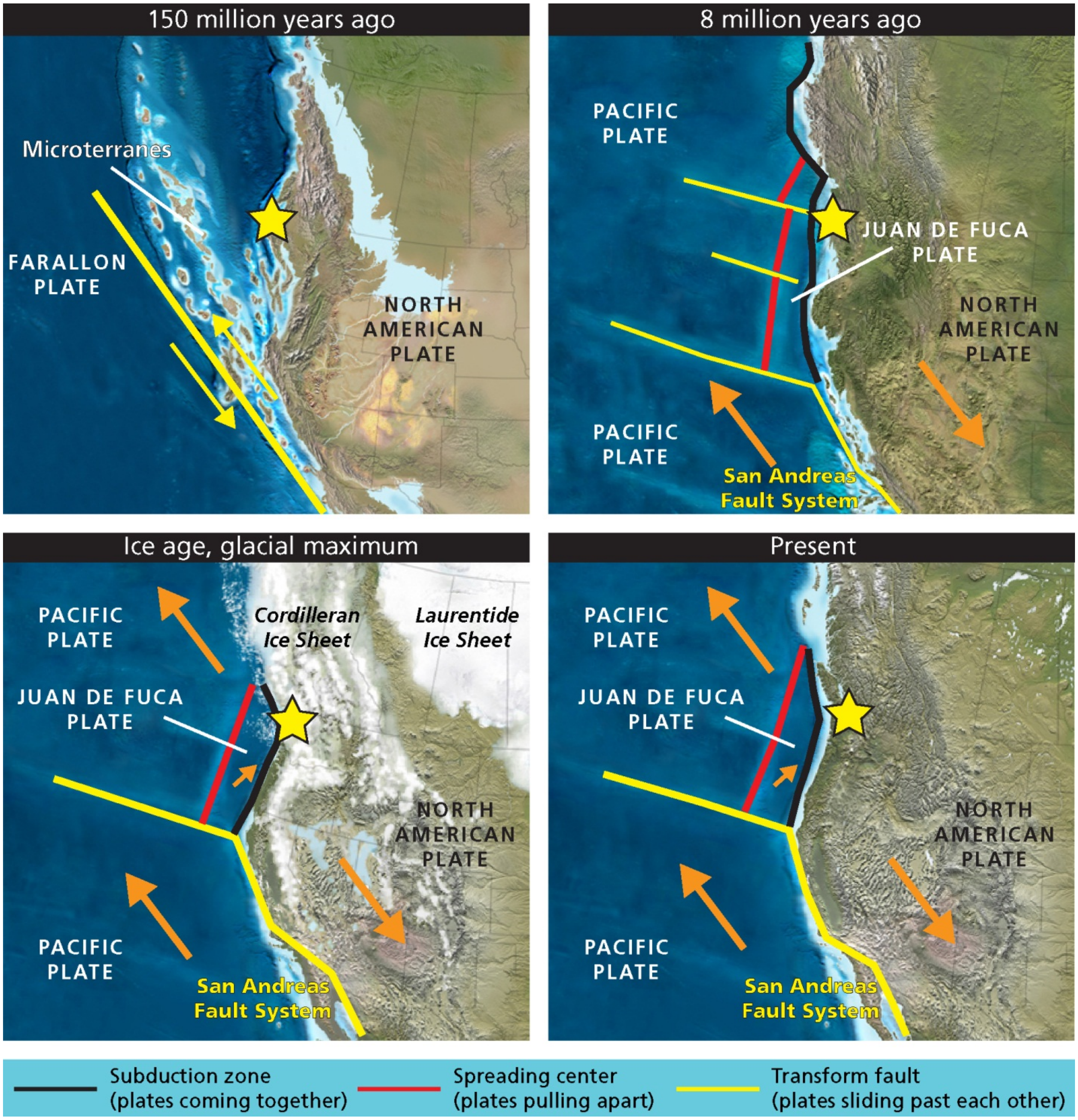



**Figure 25. Paleogeographic maps showing the evolution of the San Juan Islands. In the Mesozoic (Jurassic, upper left map), microterranes began to collide with North America. By 8 million years ago (Miocene Epoch), these microterranes had attached to North America, and the Farallon Plate had split into two plates: the Juan de Fuca Plate and the Cocos Plate, south of the San Andreas Fault System (not shown). The Cordilleran Ice Sheet periodically covered the region in the Pleistocene. During glacial episodes (lower left map), alpine glaciers filled surrounding mountain valleys in the Puget Lowland. Today, the island landscapes and straits in Puget Sound are visible evidence of the erosional power and depositional history of the Pleistocene ice age. Yellow stars indicate the approximate location of San Juan Island National Historical Park. Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 27 November 2012). Annotations by Jason Kenworthy (NPS Geologic Resources Division).Mesozoic and Cenozoic plate directions are from Atwater (1998) and the US Geological Survey (fig. 10).**

(Brandon et al. 1988). The schist may have been a component of the basement rocks underlying the Constitution Formation prior to thrusting (Brandon et al. 1988). This association would explain the presence of Garrison clasts in the Constitution Formation. The stratigraphic sequence suggests that the metamorphosed basalts, minor chert, and limestone were originally deposited on the ocean floor. Metamorphism and deformation probably occurred at a subduction zone, but we currently lack evidence of this setting (Brandon et al. 1988).

### Upper Half of the San Juan Thrust System

In the San Juan Islands, three major units form the upper part of the Rosario Thrust in the San Juan Thrust System. In ascending order, these units are the thick clastic sequence of the Constitution Formation [KJmm(c)], the imbricated fault zone of the Lopez Structural Complex

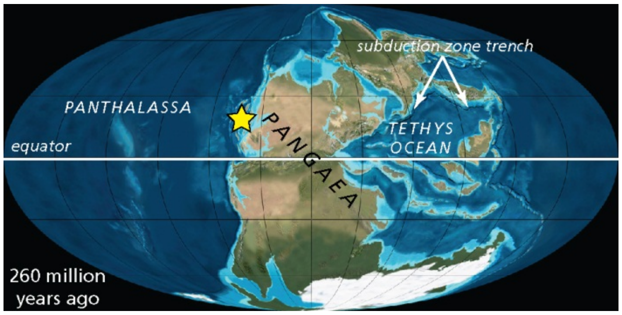



**Figure 26. Pangaea. During the Permian and Early Triassic, North America became part of the supercontinent Pangaea. This C-shaped landmass stretched from pole to pole and surrounded the Tethys Ocean. The spine of the "C" was adjacent to a long subduction zone. Much of Earth's surface was covered by a large ocean called Panthalassa. The terranes that accreted to present-day Washington (yellow star) during the Mesozoic originated some distance from the western margin, and the Deadman Bay terrane originated in the Tethys Ocean. Base paleogeographic image by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 25 January 2012). Annotations by Jason Kenworthy (NPS Geologic Resources Division).**

[KJm(ll)], and the Decatur terrane, which is exposed east of San Juan Island (Brandon et al. 1988).

Although jumbled blocks of limestone in the lower part of the Constitution Formation contain Triassic conodonts, Late Jurassic to Early Cretaceous radiolarians in the upper part of the formation constrain the age of this unit to no older than Middle or Late Jurassic (Whetten et al. 1978; Brandon et al. 1988). Some radiolarian samples were collected from exposures adjacent to Griffin Bay and Eagle Cove, just north of American Camp (table 2; Whetten et al. 1978; Brandon et al. 1988).

Thrust faults bracket the Constitution Formation, but its middle and upper members are relatively intact on southern San Juan Island. The predominance of mudstone and presence of pebbly mudstone and soft-sediment deformational features in the upper member of the formation suggest a slope or base-of-slope setting. The massive sandstone and conglomerate in the middle unit may represent large channelized deposits typical of a submarine fan system. Interbedded black mudstone, radiolarian chert, cherty sandstone, and volcaniclastic sandstone represent deposition at a continental margin in the proximity of an extensive volcanic-arc terrane (Brandon et al. 1988).

The upper unit of the Constitution Formation also contains pillow lavas, which imply deposition at or near a spreading center. However, the depositional nature of the contacts of the pillow lavas with surrounding units suggests that these lavas represent submarine slide blocks that eroded from an older volcanic unit (Brandon et al. 1988). The formation also contains clasts of Garrison Schist and a limestone clast at Bell Point with Tethyan fusulinids from the Deadman Bay terrane (Danner 1977; Brandon et al. 1988). The Constitution Formation forms an important link between a Jurassic volcanic-arc setting and these older, uplifted terranes.

The Lopez Structural Complex [KJm(ll)] occurs on the southern promontory of San Juan Island. It consists of a series of fault slices, probably derived from the Constitution Formation or Decatur terrane. No fossil has been documented from the Lopez Structural Complex on San Juan Island, but Jurassic to Mid-Cretaceous fossils have been found on Lopez Island (Whetten et al. 1978; Brandon et al. 1988). These fossils include Jurassic radiolarians, a Late Jurassic or Early Cretaceous belemnite (an extinct, squid-like cephalopod), and Cretaceous foraminifera and bivalves (*Buchia pacifica*). As with the other rock units in the San Juan Thrust System, the Lopez Structural Complex experienced Late Cretaceous high-pressure metamorphism, although this metamorphism did not destroy all fossils in the unit (Brandon et al. 1988).

Following thrusting and metamorphism, the rock units in the San Juan Thrust System were uplifted in the Late Cretaceous. Erosion of the Deadman Bay terrane produced clasts that became part of conglomerates present in the Late Cretaceous Nanaimo Formation (Brandon et al. 1988).

#### Marine Rocks Deposited in Front of the San Juan Thrust System

The Haro Formation (TRn), which has been mapped only on San Juan Island, is considered to be external to the San Juan Thrust System because it lacks the high-pressure metamorphic mineral assemblages common to the units involved in the thrust system (Brandon et al. 1988). The steeply dipping, 700-m- (2,300-ft-) thick section exposed at Davison Head, the northernmost tip of San Juan Island, consists of well-bedded siltstone, sandstone, tuff, conglomerate, breccia, and abundant volcanic detritus. Some of the sedimentary rocks have undergone low-pressure, low-temperature metamorphism. The nearshore sedimentary rocks of the Haro Formation suggest that shallow marine environments existed in front of the leading edge of the San Juan Thrust System during the last stages of San Juan thrusting (Brandon et al. 1988).

### A Landscape Carved by Ice-Age Glaciers

Although the bedrock of San Juan Island was in place by the end of the Mesozoic, the current landscape of the San Juan Archipelago is geologically young. The bedrock was carved by ice into its current form during the Pleistocene (2.6 million to 11,600 years ago) ice ages (fig. 25). In the Pleistocene, the Cordilleran Ice Sheet (fig. 27) expanded from coastal Alaska along the Coast Mountains of British Columbia and into northern Washington and northwestern Montana (Booth et al. 2004). At times, the Cordilleran Ice Sheet likely coalesced with the western margin of the larger Laurentide Ice Sheet to form a continuous sheet of ice that extended more than 4,000 km (2,500 mi) across North America (Booth et al. 2004).

The documentation of ice-age chronology in the Puget Lowland is an active field of research. Ice sheets have advanced into western Washington lowlands at least six

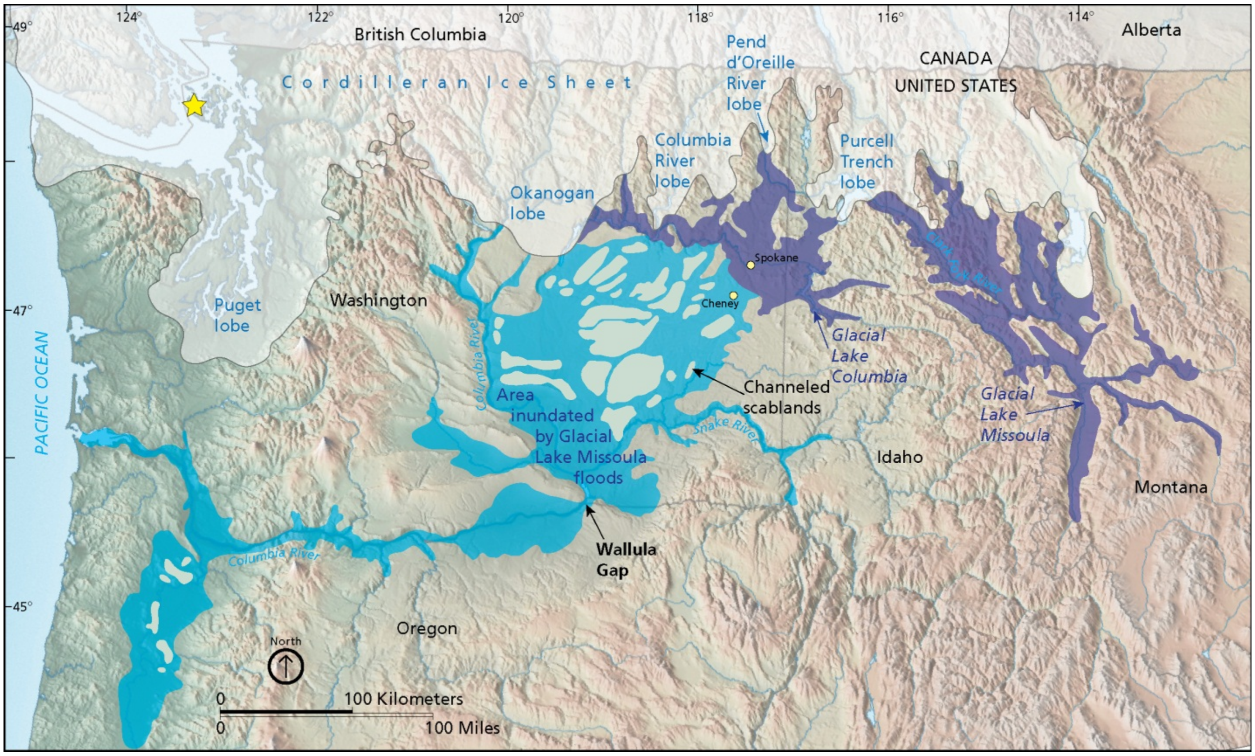



**Figure 27. Cordilleran Ice Sheet. The Puget Lobe flowed into the Puget Lowland, covering the region of today's San Juan Islands and San Juan Island National Historical Park (yellow star). Graphic by Trista Thornberry-Ehrlich (Colorado State University), produced with information from US Geological Survey diagram available at http://vulcan.wr.usgs.gov/Glossary/Glaciers/IceSheets/Maps/map_missoula_floods.html (accessed 15 July 2013). Base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 15 July 2013).**

times and probably more, with initial glaciation occurring approximately 1.6 million to 2.0 million years ago (Easterbrook 1986; Booth et al. 2004). With each ice advance, glaciers typically deposited thick accumulations of outwash and till in the Puget Sound Basin. The advancing ice reworked these deposits and scoured deep channels into them. As an ice sheet rapidly melted, rivers beneath the glacier cut large recessional outwash channels and left behind ice-contact deposits and glaciomarine drift in the northern lowland, such as the deposits found in San Juan Island National Historical Park.

During the Olympic nonglacial period (60,000–30,000 years BP), alpine glaciers were much larger than today, but no ice sheet flowed into the Puget Lowland. Following the Olympia nonglacial period, the Puget Lobe of the Cordilleran Ice Sheet advanced from British Columbia to just south of Olympia, covering the entire Puget Lowland with ice that was more than a mile thick in the north. This was the last major ice advance to cover the San Juan Islands (Easterbrook 2003; Booth et al. 2004; Washington State Department of Natural Resources 2010).

The Fraser Glaciation consisted of three stades (periods of ice expansion) and two intervening interstades (periods of glacial retreat) (Armstrong et al. 1965; Dethier et al. 1996). In the northern Puget Lowland, the ice sheet associated with the Vashon Stade, the second stade of the Fraser Glaciation, entered northern Washington after about 18,925 calendar years BP (Porter and Swanson 1998). This ice-sheet glaciation is largely responsible for the present-day landscape of the San Juan Islands (Pessl et al. 1989; Easterbrook 2003). The glacier left behind unstratified, highly compacted lodgment till (Qgt) that was deposited at its base.

Rapid and extensive glacial retreat characterized the Everson Interstade, which lasted from approximately 16,400–14,000 calendar years BP (Dethier et al. 1996; Booth et al. 2004). Early in this episode of the Fraser Glaciation, high-energy meltwater streams flowed from the front of the glacier and deposited sand and gravel (Qvrmo) over the island. These well-sorted, cross-bedded deposits of glaciomarine outwash contain barnacles and bivalves with an estimated age of 16,400 calendar years BP (table 1; Dethier et al. 1996). In San Juan Island National Historical Park, outwash deposits have been mapped south of Mt. Finlayson along a south-facing beach.

Marine diamicton [Qvrmd and Qgdm(e)] and subtidal deposits [Qvrms and Qgdm(es)] accumulated over the outwash deposits. Fossil bivalves, barnacles, tubeworms, and urchins collected from glaciomarine diamicton (Qvrmd) exposed along Griffin Bay, between Jakles and Old Town lagoons, have approximate ages of 15,500–15,100 calendar years BP (table 1). The fossil assemblage, which includes *Nuculana*, *Serripes*, and *Clinocardium*, represents moderately deep to subtidal marine water that inundated southern San Juan Island (Dethier et al. 1996).

Exposures of 3–5-m- (10–15-ft-) thick sands and silts (Qvrms) along a south-facing beach south of Mt. Finlayson yielded fossil assemblages that contain the bivalve *Saxidomus*, characteristic of shallow subtidal to intertidal marine environments (table 1). These marine environments developed during the period of rapid emergence, about 14,800 calendar years BP (Dethier et al. 1996).

Radiocarbon data suggest that the Puget Lowland marine environments emerged from the sea approximately 11,500 years BP (Easterbrook 2003). Shell fragments of the bivalve *Saxidomus* from emergent deposits (Qvrme) have been dated to approximately 15,000–14,200 calendar years BP (Dethier et al. 1996). Fossil assemblages from emergent deposits also include the gastropod *Limnophysa*, which lived in lagoons and coastal wetlands approximately 15,200 calendar years BP (table 1).

Following the initial retreat of the Puget Lobe, sea level rose approximately 100 m (300 ft) in the Puget Lowland (Clark and Steig 2008). A late-glacial readvance of the Cordillera Ice Sheet occurred about 11,700 years ago (Sumas Stade), but extended only slightly across the present-day Canadian border (Dethier et al. 1996; Clague et al. 1997).

When the glaciers finally receded and the tremendous weight of glacial ice was removed, isostatic rebound caused the San Juan Archipelago to rise at a rate faster than relative sea-level rise. Beaches deposited by wave erosion during the retreat of the ice sheet now form raised beaches or terraces above South Beach at American Camp (fig. 17). Relative sea level then fell to at least 40 to 60 m (130–200 ft) below modern levels before rising steadily as it outpaced the isostatic rebound. Isostatic rebound was rapid and largely completed within 1,000 years of deglaciation (Fay et al. 2009).

As the Pleistocene ice ages drew to a close, megafauna accessed the San Juan Islands and Vancouver Island via a corridor that connected to the mainland (Wilson et al. 2009). Bison bones dating to approximately 13,600–12,600 calendar years BP have been found on Orcas Island, and bison vertebrae and a jaw bone belonging to the bear *Arctodus simus* were discovered on private land between Friday Harbor and Cattle Point on San Juan Island. The jaw-bone site also contained shell material of an age similar to that of the Orcas Island bison remains (Fay et al. 2009; Wilson et al. 2009). Smaller mammals have not been discovered on the islands, suggesting that the corridor was a series of islands separated by water, rather than a continuous land bridge.

### Modern Landscapes Shaped by Sea and Wind

#### The Holocene (11,600 years ago to present)

Holocene beach, dune, marsh, and fill deposits (Qb, Qd, Qm, and Qf, respectively) represent the most recent landscape features in San Juan Island National Historical Park. As post-glacial erosion has removed most glacial deposits along the coast, beach deposits (Qb), which may be more than 2 m (7 ft) thick, overlie bedrock in many areas. Waves and surf continue to pummel the bedrock headlands. Pocket beaches have formed in protected shorelines. Abundant driftwood and other debris accumulates on the more exposed beaches, such as South Beach (fig. 28).

**Figure 28. Rocky headlands, dunes, and beaches have formed along the southern coast of American Camp. American Camp's South Beach is the longest public beach on San Juan Island. Onshore winds, waves, and tides modify the beach on a daily basis. Abundant driftwood accumulates on the beach. National Park Service photograph courtesy of Marsha Davis (NPS Pacific West Regional Office).**

Strong onshore winds produced dune deposits (Qd) adjacent to exposed beaches. The overall thickness of the dunes ranges from 2 to 5 m (7–16 ft). They overlie glaciomarine deposits and are most extensive near American Camp's South Beach. Paleosols (buried soil intervals) may be found interlayered within the dune deposits. On Whidbey Island to the south, a fossil assemblage in dune sand above a paleosol at Cedar Hollow indicates that the climate was warmer and drier than present approximately 10,000 years ago (Mustoe et al. 2005; Graham 2011).

San Juan Island is one of the jewels of Puget Sound. The island records millions of years of dynamic tectonic activity that set the stage for a landscape carved by ice. The grinding and gouging activity of continental glaciers shaped the region into a complex archipelago of islands and straits that became strategically important to an expanding America and a colonizing Great Britain. San Juan Island National Historical Park preserves a geologic history that records the extraordinary growth of a continent, as well as the growing pains of a young America.

# Geologic Map Data

*This section summarizes the geologic map data available for San Juan Island National Historical Park. Posters (in pocket) display the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.*

#### Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Because many important surficial features are not recorded on small-scale bedrock geology maps, the NPS mapped the surficial geology of San Juan Island National Historical Park. This map is currently (July 2014) being finalized. Map units include landforms (table 3), which are linked to specific geologic processes. When completed, the landform map will provide another resource for park management that will complement data on soils, bedrock, and surficial geology.

#### Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following sources to produce the digital geologic data set forSan Juan Island National Historical Park. These sources also provided information for this report.

Dethier, D. P., D. P. White, and C. M. Brookfield. 1996. Maps of surficial geology and depth to bedrock of the False Bay, Friday Harbor, Richardson, and Shaw Island 7.5-minute quadrangles, San Juan County, Washington. Open File Report 96-7 (scale 1:24,000). Washington Division of Geology and Earth Resources, Olympia, Washington.

Pessl, F., Jr., D. P. Dethier, D. B. Booth, and J. P. Minard. 1989. Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington. Miscellaneous investigations series map I-1198-F (scale 1:100,000, with 13 pp. text). US Geological Survey, Reston, Virginia.

Schasse, H. W. 2003. Geologic map of the Washington portion of the Port Angeles 1:100,000 quadrangle. Open file report 2003-6 (scale 1:100,000). Washington State Department of Natural Resources, Division of Geology and Earth Resources, Olympia, Washington.

Logan, R. L. 2003. Geologic map of the Washington portion of the Roche Harbor 1:100,000 quadrangle. Open file report 2003-17 (scale 1:100,000). Washington State Department of Natural Resources, Division of Geology and Earth Resources, Olympia, Washington.

Lapen, T. J. 2000. Geologic map of the Bellingham 1:100,000 quadrangle, Washington. Open file report 2000-5 (scale 1:100,000, two plates with 36 pp. text). Washington State Department of Natural Resources, Division of Geology and Earth Resources, Olympia, Washington.

Washington Division of Geology and Earth Resources Staff. 2005. Digital 1:100,000-scale geology of Washington State. Open file report 2005-3 version 1.0 (scale 1:100,000). Washington State Department of Natural Resources, Division of Geology and Earth Resources, Olympia, Washington.

#### GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for San Juan

Island National Historical Park using data model version 2.1. GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select San Juan Island National Historical Park from the unit list.

The following components and geology data layers are part of the data set:

- A GIS readme file (.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase and shapefile GIS formats for the entire island (1:100,000 scale; "SAJH" files) and American Camp and vicinity (1:24,000 scale; "SJIS" files).
- Layer files with feature symbology (tables 4 and 5)
- Federal Geographic Data Committee (FGDC)-compliant metadata
- An ancillary map information document (.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document file (.mxd) that displays the digital geologic data

**Table 3. List of landforms to be included on landform map (in preparation as of July 2014) for San Juan Island National Historical Park. Symbols (Sym.) refer to those on the landform map, not those on the GRI GIS data set.**

| # | Unit Name | Sym. | # | Unit Name | Sym. |
|---|---|---|---|---|---|
| | ***Shoreline landforms*** | | | ***Upland landforms*** | |
| 1 | Tidal/mud flat | Tmf (MF) | 16 | Dune field | Du |
| 2 | Beach (sediment in motion along shore) | B | 17 | Fluvial terrace (sp 100) | FT |
| 3 | Beach cusp | Bc | 18 | Stream channel | S |
| 4 | Back beach (includes berm with large woody debris (LWD) + back beach →□ complex: berm + beach, area affected by storms) | Bs | 19 | Glacial ground moraine | GM |
| 5 | Gravel barrier | GB | 20 | Glacial moraine (end) | EM |
| 6 | Lagoon (also old dry lagoons on raised marine terraces) | L | 21 | Outwash sandur plain | Sop |
| 7 | (Rocky) Headland/cape (includes cliffs) | RH | 22 | Bedrock | BR |
| 8 | Marine terrace (unconsolidated; SA 305, SA 307 – old beach/shoreline deposits or lagoons) | MT# | 23 | Bedrock bench | BRb |
| 9 | Shore (glacial) platform (shallow soils – bedrock control/near surface; could be wave cut &/or glacial processes) | SP / GP | 24 | Bedrock bluff slope | BRbs |
| 10 | Dunes | D | 25 | Debris apron | DA |
| 11 | Dune blowout | Dbo | 26 | Mass movement | MM |
| 12 | Bluff (Mt. Finlayson; includes small terraces) | BL | 26a | slump (marine drift and lodgment till) | MMs |
| 13 | Bluff slope (e) = eroding | BLs | 26b | debris slide (in outwash and meltout till) | MMds |
| 14 | Human midden | Hmd | 26c | Rock fall and topple | MMf |
| 15 | Human military | Hml | 27 | Kettle | K |
| | | | 28 | Depression (unknown origin) | Ud |

***Source: Marsha Davis (NPS Pacific West Region), written communication, 17 March 2014.***

**Table 4. Geology data layers in the GIS data for San Juan Island National Historical Park and vicinity.**

| Data Layer | Data Layer Code | On Poster? |
|---|---|---|
| Geologic cross-section lines | sajhsec | No |
| Geologic attitude observation localities | sajhatd | No |
| Fold map symbology | sajhsym | Yes |
| Folds | sajhfld | Yes |
| Faults | sajhflt | Yes |
| Geologic contacts | sajhglga | Yes |
| Geologic units | sajhglg | Yes |

**Table 5. Geology data layers in the GIS data for American Camp and vicinity.**

| Data Layer | Data Layer Code | On Poster? |
|---|---|---|
| Depth to bedrock lines | sjiscn1 | No |
| Strand lines | sjiscn2 | Yes |
| Direction of glacial ice movement | sjisgfp | Yes |
| Measured section localities | sjisgol | No |
| Rocks/boulders | sjisgpf | Yes |
| Geologic sample localities | sjisgsl | No |
| Small landslide localities | sjishzp | No |
| Mine and well features | sjismin | No |
| Geologic contacts | sjisglga | Yes |
| Geologic units | sjisglg | Yes |

### GRI Map Posters

Posters of the GRI digital geologic data draped over a shaded relief image of the park and surrounding area are included with this report. Not all GIS feature classes may be included on the posters (tables 4 and 5). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

### Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

### Use Constraints

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

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

# Glossary

*This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute* Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

**absolute age.** The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

**accretion.** The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

**active margin.** A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

**alluvial fan.** A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

**alluvium.** Stream-deposited sediment.

**alpine glacier.** A glacier occurring in a mountainous region; also called a valley glacier.

**aquifer.** A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

**argillaceous.** Describes a sedimentary rock composed of a substantial amount of clay.

**argillite.** A compact rock, derived from mudstone or shale, more highly cemented than either of those rocks. It does not easily split like of shale or have the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

**ash (volcanic).** Fine material ejected from a volcano (also see "tuff").

**axis (fold).** A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.

**basalt.** A dark-colored, often low-viscosity, extrusive igneous rock.

**beach.** A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

**beach face.** The section of the beach exposed to direct wave and/or tidal action.

**bed.** The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

**bedding.** Depositional layering or stratification of sediments.

**bedrock.** A general term for the rock that underlies soil or other unconsolidated, surficial material.

**berm.** A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge on the backshore of a beach.

**braided stream.** A sediment-clogged stream that forms multiple channels which divide and rejoin.

**calcareous.** Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

**calcite.** A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

**carbonaceous.** Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

**carbonate.** A mineral that has $CO_3^{-2}$ as its essential component (e.g., calcite and aragonite).

**carbonate rock.** A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

**cementation.** Chemical precipitation of material into pores between grains that bind the grains into rock.

**chemical sediment.** A sediment precipitated directly from solution (also called nonclastic).

**chemical weathering.** Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

**chert.** A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

**clast.** An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

**clastic.** Describes rock or sediment made of fragments of pre-existing rocks (clasts).

**clay.** Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

**claystone.** Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

**conglomerate.** A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

**conodont.** One of a large number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition and commonly tooth-like in form but not necessarily in function.

**contact metamorphism**. Changes in rock as a result of contact with an igneous body.

**continental crust.** Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

**continental rifting.** Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

**convergent boundary.** A plate boundary where two tectonic plates are colliding.

**cordillera.** A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

**country rock**. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

**craton.** The relatively old and geologically stable interior of a continent (also see "continental shield").

**cross-bedding.** Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

**cross section.** A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

**crust.** Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

**cryptocrystalline.** Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

**crystalline**. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

**deformation**. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

**diamictite**. Poorly sorted, noncalcareous, sedimentary rock with a wide range of particle sizes.

**diamicton.** A general term for nonlithified, nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes, such as a rock with sand and/or larger particles in a muddy matrix.

**diorite.** A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

**divergent boundary.** An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

**drift.** All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier. Includes unstratified material (till) and stratified deposits (outwash plains and fluvial deposits).

**dune.** A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

**epicenter.** The point on Earth's surface that is directly above the focus (location) of an earthquake.

**estuary.** The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

**extension.** A type of strain resulting from forces "pulling apart." Opposite of compression.

**extrusive.** Describes molten (igneous) material that has erupted onto Earth's surface.

**fault.** A break in rock along which relative movement has occurred between the two sides.

**feldspar.** A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

**fold.** A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

**foliation.** A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

**footwall**. The mass of rock beneath a fault surface (also see "hanging wall").

**foraminifer**. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite or of agglutinated particles.

**formation.** Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

**fusulinid.** Any foraminifer belonging to the suborder Fusulinina, family Fusulinidae, characterized by a multichambered elongate calcareous microgranular test, commonly shaped like a grain of wheat.

**gabbro.** A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

**glacial erratic.** Boulders transported by glaciers some distance from their point of origin.

**glaciomarine.** Describes the accumulation of glacially eroded, terrestrially derived sediment in the marine environment.

**granite.** An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

**granodiorite.** A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

**greenschist.** A metamorphic rock, whose green color is due to the presence of the minerals chlorite, epidote, or actinolite, corresponds with metamorphism at temperatures in the 300–500°C (570–930°F) range.

**greenstone.** A general term for any compact dark green altered or metamorphosed basic igneous rock owing its color to chlorite, actinolite, or epidote minerals.

**hanging wall.** The mass of rock above a fault surface (also see "footwall").

**hornblende.** The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

**igneous.** Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

**imbricate.** Overlapping, as tiles on a roof. An imbricate fault zone consists of nearly-parallel, overlapping thrust faults.

**intrusion.** A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

**island arc.** A line or arc of volcanic islands formed over and parallel to a subduction zone.

**isostacy.** The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

**isostatic rebound.** See "isostacy."

**isotopic age.** An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

**isotropy.** The condition of having uniform properties in all directions.

**landslide.** Any process or landform resulting from rapid, gravity-driven mass movement.

**lava.** Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

**left lateral fault.** A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

**limestone.** A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

**liquefaction.** The transformation of loosely packed sediment into a more tightly packed fluid mass.

**lithification.** The conversion of sediment into solid rock.

**lithify.** To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

**lithology.** The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

**lithosphere.** The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

**lodgment till.** The plastering beneath a glacier of successive layers of basal till commonly characterized by compact fissile structure and containing stones oriented with their long axes generally parallel to the direction of ice movement.

**longshore current.** A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

**magma.** Molten rock beneath Earth's surface capable of intrusion and extrusion.

**mantle.** The zone of Earth's interior between the crust and core.

**marine terrace.** A narrow coastal strip of deposited material, sloping gently seaward.

**mass wasting.** A general term for the downslope movement of soil and rock material under the direct influence of gravity.

**mechanical weathering.** The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

**member.** A lithostratigraphic unit with definable contacts; a member subdivides a formation.

**meta–.** A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

**metamorphic.** Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

**metamorphism.** Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

**metavolcanic.** An informal term for volcanic rocks that show evidence of metamorphism.

**mid-ocean ridge.** The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

**mineral.** A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

**moraine.** A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

**nappe.** Sheetlike body of rock that has moved on a predominantly horizontal surface by thrust faulting, recumbent folding, or both.

**normal fault.** A dip-slip fault in which the hanging wall moves down relative to the footwall.

**oblique fault.** A fault in which motion includes both dip-slip and strike-slip components (also see "dip-slip fault" and "strike-slip fault").

**oceanic crust.** Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

**outcrop.** Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

**outwash.** Glacial sediment transported and deposited by meltwater streams.

**paleogeography.** The study, description, and reconstruction of the physical landscape from past geologic periods.

**paleosol.** A ancient soil layer preserved in the geologic record.

**parent material.** The unconsolidated organic and mineral material in which soil forms.

**parent rock.** Rock from which soil, sediments, or other rocks are derived.

**passive margin.** A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

**pebble.** Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

**permeability.** A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

**phyllite.** A metamorphosed rock, intermediate in grade between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart a silky sheen to the surfaces ("schistosity").

**plagioclase.** An important rock-forming group of feldspar minerals.

**plate tectonics.** The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

**pluton (plutonic).** A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

**porosity.** The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

**potassium feldspar.** A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

**provenance.** A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

**radiolarian.** Occurring from the Cambrian Period to the present, radiolarians are zooplankton that occurs throughout the ocean; their skeletal remains (often siliceous spicules) cover large portion of the ocean bottom.

**radiometric age.** An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

**recharge.** Infiltration processes that replenish groundwater.

**regression.** A long-term seaward retreat of the shoreline or relative fall of sea level.

**relative dating.** Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

**reverse fault.** A contractional high-angle (greater than $45^{\circ}$) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

**rock.** A solid, cohesive aggregate of one or more minerals.

**sand.** A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

**sandstone.** Clastic sedimentary rock of predominantly sand-sized grains.

**schist.** A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

**schistosity.** The foliation in schist or other coarse-grained, crystalline rock due to the parallel alignment of platy mineral grains (mica) or crystals of other minerals.

**seafloor spreading.** The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

**sediment**. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

**sedimentary rock.** A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

**shale.** A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

**shear zone.** A zone of rock that has been crushed and brecciated by many parallel fractures due to shear strain.

**shoreface.** The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

**silicate.** A compound whose crystal structure contains the $SiO_4$ tetrahedra.

**silt.** Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

**siltstone.** A variably lithified sedimentary rock composed of silt-sized grains.

**slate.** A compact, fine-grained metamorphic rock that can be split into slabs and thin plates. Most slate was formed from shale.

**soil.** Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

**spreading center.** A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

**spring.** A site where water issues from the surface due to the intersection of the water table with the ground surface.

**stade.** An interval of a glacial stage marked by a readvancing of glaciers.

**strata.** Tabular or sheet-like masses or distinct layers of rock.

**stratification.** The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

**striations.** Parallel scratches or lines.

**strike.** The compass direction of the line of intersection of an inclined surface with a horizontal plane.

**strike-slip fault.** A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

**structure.** The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

**subduction zone.** A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

**syncline.** A downward curving (concave-up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

**tectonic.** Relating to large-scale movement and deformation of Earth's crust.

**terrace.** A relatively level bench or step-like surface breaking the continuity of a slope (also see “stream terrace”).

**terrane.** A large region or group of rocks with similar geology, age, or structural style.

**terrestrial.** Relating to land, Earth, or its inhabitants.

**thrust fault.** A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

**till.** Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

**transcurrent fault.** A term for a continental strike-slip fault that does not terminate at lithospheric plate boundaries.

**transform fault.** A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

**transgression.** Landward migration of the sea as a result of a relative rise in sea level.

**trend.** The direction or azimuth of elongation of a linear geologic feature.

**tuff.** Generally fine-grained, igneous rock formed of consolidated volcanic ash.

**tuffaceous.** A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

**turbidite.** A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

**unconfined groundwater.** Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.

**unconformity.** An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

**undercutting.** The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

**volcanic.** Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth’s surface (e.g., lava).

**volcanic arc.** A commonly curved, linear, zone of volcanoes above a subduction zone.

**volcaniclastic.** Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

**weathering.** The physical, chemical, and biological processes by which rock is broken down.

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# Additional References

*This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of July 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.*

### Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

### NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

### Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

### Geological Surveys and Societies

Washington State Division of Geology and Earth Resources: http://www.dnr.wa.gov/researchscience/geologyearthsciences/pages/home.aspx.

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

### US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

# Appendix: Scoping Meeting Participants

*The following people attended the GRI scoping meeting San Juan Island National Historical Park, held on 10–12 September 2002, or the follow-up report-writing conference call, held on 29 November 2012. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.*

**2002 Scoping Meeting Participants**

| Name | Affiliation | Position |
|---|---|---|
| Andrascik, Roger | NPS – Voyageurs National Park | Natural resources |
| Beavers, Rebecca | NPS – Geologic Resources Division | Geologist |
| Connors, Tim | NPS - Geologic Resources Division | Geologist |
| Dalby, Craig | NPS – Columbia Cascades Support Office | GIS |
| Davis, Marsha | NPS – Pacific West Region | Geologist |
| Doyle, Rebecca | NPS – Mount Rainier National Park | Biologist |
| Graham, John | Colorado State University | Geologist |
| Haugerud, Ralph | US Geological Survey | Geologist |
| Heise, Bruce | NPS - Geologic Resources Division | Geologist |
| Latham, Penny | NPS - Columbia Cascades Support Office | Regional Inventory and Monitoring |
| Norman, Dave | WA Department of Natural Resources | Geologist |
| Pringle, Pat | WA Department of Natural Resources | Geologist |
| Riedel, Jon | NPS – North Cascades National Park | Geologist |
| Samora, Barbara | NPS - Mount Rainier National Park | Natural resources |
| Swinney, Darin | NPS - Mount Rainier National Park | GIS |
| Teissere, Ron | WA Department of Natural Resources | Geologist |

**2012 Conference Call Participants**

| Name | Affiliation | Position |
|---|---|---|
| Connors, Tim | NPS - Geologic Resources Division | Geologist |
| Graham, John | Colorado State University | Geologist, GRI report writer |
| Kenworthy, Jason | NPS Geologic Resources Division | Geologist, GRI reports coordinator |
| Mack, Greg | NPS – Pacific West Region | GIS specialist |
| Riedel, Jon | NPS – North Cascades National Park | Geologist |
| Taylor, Lee | NPS – San Juan Island National Historical Park | Superintendent |
| Weaver, Jerald | NPS – San Juan Island National Historical Park | Chief of Integrated Resources |

# Appendix B: Geologic Resource Laws, Regulations, and Policies

*The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of July 2014. Contact the NPS Geologic Resources Division for detailed guidance.*

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Paleontology | **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects.<br><br>**Paleontological Resources Preservation Act of 2009**, **16 USC § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands. | **36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.<br><br>**Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted.<br><br>Regulations in association with 2009 PRPA are being finalized (May 2014). | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.<br><br>**Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria. |
| Rocks and Minerals | **NPS Organic Act**, **16 USC § 1 *et seq.*** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.<br><br>**Exception: 16 USC § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone). | **36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.<br><br>**Exception: 36 CFR § 7.91** allows limited gold panning in Whiskeytown.<br><br>**Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment. | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Park Use of Sand and Gravel | **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.<br><br>**Exception:** 16 USC §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area. | None applicable. | **Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and:<br>-only for park administrative uses;<br>-after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment;<br>-after finding the use is park's most reasonable alternative based on environment and economics;<br>-parks should use existing pits and create new pits only in accordance with park-wide borrow management plan;<br>-spoil areas must comply with **Part 6** standards; and<br>-NPS must evaluate use of external quarries.<br><br>Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director. |
| Soils | **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.<br><br>**Farmland Protection Policy Act, 7 USC § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS). | **7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements. | **Section 4.8.2.4** requires NPS to<br>-prevent unnatural erosion, removal, and contamination;<br>-conduct soil surveys;<br>-minimize unavoidable excavation; and<br>-develop/follow written prescriptions (instructions). |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
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| Coastal Features and Processes | **NPS Organic Act, 16 USC § 1 *et. seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).<br><br>**Coastal Zone Management Act, 16 USC § 1451 *et. seq.*** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone.<br><br>**Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit.<br><br>**Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs.<br><br>**Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. | **36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands.<br><br>**36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. | **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress.<br><br>**Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.<br><br>**Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties.<br><br>**Section 4.8.1.1** requires NPS to:<br>-Allow natural processes to continue without interference,<br>-Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions,<br>-Study impacts of cultural resource protection proposals on natural resources,<br>-Use the most effective and natural-looking erosion control methods available, and<br>-Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present. |

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Upland and Fluvial Processes | **Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE.<br><br>**Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]).<br><br>**Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**)<br><br>**Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**) | None applicable. | **Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems.<br><br>**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress.<br><br>**Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.<br><br>**Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding.<br><br>**Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams.<br><br>**Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.<br><br>**Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue. |

NPS 438/125611, August 2014

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