National Park Service
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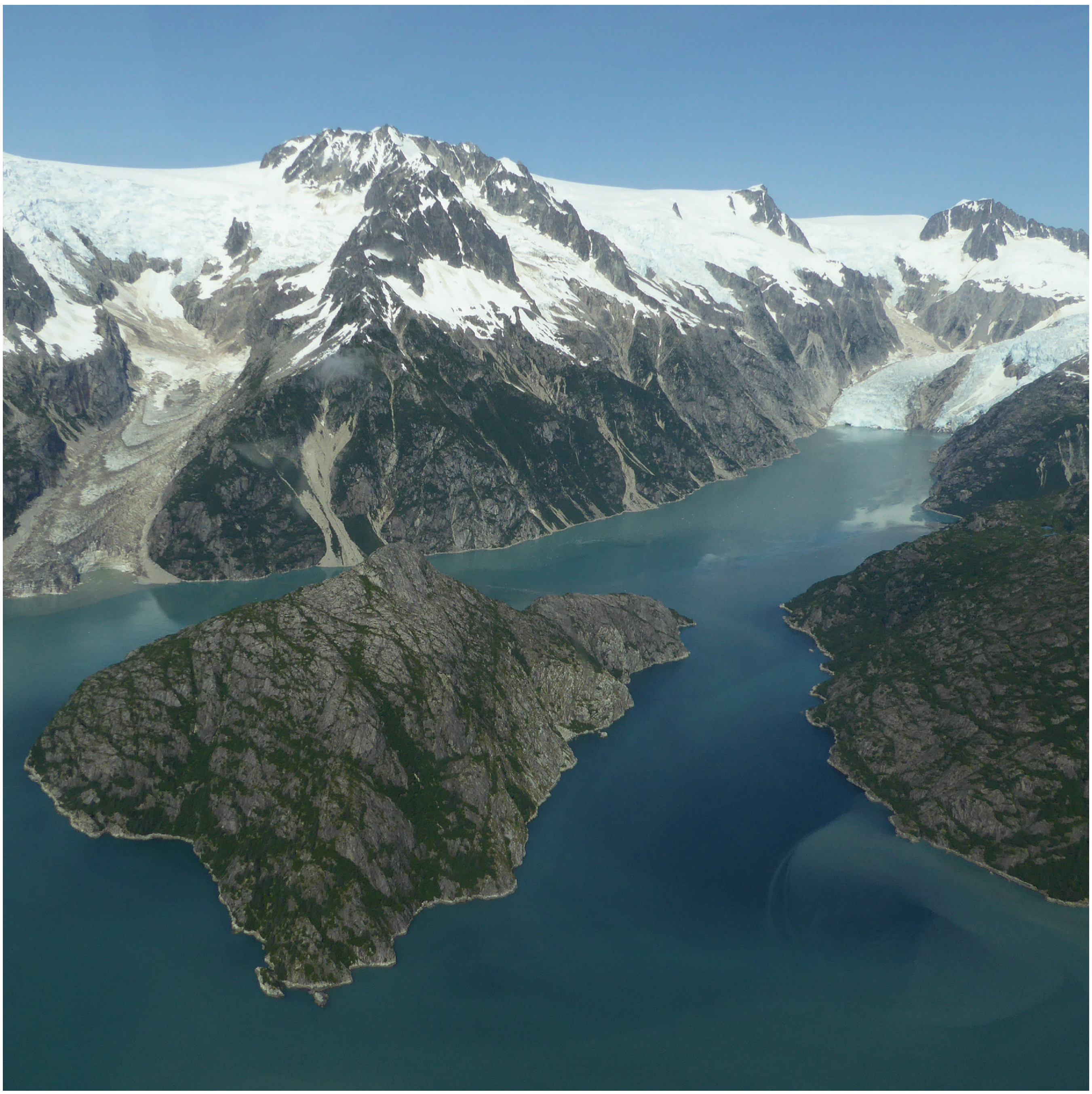
Natural Resource Stewardship and Science

Kenai Fjords National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1581



ON THE COVER

Photograph of Harris Bay, with Northwestern Glacier seen in the top right and the Harding Icefield visible along the top of the photograph. Northwestern Glacier is one of the park's six tidewater glaciers and has retreated over 6 km (3.7 mi) since the creation of the USGS topographic map in the 1950s. On the USGS topographic map, the toe of Northwestern Glacier buries part of the island seen in the foreground of the photograph. Landslides are seen all along the sides of the fjord where the glacier retreated. These landslides may be produced by "glacial debuttressing," a process where recently deglaciated slopes are unstable and prone to sliding. NPS photograph by Deborah Kurtz.

THIS PAGE

Photograph of pillow basalts of the Resurrection ophiolite. Pillow basalts form when lava comes into contact with cold water, causing a solid outer crust to form as the lava cools rapidly. As more lava is fed into the structure it will inflate and produce the pillow-like morphology seen in the photograph. NPS photograph.

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) program provides 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. The 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 held in 2005 and a follow-up report writing meeting in 2015 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. A poster (Plate 1, in pocket) illustrates these data.

Kenai Fjords National Park encompasses the steep, coastal side of the Kenai Peninsula, where rugged glacier-covered mountains rise abruptly out of the ocean to heights of as much as 1,996 m (6,450 ft). Today, nearly half of the park is covered by glaciers, but during the last ice age nearly the entire area was blanketed by glaciers that extended far out onto the continental shelf. Past and recent glaciation has left its mark on the park's landscape, which includes carving out the characteristic fjords that give the park its name. Kenai Fjords National Park was established in 1980 primarily to preserve these fjords, the abundant ecosystems they host, and the glaciers that feed into them.

The primary geologic features and processes within the park are associated with glaciers, both past and modern, in the park.

- **Glacial Features and Deposits**. The majority of park glaciers flow from the Harding Icefield, which is the largest icefield wholly contained within the United States. Other glaciers in the park include those flowing from the smaller Grewingk-Yalik Glacier Complex in the southwest, and scattered cirque glaciers. The Harding Icefield is a vast expanse of glacial ice that blankets much of the higher elevations of the park, stretching from the Nuka River drainage in the southwest almost to the Resurrection River in the northeast. Only the highest peaks of the Kenai Mountains rise above the Harding Icefield, forming islands of rock called nunataks that are isolated by the surrounding ice. Glaciers that emanate from the Harding Icefield include land-terminating glaciers (e.g., Exit Glacier), lake-terminating glaciers (e.g., Bear Glacier), and tidewater glaciers (ocean-terminating; e.g., Aialik Glacier). These three different types of glaciers have differing mechanisms that control their advance and retreat, making Kenai Fjords an ideal place to study and interpret them.
- **Past Glaciations**. During the Last Glacial Maximum (25,000–11,000 yr ago) glaciers covered nearly the entire park. The increased ice volume, in combination with lowered sea level, resulted in intense erosion of the underlying bedrock. Glaciers carved out the deep, steep-sided fjords and sharpened the mountain's peaks and ridges. Since the Last Glacial Maximum, the earth has warmed, causing the glaciers to melt and sea level to rise. Despite this overall trend of glacial retreat, there were short periods of glacial advance during the Holocene (11,000 yr ago–present). The Little Ice Age (1540s–1710s and 1810s–1880s) is the most recent major glacial advance in southcentral Alaska. The Little Ice Age is recorded in the park's geologic record by terminal moraines (ridges of sediment deposited at the end of a glacier) that have been dated to this period.
- **Modern Glacier Change**. Long term monitoring of glacier extent and volume records park-wide glacier retreat that is consistent with global trends. Monitoring efforts include dating glacial deposits from past glacial advances, repeating historic photographs of glaciers, comparing maps produced in the 1950s with more modern imagery to calculate change, and direct and remote sensing measurements of glacier terminus positions. In-situ glacier mass balance measurements on the northern Harding Icefield document surface mass changes resulting from annual accumulation and ablation processes. These studies all point to an increasing

glacial retreat rate that is a result of global climate change. The dramatic observable changes in Kenai Fjords over just the past century represents an important opportunity to learn and teach others about how climate change is affecting the park's natural systems now, and what continued climate change will mean for the future of this landscape.

- **Glacier Lake Outburst Flooding**. Ice-dammed lakes can form in, under, or adjacent to glaciers when ice blocks the flow of water either from the glacier itself or, more commonly, from surrounding drainages. At Bear Glacier, an ice-dammed lake has formed where the glacier blocks water draining from a valley upstream. When the ice damming the water is breached, it can cause catastrophic flooding (termed a glacier lake outburst flood) in Bear Glacier's downglacier proglacial lake. Outburst floods at Bear Glacier have been documented in 2008, 2009, 2010, 2012, and 2014. Although not an annual event, drainage of this ice-dammed lake is cyclic and often occurs in late summer to early fall.

In addition, Kenai Fjords National Park contains other significant geologic features and processes, including the following:

- **Exit Creek Geomorphology**. Many rivers and streams in the park display a braided morphology, meaning multiple channels are prone to migration. Braided streams form in glaciated areas because of a high influx of coarse sediment shed from upstream glaciers. One such braided stream of interest in the park is Exit Creek, which emanates from the toe of Exit Glacier and runs eastward to the Resurrection River. Exit Creek can be split into three geomorphically distinct sections: the outwash plain, the portion of the creek controlled by a series of moraines left by the retreat of Exit Glacier, and the alluvial fan where the creek flows into the Resurrection River. The alluvial fan portion of Exit Creek corresponds to a portion of the park-maintained access road to Exit Glacier that has flooded repeatedly in the past few years.
- **Coastal Features**. The coast of Kenai Fjords is characterized by deposits, such as beaches, and erosional features. Coastal erosional features include sea caves, stacks, and arches, which form through the action of waves on a cliff face. 488 caves, 122 shelters (smaller voids than caves), 68 arches, and 76 stacks have been identified along the coast of Kenai Fjords. These features form with equal frequency in both the granite and metasedimentary rocks exposed along the coast. However, sea cave morphology in Kenai Fjords does seem to be related to rock type.
- **Landslides**. Landslides and rockfall are common in the park because of the steep, glacially eroded slopes that characterize the coastline. Landslides are generally triggered by heavy rain. Warmer winters have recently increased the amount of rain at low elevations, and park staff have observed a corresponding increase in the number of landslides along the coast. Landslides can initiate along weak or fragile structures in rock, such as faults, dikes, bedding planes, or cleavage planes. Many slopes in the park are especially prone to landslides because of a process known as glacial debuttressing. As glaciers retreat, the glacially eroded slopes that were formerly propped up by ice are exposed and prone to sliding. This process can be observed on the western side of Bear Glacier's proglacial lake, where rapid ice retreat has resulted in unstable slopes that are actively sliding.
- **Earthquake Features and Active Margin Tectonics**. Kenai Fjords is situated atop a zone where the Pacific plate is plunging beneath the North American plate, in a process known as subduction. As the Pacific plate subducts, friction causes the upper portion of the plate to lock to the overlying North American plate, resulting in a build-up of stress. The stress causes the land above the subduction zone, including Kenai Fjords, to slowly bulge up until that stress is released during an earthquake. On Friday, March 17, 1964, the built-up stress released and generated a magnitude 9.2 earthquake (called the Great Alaska Earthquake). This was the largest earthquake ever recorded in the United States and second largest earthquake ever recorded worldwide. This earthquake caused widespread destruction in the nearby town of Seward, and caused the area that later became Kenai Fjords National Park to subside (drop down) by 1–2.5 m (3–8 ft). Research suggests that the recurrence interval of large, megathrust earthquakes in the Prince William Sound ranges from 400 to 1,200 years, with an average of 800 years.
- **Bedrock**. The bedrock of Kenai Fjords is composed of metamorphosed igneous and sedimentary rock ranging in age from Mississippian to Paleocene (358.9–56.0 MYA [million years ago]).

These rocks accumulated at a long lived subduction zone, where Pacific and proto-Pacific oceanic crust subducted beneath an oceanic arc that later accreted to the margin of North America. The bedrock includes the McHugh Complex, a chaotic mixture of rocks sourced from both the subducting oceanic plate and the upper continental plate; the Valdez Group, a thick package of metamorphosed sedimentary rocks that were shed off the upper continental plate; the Orca Group, including a portion of oceanic crust called the Resurrection ophiolite; and granitic plutons that formed through partial melting of the sediments of the Valdez and Orca Groups. There are minor gold deposits in quartz veins associated with the formation of the granitic plutons.

- **Paleontological Resources**. Paleontological resources, or fossils, have been found outside the park in the Valdez Group and McHugh Complex, and within the park in the McHugh Complex. The fossils found within the park include crinoids, bivalves, and fusulinids. The fossils recovered are Permian (298.9–251.9 MYA) in age, and the bivalve and fusulinid species are different from other similar-aged species found in North America. These species are more similar to fossils found in rocks from South China, Japan, and the Middle East, all of which were located in the vicinity of the Paleo-Tethys Ocean during the Permian. The exotic affinity of the fossils in Kenai Fjords demonstrate the enormous distance (thousands of miles) some of the rocks in the McHugh Complex have been transported by tectonic forces.

Two meetings were held (February14-18, 2005 and November 20, 2015) to discuss GRI products, geology of the park units, and resource management issues. Participants included NPS natural resource managers, NPS Southwest Alaska Network staff, NPS Alaska Region specialists, and geologists with experience in the Kenai Fjords area. At these meetings, participants discussed the following geologic resource management issues:

- **Glacier Monitoring**. Protecting the Harding Icefield and its outflowing glaciers is at the core of the park's mission. Glaciers in the park have a profound impact on downstream fluvial and nearshore marine ecosystems, and provide benefits to local communities such as Seward. Additionally, the melting of mountain glaciers contributes to sea level rise, a global issue that is projected to increase with further glacial mass loss. Monitoring of both past and current glacier retreat enables park staff to better predict and respond to future glacier loss (See "Past Glaciations and Modern Glacier Change" for more details).
- **Exit Creek Flooding**. Exit Glacier is the park's most visited destination. Access to Exit Glacier is provided by the Herman Leirer road, but flooding of the road by Exit Creek has become a recurring problem. Flooding frequency increased substantially between 2009 and 2014, with road flooding occurring one to three times per year during that timeframe. The portion of the road that was repeatedly flooded corresponds to the area where Exit Creek spreads out into an alluvial fan consisting of active and historic channels. Recent flooding was the result of channels migrating northward within the alluvial fan and across the road during times of high water. During the summer of 2016, the road was raised by five feet and four box culverts were installed to mitigate the effects of future flooding.
- **Coastal Issues**. Kenai Fjords encompasses 877 km (545 mi) of shoreline, including depositional features such as beaches and erosional features such as sea caves, arches, and stacks. Sea caves provide important habitat for birds and marine organisms and are protected under the Federal Cave Resources Protection Act of 1988. Kenai Fjords has also been identified as a park susceptible to sea level change. Currently, tectonic stress causes slow, gradual uplift of the coast of Kenai Fjords, but a large earthquake could cause rapid subsidence and local sea level rise similar to that seen during the 1964 Great Alaska Earthquake. Current regional uplift is outpacing global sea level rise caused by climate change. Climate change could, however, increase storm strength and erosion of the coastline, as well as increase ocean acidification.
- **Geohazards**. Geological hazards (geohazards) that pose a threat include earthquakes, tsunamis, landslides, floods, and glacial lake outburst floods. All of these geohazards could cause significant impacts to visitor safety and park resources. A vulnerability assessment and response plan could be created to address these issues.

- **Abandoned Mineral Lands Mitigation and Mineral Development Potential**. Past mining in the park, primarily for gold, left behind Abandoned Mineral Lands (AML) features that include facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. The majority of AML features on park-owned land have already been mitigated. Only non-historic machinery and two non-historic structures remain that may require removal. Much of the land in the historic Nuka Bay Mining district is not entirely owned by the federal government, and there is the potential of future mineral development on park land that is either entirely non-federally owned or the subsurface rights are non-federally owned. During May 2016, the park received a request for subsurface mineral testing by mineral owners.
- **Paleontological Resources Inventory, Monitoring, and Protection**. Paleontological resources, or fossils, are nonrenewable resources that are subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. The only Paleozoic fossils in Kenai Fjords are from the McHugh Complex, located in a remote area of the park. These fossils are primarily small, poorly preserved invertebrates that are not at a great risk of fossil theft. The fossils are being actively eroded by a glacier, and since these fossils are sourced from limestone blocks of an unknown size, the potential for complete loss via erosion is possible. Further surveys to locate the source outcrop for the fossils collected during the summer of 2016 could assess any management concerns associated with fossil erosion.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Geologists from US Geological Survey, Carleton College, and the National Park Service compiled the source maps and/or reviewed GRI content.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (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 GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter 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://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

This compilation could not have accomplished without the research produced by countless scientists working in the Kenai Fjords area for over a century; thank you. The authors would like to thank our reviewers, **Robert Witter** (research geologist, USGS Alaska Science Center), **Cameron Davidson** (professor of geology, Carleton College), and **Michael Loso** (physical scientist, Wrangell-St. Elias National Park and Preserve), for sharing their expertise and providing valuable feedback. We would like to thank all the people who participated in the pre-report meeting, for providing ideas about topics to address and pointing the authors to sources of information that may have otherwise been overlooked. Thank you to **Sarah Venator** (NPS Alaska Regional Office) for providing data, discussion, and review for sections relating to mining and Abandoned Mineral Lands; **Paul Burger** (NPS Alaska Regional Office) for providing data, discussion, and review for sections relating to hydrology and caves; and **Tahzay Jones** (NPS Alaska Regional Office) for providing data and discussion for the sections relating to coastal issues. Additional thanks goes to **Trista L. Thornberry-Ehrlich** (Colorado State University) for producing some of the graphics used in this report.

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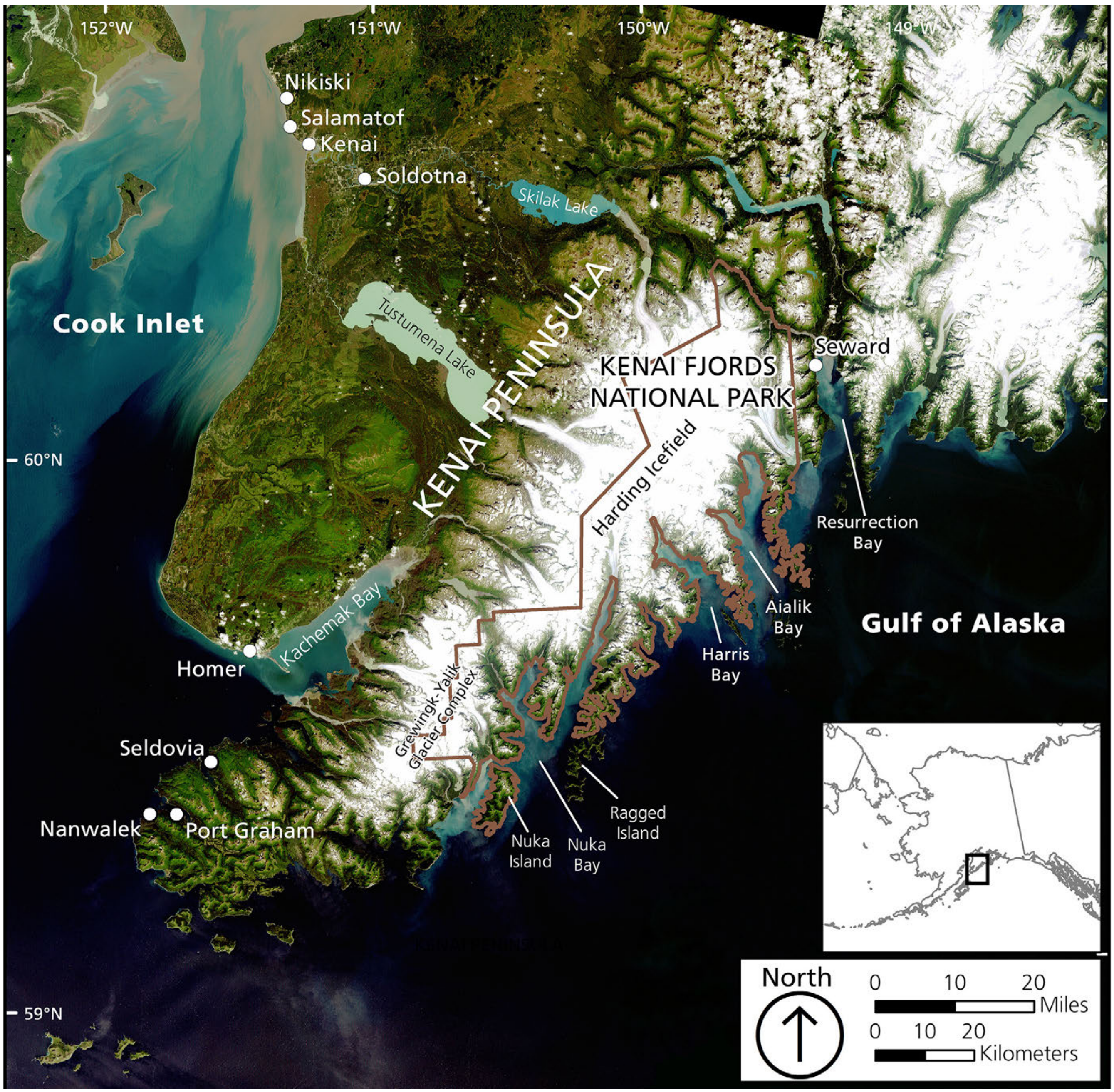


Figure 1. Map of Kenai Fjords National Park. Map shows the location of the park (brown line) and the geographic features of the park and surrounding area mentioned in the text. The base map image was created by the NPS Alaska Landcover Mapping Program using satellite imagery that was collected on August 9, 2000, and July 26, 2000.

Geologic Setting and Significance

This chapter describes the regional geologic setting of the park and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment

The term "Kenai Fjords" was first coined by NPS employee Bailey Breedlove during a flight from Seward to Anchorage in 1967 (Cook and Norris 1998). The name alludes to the geographic similarity Breedlove observed between the southern coast of the Kenai Peninsula and the fjords and glaciers of Norway (Cook and Norris 1998). The name stuck, and in 1978 President Jimmy Carter established Kenai Fjords National Monument to encompass the glacial-fjord ecosystem on the southeastern flank of the Kenai Peninsula. Two years later, in 1980, the Alaska National Interest Land Conservation Act (ANILCA) was passed, redesignating the monument as Kenai Fjords National Park, hereafter also referred to as "Kenai Fjords" or "the park" (Figure 1). Kenai Fjords was created "to maintain unimpaired the scenic and environmental integrity of the Harding Icefield, its outflowing glaciers, and coastal fjords and islands in their natural state; and to protect seals, sea lions, other marine mammals, and marine and other birds and to maintain their hauling and breeding areas in their natural state, free of human activity which is disruptive to their natural processes" (Alaska National Interest Lands Conservation Act 1980).

Located on Alaska's Kenai Peninsula, Kenai Fjords encompasses the southeastern coastal side of the Kenai Mountains. The park stretches from Resurrection Bay in the northeast to the Grewingk-Yalik Glacier Complex in the southwest (Figure 1). Kenai Fjords straddles the interface between the Gulf of Alaska and the Kenai Mountains, with elevations rising rapidly from sea level to as much as 1,996 m (6,450 ft). The park contains 669,984 acres of rugged terrain that is the result of ancient and active geologic processes, as well as biological and environmental factors. Prominent landforms in the park include steep-sided fjords, rocky cliffs, recently deglaciated mountainsides, active glaciers, and looming above all, the vast expanse of the Harding Icefield.

Kenai Fjords is 203 km (126 mi) southwest of Anchorage—Alaska's largest city—and is accessible by automobile, train, boat, and plane. The park's headquarters and one of two visitor centers are located in the nearby city of Seward, which is situated just to the east of the park at the head of Resurrection Bay (Figure 1). Kenai Fjords is one of the smaller park units in Alaska, but in 2016, 346,534 people visited the park, making it the fourth-most visited park in Alaska behind Klondike Gold Rush, Glacier Bay, and Denali. Popular visitor activities include visiting Exit Glacier (the only glacier in the park accessible by car), tour boat trips to view glaciers and marine life, and kayaking in the fjords.

Alaska Natives have utilized and lived on the outer coast of the Kenai Peninsula for hundreds, if not thousands, of years (Cook and Norris 1998). The natives who occupied this area were called Unegkurmiut, which means "people out that way." The modern villages of Nanwalek, Port Graham, and Seldovia, located west of the park on the southern tip of the Kenai Peninsula (Figure 1), all have historic cultural ties to lands now within park boundaries (Cook and Norris 1998). The park's archeological record only stretches back 800 years, which is a result of geologic processes obscuring or destroying earlier evidence of occupation (see "Earthquake Features and Active Margin Tectonics" for more information about earthquake-induced subsidence of the Kenai Peninsula; Crowell and Mann 1996).

The outer coast of the Kenai Peninsula was first explored by Europeans in the late 1700s, when Russian fur traders traveled eastward from the Aleutian Islands (Catton 2010). While early Europeans visited this area to trap and trade for fur, the treacherous coastal waters and prominent glaciers largely discouraged European settlement until the early 1900s (Cook and Norris 1998).

In 1903, Seward was established to serve as the southern terminal for the Alaska Central Railway (later becoming the Alaska Railroad). This railroad now extends all the way to Fairbanks, connecting interior Alaska with the coast (Cook and Norris 1998). Today, the park's headquarters and visitor center are located in Seward, and a large part of Seward's economy is geared toward tourism in and around the park. Tour boats carry interpretive rangers and visitors from the harbor to some of the park's tidewater glaciers; water taxis ferry visitors out to the fjords to enjoy boating and camping; and the Herman Leirer Road runs from Seward to Exit Glacier, the park's most accessible and, therefore, popular destination.

Several historic events occurred prior to the foundation of the park that continue to impact management of the park's modern geologic resources. In 1909, the glaciers of the southern Kenai Peninsula coast were mapped by USGS scientists U. S. Grant and D. F. Higgins (Grant and Higgins 1913). Photographs taken by Grant and Higgins are used today by park staff to visually document the amount of glacial retreat since that time. In 1918, gold was discovered in areas that would later become park land. Mining activity, focused primarily in the Nuka Bay historic mining district, reached its peak in the 1930s (Richter 1970) . The effects of mining are still felt today, which include mitigation and monitoring of abandoned mine sites, and the potential for future mineral development on non-federally owned lands within the park (see "Abandoned Mineral Lands Mitigation and Mineral Development Potential" for more details).

In 1964, a magnitude 9.2 earthquake occurred in southcentral Alaska. This earthquake, now called the 1964 Great Alaska Earthquake, is the largest earthquake ever recorded in the United States and the second largest earthquake ever recorded globally. In addition to causing widespread destruction in many southcentral Alaskan communities (including the city of Seward), this earthquake impacted the landscape that just 16 years later would become Kenai Fjords National Park. The area of Kenai Fjords subsided (dropped down) 1–2.5 m (3–8 ft), and the earthquake and resulting tsunamis produced physical changes in the park's coastal areas. The potential for a similar large-scale earthquake, and the threat such an event would pose to visitor safety and park resources, must be considered when managing the park for future generations.

Geologic Setting

The landscape of Kenai Fjords is dominated by glaciers, with nearly half of the park covered by persistent snow and ice (Figure 1). The abundance of glaciers is a product of the park's high latitude and geographic position. As warmer, moist air moves across the Gulf of Alaska, it collides with colder air in the coastal Kenai Mountains, resulting in heavy precipitation. This precipitation is heaviest during the fall and winter months, occurring as snow in high elevations and feeding the many glaciers that ring the Gulf of Alaska, including those found in Kenai Fjords.

The majority of the park's glaciers flow from the Harding Icefield, but there are also glaciers in the southwest of the park that flow from the smaller Grewingk-Yalik Glacier Complex, as well as isolated cirque glaciers scattered throughout the park. Covering an area of about 1,800 km^2 (695 mi^2), the Harding Icefield is the largest icefield wholly contained within the United States (Aðalgeirsdóttir et al. 1998). The

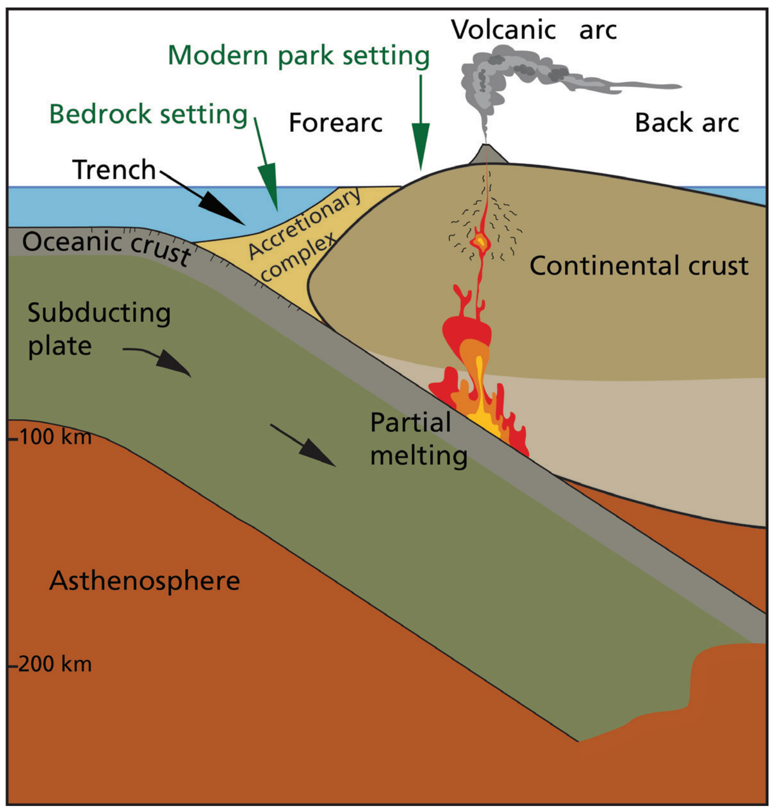


Figure 2. Diagram of a cross-section of oceanic crust subducting under continental crust. Water in the subducting plate reacts with the dry mantle, which causes melt to form and rise into the overlying plate. Volcanoes form where this melt reaches the surface of the earth and erupts as lava. The green arrows point to Kenai Fjords' modern tectonic setting in the Aleutian-Alaska subduction zone, and the approximate tectonic setting when the park's bedrock formed. Kilometers marked on the left indicate depth. Modified from original graphic provided by Trista L. Thornberry-Ehrlich (Colorado State University).

Harding Icefield buries much of the surrounding Kenai Mountains, with only the tallest peaks rising above the ice as nunataks. The Harding Icefield is separated from the Grewingk-Yalik Glacier Complex by the Nuka River drainage, but these icefields were connected in the past during times of greater glacial extent.

Tectonically, Kenai Fjords is situated northwest of the Aleutian-Alaska subduction zone. The Aleutian-Alaska subduction zone forms where the oceanic Pacific plate is subducting beneath the North American plate (Figure 2). Modern collision along the Aleutian-Alaska subduction zone in southcentral Alaska is responsible for creating the Kenai Mountains, the dominant topographic feature within the park. Kenai Fjords' proximity to the subduction zone makes the park prone to large-scale megathrust earthquakes. Earthquakes in the region are concentrated along the Aleutian megathrust and, moving landward, have epicenters that get progressively deeper (Figure 3). The Aleutian-Alaska subduction zone also forms volcanoes all along the southwestern margin of Alaska, but these volcanoes are situated to the north and west of Kenai Fjords (Figure 3).

The bedrock geology records a geologic setting similar to the modern Aleutian-Alaska subduction zone However, the bedrock in and around the park formed further offshore, in the vicinity of the subduction trench (Figure 2). The rocks of Kenai Fjords are part of the Chugach-Prince William accretionary complex. This accretionary complex is a wedge of rocks and

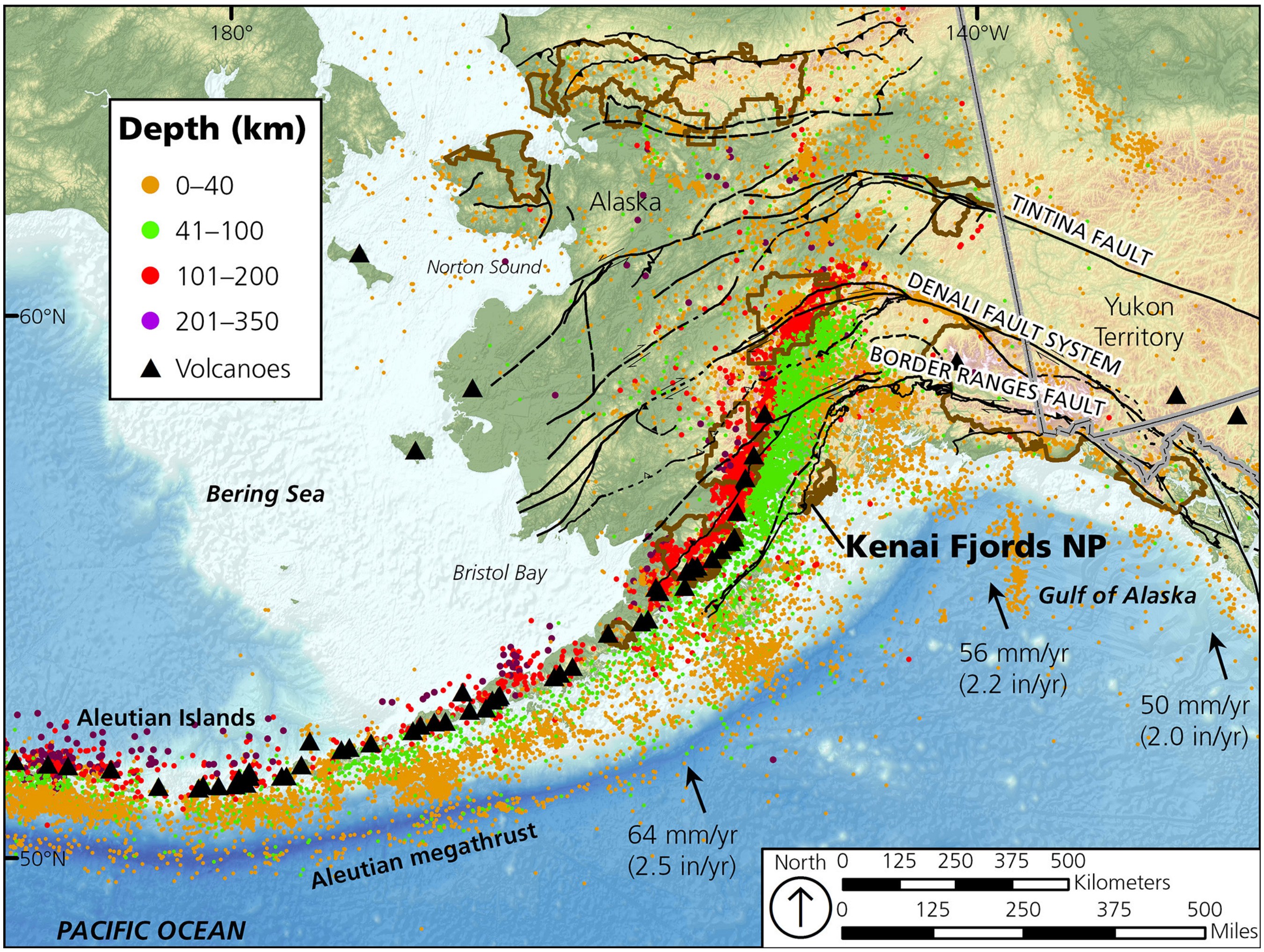


Figure 3. Map of earthquake epicenters greater than magnitude 3.0, colored by depth (1889 to present). The Aleutian arc volcanoes (black triangles) form above the subduction zone where the Pacific plate reaches a depth of 100 km (where the earthquake epicenters transition from red to purple). The Pacific plate motion is shown with arrows. NPS areas outlined in brown. Earthquake data downloaded from http://www.aeic.alaska.edu (accessed January 1, 2015).

sediments that formed as oceanic crust subducted beneath an ancient landmass termed the "Wrangellia composite terrane" (see "Geologic and Plate Tectonic History" for more details). The Chugach-Prince William accretionary complex ranges in age from Jurassic to Eocene (201.3–33.9 MYA), and incorporates rocks scraped off the subducting oceanic plate, as well as sediments shed from the overriding landmass (Figure 2; Figure 4). The Chugach-Prince William accretionary complex initially formed in the middle of the proto-Pacific ocean, but was subsequently transported and accreted to the margin of North America by tectonic forces.

Geologic Significance and Connections

The geology and ongoing geologic processes in Kenai Fjords represent important natural resources and interpretive opportunities for the park, as well as factors that are vital in addressing visitor safety and resource management. The Harding Icefield and its outflowing glaciers were identified as a main impetus for establishing the park (Alaska National Interest Lands Conservation Act 1980), and glacier monitoring, research, and education remains at the core of many park activities. Glacial erosion is responsible for carving the park's landscape, including the fjords which give the park its name. The fjords formed when past glaciers carved deep, U-shaped valleys that were later exposed by ice retreat, and flooded by rising sea level. The beauty of the glaciers and the glacially-carved landscape draw visitors to the park and provide visitors with the opportunity to experience an active glacier up close. Glacial retreat, however, is reducing the accessibility to the park's glaciers. The continuation of this trend may make accessing some glaciers, including Exit Glacier (the only park glacier accessible by road), prohibitively difficult for many visitors.

The glaciers in the park also contribute to issues that threaten visitor safety and park resources. As glaciers retreat, the slopes exposed have an increased chance for landslides. Landslides induced by glacial retreat can be underwater or slide into water and cause local tsunamis. Additionally, ice-dammed lakes form around and within glaciers, and can drain rapidly when the ice is breached. This produces floods down-glacier from the ice-dammed lake. Ice that calves, or breaks off the front of a glacier, can be dangerous to visitors that are too close to the glacier face. When ice calves into water, it can also produce large waves or local tsunamis depending on the size of the calving event.

The tectonic setting of Kenai Fjords makes the park and surrounding area prone to large, subduction-related earthquakes. This is because stress builds up when the Pacific plate is locked with the North American plate. This build-up of stress is partly responsible for uplift (land moving upward) that is currently recorded in the park and Seward. When the stress overcomes the strength of the locked zone between the plates, the Pacific plate will slip downward, producing an earthquake. This is the mechanism that was responsible for the 1964 Great Alaska Earthquake. The release of the stress also causes the land that was formerly uplifting to rapidly subside. This periodic, rapid subsidence has great effects on coastal areas and may be partly responsible for the park's "drowned" coastal geomorphology (for details see "Earthquake Features and Active Margin Tectonics").

The 1964 Great Alaska Earthquake affected the natural features in the park in ways that can still be seen today. Subsidence and inundation of saltwater drowned coastal forests, creating "ghost forests." In addition, landslides triggered by the earthquake covered some of the glaciers in the park. The landslide deposits have insulated these glaciers, causing them to advance despite a larger pattern of glacial retreat.

The 1964 Great Alaska Earthquake resulted in widespread destruction in southcentral Alaska. Most importantly for the later development of the park, the destruction of Seward's port facilities caused a diversification of the town's economy, including a shift towards tourism. Herman Leirer, among other citizens of Seward, spearheaded a project to construct a road to Exit Glacier that would allow visitors to easily access the glacier and increase tourism to the area. With the formation of the park, Exit Glacier and a portion of this road was reassigned as park land. Exit Glacier, largely thanks to the Herman Leirer Road providing easy access, continues to be the most visited area of the park.

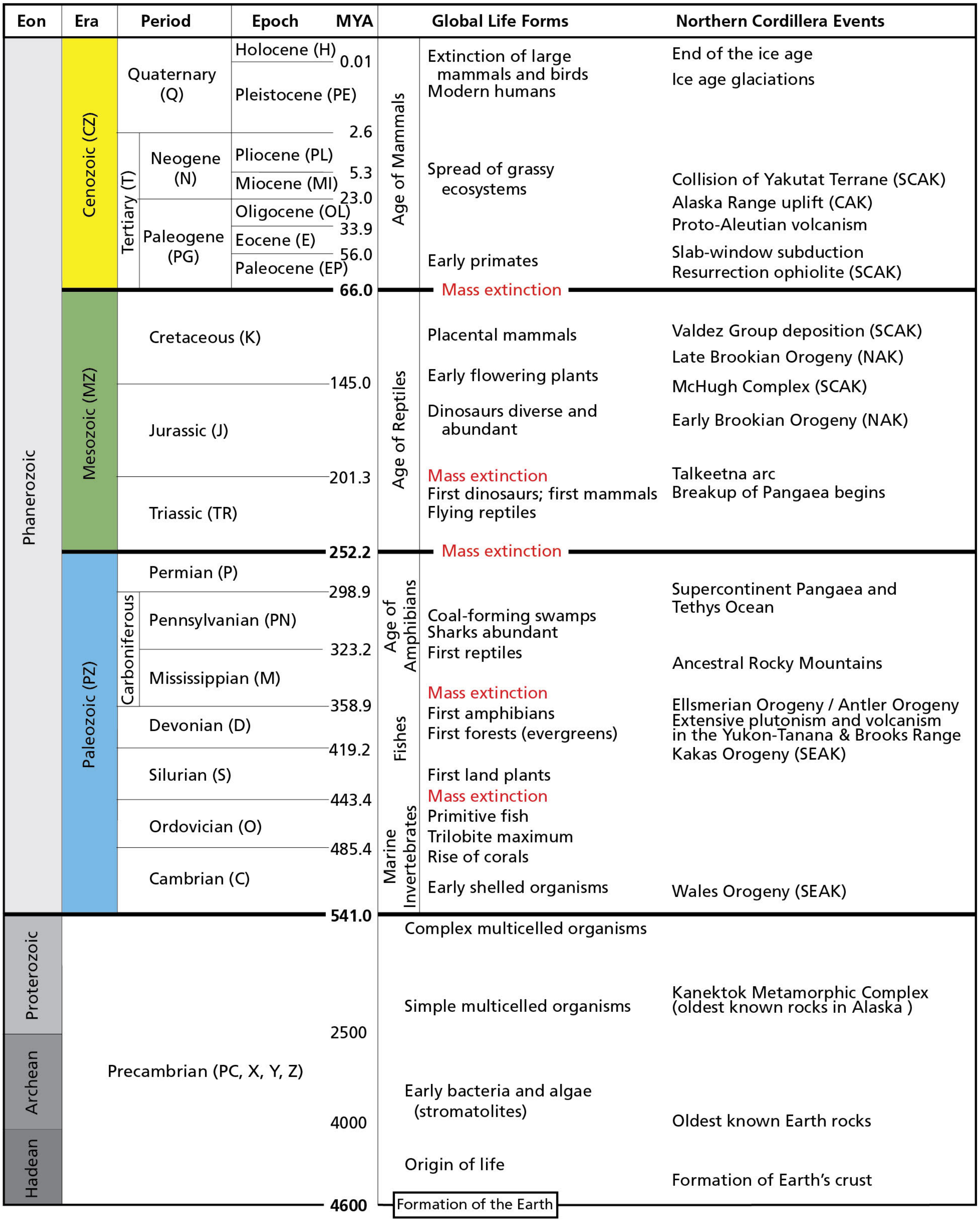


Figure 4. Geologic time scale showing the onset of major global evolutionary and tectonic events of the North American continent and the Northern Cordillera (SCAK, south-central Alaska; SEAK, southeast Alaska; NAK, northern Alaska; CAK central Alaska). The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Ages are millions of years ago (MYA). Ages are from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 7 May 2015).

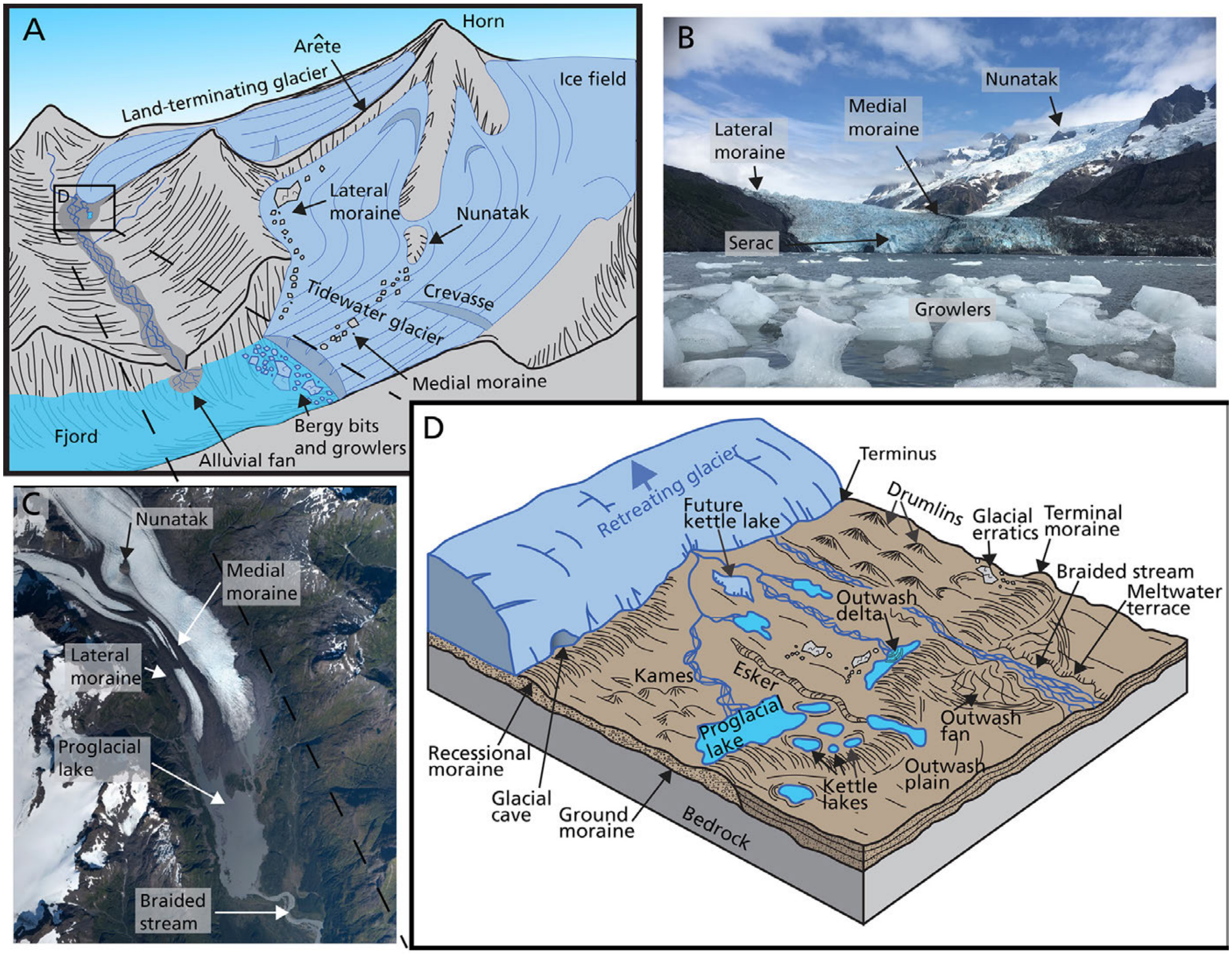


Figure 5. Diagrams and photographs of common glacial features and deposits. A: Diagram showing common mountain glacier features for land-terminating and tidewater glaciers. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). B: Annotated photograph of McCarty Glacier (tidewater glacier) with features labeled. NPS photograph by Emily Baker. C: Annotated aerial imagery of Yalik Glacier (land-terminating glacier) with features labeled. Aerial imagery collected by Mark Laker (US Fish and Wildlife Service) in 2016. D: Diagram showing common types of glacial deposits. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Features and Processes

This section describes the distinctive geologic features of Kenai Fjords, the past geologic processes that formed those features, and the ongoing geologic processes that shape the landscape today. Glacial features and processes are presented first, starting with the general types of glacial deposits and moving to a discussion of past glaciations and modern glacier change. Surficial features and the ongoing processes that form them are discussed, including fluvial and coastal geomorphology. The 1964 Great Alaska Earthquake and resulting tsunamis are described, which is tied to a discussion of the tectonic setting of the park and modern uplift. Lastly, the underlying bedrock units are presented from oldest to youngest, including a discussion of the mineral and paleontological resources the bedrock contains.

Glacial Features and Deposits

Map Units: Qs, Qm, Qao, Qgn, Qogo, Qch (Plate 1)

Kenai Fjords has been shaped by glaciers, with active glacial processes and past glaciations being largely responsible for the fundamental morphology of the landscape. There are two primary glaciated areas in the park: the Harding Icefield and the Grewingk-Yalik Glacier Complex. As of 2014, 287 glaciers cover approximately 48.5% of the park (Loso et al. 2014). These glaciers range from small glaciers that cover less than 1 km^2 (0.4 mi^2), to Bear Glacier, the largest glacier in the park, at 198 km^2 (76.4 mi^2). Many glaciers in the park emanate from the Harding Icefield, which is the largest icefield contained entirely within the United States (Aðalgeirsdóttir et al. 1998). The Harding Icefield buries the surrounding landscape except for the higher peaks of the Kenai Mountains, which rise as nunataks above the ice (Figure 5).

Glaciers are perennial masses of ice that flow from high elevations, where more snow falls than melts (accumulation zone), to lower elevations, where more melting than snowfall occurs (ablation zone). Globally, glaciers vary in size, ranging from small cirque glaciers, to medium-sized mountain glaciers, to the huge continental glaciers that covered a large portion of North America during the Pleistocene. In Kenai Fjords, there are cirque and mountain glaciers, some of which flow from the continuous expanse of the Harding Icefield or the Grewingk-Yalik Glacier Complex. The dynamic nature of glaciers can lead to significant change in mere decades and strongly influences the surrounding hydrologic, geologic, and ecological systems. Glaciers generally change in response to precipitation and especially temperature, making them excellent indicators of regional and global climate changes (Larsen et al. 2015). For additional information about glaciers throughout the National Park System, visit the NPS Geologic Resources Division glacier monitoring website, http://go.nps.gov/glacier_monitoring.

Glacial features and deposits found in the park include landforms formed through modern glacial processes and relict deposits formed when glaciers were more extensive than today. The two major categories of glacial deposits and features are (1) those created or carved by glaciers; and (2) those deposited by water flowing out of glaciers (glaciofluvial). See Figure 5 for schematic illustrations of these deposits and features. Deposits and features formed directly by glacial ice in the park include fjords, horns, arêtes, nunataks, till, moraines, kettles, and glacial erratics. Glaciofluvial deposits and features in the park include braided streams, alluvial fans and outwash fans. In addition, the ice itself forms distinctive features on the glacier such as crevasses, glacial caves, and seracs; ice that is calved off of a glacier into water breaks up into bergy bits (medium-sized icebergs that extend 1–5 m (3–16 ft) above sea level), and growlers (small icebergs that extend less than 1 m (3 ft) above sea level).

The Kenai Peninsula contains glaciers that end in the ocean (tidewater glaciers), glaciers that end in a lake (lake-terminating glaciers), and glaciers that end on land (land-terminating glaciers; Figure 5). While tidewater glaciers make up only about 0.1 percent of the tens of thousands of glaciers found in Alaska (Molnia 2008), six tidewater glaciers are currently found in Kenai Fjords (Table 1). In recent years, these tidewater glaciers have been retreating and appear to be on the cusp of pulling away from the marine environment. Kenai Fjords also contains land-terminating and lake-terminating glaciers (Table 1). For the most part, the retreat and advance of land-terminating glaciers is controlled by climate. On

Table 1. List of glaciers in Kenai Fjords, their size, and whether they are tidewater, lake-terminating, or land-terminating.

Name	Size (km^2)	Type
Lowell Glacier	14.5	Land-terminating
Exit Glacier	26.6	Land-terminating
Bear Glacier	146.6	Lake-terminating
Aialik Glacier	71.7	Tidewater
Pedersen Glacier	32.4	Lake-terminating
Holgate Glacier	77.8	Tidewater
Northwestern Glacier	34.8	Tidewater
McCarty Glacier	116.7	Tidewater
Dinglestadt Glacier	24.3	Land-terminating
Split Glacier	13.6	Land-terminating
Yalik Glacier	41.7	Lake-terminating
Petrof Glacier	42.9	Land-terminating

Glaciers included on this list are those that are formally named, greater than 10 km^2 (3.9 mi^2), and have the majority of their surface area within park boundaries. The other two tidewater glaciers in the park are informally named. This glacier size was taken from the Randolf Glacier Inventory GIS data (https://www.glims.org/RGI/). Glaciers are listed geographically from northeast to southwest.

the other hand, tidewater glaciers and lake-terminating glaciers go through advance-retreat cycles that are not wholly forced by climate.

Tidewater glaciers have different mechanisms that control their advance and retreat when compared to land-terminating glaciers. Tidewater glaciers go through advance-retreat cycles that contain four phases: advancing, extended, retreating, and retracted (Figure 6). Unlike land-terminating glaciers, tidewater glaciers lose the majority of their mass through calving (breaking off) of ice at the front of the glacier (Molnia 2008). The amount of material calved off is closely related to water depth, with larger icebergs calving off when the glacier's terminus is in deeper water and smaller icebergs calving off in shallower water (Molnia 2008; Figure 6). Due to this relationship, tidewater glaciers often advance slowly, with the speed being largely controlled by the depth of the water into which the glacier is moving (Nick et al. 2007). The same correlation between water depth and iceberg size that causes tidewater glaciers to advance slowly also causes their retreat to be particularly fast; as a tidewater glacier retreats back from its terminal moraine, the increase in water depth causes iceberg size to increase dramatically (Molnia 2008; Figure 6). While climatic pressure can initiate a retreat from the terminal moraine (Pfeffer 2007), tidewater glaciers will progress through the advance-retreat cycle without external climate change (Brinkerhoff et al. 2017). Other factors such as water depth, sedimentation rate, and fjord geometry play a major role in tidewater glacial fluctuations (Nick et al. 2007; Molnia 2008; Brinkerhoff et al. 2017). Brinkerhoff et al. (2017) found that future warming could even be expected to trigger tidewater glacier advance, because increased meltwater may cause increased sedimenation on the terminal moraine. The decoupling of tidewater glacier advance-retreat cycles and climate is reflected in the Holocene glacial record, when many tidewater glaciers fluctuated asynchronously with respect to adjacent tidewater and land-terminating glaciers alike, regardless of the climatic regime (Wiles and Calkin 1993; Barclay et al. 2009).

Lake-terminating glaciers share many characteristics with tidewater glaciers, but differences are present that stem from terminus interactions with freshwater rather than seawater. Like tidewater glaciers, lake-terminating glaciers lose a significant amount of mass via calving. However, calving rates into freshwater tend to be slower when compared to glaciers calving into equivalent seawater depths (Benn et al. 2007). This is because proglacial lakes are colder, and do not have the same temperature- and salinity-related density gradients seen in marine environments that experience high glacial meltwater input (Trüssel et al. 2013). The lack of buoyancy-driven circulation at the terminus of a lake-terminating glacier allows lake-terminating glaciers to develop a more gradual (Figure 7) and sometimes floating terminus (Trüssel et al. 2013).

Past Glaciations and Modern Glacier Change

Map Units: Qm, Qao, Qgn, Qogo, Qch, g (Plate 1)

The fjords of Kenai Fjords were filled by glaciers during the Last Glacial Maximum (most recent Pleistocene "ice age", 25,000–11,000 yr ago) when ice covered nearly the entire park (Figure 8). The glaciers flowing southeast from the Kenai Mountains coalesced and formed an

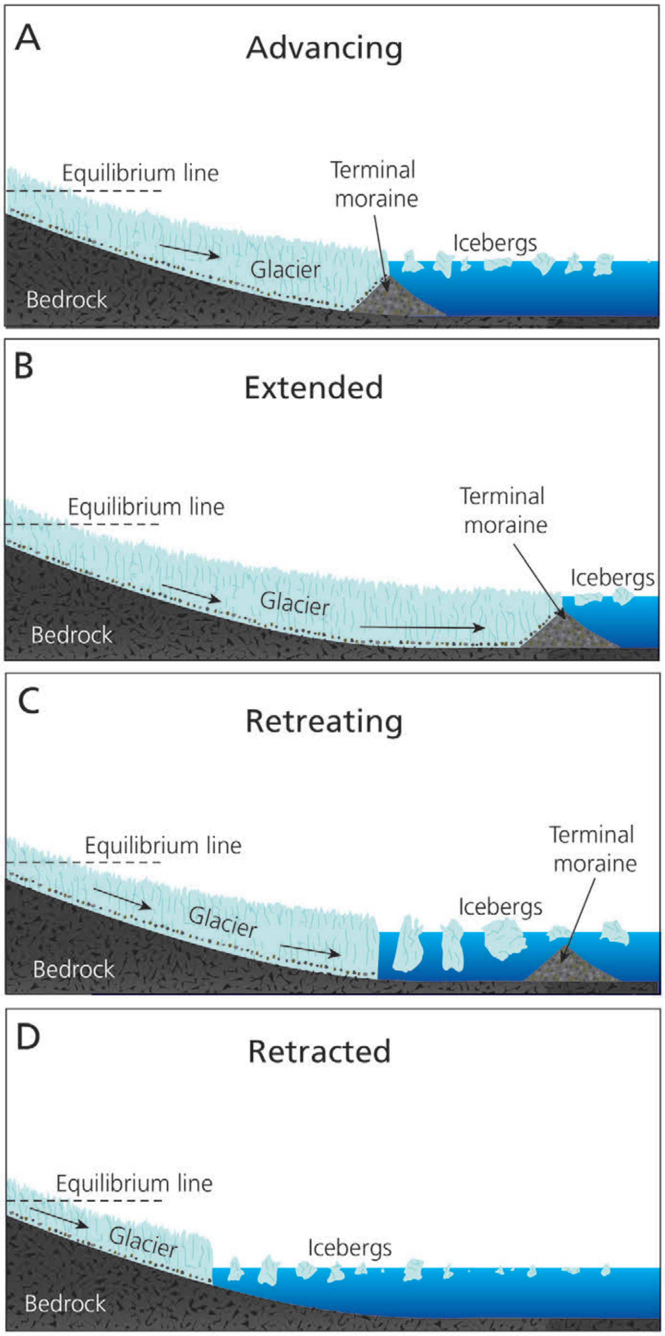


Figure 7 (above). Photographs showing the difference in terminus morphology between tidewater and lake-terminating glaciers. The tidewater glacier (McCarty Glacier) has a steeper terminus, while the lake-terminating glacier (Bear Glacier) has a terminus with a gentler gradient. Also, note the larger icebergs calving off Bear Glacier compared to McCarty Glacier. Lake-terminating glaciers can develop a floating terminus, which breaks into larger pieces than those typically calved off a grounded terminus. NPS photographs by Deborah Kurtz.

Figure 6 (above). Diagram of the advance-retreat cycle of tidewater glaciers. A (Advancing): Modeling has shown that a tidewater glacier cannot advance through water greater than 300 meters deep (Nick et al. 2007). Water depth at the terminus of an advancing tidewater glacier is decreased by the presence of a terminal moraine and iceberg sizes are small (Molnia 2008). B (Extended): As the glacier continues to advance the terminal moraine is pushed forward, maintaining that shallow water depth, keeping iceberg size small, and allowing the glacier to move forward (Molnia 2008). C (Retreating): The tidewater glacier will start to retreat once it is no longer grounded on the terminal moraine. This can occur either when the glacier's terminus retreats or when the moraine progrades seaward at a faster pace than the terminus (Brinkerhoff et al. 2017). With the initiation of retreat, a tidewater glacier's terminus moves into deeper water, causing the size of calving icebergs to increase dramatically (Molnia 2008). D (Retracted): This increased loss of volume at the toe of the glacier results in accelerated rates of retreat, only stabilizing as the terminus once again occupies shallow water, usually near the head of the fjord (Molnia 2008). Modified from Molnia (2008).

ice sheet that flowed far out onto the continental shelf (shown as purple in Figure 8). Other than the shapes of the fjords themselves, little evidence in the way of deposits is preserved in the park. However, evidence for this glaciation is well preserved as a series of glacier moraines on the lowlands of the Kenai Peninsula (shown as blue lines in Figure 8). These moraines are grouped in what is called the Naptowne glaciation (**Qgn**) that range in age from approximately 30,000 to 11,000 calendar years before present (Karlstrom 1964; Reger et al. 1996; Reger and Pinney 1997; Reger et al. 2007).

A moraine forms when the terminus of a glacier is relatively stable for a time, allowing sediment melting out of the toe of the glacier to accumulate. If the glacier advances forward after this stable period, the moraine will often be bulldozed by the advancing ice and reworked into new deposits. However, if the glacier subsequently retreats, the moraine may be preserved, providing a record of the former extent of the glacier.

Moraines record the former extent of park glaciers. The glaciers have been generally receding since the Last Glacial Maximum, but experienced minor re-advances during the Holocene (11,700 yr ago to present). In coastal southern Alaska, the largest of these Holocene advances occurred in two pulses (1540s–1710s and 1810s–1880s) that have been termed the Little Ice Age (Figure 8; Barclay et al. 2009). The Little Ice Age advance is recorded in the park by terminal moraines, which are ridges of sediment and boulders deposited at the toe of a glacier (Figure 5). At Exit Glacier, a series of moraines show the retreat of the glacier through the last 200 years (see "Terminus Positions" for more details). Moraines dating to the Little Ice Age show the maximum Holocene extent for many of the glaciers in the park (Cremis 1993; Wiles and Calkin 1993; Wiles and Calkin 1990).

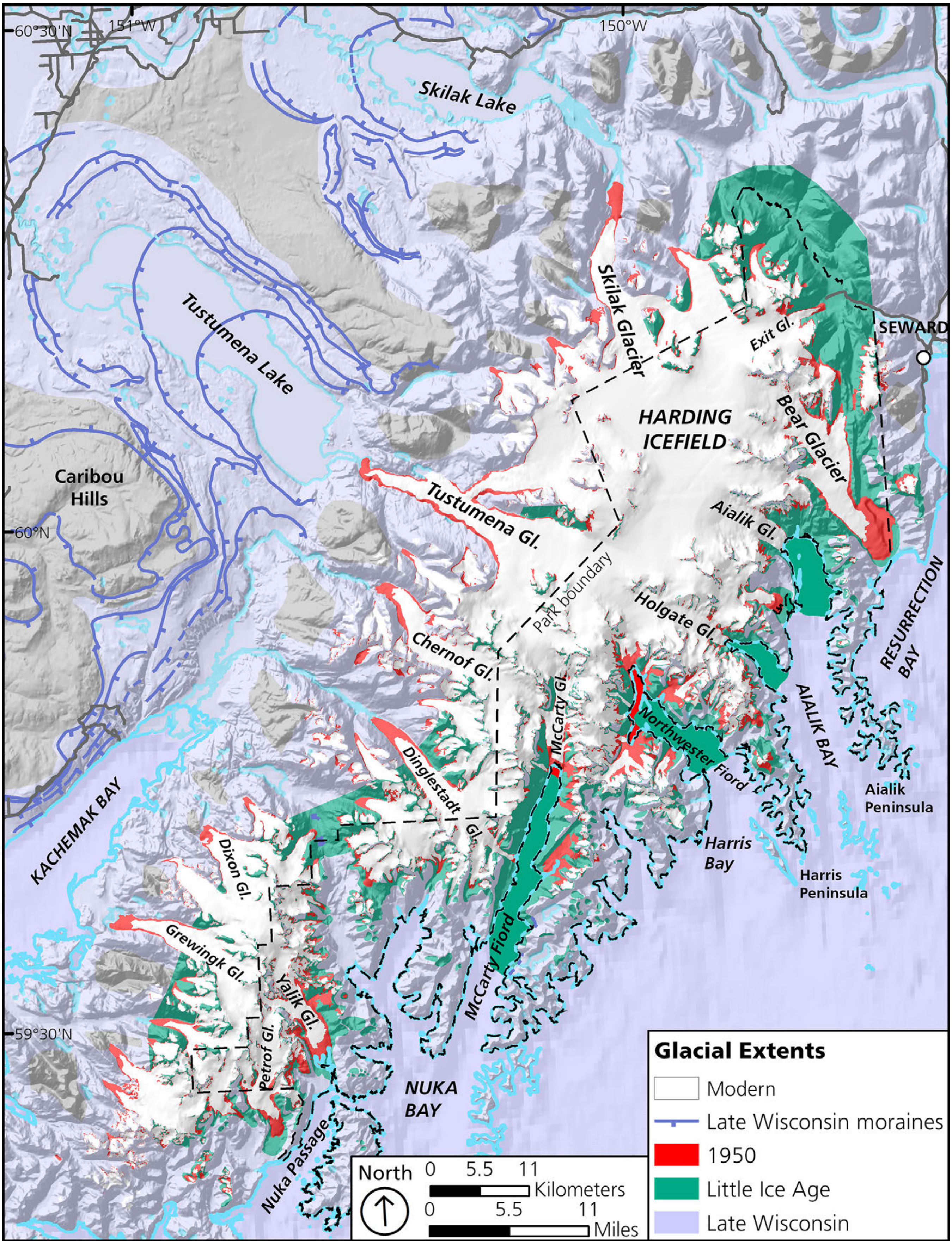
Since the end of the Little Ice Age, glacier coverage has decreased significantly, and Kenai Fjord's glaciers continue to retreat today (Loso et al. 2014). Land-terminating glaciers and, to a lesser extent, tidewater glaciers are sensitive to climatic changes, expanding during cold periods and retreating during warm periods (Wiles et al. 2008). Understanding the current retreat of glaciers is important for understanding how changes in ice volume are currently affecting surrounding biological and physical processes and modeling how glaciers will respond to further climate change. University researchers, the National Park Service's Southwest Alaska Network of the Inventory and Monitoring program, and Kenai Fjords staff track glacier change by looking at overall fluctuations of the Harding Icefield, and the retreat of park glaciers on an individual basis, with the greatest focus on Exit Glacier (Kurtz and Baker 2016; Loso et al. 2014; Giffen et al. 2014).

Glacier Extent

Between 1950 and 2005 the glacial coverage of Kenai Fjords National Park decreased 11%—from 2,326 km^2 to 2,074 km^2 (1,445 mi^2 to 1,289 mi^2; Figure 9; Loso et al. 2014). Most of the mapped glacial extent was lost at elevations below 600 m (1,969 ft). The loss of glacier cover is dominated by terminus retreat, which is distributed fairly evenly throughout all large glaciers in the park. For more information about terminus retreat monitoring for specific glaciers, see the "Terminus Positions" section of this report.

Glacier coverage and terminus retreat do not reflect all aspects of glacier change. These measures alone do not take into account ice thinning, which is an essential component when calculating glacial mass balance. Glacier coverage combined with glacier surface elevations provide a more robust measure of glacial mass balance. Surface elevation change can be used to determine the change in glacier thickness

Figure 8 (facing page). Map showing the extent of glacial advances since the last glacial maximum, with the park boundary marked with a dashed line and modern water bodies outlined in light blue. During the last glacial maximum (Late Wisconsin, approximately 20,000 yr ago), the entire park and all the fjords were covered in ice (Kaufman et al. 2011). Following the last glacial maximum, the glaciers retreated farther than the present day glacial extent. During the Little Ice Age (approximately 1850) glaciers advanced, which left moraines in some of the park's fjords (the Little Ice Age extent is incomplete for the areas west of Kenai Fjords [Wells et al. 2014]). The glaciers have been retreating since the Little Ice Age. The glacial extent during the 1950s is from the USGS topographic maps, the modern glacial extents are from satellite imagery taken between 2005 and 2007 (Loso et al. 2014), the Late Wisconsin glacial extent is sourced from the Alaska PaleoGlacier Atlas (http://instaar.colorado.edu/groups/QGISL/ak_paleoglacier_atlas/), and the Little Ice Age extent is from Wells et al. (2014). Hillshade derived from National Elevation Dataset.


60°30'N
151°W
150°W
Skilak Lake
Tustumena Lake
Caribou Hills
60°N
Skilak Glacier
Exit Gl.
SEWARD
HARDING ICEFIELD
Bear Glacier
Tustumena Gl.
Aialik Gl.
Park boundary
Holgate Gl.
RESURRECTION BAY
Chernof Gl.
McCarty Gl.
Northwester Fiord
AIALIK BAY
Dinglestadt Gl.
Aialik Peninsula
KACHEMAK BAY
Harris Bay
Harris Peninsula
Dixon Gl.
Grewingk Gl.
Yalik Gl.
McCarty Fiord
59°30'N
Petrof Gl.
NUKA BAY
Nuka Passage
Glacial Extents
Modern
Late Wisconsin moraines
1950
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0 5.5 11 Kilometers
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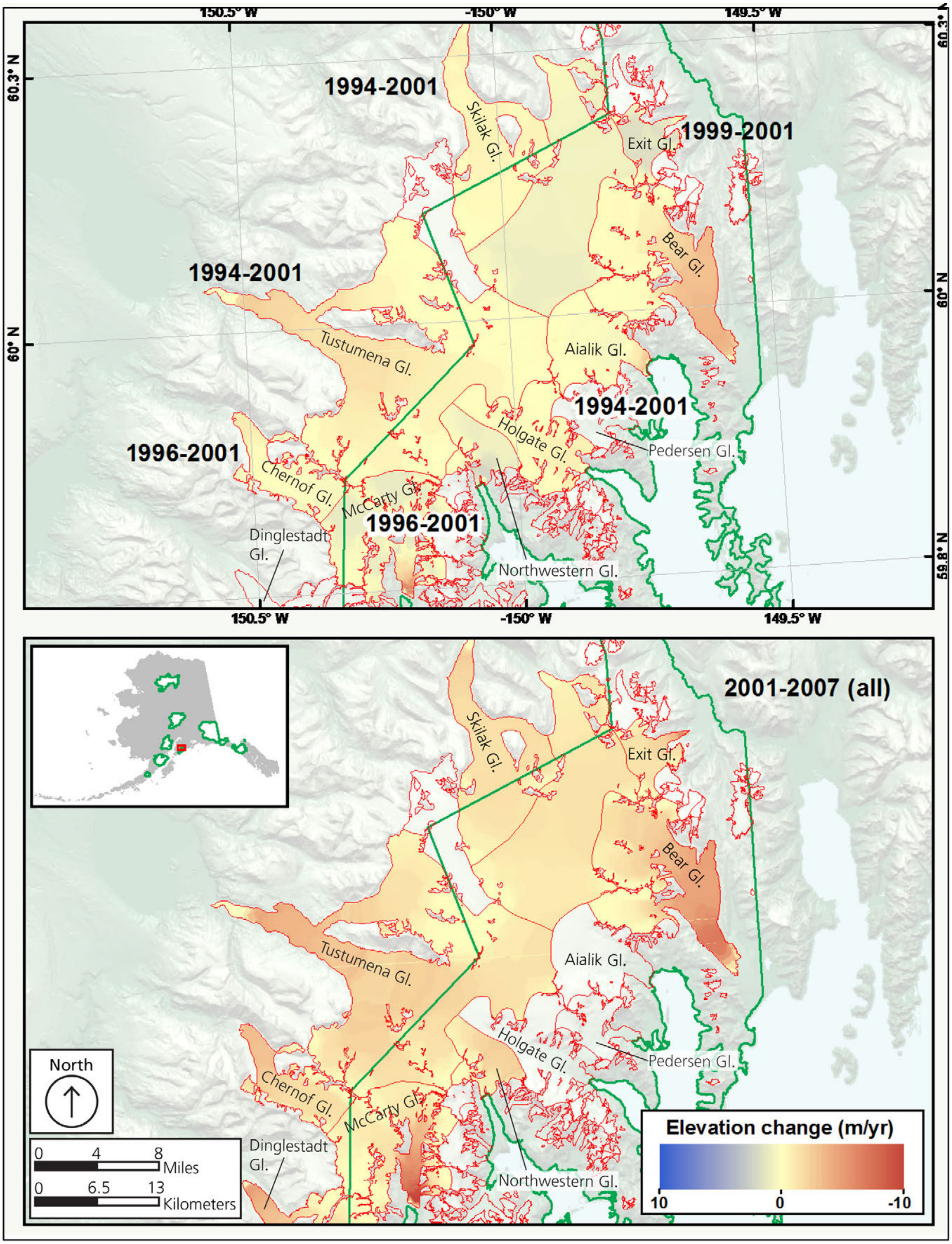


Figure 9. Maps showing the rates of surface elevation change for the park's glaciers between 1994–1999 and 2001, and between 2001 and 2007. Modified from Loso et al. (2014).

over time. Combined with glacier coverage, these data are used to estimate a glacier's volume and track how that volume is changing (Loso et al. 2014). Initial surface elevation change calculated for the period of 1950s–1990s determined that the Harding Icefield underwent an area-average elevation change of -21 m (-69 ft; Aðalgeirsdóttir et al. 1998). More recent research indicates that, since the mid-1990s, the park's glaciers have continued to lose surface elevation, and, by extension glacial thickness (Figure 9). From the mid-1990s to 2001, glacier surface elevation changes were a mix of slight elevation gains at higher elevations, and modest elevation losses (Loso et al. 2014). During the period from 2001–2007 all glacier surfaces lost elevation; some low-elevation glacier surfaces lost as much as 10 m/year (33 ft/year).

Ice thickness has been measured for the northern Harding Icefield, including the distributaries of Bear and Exit Glaciers (Figure 10; Truffer 2014). Measuring absolute thickness enables researchers to estimate the total volume of ice stored in the glacier and determine the topography of the landscape beneath the ice. If the underlying topography deepens up-glacier, unstable retreat could be triggered; conversely, an up-glacier rise in topography can have a stabilizing effect on glacier retreat (Truffer 2014). Truffer (2014) found that ice thickness was greatest at Bear Glacier, with a maximum depth of just more than 600 m (1969 ft), which is grounded below sea level. This indicates that continued retreat of Bear Glacier could result in the formation of a lake that is more than double the current size of Bear Glacier's proglacial lake, if there is not a bedrock ridge dividing the current proglacial lake from the underlying depression up-glacier (Truffer 2014). Depth measurements on the Harding Icefield indicate that the base of the icefield is situated below the current equilibrium line altitude (the altitude that separates lower elevations with more ice melt and higher elevations with more ice accumulation). If continued warming raises the equilibrium line altitude above the level of most of the Harding Icefield, it will trigger an unstable retreat resulting in the loss of all but the smallest, high elevation glaciers (Truffer 2014). A similar phenomenon is occurring on the Yakutat Glacier, east of Kenai Fjords near Yakutat Bay, Alaska (Trüssel et al. 2013).

Figure 10. Photograph of ice thickness fieldwork in 2010. Ice thickness was determined using a technique called radio echo sounding. This technique uses the reflection of an electromagnetic wave off the underlying bedrock to determine ice thickness. NPS photograph by F. Klasner.

Terminus Positions

The most visible part of the glaciers in Kenai Fjords are the termini. Whether visiting Exit Glacier or the tidewater glaciers in Aialik Bay or Northwestern Fiord, most visitors only view the lowest elevation of the glacier. Changes in a glacier's terminus position are important to the park not only because this is region most accessible to people, but it is also the part of the glacier that displays the most apparent change. Terminus change is monitored through repeat photography, and through the use of direct measurements using GPS mapping techniques, moraine mapping and dating, and digitization of historic aerial and satellite imagery.

Repeat Photography

Repeat photography visually captures changes in glacier volume and terminus position by taking photographs of a glacier from the same position over a number of years (Figure 11; Figure 12). The glaciers of Kenai Fjords have a photographic history dating back to 1909, when U. S. Grant and D. F. Higgins of the USGS surveyed the outer coast of the Kenai Peninsula (Figure 11; Figure 12; Cook and Norris 1998). Repeats of these photographs document glacier change that has occurred over the past 100 years (Figure 11; Figure 12; Pister 2016). Some glaciers show a dramatic change in terminus position since 1909, and some glaciers, such as Pedersen Glacier (a lake-terminating glacier in Aialik Bay), show an increased rate of change in the last three years (Figure 12). In many cases, historic photographs are the most reliable information available for estimating terminus positions before topographic maps were produced in the 1950s. They are also striking visual aids for communicating the magnitude of glacier change that has occurred here in just the last century.

Figure 11. Repeat photographs of glaciers in Holgate Arm. 1909 photograph by U. S. Grant (USGS), 2004 photograph by B. Molina (USGS), and 2011 and 2016 photographs by D. Kurtz (NPS).

Figure 12. Repeat photographs of Pedersen Glacier. NPS photographs: 1990 Photograph by M. Tetreau; 2013, 2015, and 2016 photographs by D. Kurtz.

Exit Glacier Terminus Change

Exit Glacier is the only glacier in the park that is accessible by car, and it receives more than 150,000 visitors a year. Easy access, high public interest, and the dynamic retreat of Exit Glacier have made this glacier a research focus since the park was established. Mapping and dating of Exit Glacier's moraines (Cusick 2001; Wiles 1992) enables the tracking of the terminus since the Little Ice Age; aerial photographs show the positioning of the terminus since 1950; and direct measurements by park staff have monitored the terminus location since 1987 (Kurtz and Baker 2016). Kurtz and Baker (2016) recently refined and compiled the available data regarding Exit Glacier's retreat from 1815 to 2015.

Exit Glacier reached its most recent maximum extent during the Little Ice Age, which is recorded by a terminal moraine dating to 1815 (Cusick 2001; Figure 13). After remaining relatively stable at this position until about 1889, Exit Glacier started to retreat. Since then, Exit Glacier's terminus has retreated 2.5 km (1.55 mi) to its present-day position (Kurtz and Baker 2016). During this retreat, there were several pauses that allowed sediment at the toe of the glacier to build up, leaving behind a series of recessional moraines (Figure 13).

The rate of retreat has fluctuated between 1889 and 2015, with an average retreat of 19.7 m/yr (64.6 ft/yr). The three intervals with the highest rate of retreat were between 1889 and 1899 (57.6 m/yr, 189 ft/yr), 1914 and 1926 (49.4 meters per year, 162 ft/yr), and the current retreat, recorded between 2010 and 2015 (44.5 m/yr, 146 ft/yr). The 44.5 m/yr rate seen since 2010 is the third fastest rate recorded in the past 200 years and represents an increase from the previous 5 year period, which had a slower rate of 29.4 m/yr (96.5 ft/yr). In addition, there was one period of glacier expansion, when from about 1983 to 1993 Exit Glacier advanced approximately 150 m (492 ft) and overran a part of the trail system that was present at the time.

Since 2010, park staff have mapped Exit Glacier's terminus position in the spring and fall. This allows staff to differentiate summer (late May/early June to late

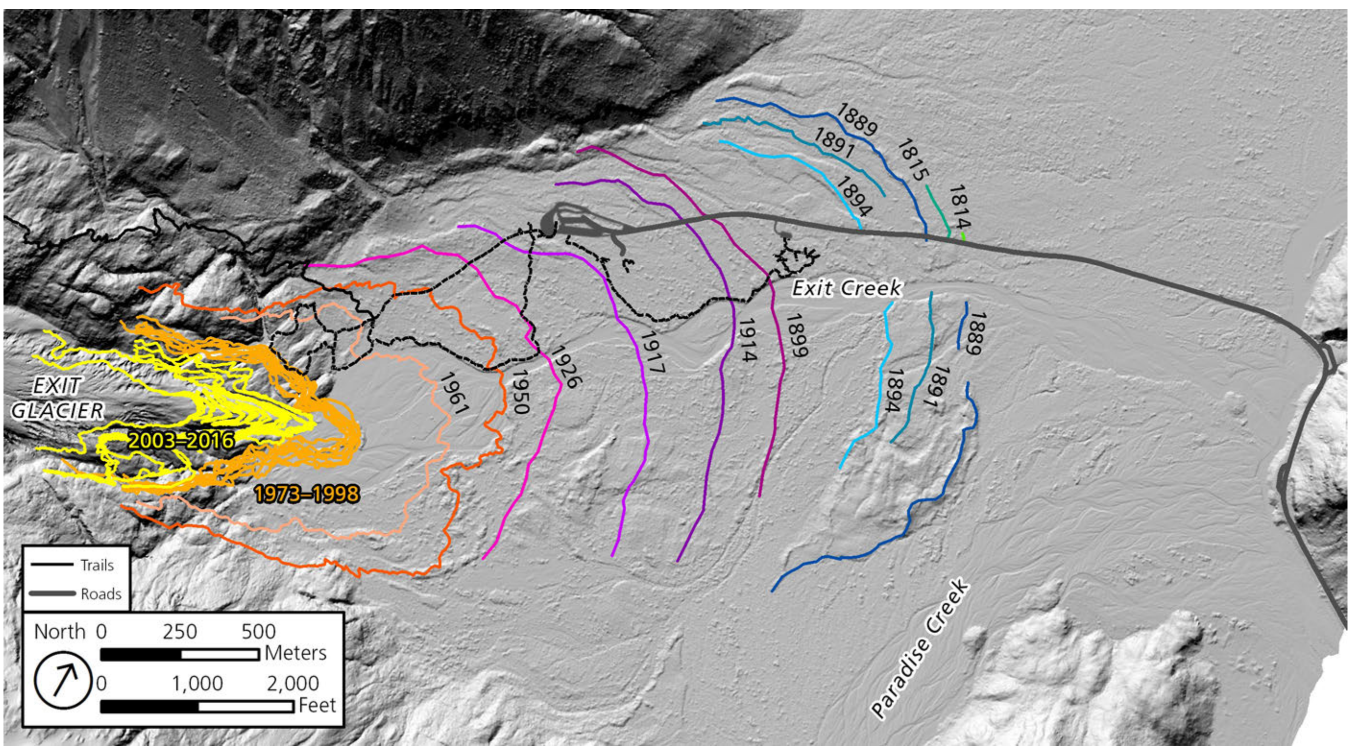


Figure 13. Map showing the locations of the Exit Glacier terminus and moraines from 1814 to 2016. The glacier has retreated approximately 2.5 km (1.55 mi) since 1814. Between 1814 and 1894, the terminus of Exit Glacier remained relatively stable. Following this period, Exit Glacier started to retreat. The three most rapid periods of retreat were between 1889 and 1899 (57.6 m/yr, 189 ft/yr), 1914 and 1926 (49.4 meters per year, 162 ft/yr), and the current retreat, recorded between 2010 and 2015 (44.5 m/yr, 146 ft/yr). Colored lines with dates are the former position of the Exit Glacier Terminus. Basemap hillshade derived from 2008 LiDAR.

Figure 14. Photographs of the toe of Exit Glacier, showing terminus retreat during the summer of 2016. From May to September, the terminus retreated an unprecedented 78 m (256 ft). NPS photographs.

September) and winter (late September to late May/early June) retreat. Between 2010 and 2015, retreat occurred during both the summer and winter seasons, with summer retreat rates being on average 6.6 times faster than winter retreat rates. During the summer of 2016, Exit Glacier retreated 78 m (256 ft), representing the largest summer retreat recorded at Exit Glacier (Figure 14). This rapid retreat may have been a product of a change in the hydrology of Exit Creek, which caused an increase in undercutting and calving at the toe of the glacier. Exit Creek's shift during the summer of 2016 is discussed in more detail in the "Exit Creek Geomorphology" section of this report.

Harding Icefield Mass Balance

In 2009, park staff initiated a glacier mass balance monitoring project of the northern Harding Icefield (Figure 15). Surface mass balance is the sum of accumulation that occurs during the winter (winter mass balance) and ablation during the summer (summer mass balance), measured as meters of water equivalence (m w.e.). Winter mass balance is determined by measuring and weighing snow at the end of the accumulation period, typically late April, to calculate the water equivalence. Summer mass balance is a measure of the amount of ablation, primarily resulting from melt, at the end of the water year, occurring approximately October 1st. This is calculated based on measurements of any remaining accumulation from the previous winter. If all accumulation has melted resulting in a surface stratum of bare ice at the end of the season, changes in the ice surface elevation is determined based on the relative stake height compared to the previous fall measurement. Annual variations in temperature and precipitation result in changes in surface mass balance. Long-term positive mass balance trends indicate future glacier growth (ice thickening and terminus advance) while long-term negative mass balance trends indicate future glacier shrinkage (ice thinning and terminus retreat).

Kenai Fjords' mass balance project consists of four sites on Exit Glacier and two sites on an unnamed glacier between Skilak and Lowell Glaciers (Figure 16). A mass balance site consists of a stake inserted in the ice against which snow accumulation/melt and flow velocity are measured (Figure 17). Two of the sites are located in the ablation zone, two sites are in the accumulation zone, and two sites are located approximately at the equilibrium line of altitude, as they fluctuate between ablation and accumulation.

Over the first seven year period of record (2010–2016), cumulative annual site balances indicate increased surface mass balance at sites located at the highest elevations in the study area (on the upper plateau of the ice field) and decreased surface mass balance at sites at lower elevations on the outflowing portion of Exit Glacier (Figure 18). These results are consistent with surface elevation changes calculated by Loso et al. (2014) described in an earlier section of this report. Kurtz (in preparation) provides a detailed summary of the results from the first seven years of mass balance measurements.

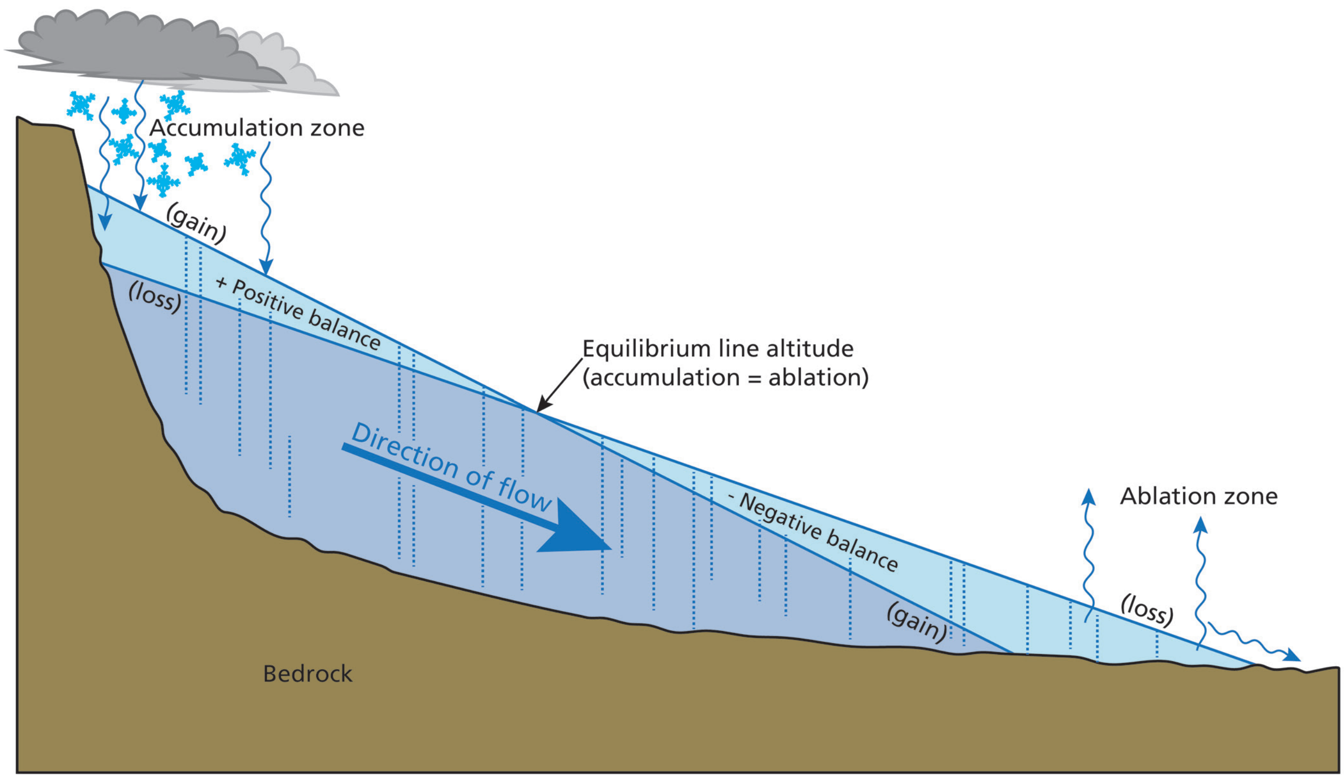


Figure 15. Diagram showing the processes and concepts behind glacier mass balance, which is the annual net gain or loss of glacier mass measured at the surface. Accumulation is a gain of mass in the form of direct snowfall, avalanches, and windblown snow; ablation is the loss of mass through surficial melt, meltwater runoff, sublimation, and the calving of ice pieces either onto dry land or the water. The accumulation zone is the portion of the glacier at higher elevation that receive more mass gain during the winter months than mass loss during the summer months, leading to an overall positive balance. The ablation zone is the lower elevation portion of the glacier where more mass is lost during summer months than gained during winter months, leading to an overall negative balance. The equilibrium line altitude divides the accumulation and ablation zones, and is the altitude where winter accumulation equals summer ablation. Annual mass balance is calculated by combining the total mass lost and the total mass gained across the entire glacier. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

In addition to surface mass balance, flow velocities and vectors are measured based on seasonal mapping grade Trimble GPS positioning of each stake. Annual flow velocities at the six sites range from 0.02–0.29 m/day (0.07–0.95 ft/day). Winter velocities range from 0.01–0.2 m/day (0.03–0.7 ft/day) and summer velocities range from 0.03–0.32 m/day (0.10–1.0 ft/day). Modelled winter surface velocity maps are available for all glaciers on the Kenai Peninsula, including the Harding Icefield, and indicate the variability of glacier flow velocities within the park's glaciers (Burgess et al. 2013).

Glacier Lake Outburst Flooding

Glacial ice can sometimes block the flow of water from surrounding drainages, causing water to accumulate behind a dam of ice. These lakes are termed "ice-dammed lakes" and can form supraglacially (on a glacier), subglacially (within a glacier), or at the margin of a glacier. Depending on where they are situated, ice-dammed lakes result from various mechanisms and parameters (see Tweed and Russell [1999] for a review). Ice-dammed lakes typically go through cyclic episodes of filling and emptying; the emptying of an ice-dammed lake can occur by slow leakage, or during one catastrophic event called a glacier lake outburst flood (Post and Mayo 1971).

A glacier lake outburst flood, sometimes referred to by the Icelandic term *jökulhlaup*, results from the catastrophic draining of water in an ice-dammed lake (Tweed and Russell 1999). During an outburst flood, down-glacier flooding will increase over a period of a few days followed by a decrease to normal water levels. Glacier lake outburst floods are known to occur

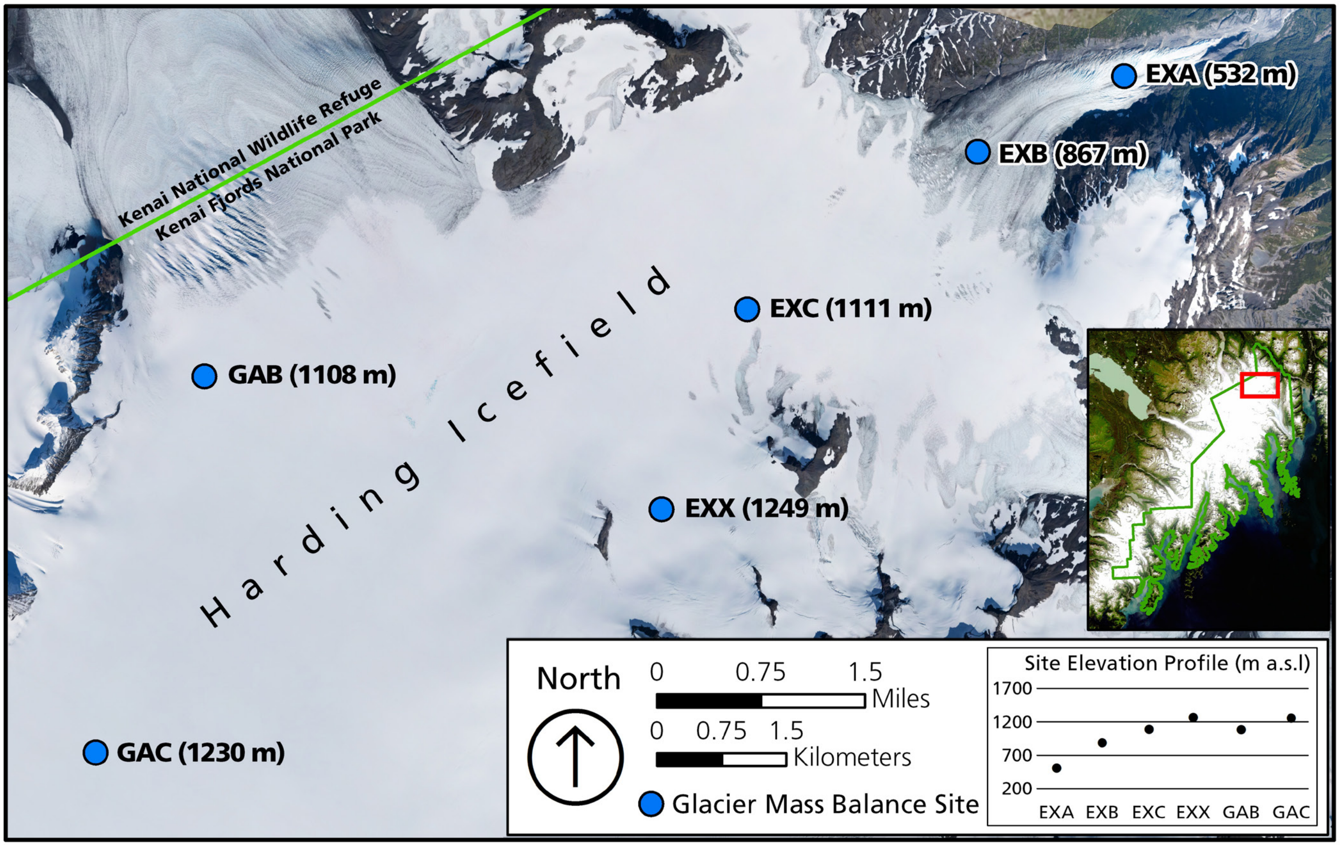


Figure 16. Map of the northern Harding Icefield showing the locations of mass balance sites. The elevation of each site is noted in parentheses next to the site name, and an elevation profile is shown in the bottom right corner. The site names correspond to data presented on Figure 18. Modified from Kurtz (in preparation).

Figure 17. Photograph of mass balance monitoring on the Harding Icefield. NPS photograph by Sarah Venator.

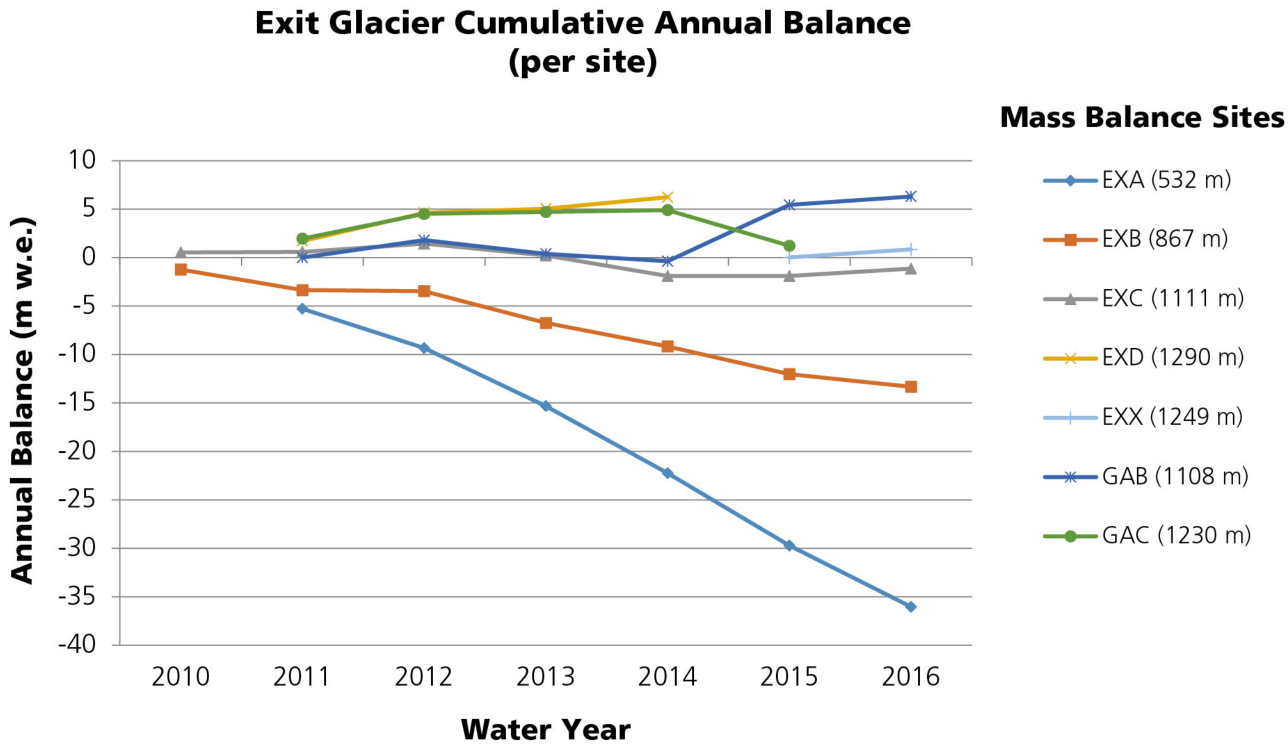


Figure 18. Graph showing the cumulative annual mass balance at each site on the Harding Icefield by water year. Some of the higher elevation sites, such as GAC (1230 m, 4035 ft), GAB (1108 m, 3635 ft), EXD (1290 m, 4232), and EXX (1249 m, 4098 ft), have increased surface mass balance during the time interval. Other sites at lower elevations, such as EXA (532 m, 1745 ft) and EXB (867 m, 2844 ft), show significantly decreased surface mass balance during this same time interval. Figure from Kurtz (in preparation).

regularly (annually, biennially, or triennially) at several locations on the Kenai Peninsula, including Bear Glacier, Skilak Glacier, and Snow Glacier (Wilcox et al. 2013).

In the park, outburst floods emanating from an ice-dammed lake adjacent to and under Bear Glacier have been documented (Wilcox et al. 2013). The ice-dammed lake sourcing these glacier lake outburst floods is located at the top of a small tributary glacier, approximately 8 miles from the terminus of Bear Glacier (Figure 19; Figure 20). Water from snow melt, ice melt, and rain collects in the basin that is carved out by retreating ice. This basin extends within and under the ice before being dammed by the ice itself. Researchers and NPS staff have documented the drainage of this lake through repeat photography and in-situ methods for 2008, 2009, 2010, 2012, and 2014 (Figure 20). The ice-dammed lake often drains in late summer, when the area of the lake ranges between 0.35 and 0.5 km^2 (0.14 and 0.2 mi^2) (Wilcox et al. 2013; Wilcox et al. 2014). Flooding was not observed in 2015 or 2016. It is possible, however, that flooding could have occurred in the fall of those years when few to no visitors were around.

Although not an annual event, drainage of Bear Glacier's ice-dammed lake consistently occurs in late summer to early fall, with the 2014 flood occurring only five days earlier in the year than the 2008 flood. Analysis by Wilcox et al. (2013) found there is currently not enough data to determine trends in the frequency of flooding. Kenai Fjords staff continue to monitor the source lake with opportunistic overflights, mostly occurring in the summer. In 2017, NPS staff initiated a more concerted effort to document and understand the timing, frequency, and volume of water involved with the filling and drainage of this lake. The park installed a satellite-telemetered time-lapse camera that takes a daily photo of the ice-dammed lake and emails it to park staff. A second time-lapse camera was installed at the proglacial lake along with a pressure transducer to document changes in volume at the proglacial lake as well as any calving that may occur following a flood event.

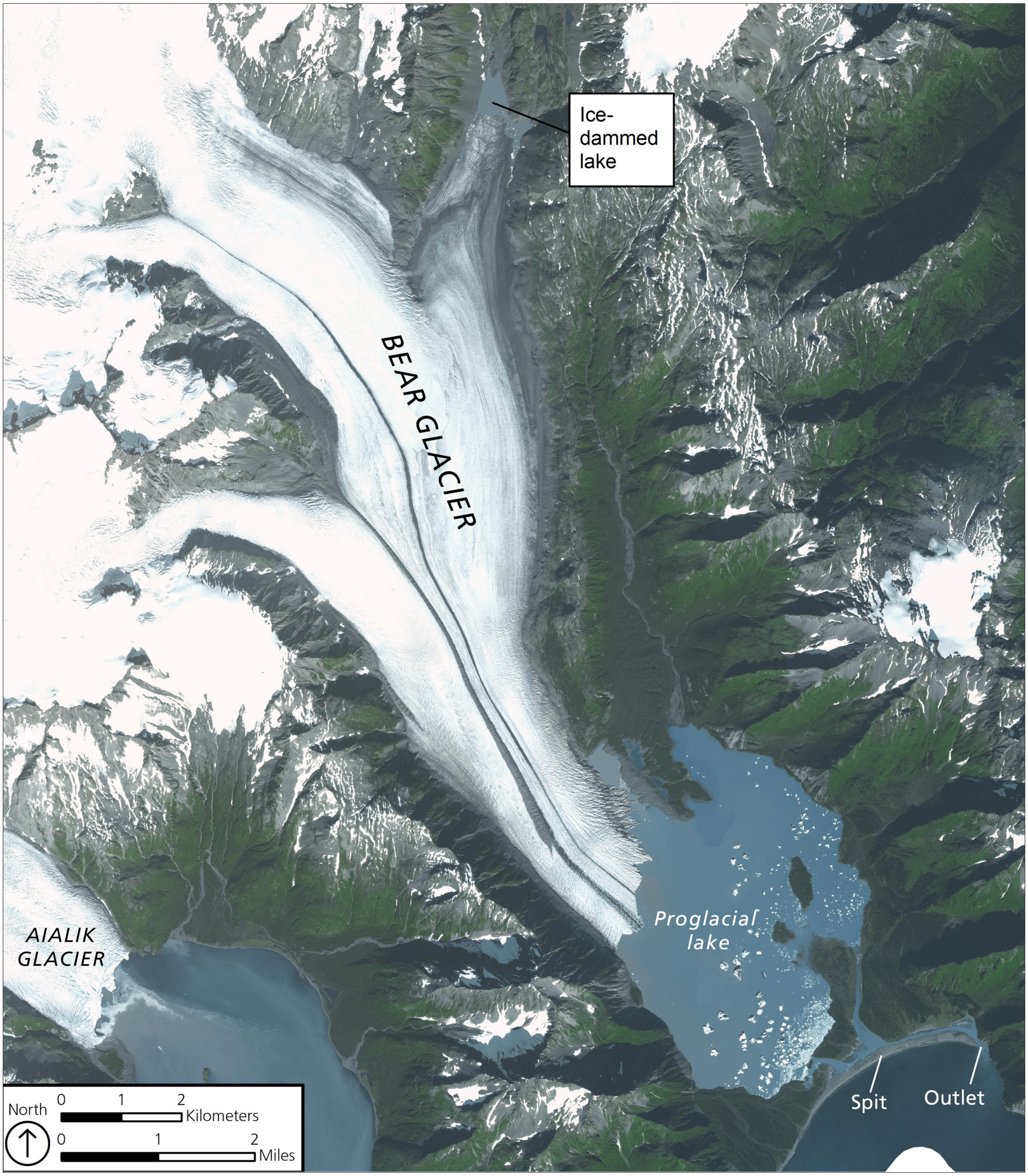


Figure 19. SPOT 2010 satellite image of Bear Glacier showing the location of the ice-dammed lake, Bear Glacier's proglacial lake, and the spit that deflects the outlet of the proglacial lake.

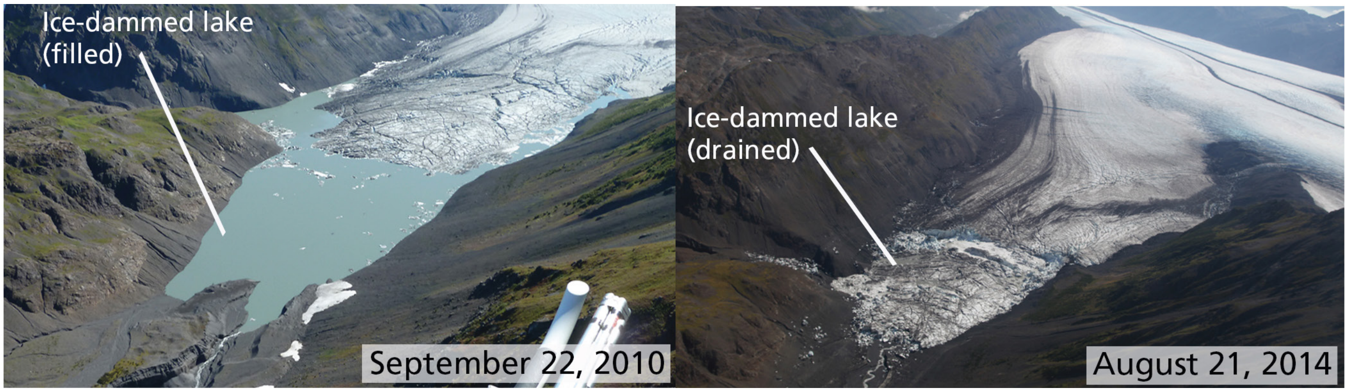


Figure 20. Photographs of the ice-dammed lake sourcing the Bear Glacier outburst floods. The left photo shows full water levels in the lake on September 22, 2010. The right photo shows Ice Lake after it has been drained on August 21, 2014. NPS photographs.

Exit Creek Geomorphology

Map Units: Qs, Qat (not Exit Creek, but similar deposits outside the park; Plate 1)

Braided streams are found throughout the glacially-fed drainage systems of Kenai Fjords. One braided stream in the park that has received particular attention is Exit Creek (**Qs**; Figure 21). Exit Creek is located in the northeastern part of the park, adjacent to the visitor-use area of Exit Glacier. Exit Creek has a history of flooding, causing damage to the park-maintained road and trails, and interrupting access to the park's most visited area. For more information, see the "Exit Creek Flooding" section of this report.

Rivers that are fed by glacial meltwater often display a braided morphology, meaning there are multiple interwoven channels separated by ephemeral bars that develop and migrate as the stream aggrades (fills with sediment). Conditions under which braided streams develop include high sediment influx, relatively little lateral constraint for channel development, and banks composed of non-cohesive sand and gravels that erode easily (Surian 2015). These conditions are found in glaciated areas because glacier meltwater feeds a large amount of coarse sediment (sands and gravels) to the surrounding river systems, which fills valleys and forms wide outwash braid plains.

Originating at the toe of Exit Glacier, Exit Creek is a proglacial stream that runs northeast for a little more than 3.2 km (2 mi) before its confluence with the Resurrection River (Figure 21; Figure 22). Exit Creek is fed by meltwater coming from Exit Glacier, as well as by snowmelt and rain runoff from the surrounding watershed (Stark et al. 2015). Adjacent to Exit Creek is the Paradise Creek drainage, which presently drains separately into the Resurrection River (Figure 22). However, there is evidence of times in the past when a portion of Paradise Creek was captured by Exit Creek, temporarily increasing the flow and sediment supply to Exit Creek (Curran et al. 2017).

Figure 21. Photograph showing Exit Creek's braided morphology. As is typical of a braided stream, Exit Creek has multiple interwoven channels that are separated by numerous bars. As sediment builds up in the channels, the channels will migrate to other areas of the braid plain. Exit Creek is seen in the middle of the photograph, and at the top of the photograph is its confluence with the Resurrection River. The Herman Leirer road is seen on the left side of the photograph, as well as the bridge spanning the Resurrection River. NPS photograph by Deborah Kurtz.

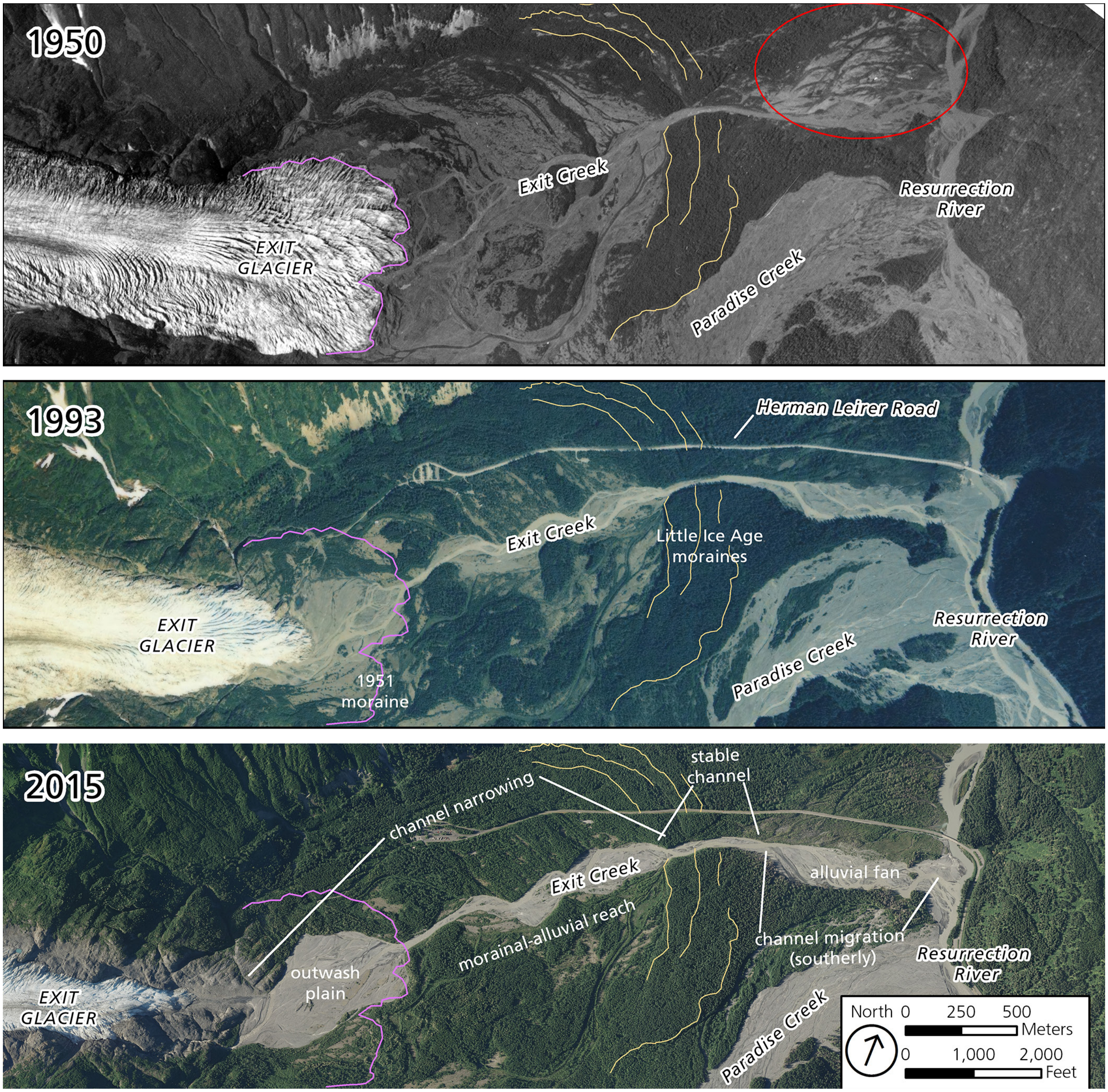


Figure 22. Aerial photographs of the Exit Glacier area showing channel migration patterns of Exit Creek from 1950, 1993, and 2015. Marked in yellow and purple are moraines that inhibit braiding (Curran et al. 2017). Stark et al. (2015) observed three general trends in Exit Creek channel migration by examining aerial photos between 1950 and 2005 (marked on 2015 imagery). (1) The part of the creek closest to the receding toe of Exit Glacier (including the outwash plain) has experienced narrowing of the active channel since 1950; (2) Just downstream of this narrowing part, the active channel is reduced to a single, stable channel, which shows little spatial variation; and (3) The most downstream part of Exit Creek has migrated slightly southward since 1950. This downstream part corresponds to the area with active or recently active channels in 1950 (circled in red) and the part of the Herman Leirer Road that has repeatedly experienced flooding.

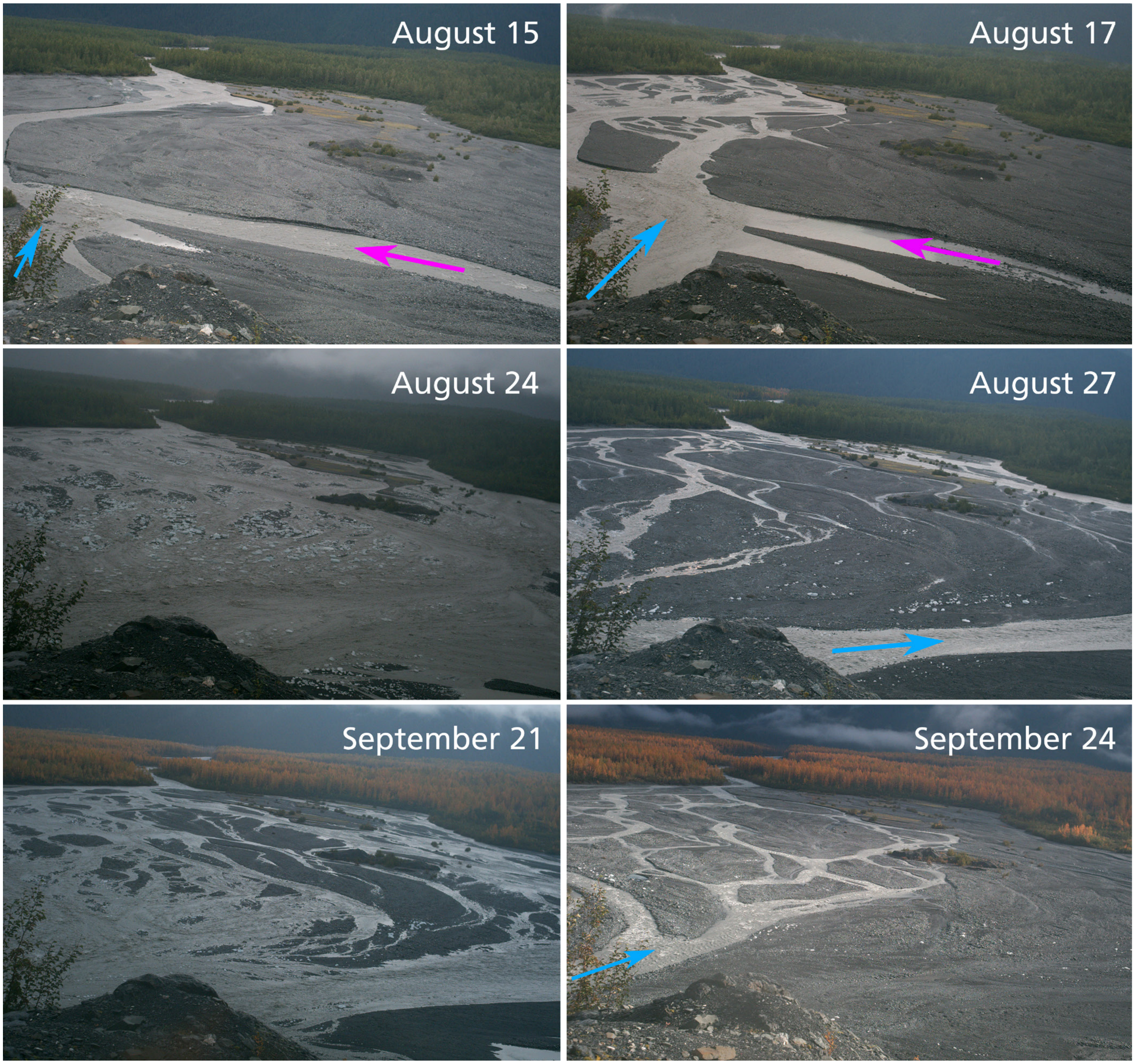


Figure 23. Time-lapse photographs of the Exit Creek outwash plain showing channel migration during the summer 2016. Blue arrows indicate flow that is coming out of the toe of Exit Glacier and pink arrows indicate flow that is coming out of the side of the glacier from a canyon to the south. August 15th: Configuration prior to the change in englacial and subglacial channels, with the majority of flow from the south (pink arrow). August 17th: New channel configuration, with more of the flow going through the northern channel (blue arrow). August 24th: The outwash plain flooded because an increase in rainfall and discharge shift from Exit Glacier. August 27th: All of the flow is from the toe of the glacier (blue arrow), but the channel is now running to the south side of the outwash plain. September 21st: Another large flood covers the plain and fills in the southern channel. September 24th: Final configuration of the season, with all the water being sourced from the toe of the glacier (blue arrow). NPS photographs from Paul Burger.

Exit Creek can be divided into three geomorphically distinct sections (Figure 22): the outwash plain (a highly dynamic area between the modern toe of the glacier and the 1951 moraine), the morainal-alluvial reach (part between the 1950 moraine and the Little Ice Age moraines where channel morphology is largely controlled by morainal material), and the alluvial fan (downstream-most part between the Little Ice Age moraines and the Resurrection River; Curran et al. 2017). The alluvial fan is beyond the limit of the Little Ice Age glacial advance, and therefore moraines do not constrain channel morphology and channel migration is to be expected (Curran et al. 2017).

Exit Creek, like other braided streams, is a dynamic system characterized by frequent shifts in channel location. The dynamic nature makes it difficult to measure flow conditions using typical, long-term monitoring equipment (Stark et al. 2015). However, historical aerial photographs have been used to observe channel migration of Exit Creek since 1950 (Figure 22; Stark et al. 2015) and time-lapse photography is currently being used to monitor the flow of Exit Creek (Paul Burger, NPS Alaska Regional Office, hydrologist, personal communication, 7 June 2017).

In 1950, active channels or recently active channels of the alluvial fan extended north into the area where the Herman Leirer Road was later constructed (Figure 22; Tetreau, 1993; Stark et al. 2015). During times of flooding, high water flows into these abandoned channels and eventually intersect the road (Tetreau, 1993). Observation that the abandoned channels continue on the far side of the road led Tetreau to conclude that without the road, flood waters would flow freely to the north. In addition, Tetreau suggested that the construction of the road may have contributed to the abandonment of the north side of the alluvial fan.

The recent road flooding is a product of incipient channel migration to the northern part of the alluvial fan (Curran et al. 2017). So far, channels that intersect the road only conduct water during high flow events, but these channels were active as recently as the 1950s and there is no reason to believe they may not become active again as the channels migrate (Curran et al. 2017). Curran et al. (2017) provides a more complete discussion of the hydrology and geomorphology of Exit Creek in relation to flooding of the Herman Leirer Road. For more information about the history and impacts of flooding in the Exit Glacier area, see the "Exit Creek Flooding" section.

Similar aggradation to that seen at Exit Creek has been observed in glacial streams on the coast. The unnamed stream flowing from a cirque glacier next to the ranger station in Aialik Bay has also demonstrated recent alluvial fan building and beach steepening through increased deposition. Park managers have relocated some of the smaller, more portable structures at the facility to prevent infrastructure damage or loss.

Exit Creek's discharge location from Exit Glacier and channel positions on the outwash plain changed significantly during the summer of 2016 (Figure 23). These channel migrations, which occurred in August and late September, were captured by time-lapse photography of the outwash plain (Figure 23). Since 2007, when Exit Glacier retreated into a bedrock constrained valley, the majority of meltwater has discharged out of the south side of the glacier, rather than the toe. Most of the water ran through a small canyon in the bedrock before turning north to reconnect with a smaller stream that flowed directly out of the toe. In mid-August 2016, however, a shift in the englacial (within the glacier) and subglacial (under the glacier) channels redirected the majority of water to the toe of the glacier, abandoning the former channel through the canyon and causing more melting and calving at the toe. For more information on the resultant high rate of retreat during the 2016 summer season, see the "Terminus Positions" section.

Coastal Features

The coast of Kenai Fjords encompasses 877 km (545 mi) of shoreline (Curdts 2011). The protection of Kenai Fjords' "coastal fjords and islands in their natural state" is a central part of the park's mission (Alaska National Interest Lands Conservation Act 1980). The southern coast of the Kenai Peninsula displays a "drowned" coastline geomorphology, which means that, locally, sea level has risen relative to the land (Plafker 1969). This includes the characteristic fjords of Kenai Fjords, which are glacially carved valleys inundated by the sea, as well as islands formed by peaks of the Kenai Mountains that were cut off from the mainland by rising sea level. The park's rugged shoreline is characterized primarily by steep, rocky cliffs, but also contains sand and gravel beaches (**Qb**), mudflats, and alluvial fan deltas (Figure 24). GIS data showing the classification of the park's shore-zone geomorphology was produced by Dan Mann in 1997 (citation). This data utilized aerial photography from the 1980s and 1990s.

The coast of Kenai Fjords is dynamic. The park's coastal geomorphology is a product of continuous surficial processes including erosion, deposition, and sediment transport; glacial advance and retreat; relative sea level change resulting from regional tectonic motion combined with global sea level rise; and geologic processes, such as earthquakes, landslides, and tsunamis, that enact a large amount of change over a short period of time. Areas of Kenai Fjords' coast rapidly subsided during the 1964 Great Alaska Earthquake (see "Earthquake Features and Active Margin Tectonics" for more information). In these areas, changes to shoreline processes and beach morphology produced in a matter of hours were comparable to changes seen over hundreds of years of typical sea level change (Stanley 1968). The beach deposits (**Qb**) on the Kenai Fjords geologic map (Plate 1) were mapped by Tysdal and Case (1979) and represent new strandline deposits formed in areas that were submerged during the 1964 Great Alaska Earthquake. However, vertical movement on the Kenai Fjords coastline is complicated and must be considered based on process and timescale, as data recorded at Seward's tide gauge indicate an annual uplift rate of 10.4 mm/year (0.4 in/year; see "Modern Uplift and Long-Term Submergence" for more information; Larsen et al. 2003).

Sea Caves, Arches, and Stacks

Map Units: Kvs, Tgh (Plate 1)

Sea caves, arches, and stacks are erosional coastal features that are present along the coastline of Kenai Fjords (Figure 25). These scenic, rocky features are recreationally appealing to park visitors and provide significant habitat for sea birds and other marine organisms. In a recent survey conducted by park staff, 829 coastal features were identified along the Kenai Fjords coast, including 488 caves, 122 shelters (smaller voids than caves), 68 arches, 76 stacks, and 75 unique features (Markus and Kurtz 2015).

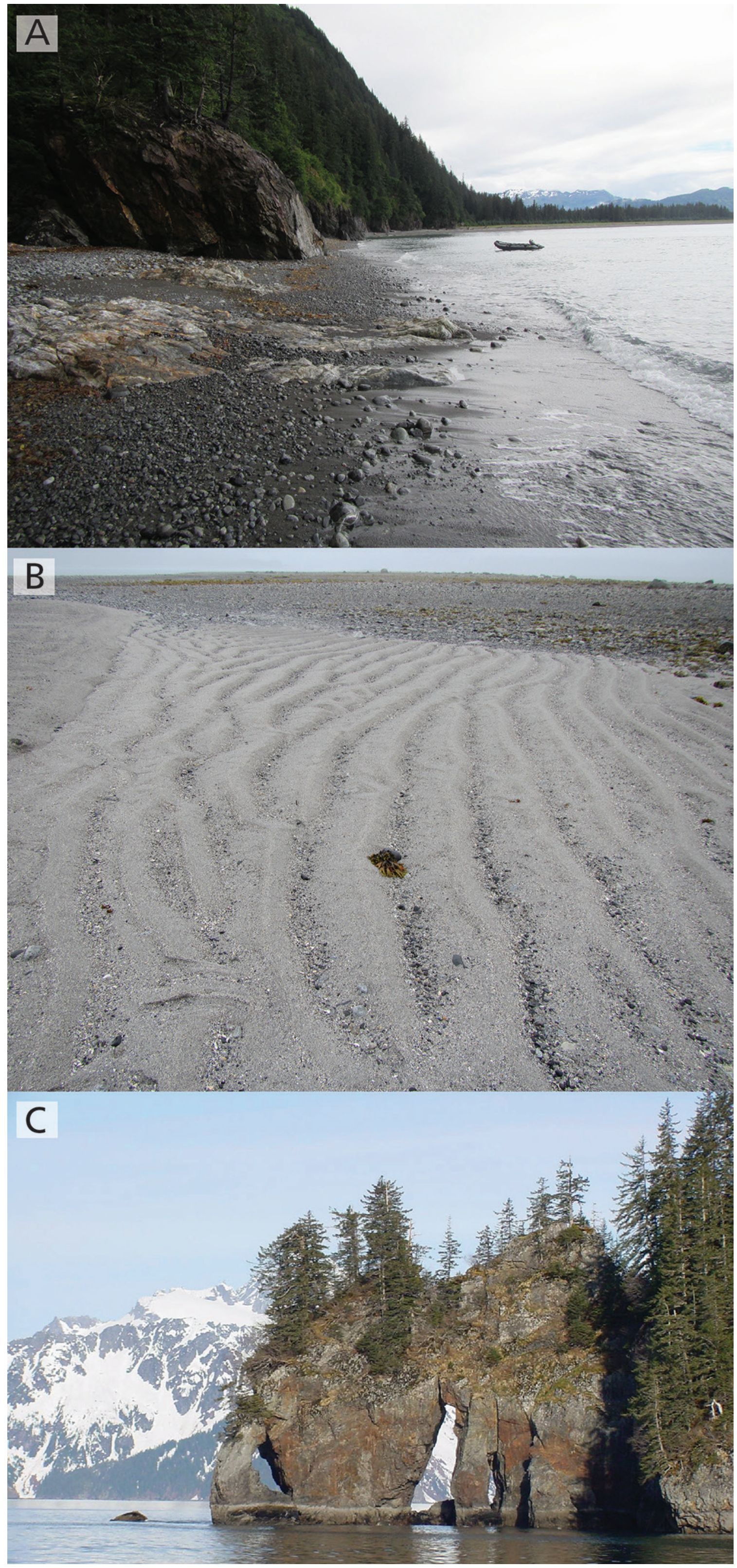


Figure 24. Photographs showing three of the typical coastline morphologies in Kenai Fjords. A: Cobble beach; B: Sand and pebble beach, with ripple marks; C: Steep rock cliff, with sea arches forming at the base. NPS photographs.

Figure 25. Photographs of sea caves, an arch, and a stack in Kenai Fjords. A: Multiple sea caves eroding into the metasedimentary rock of the Valdez Group (Kvs). B: A sea arch forming along bedding planes in the metasedimentary rock of the Valdez Group (Kvs). C: A sea stack. NPS photographs by Paul Burger.

Sea caves form through the erosional action of waves and currents with a cliff face unprotected by the buffering effects of a beach (Figure 26). To form caves, erosion cannot occur uniformly along the rock face, but must occur preferentially in preexisting weak areas of the rock (Moore 1954). These weak, erosion-prone areas can correspond to primary bedrock depositional features, such as changes in sedimentary bedding, or secondary structural features, such as faults or joints (Moore 1954). In Kenai Fjords, sea cave development is initiated along fractures (**Tgh**, **Kvs**) and bedding planes (**Kvs**).

Sea caves are mainly expanded by the continuous abrasion of particles carried in waves. Other factors such as blasts of air pressure produced by storm waves, boring organisms, and chemical weathering can all act to expand a cave (Moore 1954). As a sea cave expands, it may erode entirely through the cliff, creating a sea arch (Figure 26). The eventual collapse of a sea arch results in a jagged pillar of rock isolated from the main cliff, termed a sea stack (Figure 26).

There are two rock units exposed along the coast of Kenai Fjords that contain sea caves: the metasedimentary rocks of the Valdez Group (**Kvs**) and the granitic rocks of the Harding Icefield (**Tgh**). Sea caves are present in both of these geologic units, and there is no evidence of a correlation between the prevalence of sea cave development and rock type (Markus and Kurtz 2015). Instead, small caves are distributed randomly and the largest caves are concentrated in areas with high wave exposure (Markus and Kurtz 2015). Overall cave morphology is, in most cases, related to rock type. Caves found in the metasedimentary rocks primarily form along bedding plane weaknesses, and generally have wider, arched entrances (Figure 27; Markus and Kurtz 2015). In contrast, caves found in the granite form along fractures in the rock and tend to have narrower, blocky entrances (Figure 27; Markus and Kurtz 2015).

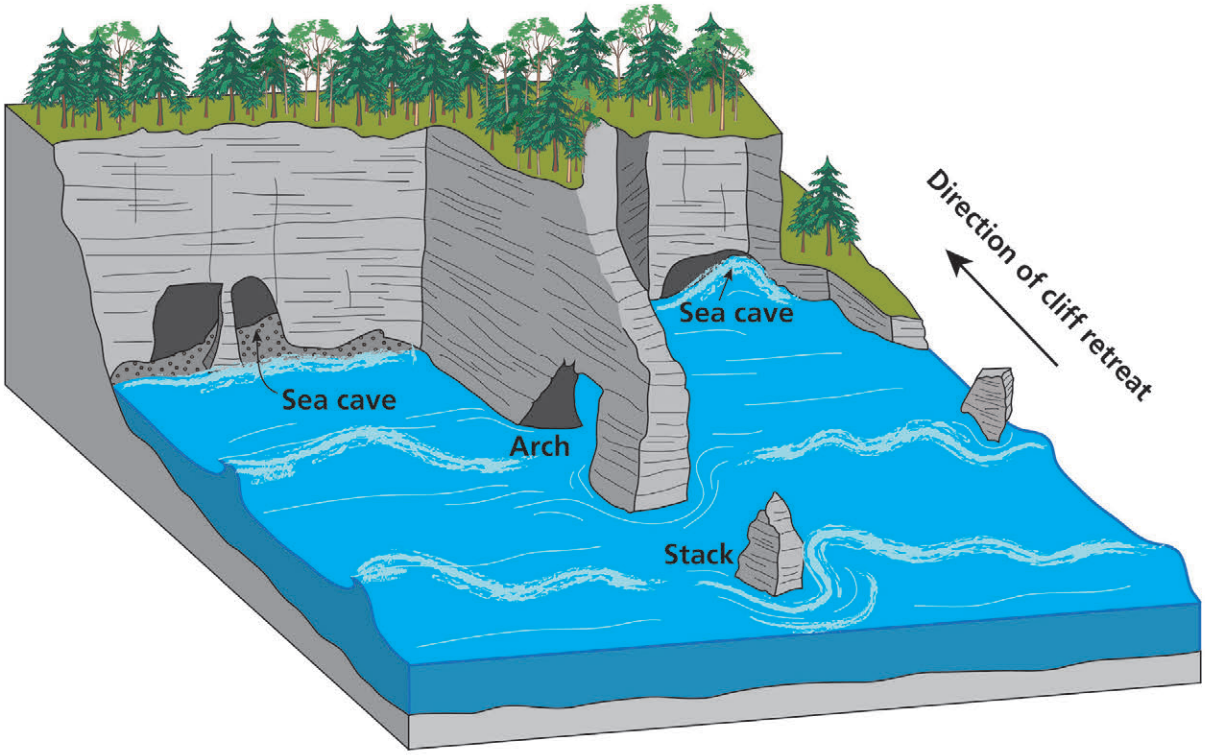


Figure 26. Diagram of coastal erosional features. Sea cave, arches, and stacks form as waves preferentially erode away weak areas of the rock. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

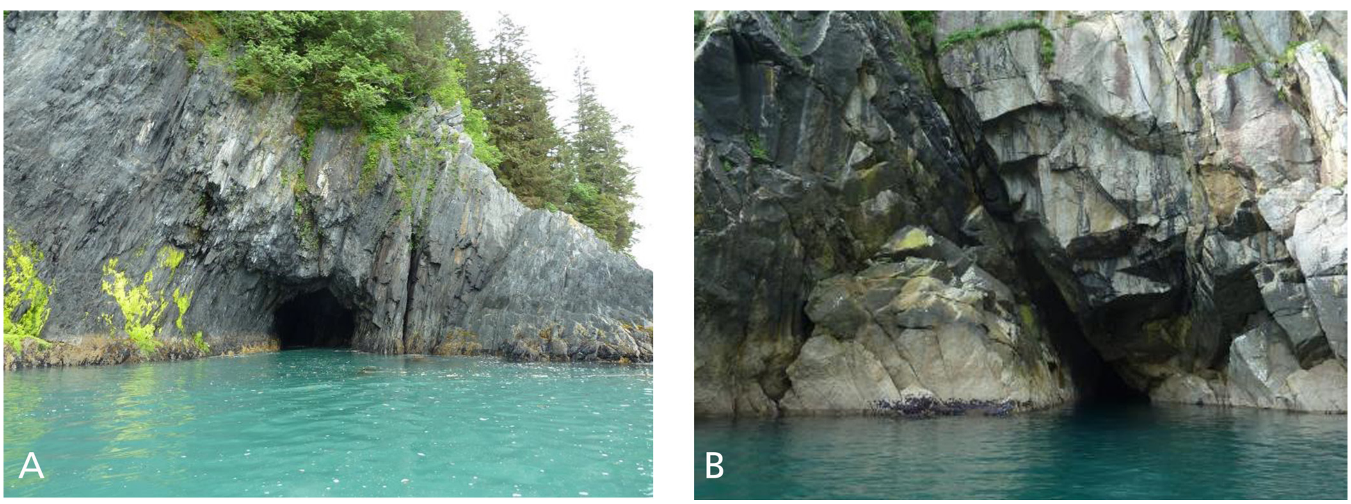


Figure 27. Photographs showing the differences in cave morphology depending on rock type. A: A sea cave formed in metasedimentary rock that displays the characteristic arched entrance. B: A sea cave formed in granitic rock that display a smaller, blocky entrance. NPS photographs from Markus and Kurtz (2015).

Landslides

Map Units: Kvs, Tgh (Plate 1)

Slope movements, also known as "mass wasting" and commonly grouped as "landslides," are the downslope transfer of soil, unconsolidated surficial deposits, or rock under the influence of gravity. Slope movements occur on time scales ranging from slow, continuous downslope creep, termed "soil creep," to rapid, catastrophic slope failure such as rockfalls, and avalanches. Hazards and risks associated with slope movements in Kenai Fjords are described in more detail in the "Geohazards" section of this report.

Landslides occur on steep slopes, particularly those greater than 30°. Retreating glaciers increase the risk for landslides because of a process known as glacial debuttressing (Figure 28). As a glacier retreats, slopes

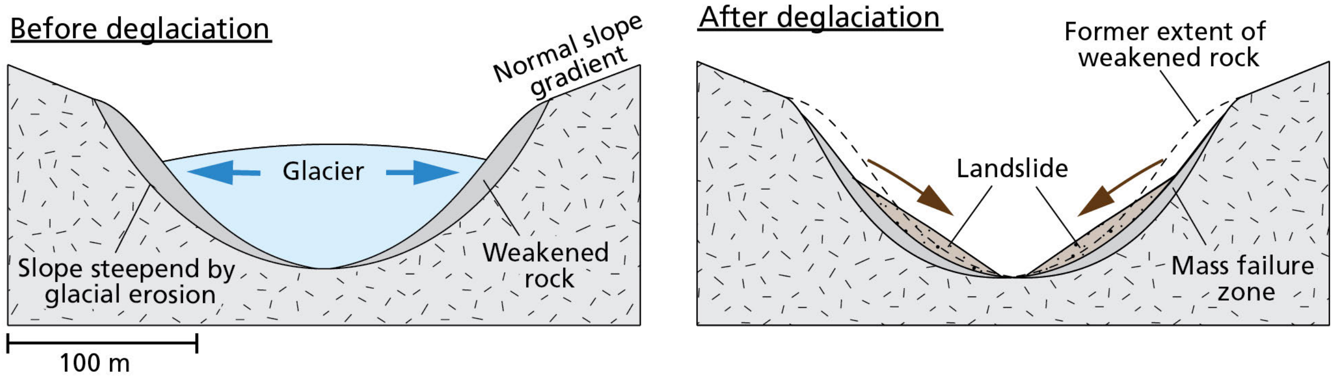


Figure 28. Diagram showing the process of glacial debuttressing. The erosion and weight of the glacier produces an area of weakened rock and steep slopes. Once the glacier moves away, the lateral support provided by the glacier's presence is removed and the newly exposed slopes are prone to mass movement. Figure modified from Ballantyne (2002).

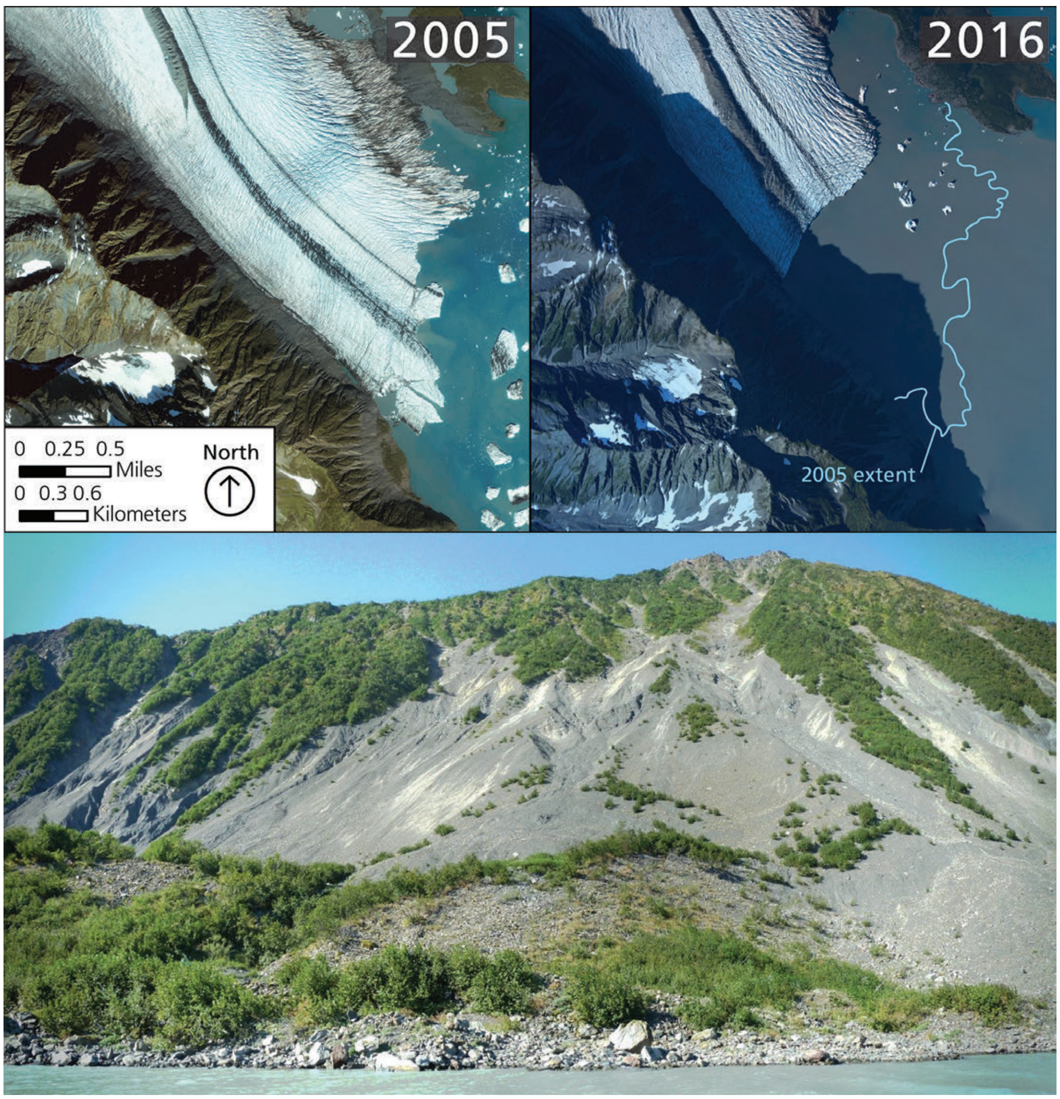


Figure 29. Imagery and photograph of unstable, sliding slopes on the south shore of Bear Glacier's proglacial lake. The satellite (IKONOS) imagery shows the extent of Bear Glacier in 2005 and aerial imagery (Mark Laker, US Fish and Wildlife Service) shows its extent in 2016, highlighting the rapid retreat during this 11 year period. 2005 NPS photograph by Deborah Kurtz.

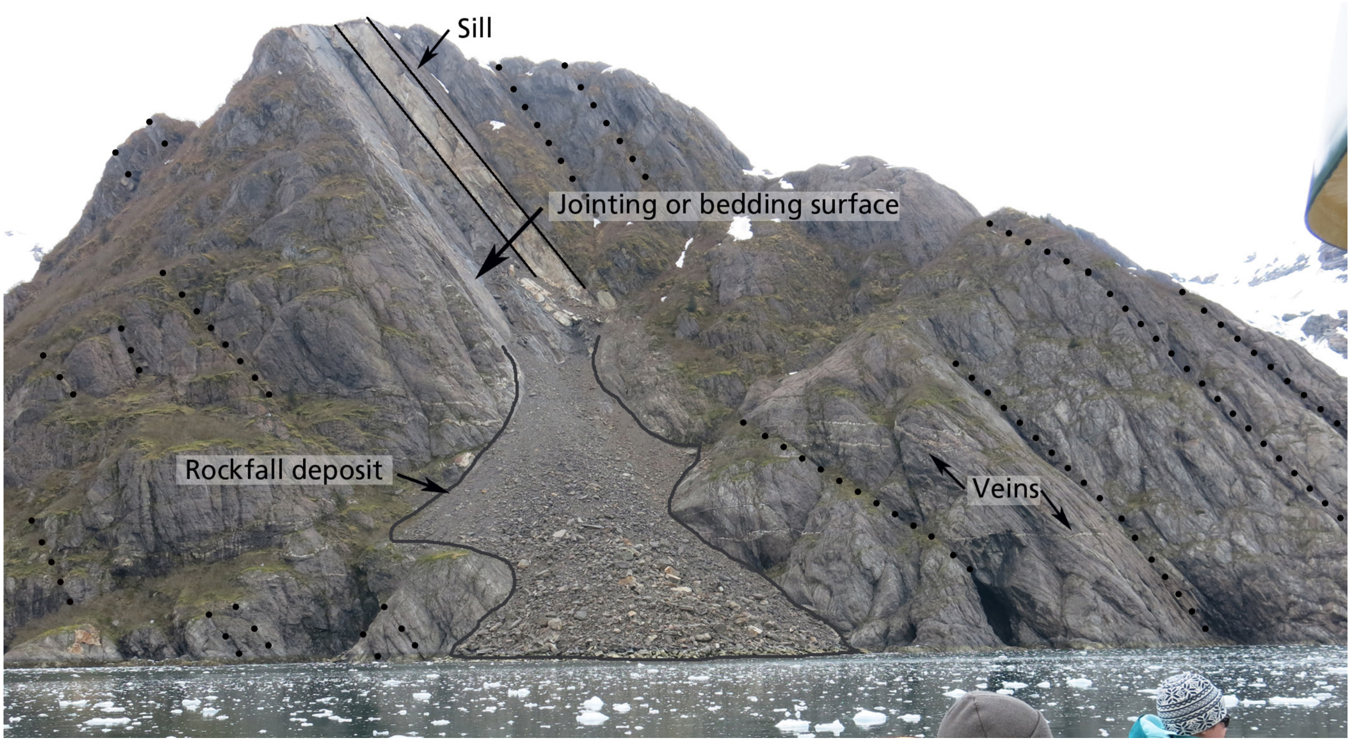


Figure 30. Photograph of a rockfall near Holgate Glacier. This rockfall occurred along an apparent weakness formed were a sill intruded into the Valdez Group (Kvs). Dotted lines are showing the structural fabric that is parallel to the slip-face, which may have also contributed to the slide. NPS photograph by Chad Hults.

over-steepened by glacial erosion, which were formerly propped up by ice, no longer have that lateral support and are prone to landslides. This is occurring in the park on the south shore of Bear Glacier's proglacial lake, which has steep, unvegetated, unstable slopes that are prone to sliding as a result of the recent retreat of Bear Glacier (Figure 29). Bear Glacier's proglacial lake is a popular site for kayaking and camping; landslides in this area have the potential to generate dangerous tsunamis.

Glacial debuttressing, like that seen in the vicinity of Bear Glacier, has the potential to trigger large-scale landslide events. During October 2015, a massive landslide occurred in Taan Fjiord, approximately 450 km (280 mi) east of Kenai Fjords (Wrangell-St. Elias National Park and Preserve). Deglaciation in the area left the slopes above Taan Fjord unstable, leading to a slide of 200 million tons of rock into the fjord. The slide generated a tsunami with a height of more than 185 m (607 ft)—the same height as the Space Needle in Seattle.

Landslides in the park are sometimes triggered by high rainfall. Recently (2014–2016) winter temperatures at sea level have averaged above freezing, causing precipitation to occur in the form of rain rather than snow. During the summer field seasons following these warm winters park staff observed several new or newly active landslides (Figure 30). These were likely induced by the increased rainfall. If above freezing winter temperatures persist, there may be a resultant increase in rainfall-induced landslides along the coast.

Landslides in the park are also triggered by earthquakes; Post (1967) reported many new rockslides onto glaciers in southcentral Alaska following the famous 1964 Great Alaska Earthquake (see "Earthquake Features and Active Margin Tectonics" for more information). In the park, the 1964 Great Alaska Earthquake caused landslides from at least five sources to extend onto a small unnamed glacier in Paguna Arm (hereafter referred to informally as Paguna Glacier) covering approximately 50 percent of its surface with rock debris. The landslide debris on Paguna Glacier resulted in a decrease in surficial melting and probably contributed to a subsequent advance of the toe of the glacier (Figure 31).

Figure 31. Photographs of Paguna Glacier and the surrounding area. A: The landslide debris-covered toe of Paguna Glacier, which acts to insulate the underlying ice, and caused the toe to advance into the surrounding area. B: The landslide debris-covered toe of Paguna glacier that moved into the surrounding forest. C: The proglacial stream emanating from Paguna Glacier and trees that have been killed by the migration of stream channels. NPS photographs by Chad Hults.

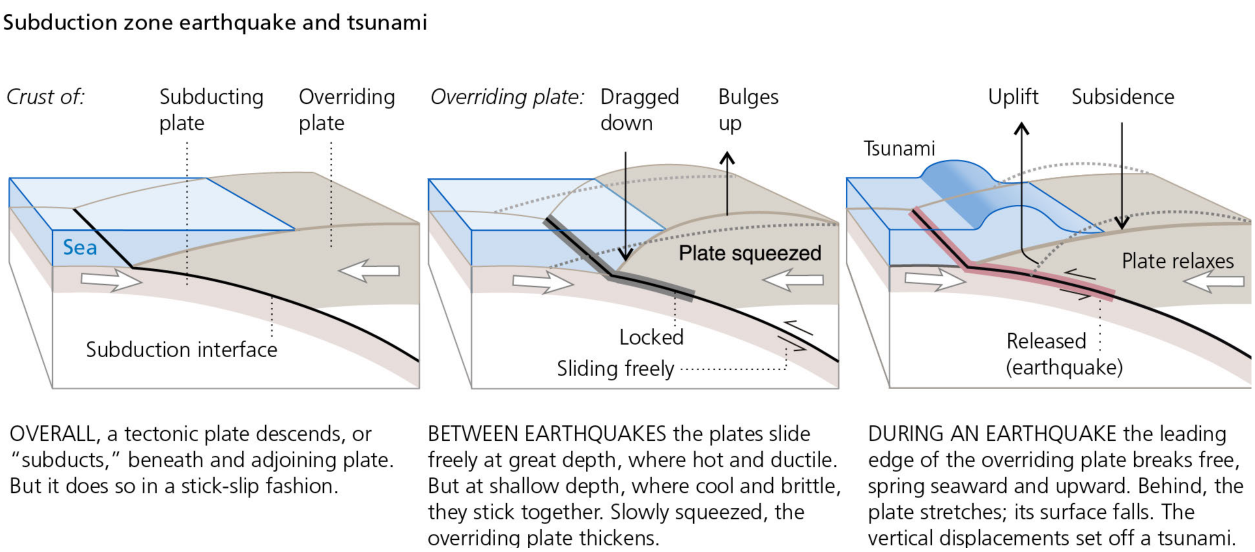


Figure 32. Diagram showing the mechanism of subduction zone earthquake and tsunami generation. When the subduction zone is locked, inboard portions of the upper plate are pushed upward by a build-up of tectonic stress. This is why the outer coast of the Kenai Peninsula is currently moving upward (see Figure 33). However, once the stress is released in the form of an earthquake, this same area that was moving upward rapidly subsides. Modified from Atwater et al. (2005).

Earthquake Features and Active Margin Tectonics

1964 Great Alaska Earthquake and Tsunamis

The magnitude 9.2 Great Alaska Earthquake was the second-largest earthquake ever recorded with seismic instruments. The earthquake struck at 5:36 pm on Friday (Good Friday), March 17, 1964. The earthquake was felt throughout Alaska and was strong enough to cause the Space Needle to sway in Seattle 1,900 km (1,200 mi) away. Locally, the earthquake caused subsidence in the area that is now Kenai Fjords National Park, and a pair of tsunamis (one generated by the earthquake and one generated by resultant underwater landslides) caused destruction in the city of Seward.

The 1964 Great Alaska Earthquake was generated by slip on the plate interface between the overlying North American plate and the underlying Pacific plate of the Aleutian-Alaska subduction zone (Figure 32). The plate interface of a subduction zone is called a megathrust fault. When the megathrust fault slips suddenly it produces seismic energy, or shaking, which we experience as an earthquake. It is the fault slip that causes shaking, subsidence, and sea floor deformation that produces tsunamis. The earthquake ruptured along an area of 280,000 km^2 (110,000 mi^2), which is about two thirds the size of California (Figure 33). The Prince William Sound area uplifted; whereas, the Kenai Peninsula subsided (Figure 33). The Kenai Fjords area dropped 1–2.5 m (3–8 ft), with the greatest subsidence of 2.4 m (7.8 ft) around Nuka Bay (Plafker 1969). The mechanism of stick-slip movement along the megathrust, and the cause of uplift and subsidence is depicted in Figure 32. Between earthquakes, the interface is locked, so stress builds in the upper plate. The stress causes the plate to bend and drives uplift and subsidence in the upper plate. When this stress is released during an earthquake, the upper plate snaps back to its previous shape and the subsiding areas closest to the interface uplifts, and the uplifted areas further inboard subside.

The 1964 Great Alaska Earthquake produced two types of tsunamis that struck the coast. The rapid (nearly instantaneous) uplift of the seafloor near the subduction zone caused a tectonic tsunami (Figure 32). The shaking from the earthquake caused underwater and coastal landslides that also generated additional local tsunamis. These tsunamis resulted in most of the deaths related to the earthquake and caused extensive damage in Alaska and as far away as Oregon and California. Locally, both types of tsunamis devastated the city of Seward.

Resurrection Bay is a steep-sided, deep glacial fjord. The city of Seward, at the head of Resurrection Bay, is built on the alluvial fan of Lowell Creek and the delta of the Resurrection River. These rapidly deposited alluvial sediments have high water content and steep fronts. The features are generally stable during normal conditions, but can become unstable during prolonged shaking from large earthquakes (Lemke 1967). The 1964 Great Alaska Earthquake struck during low tide, which meant the exposed delta fronts had high pore pressures. As a result, the earthquake almost immediately triggered submarine landslides in Resurrection Bay (Figure 34). One of these landslides caused the loss of a strip of land 15–122 m (50–400 ft) wide, which removed a portion of the port facilities of Seward. As the port facilities slid into the bay, fuel tanks ruptured and leaked, then caught fire. The landslides generated local tsunamis that initially caused a drawdown of water about 30 seconds after the ground started to shake. About 1.5–2 minutes after shaking began the first and highest wave (6–8 m, 20–26 ft) struck Seward. 25 minutes after the earthquake, the tectonic wave reached Seward. This wave was nearly as high as the first, landslide-generated wave, and was covered with the burning oil from the fuel tanks.

Thirteen people were killed, five people were injured, 86 houses were destroyed, and 269 houses were damaged. Most all the port facilities were destroyed or lost at sea. The cost of the damage was estimated at $22 million in 1964 dollars ($170 million in 2016). More information about the 1964 Great Alaska Earthquake is available at http://earthquake.usgs.gov/earthquakes/events/alaska1964/.

Earthquakes prior to 1964

At least three earthquakes prior to 1964 were investigated by analyzing evidence from raised marine terraces, buried soil layers in tidal ponds, buried tree stumps, and abrupt changes in shoreline geometries (Figure 35). A large earthquake prior to the 1964 Great Alaska Earthquake is estimated to have occurred between 1530 and 1840, which was discovered by dating buried soil layers in a tidal marsh in the park, at Quicksand Cove, Aialik Bay (Kelsey et al. 2015). This penultimate earthquake overlaps in age with a July

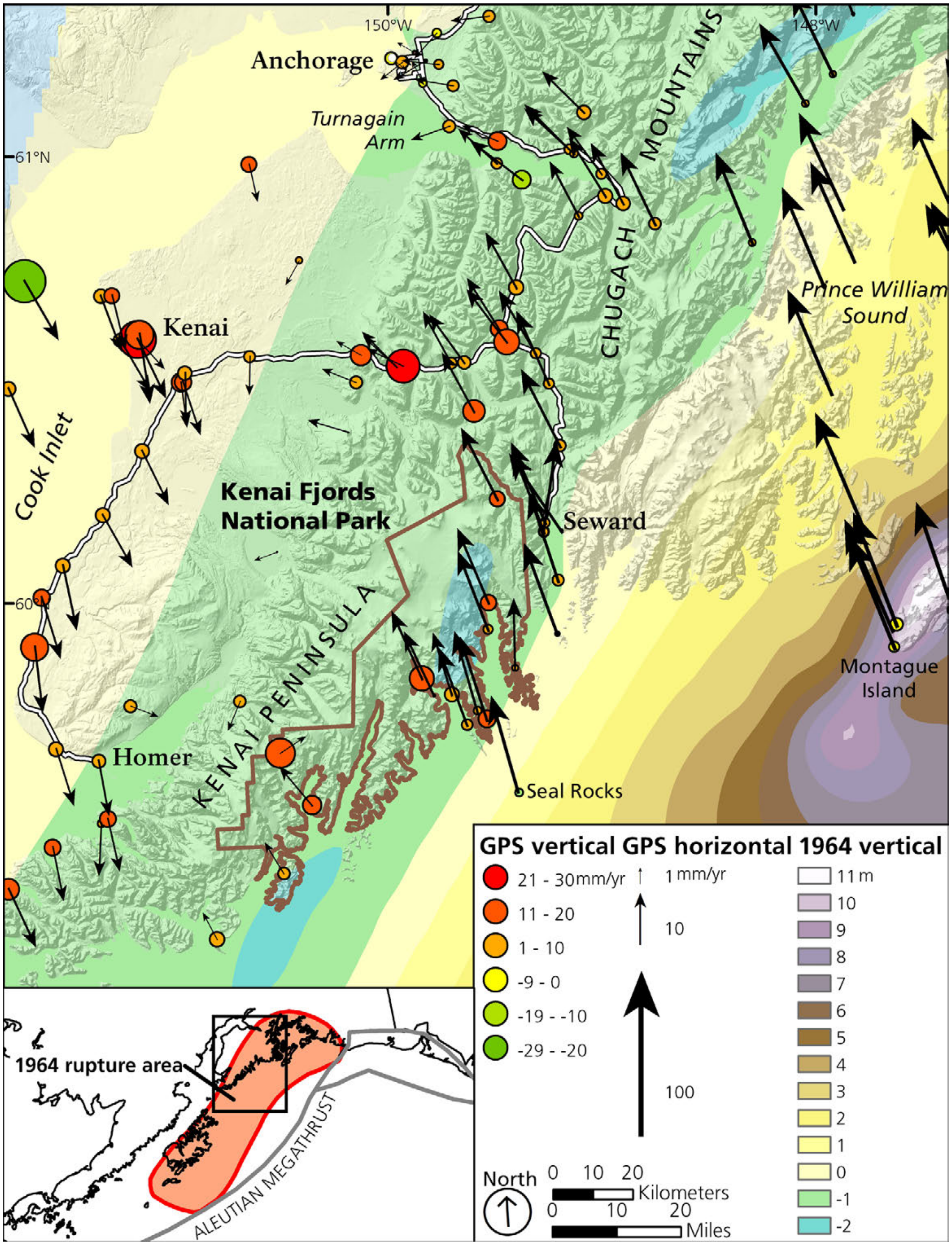


Figure 33. Map showing the rupture area and vertical deformation caused by The Great Alaska Earthquake of 1964 and modern rate of tectonic deformation. Kenai Fjords National Park (boundary line in brown) is located along the axis of maximum subsidence (green and blue area) and subsided 1–2.5 m (3–8 ft) during the earthquake (Plafker 1969). Deformation after the earthquake was measured using tide station data and heights of high tide markers, like barnacles and marine algae (Plafker 1969). Modern deformation rates, measured using GPS and displayed as dots and arrows, show that Kenai Fjords has variable uplift rate of a few millimeters to about a centimeter per year and moving northwest about a centimeter per year (horizontal motions relative to North America; Freymueller et al. 2008). Dot sizes correspond to the degree of vertical movement, with larger dots representing areas that experienced more vertical movement than smaller dots. Map created using data from Freymueller et al. (2008) and Plafker (1969). Hillshade derived from National Elevation Dataset.

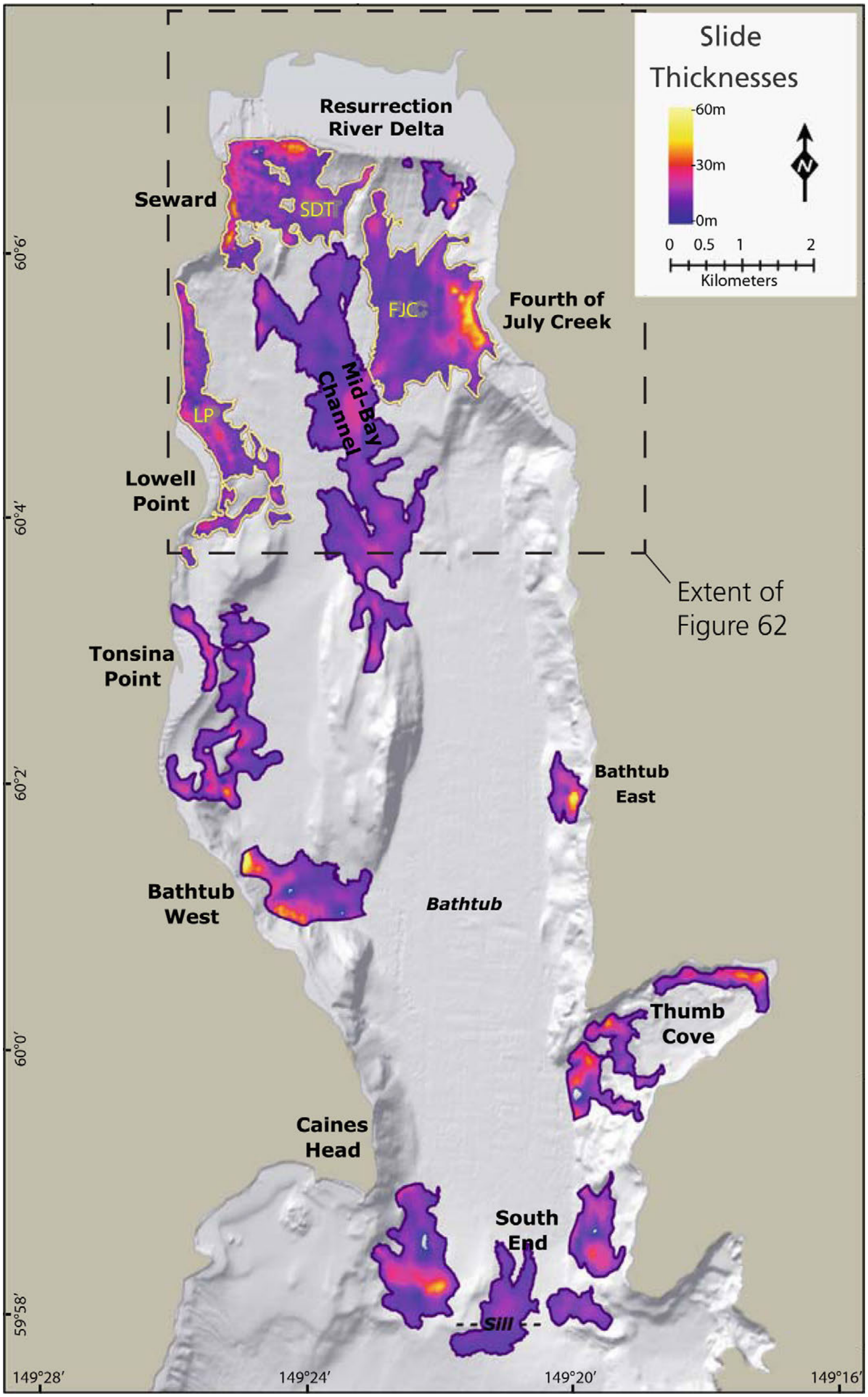


Figure 34. Map of the location and thickness of submarine landslides in Resurrection Bay caused by the 1964 earthquake. Shaking caused unconsolidated sediments to slide into Resurrection Bay, including a portion of Seward's harbor. These underwater landslides produced local tsunamis that, in combination with a tectonically produced tsunami, cause widespread destruction in Seward. Modified from Suleimani et al. (2009).

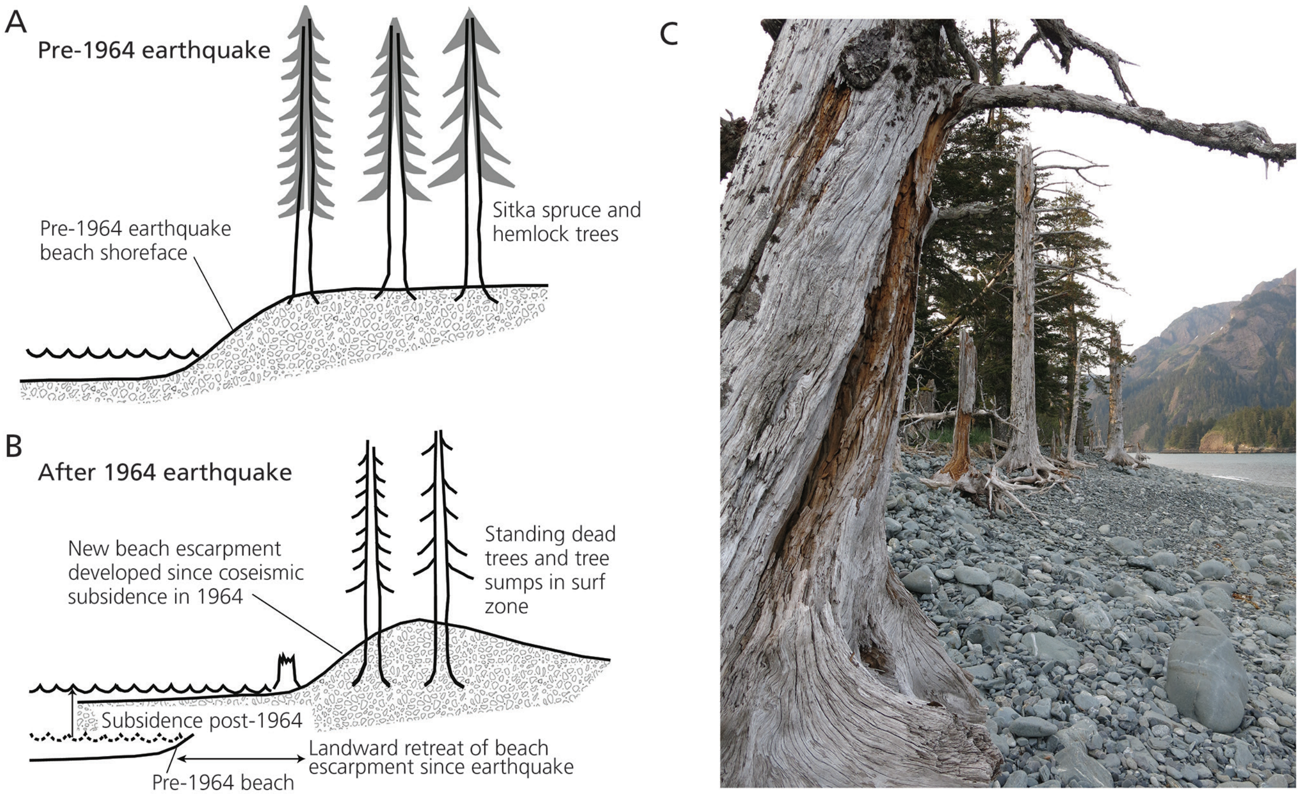


Figure 35. Sketches and photograph showing the process of subsidence and ghost forest formation during the 1964 Great Alaska Earthquake. A: Coast position and coastal forests before the earthquake. B: Coast position and ghost forests after the earthquake. C: Photograph of ghost forests still visible on the coast of the Kenai Peninsula today. Figure modified from Kelsey et al. (2015). NPS photograph by Chad Hults.

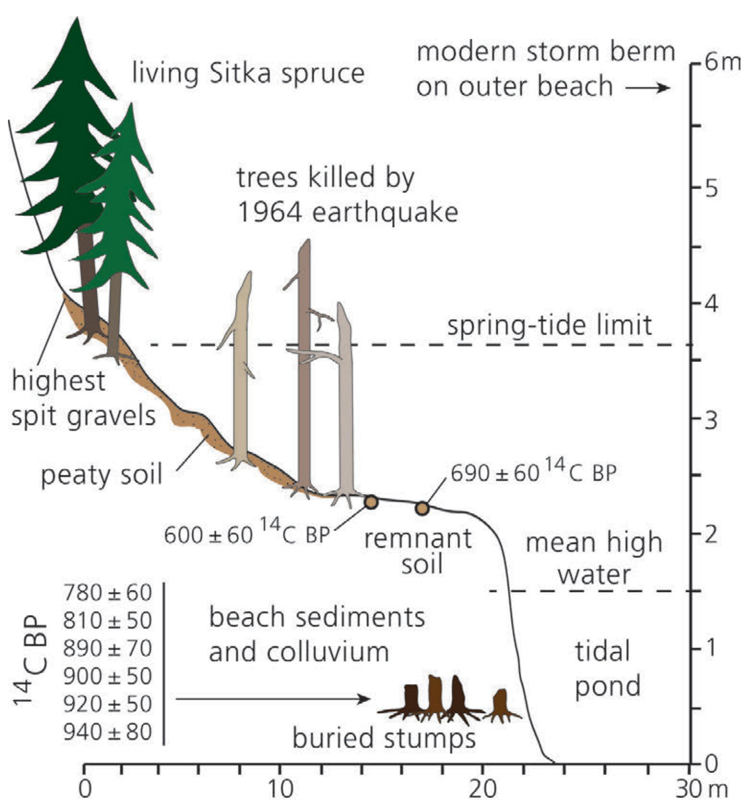


Figure 36. Diagram showing the elevation of trees near the tidal pond in Verdant Cove (Kenai Fjords National Park). Coseismic subsidence during the penultimate earthquake (700-800 yr BP), lowered trees below the spring tide limit. Subsequent wave action buried the stumps. The 1964 Great Alaska Earthquake subsided the area further, which killed a second set of trees that forms a ghost forest around the tide pool. Diagram modified from Mann and Crowell (1996).

21, 1788 earthquake documented by Russian settlers on Kodiak Island. This earthquake may have also formed a distinct beach ridge in the park, at Verdant Cove, Aialik Bay. Verdant Cove also has buried tree stumps below mean high tide surrounding a tide pool (Figure 36; Mann and Crowell 1996). The age of these stumps, along with other evidence from Prince William Sound, suggest that they were buried when the land subsided during a third earthquake occurring sometime between 1060 and 1110 (Kelsey et al. 2015). Based on radiocarbon ages of fossil driftwood from raised beach terraces on Middleton Island and near the Copper River, the recurrence interval of earthquakes in the Prince William Sound ranges from 400 to 1,200 years, with an average of 800 years (Brocher et al. 2014).

Modern Uplift and Long-Term Submergence

Deformation of the Kenai Peninsula is being driven primarily by plate tectonic forces, and glacial isostatic adjustments. These forces are causing the Kenai Peninsula to move vertically and horizontally (Figure 33). The combination of vertical movement and eustatic (global) sea level change is called relative sea level change. Despite modern measurements that indicate the coast of Kenai Fjords is uplifting, coastal geomorphology and buried soil horizons point to a longer-timescale increase in relative sea level, or submergence. The relative sea level history of the park is complex and whether the park is uplifting or subsiding over time depends on the timescale examined.

The modern day (1990s to present) motion of the Kenai Peninsula has been measured precisely using GPS (Freymueller et al. 2008). Figure 37 shows an example of a modern continuously monitoring GPS station for a site on Seal Rocks (see Figure 33). These data show that the park area is uplifting on average 10 mm/yr (0.4 in/yr), but the uplift rate is variable (for example, Seal Rocks are uplifting 4 mm/yr [0.16 in/yr], which is below average for the park; Figure 33). Most sites measured are uplifting between 5 and 12 mm/yr (0.2 and 0.5 in/yr), but the range of rates is between -1.6 and 19.5 mm/yr (-0.06 and 0.8 in/yr). The horizontal deformation direction is to the northwest, which is parallel, and nearly identical in magnitude, to the motion of the subducting Pacific Plate. Freymueller et al. (2000) suggested that the area along the eastern Kenai Peninsula and Prince William Sound are locked to the Pacific Plate along the plate interface; hence, the area is moving in a similar direction and rate as the Pacific Plate. This pattern of uplift and subduction-parallel motion is typical of locked subduction boundaries (Figure 32).

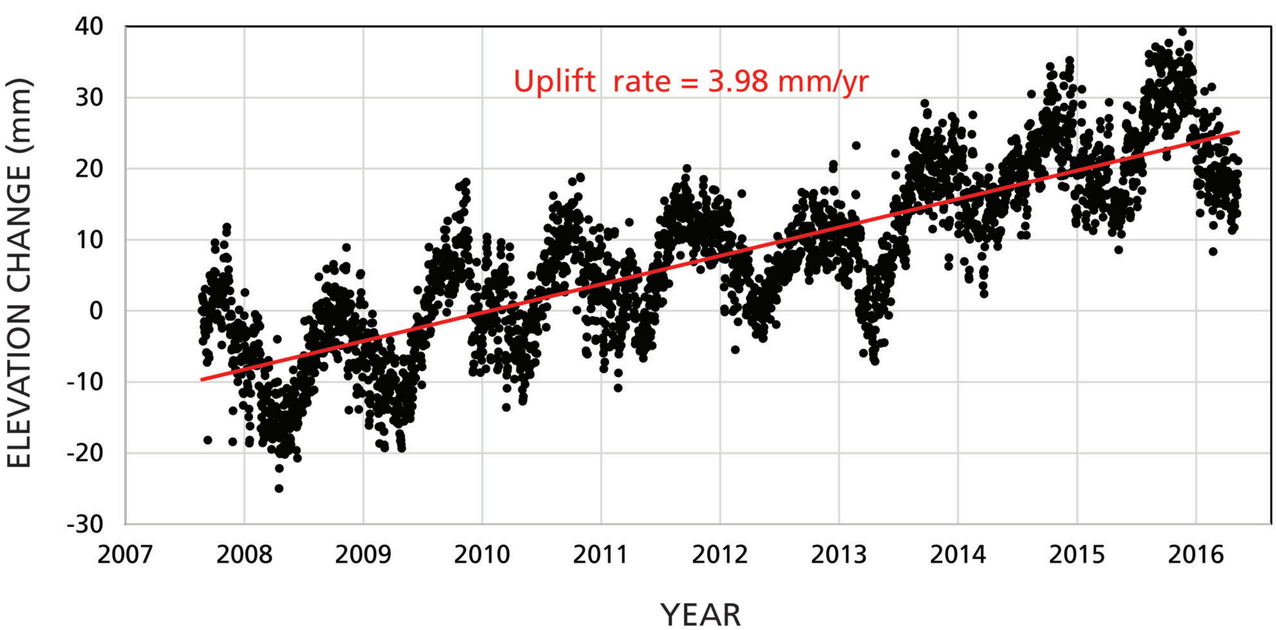


Figure 37. Time series chart showing the vertical component data for the Plate Boundary Observatory GPS station on Seal Rocks (Figure 33). The trend of the data shows an uplift rate of 3.98 mm/yr (0.16 in/year). The seasonal sinusoidal rise and fall is due to snow loading (Fu et al. 2012). Created with data from Fu et al. (2012).

In contrast, the western part of the Kenai Peninsula, and sites across Cook Inlet, are moving trenchward, which is opposite of the Pacific Plate direction (Figure 33). Freymueller et al. (2000) postulated that this region, farther inboard from the plate interface, is subsiding in response to the stress released from the 1964 Great Alaska Earthquake. The earthquake released hundreds of years of compressional stress, and, decades later, the region is still relaxing (see Figure 33) in response.

Most of southern Alaska is also uplifting due to the post-Little Ice Age glacier retreat and ice loss (see "Past Glaciations and Modern Glacier Change"). The effects of deglaciation from earlier glaciations is minimal (Larsen et al. 2005; Freymueller 2015). Freymueller (2015) calculated a preliminary uplift rate model for all of Alaska based on glacier retreat, but the modeled rates for the Cook Inlet and Kenai Fjords area are probably too high, because they do not allow for the expected added effect of post-seismic deformation from the 1964 Great Alaska Earthquake. Additionally, season snow loading can produce very small-scale oscillations, as seen in Figure 37.

Although the Kenai Fjords coast is uplifting today, physical evidence suggests the area has experienced submergence since the start of the Holocene (11,700 years ago). The physical characteristics of the coast of the park are typical of a "drowned" coast (Plafker and Rubin 1967). The rocky islands at the ends of the peninsulas were possibly connected to the peninsulas, but have been isolated during long-term subsidence and sea level rise. Scarce sea cliffs and the lack of raised marine terraces and beaches are consistent with this trend. Glacial cirque floors that form the drowned fjords are as much as 150 m (492 ft) below present sea level (Plafker and Rubin 1967). This long-term submergence of the Kenai Fjords coast is a likely reason why the oldest archeological sites are only 800 years old, as opposed to thousands of years old along the Katmai coast, which has a record of long-term uplift (Crowell and Mann 1996).

The long-term submergence is counter to the trend of uplift measured by modern day GPS, which show that the area is uplifting variably at about 10 mm/yr (0.39 in/yr; Freymueller et al. 2008). This short-term uplift is due to compressive forces of the locked subduction boundary; however, the long-term submergence is most likely the result of Holocene sea level rise combined with episodic rapid subsidence events caused by earthquakes. This is evidenced by the multiple earthquake events recorded by a series of submerged forests and soils (Mann and Crowell 1996; Kelsey et al. 2015). The long-term submergence is also counter to the longer-term uplift of the relatively young Kenai and Chugach Mountains, where the mountains have been uplifting rapidly just north of the park over the last 5 million years (Arkle et al. 2013).

Bedrock

Terrane Translation and Accretion

Alaska is a collage of displaced rocks called terranes (Figure 38). A terrane is a fault-bounded package of rocks with a geologic history that differs from surrounding rocks. Alaskan terranes have been tectonically transported from where they originally formed and accreted together to the edge of the North American craton. Only a small portion of Alaska along the Canadian border on the north end of Yukon-Charley National Preserve is an in-place, undisturbed part of the North American craton (seen in light blue on Figure 38). The rest of Alaska consists of pieces of crust that arrived from elsewhere or are offset portions of the North American craton.

The bedrock of Kenai Fjords belongs to the Chugach terrane, the Mesozoic portion of a Mesozoic-Cenozoic accretionary complex that also includes the Prince William terrane (Figure 38; Dumoulin 1988; Plafker et al. 1994). This accretionary complex is thought to have formed through subduction of oceanic crust beneath the Wrangellia composite terrane (Peninsular [PE], Wrangellia [Wr], and Alexander [AX] terranes in Figure 38). Older mélange units (e.g., McHugh Complex; see Plate 1) of the accretionary complex are composed partly of rocks formed in the deep ocean, which were transported to the edge of Wrangellia, while the younger (meta)sedimentary units (e.g., Valdez and Orca groups; see Plate 1) were more locally sourced and deposited closer to the subduction trench (see the "Valdez Group" and "Orca Group" sections for further description). The Border Ranges fault forms the inboard boundary of the Chugach-Prince William accretionary complex and represents a Mesozoic plate boundary between the subducting oceanic plate and the Wrangellia composite terrane (for more information see "Border Ranges Fault System"; MacKevett and Plafker 1974; Pavlis and Roeske 2007). The tectonic evolution and depositional environments of the Chugach-Prince William accretionary complex is illustrated in Figure 39.

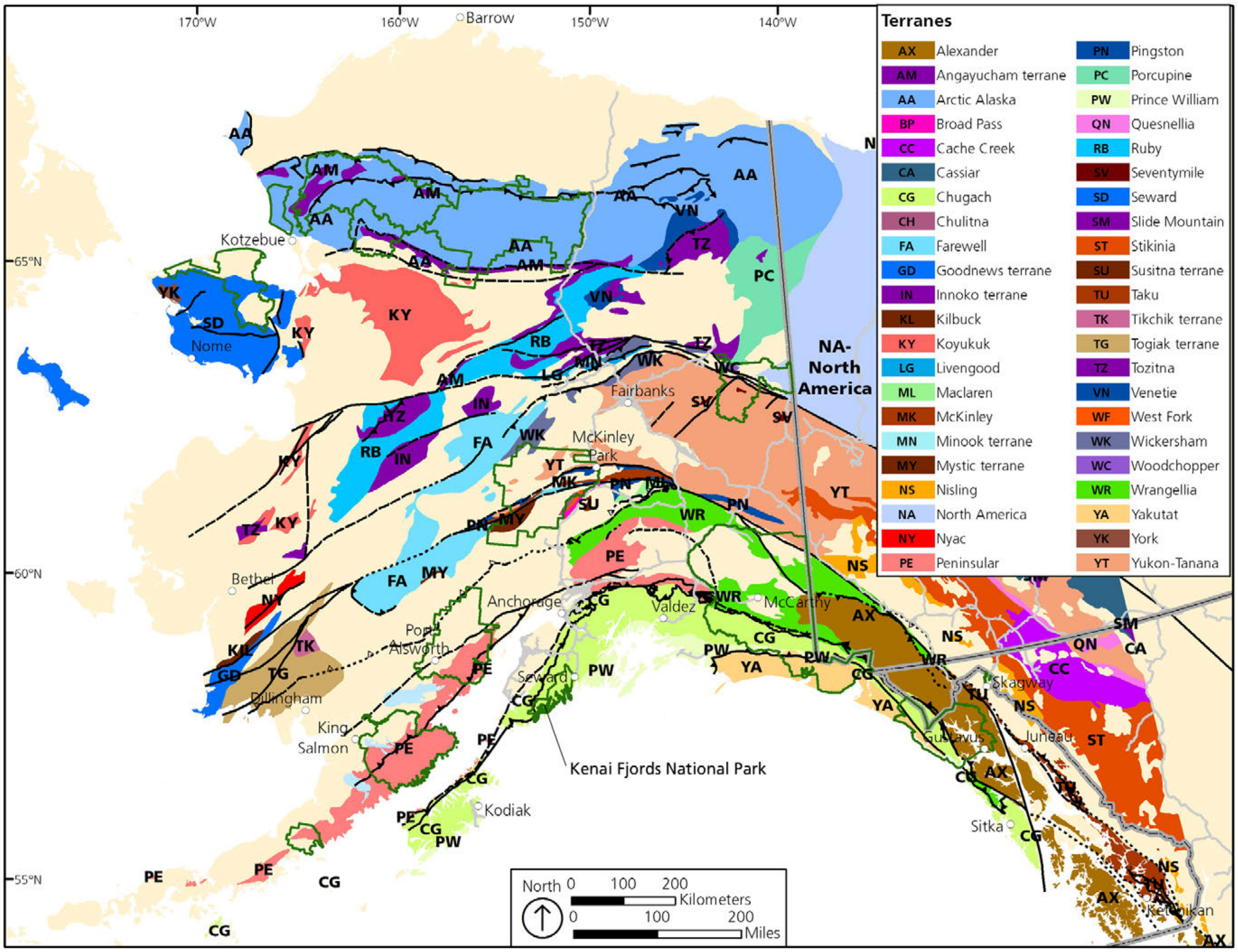


Figure 38. Map of the terranes of Alaska, with park boundaries outlined in dark green, roads in light grey, and major faults in black. The bedrock units on Plate 1 correspond to the Chugach terrane (CG) and the Prince William terrane (PW), both colored light green. Modified from Silberling et al. (1992).

Subduction of a spreading ridge during the Paleocene-Eocene is thought to be the source of unusual near-trench plutons (**Tgh**) found along the southern Alaskan margin (Figure 40). Evidence of coeval ridge subduction also occurs along the Cascadia margin, on the western edge of British Columbia and Washington (Figure 40; Cowan 2003; Haeussler et al. 2003). Two differing plate reconstructions have been put forward to explain the apparent simultaneous ridge subduction in these two areas: (1) Subduction of a single spreading ridge beneath the western coast of British Columbia/Washington, forming near-trench plutons that were later transported northward to their present-day location in southern Alaska, while the other rocks with evidence of ridge subduction remained behind in the British Columbia/Washington area (Cowan 2003; Garver and Davidson, 2015); (2) The presence of two spreading ridges, each subducting simultaneously beneath southern Alaska and British Columbia/Washington, which left behind coeval evidence of this subduction in two separate places (Haeussler et al. 2003). Both reconstructions account for the age-gradient observed in the near-trench plutons, with older ages in the west and younger in the east (Bradley et al. 1993). Paleomagnetic data from the Resurrection Peninsula ophiolite and the Ghost Rocks Formation show these rocks formed significantly south of their current location, supporting the single-ridge subduction model (Figure 40; Plumley et al. 1983; Bol et al. 1992; Housen et al. 2008). Similarities between schists of the Leech River complex on southern Vancouver Island and schists found on Baranof Island that belong to the Chugach-Prince William accretionary

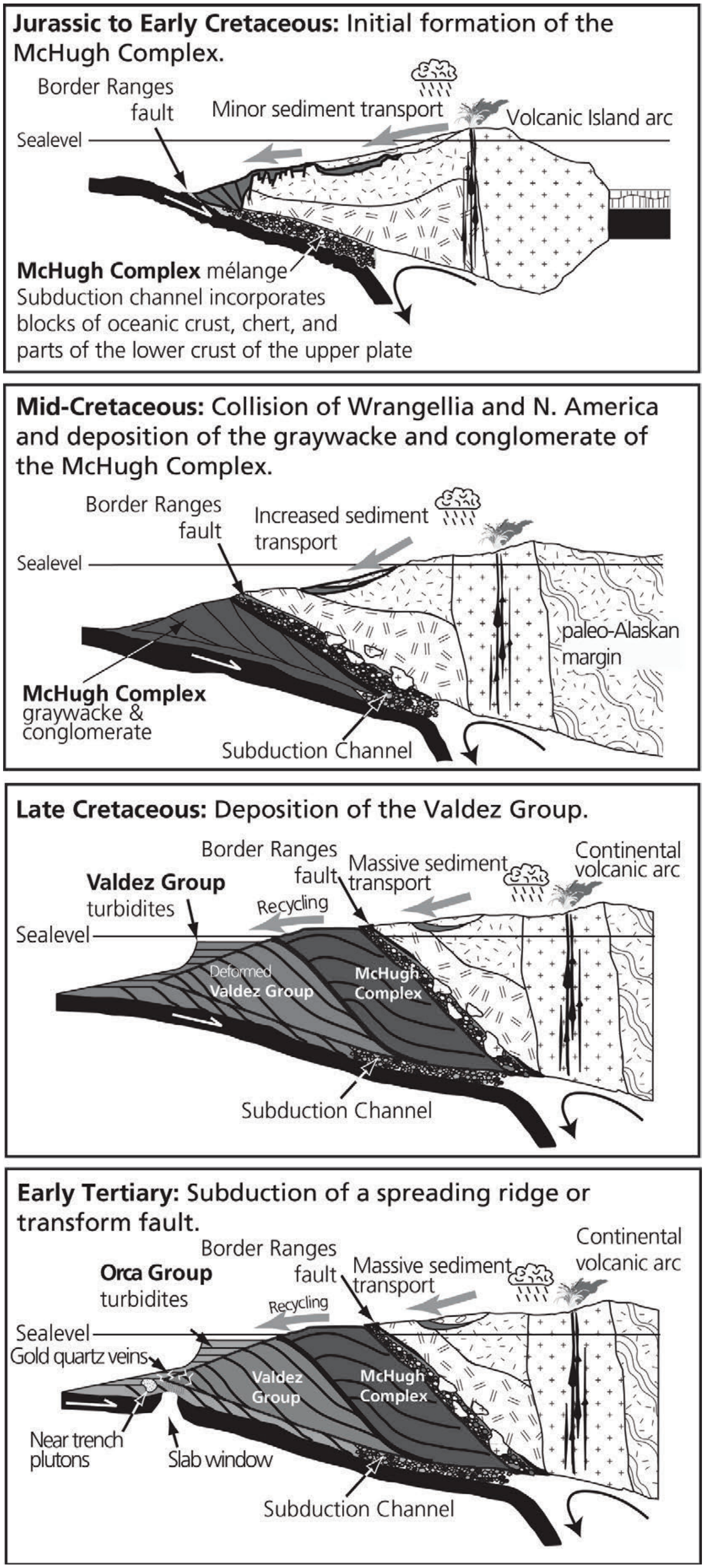


Figure 39 (left). Diagram showing cross-section detail of an evolving subduction zone showing the environments of formation of the rocks that make up Kenai Fjords National Park. From the Jurassic to Early Cretaceous, the McHugh Complex formed along the margins of a volcanic island arc (called Wrangellia), somewhere in the proto-Pacific ocean. Wrangellia collided with North America in the Mid-Cretaceous, causing more siliciclastic deposition including the greywacke and conglomerate facies of the McHugh Complex. Continued siliciclastic deposition led to the formation of the Valdez Group in the Late Cretaceous, and the turbidites of the Orca Group in the Early Tertiary. Also during the Early Tertiary, the subduction of a spreading ridge emplaced the Resurrection ophiolite, and formed near-trench plutons, sills and dikes, and gold-bearing quartz veins. Figure modified from Amato et al. (2013).

complex further strengthen the single-ridge subduction model (Figure 40; Cowan 2003). The single-ridge model also helps explain the presence of southern Laurentian (California) zircons found in the Chugach-Prince William accretionary complex (Garver and Davidson, 2015).

McHugh Complex

The McHugh Complex is a tectonic mélange mapped in the southern and western part of the park (Plate 1) that consists of the following units: **KMm** undivided, **KJms** graywacke and conglomerate, **KTRmc** basalt and chert, **MZg** Gabbro, **MZu** ultramafic plutonic rocks. Mélange is French for “mixture” and the McHugh Complex is a mixture of rock types that are entrained in a sheared matrix (Figure 41; Figure 42). Isolated and identifiable blocks range in size from centimeters (inches) to hundreds of meters (yards). The igneous rock types (basalt, gabbro, and plutonic rocks) typically represent pieces of oceanic crust that broke off and were incorporated into an accretionary wedge in a subduction zone (Figure 43). Some of the igneous plutonic rocks represent pieces of the lower crust of the overlying volcanic arc. The bioclastic

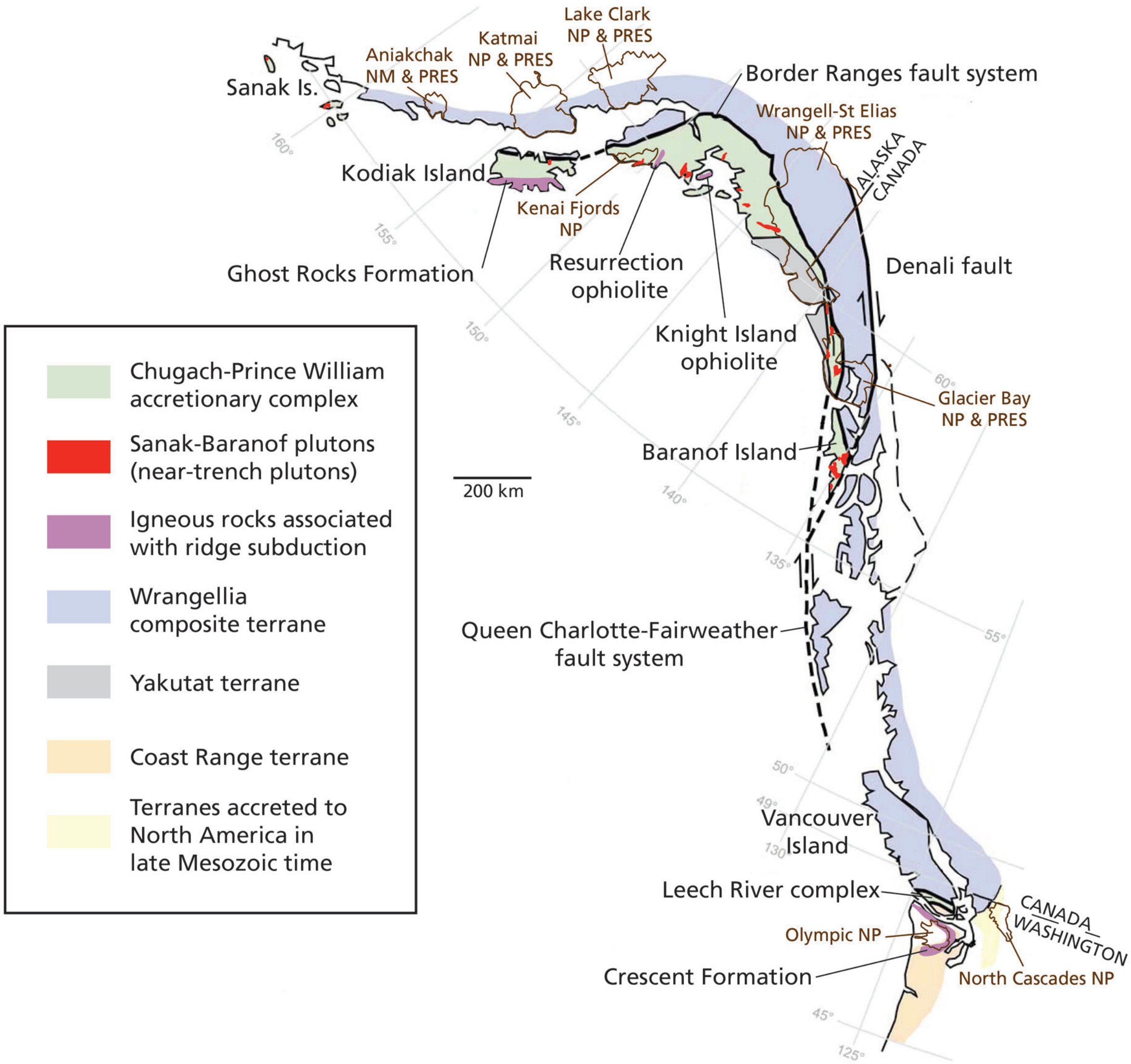


Figure 40. Map showing the geologic units associated with Paleocene-Eocene ridge subduction beneath the southern Alaska and Cascadia margins. Evidence for ridge subduction in southern Alaska includes near-trench plutons (called the Sanak-Baranof plutons) and oceanic igneous rocks such as the Ghost Rocks Formation on Kodiak Island and the Resurrection ophiolite just to the east of Kenai Fjords. Rocks formed during ridge subduction also occur along the west coast of British Columbia and Washington, including volcanic rocks of the Crescent Formation, which can be found in Olympic National Park (Glassley 1974). Modified from (Cowan 2003).

sedimentary rocks (limestone and chert) were derived from marine invertebrates. The limestone formed as reefs on the tops of seamounts (Figure 43). Chert is formed predominantly in the deep ocean from radiolarians—marine organisms that secrete siliceous shells. The clastic sedimentary portion, graywacke (muddy sandstone), siltstone, shale, and conglomerate, were derived from sediment shed from a continental source inboard of the subduction zone.

The formation age of the McHugh Complex ranges from Late Jurassic to Early Cretaceous (163.5–100.5 MYA), but blocks incorporated in the mélange are as old as Permian (298.9–251.9 MYA), and clasts in the conglomerate are as old as Mississippian (358.9–323.2 MYA). Chert bodies within the complex, outside the park, contain radiolarians that range in age from Middle Triassic (approximately 227 MYA) to Early Cretaceous (Albian, 100.5 MYA; Plafker et al. 1977; Karl et al. 1979; Bradley et al. 1999). Blocks of mafic plutonic rocks date back to the Triassic. Blocks of limestone found in the

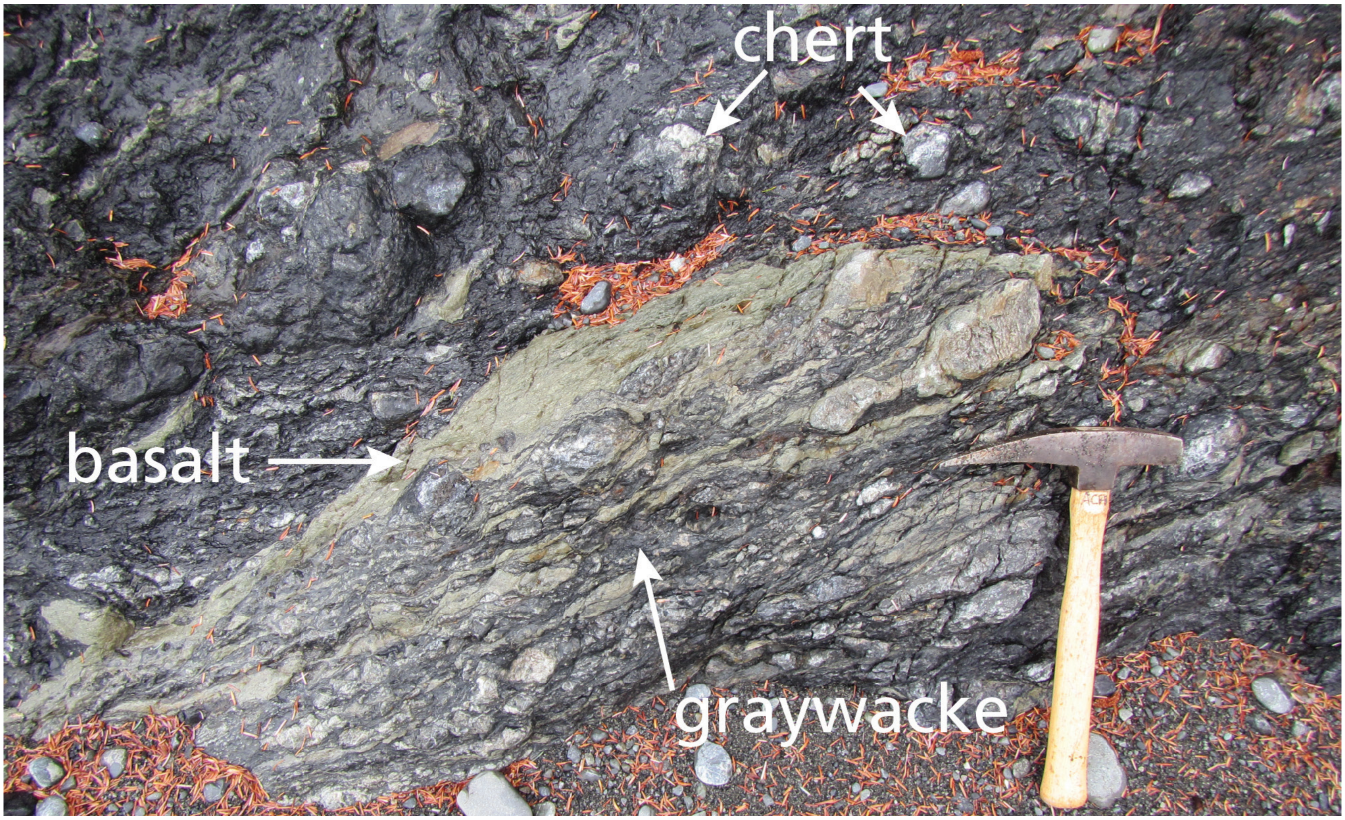


Figure 41. Photograph of the typical basalt and chert facies of the McHugh Complex showing resistant chert blocks incorporated in a sheared matrix of graywacke and green stringers of basalt. NPS photograph by Chad Hults from Petrof Point area at the southern end of the park. Head of rock hammer is 20 cm (8 in) long.

Figure 42. Photograph of the graywacke and conglomerate facies of the McHugh Complex showing stretched pebbles in a sheared matrix. Photograph by Chad Hults. Head of rock hammer is 20 cm (8 in) long.

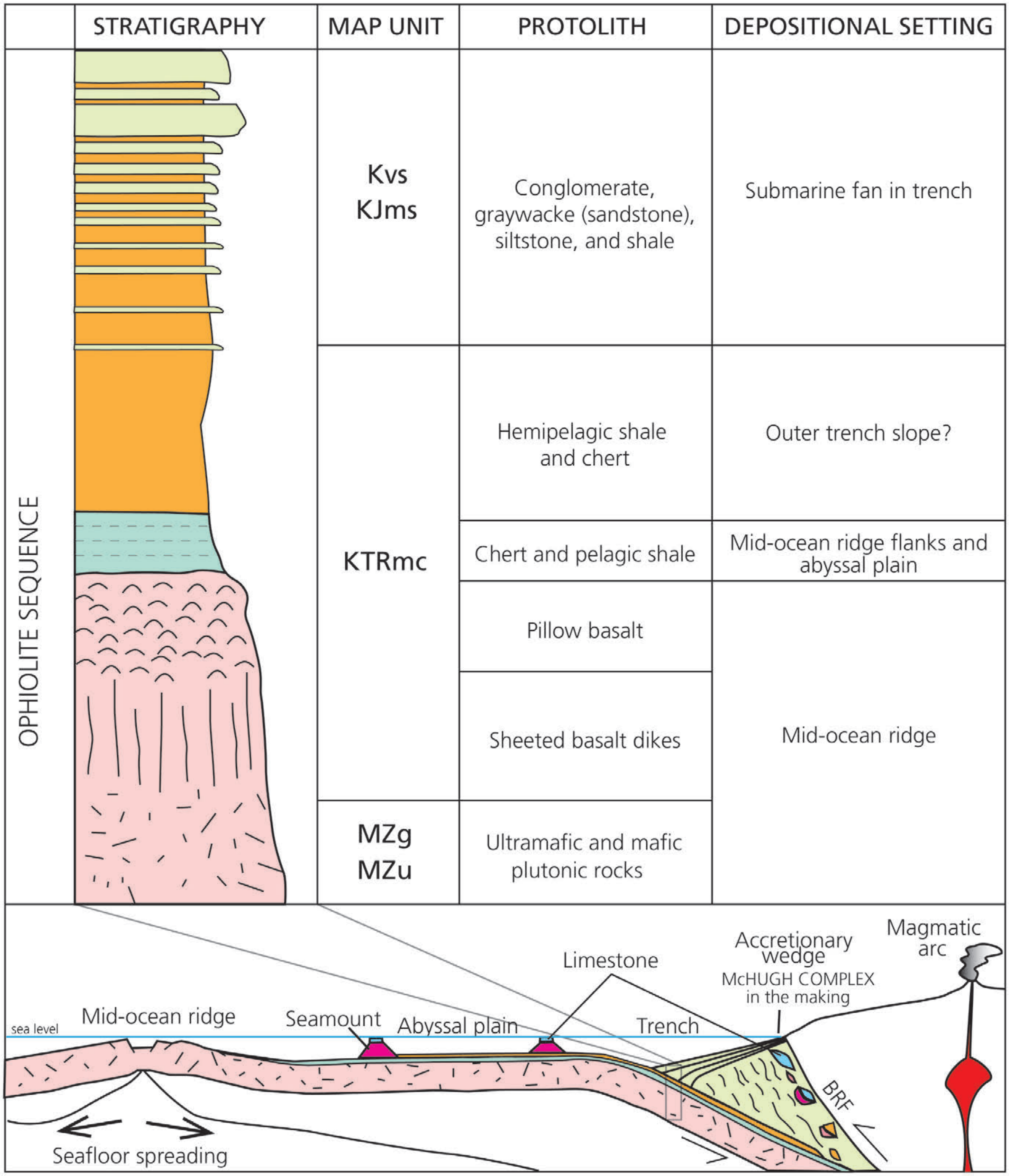


Figure 43. Stratigraphic section and diagram showing the tectonic environment of formation of the McHugh Complex and the rock types within the complex. The McHugh Complex consists of blocks of oceanic crust, broken off, and entrained in the accretionary wedge, and clastic sediments derived from a continental source and deposited into the trench. Isolated blocks of limestone suggests that seamounts may have also been entrained into the accretionary wedge. Map units correspond to the map units on Plate 1. BRF—Border Ranges fault. Modified from Bradley and Miller (2006).

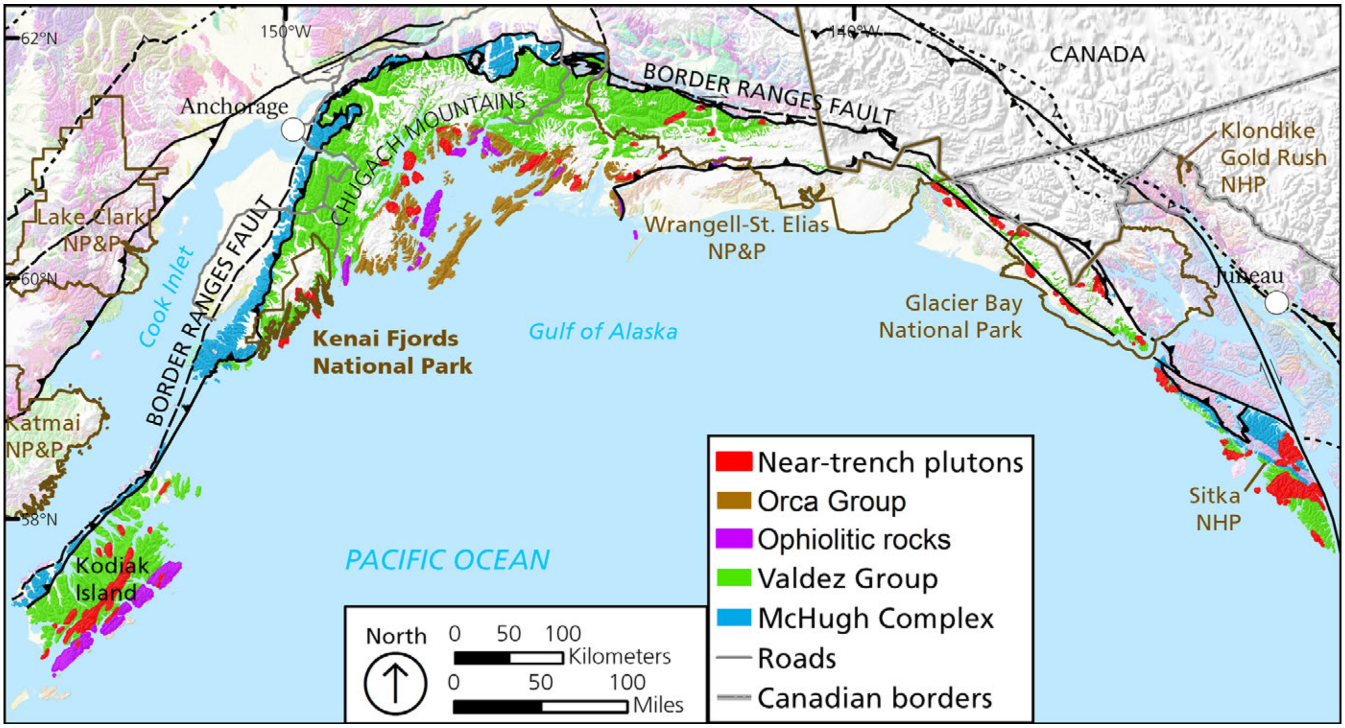


Figure 44. Map showing the regional extent of the Kenai Fjords National Park rock units, and their equivalents along the southern Alaskan margin. Jurassic to Cretaceous McHugh Complex (subduction zone mélange) is everywhere found inboard of the Cretaceous Valdez Group and early Tertiary Orca Group (trench-fill sedimentary rocks). For simplification, the Sitka Graywacke in southeast Alaska is shown as the Valdez Group, and the correlative Uyak Complex of Kodiak Island and Kelp Bay Group of southeast Alaska are included in the McHugh Complex (Plafker et al. 1977). Early Tertiary ophiolitic rocks crop out on Kodiak Island, where they are called the Ghost Rocks, along the Resurrection Peninsula, and in Prince William Sound. Paleocene to Eocene granitic near-trench plutons intrude the Orca and Valdez Groups throughout the southern Alaskan margin. Modified from Wilson et al. (2015).

southwest of the park contain Permian fossils such as crinoids, fusulinids, conodonts, alga, and large bivalves (Stevens et al. 1997; Blodgett and Isozaki 2013). The fossil assemblage is unusual for North America and is more consistent with an origin in the Tethys region of southern Eurasia, which indicates that the rocks have traveled a great distance since the Permian. See the "Paleontological Resources" section for more information.

Valdez Group

Map Units: Kvs (Valdez Group metasedimentary rocks), Kvm Iceworm Peak Mélange of Kusky et al. (1997) (Plate 1)

The Upper Cretaceous (Campanian? to Maastrichtian, 84–66 MYA) Valdez Group (**Kvs** metasedimentary rocks, **Kvm**, Iceworm Peak Mélange of Kusky et al. [1997] makes up most of the bedrock of Kenai Fjords and the Chugach Mountains (Plate 1; Figure 44). The unit is made up of sandstone, siltstone, shale, and minor conglomerate. It is weakly metamorphosed (compressed by high pressures), which changed the orientation and mineral makeup. The sandstone contains abundant clay-sized grains, so it is called graywacke. Typical bedding is graded with coarser grained material at the bottom of a bed grading up to finer material at the top. The beds are called turbidites, because they were deposited by submarine density flows composed of turbid water (water with suspended clay, silt, and sand), which causes distinctive sedimentary structures (Figure 45; Figure 46). Turbidites contain typical sedimentary structures that together are called a Bouma Sequence (Bouma 1962). These sedimentary structures can be found in whole or in part in the exposed Valdez Group in Kenai Fjords National Park.

Figure 45. Photograph showing turbidite bedding of the Valdez Group located near the terminus of Exit Glacier. The beds here are made of graded siltstone (rock with silt-sized grains, 3.9-63 µm) and shale (fissile rock with mud-sized grains, <3.9 µm) that have sedimentary structures typical of turbidite beds: convolute lamination, parallel laminations, graded bedding, and irregular bedding contacts (caused by scour during deposition). Minor faults offset the bedding. More recent glacial grooves are also visible. NPS photograph by Deborah Kurtz.

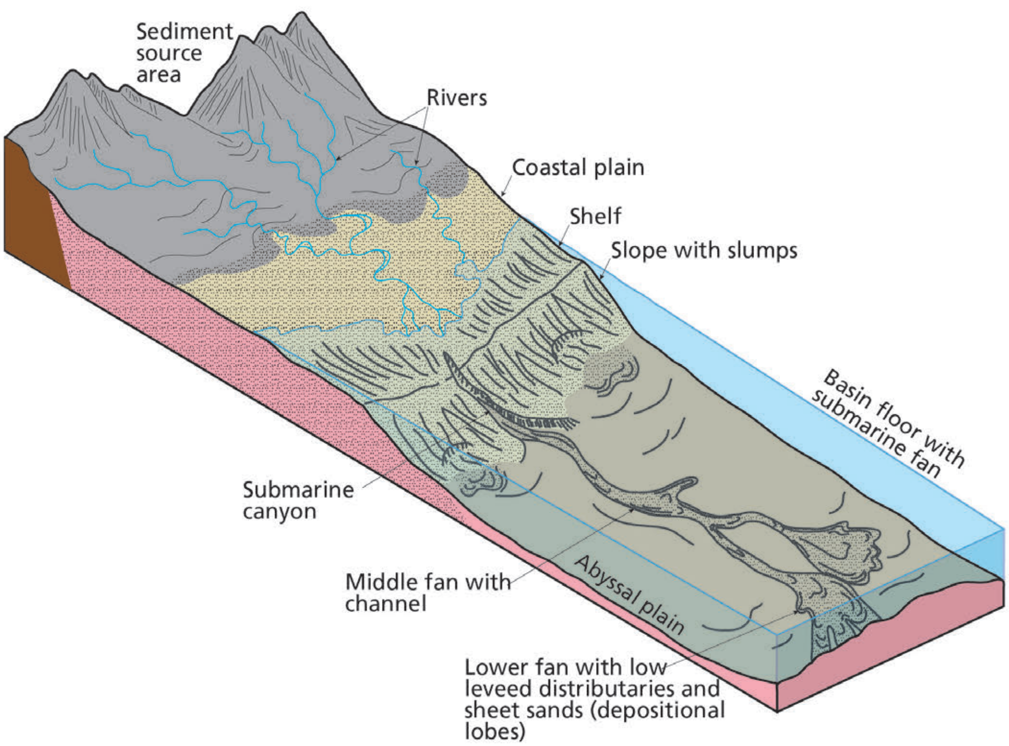


Figure 46. Diagram showing the environment of deposition of the Valdez Group. Most of the turbidite beds formed at the lower part of a submarine slope and submarine fan. Turbidites are sourced from both slope failures and density flows through submarine canyons. Local, massive, coarse-grained sandstone and conglomerate were formed in submarine channels that cut into the turbidite beds.

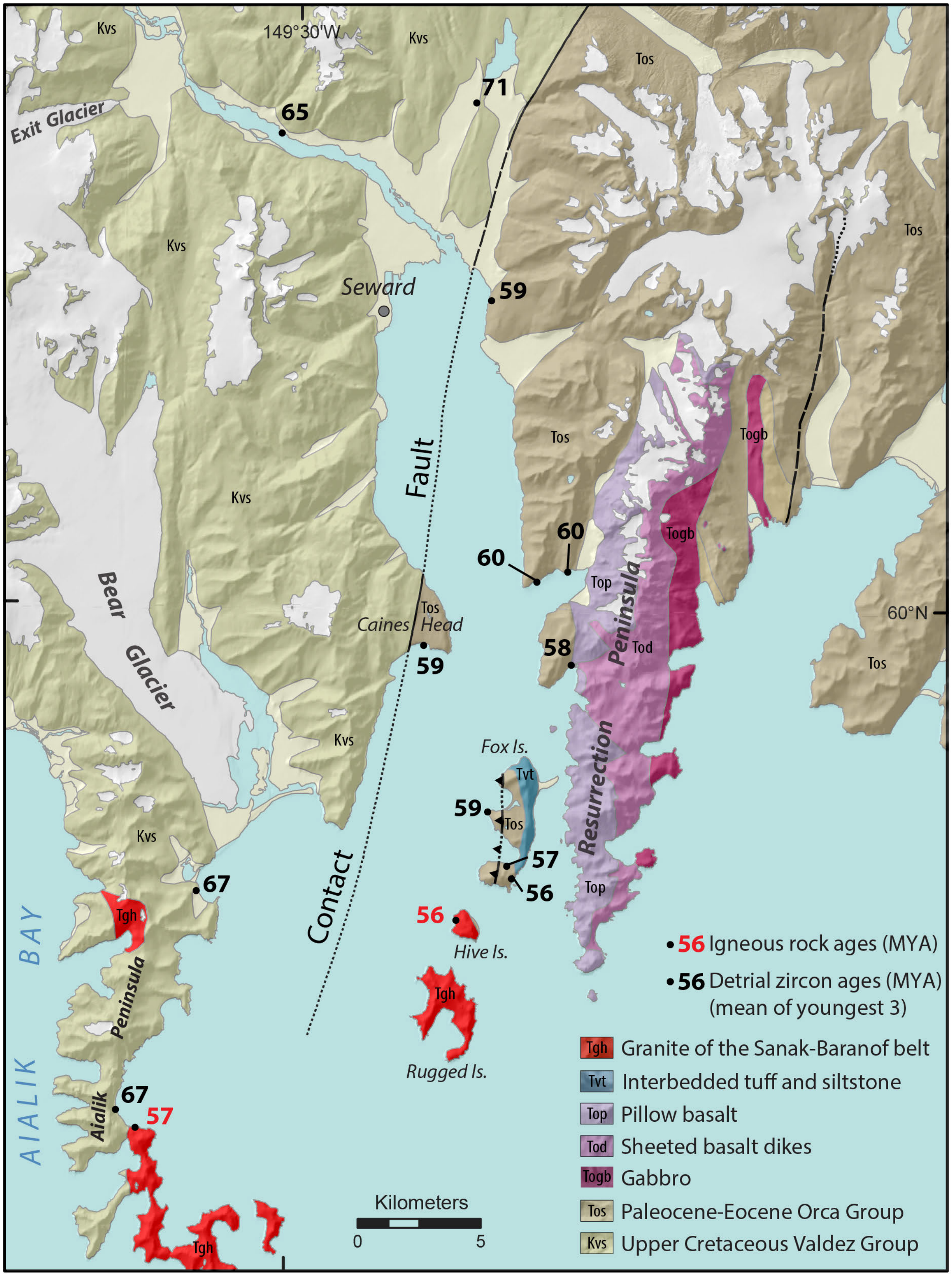


Figure 47. Geologic map of the Resurrection Peninsula and surrounding area. Map shows the ages of zircons in igneous rocks and the youngest detrital zircons in sedimentary rocks. The the Tertiary Orca Group is in fault contact with the Cretaceous Valdez Group and this contact between has been moved to the west along Caines Head. Note: the Cretaceous/Tertiary boundary is 66 MYA. Map modified from Davidson and Garver (2015).

Orca Group: Resurrection Ophiolite

Map Units: Top pillow basalt, Tod sheeted dikes, Togb gabbro, Kvs metasedimentary rocks on the west side of Resurrection peninsula, Kvvs metavolcanic and metasedimentary rocks, Kvgs schist, Kvt interbedded tuff and siltstone (based on new geochronology and interpretation, these units are actually Tertiary in age and should be considered part of the Orca Group (Davidson and Garver 2015) (Plate 1).

The Resurrection Peninsula is made up of an ophiolite sequence (stratigraphic section of mafic igneous rocks) that dips approximately 45° to the west (Plate 1, Figure 47; Figure 48). At the base of the section is gabbro (**Togb**), a coarse grained mafic igneous rock. The gabbro is mostly present low in the section, but small bodies intrude the overlying units, which can be seen in Humpy Cove. A U/Pb age on one of these plutonic rocks yielded a 57 MYA age (Nelson et al. 1989). During the time of formation, the gabbroic plutons fed fractures and faults to form sheeted basalt dikes (**Tod**; Figure 49). When these basaltic magmas reached the surface of the seafloor, they formed pillow basalt lava flows (Figure 50). Pillows form when hot lava quenches quickly as it is exposed to water. This fast quenching forms a distinctive zoning seen in pillows (Figure 51).

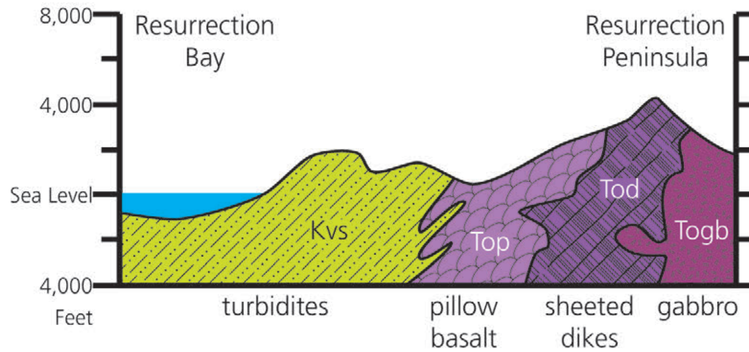


Figure 48. Cross-section through the Resurrection ophiolite, showing the typical ophiolite succession of gabbro (Togb) overlain by sheeted dikes (Tod), which is overlain by pillow basalts (Top). Note that unit Kvs in this diagram is Tertiary in age and younger than the underlying mafic igneous rocks. Labels correspond to the map units on Plate 1. Figure modified from Tysdal and Case (1979).

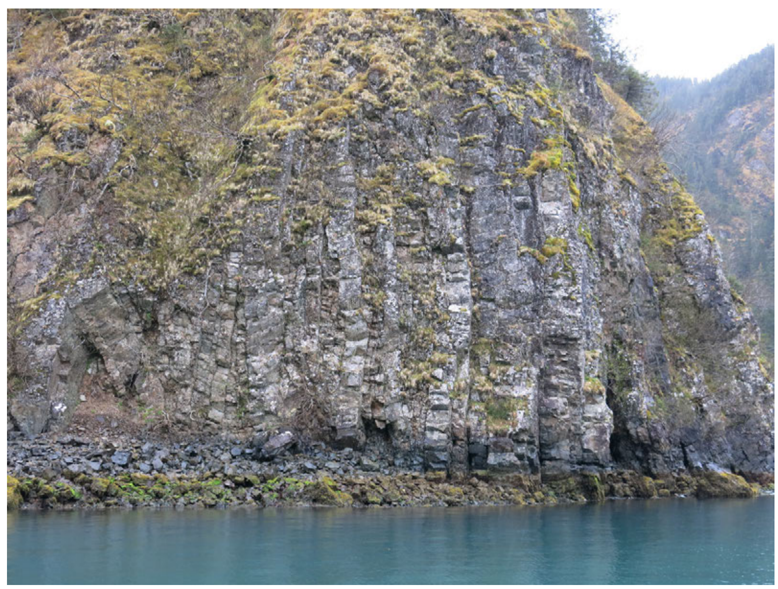


Figure 49. Photograph of sheeted dikes in Humpy Cove. Sheeted dikes are typically found in ophiolite sequences between underlying mafic and ultramafic rocks, and overlying pillow basalts. These sheeted dikes formed as magma was fed up to the ocean floor through cracks above the magma chamber. NPS photograph by Chad Hults.

Interbedded with the pillow basalt are clastic sedimentary rocks (turbidites). This relationship was recognized on the Resurrection Peninsula by Tysdal et al. (1977). The thought at that time was that the interbedded sedimentary rocks were part of the Valdez Group; hence, the ophiolitic rocks were inferred to be Cretaceous. However, the discovery of the 57 MYA age of the ophiolite put into question the age and relationship of the sedimentary rocks to the ophiolite. This new age led Nelson et al. (1989) to suggest that the contact is actually a fault contact, and that the interbedded sedimentary rocks were not related to the overlying sedimentary rocks. Careful re-mapping by Kusky and Young (1999) reinforced the original interpretation by Tysdal et al. (1977), but the fault interpretation stood until Davidson and Garver (2015) presented new geochronologic data that showed that the overlying sedimentary rocks were actually Tertiary (unit **Kvs** on the west side of Resurrection Peninsula), and that all the rocks of Fox Island (**Kvvs** metavolcanic and metasedimentary rocks, **Kvgs** schist, **Kvt** interbedded tuff and siltstone) are also Tertiary (Figure 47). These rocks should be considered part of the Tertiary Orca Group, and not the Cretaceous Valdez Group. The Tertiary rocks reach as far west as Caines Head (Figure 47). The extensive field mapping

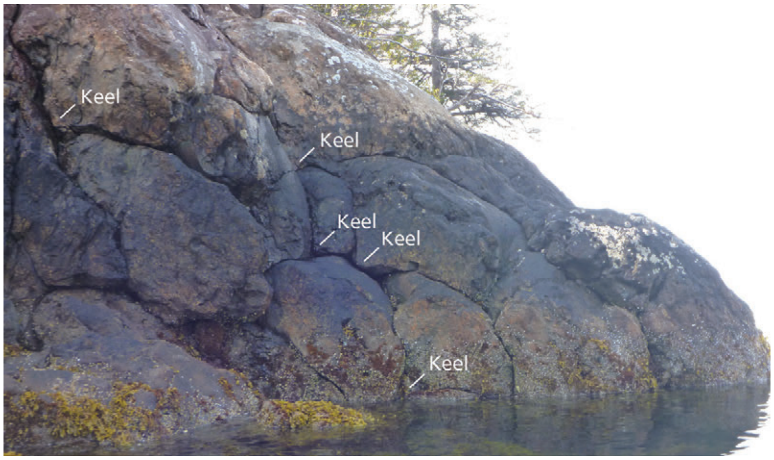


Figure 50. Photograph of pillow lava in Humpy Cove. The lava flows are dipping approximately 45° to the west (right), which is indicated by the keels of the pillows pointing down to the left. The keel of the pillow points downward where the lava filled in the space among lower pillows. Photograph by Chad Hults.

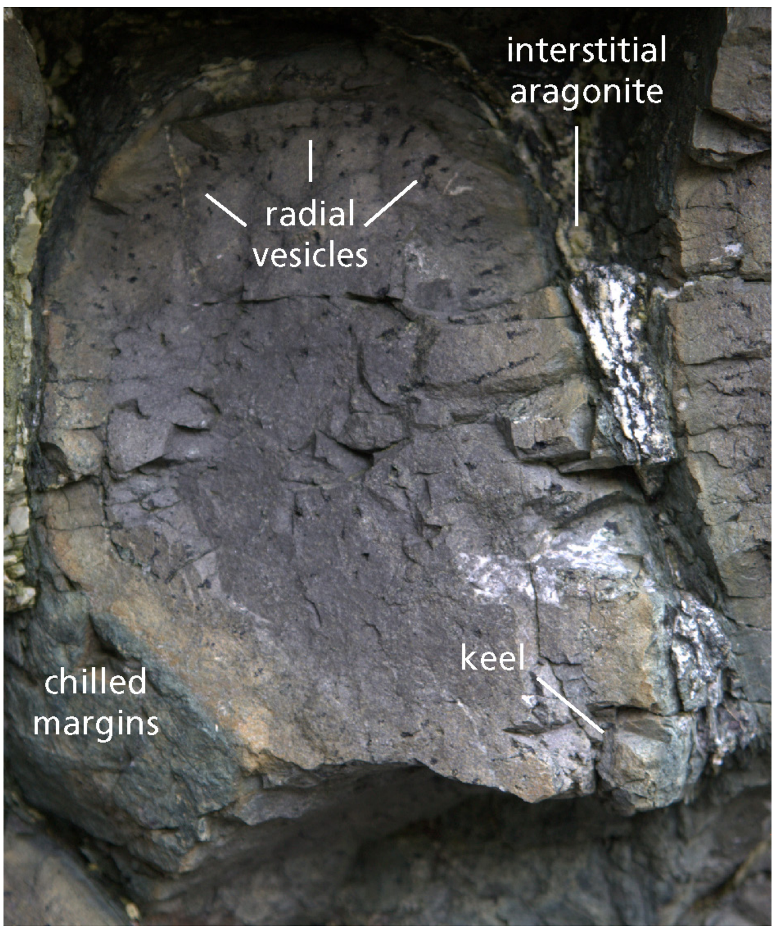


Figure 51. Photograph showing the internal structure of a pillow. The surface of a pillow is quenched by seawater, so it has a finer-grained "glassy" outer margin; whereas, the inner portions are microcrystalline. Vesicles form in a radial pattern near the top of the pillow. Voids are commonly filled with aragonite (calcium carbonate). NPS photograph by Chad Hults.

and geochronological work completed by Davidson and Garver (2015) has shown both that the field relationships indicate that the contact is depositional, not faulted, and that the age of the overlying sedimentary rocks is Tertiary, not Cretaceous. How far north the Tertiary sedimentary rocks extend is a question for future study.

The Resurrection ophiolite is a sequence of rock types that can form in various environments, but in general, ophiolites form where mantle melts are able to reach the surface of the crust at mid-ocean spreading ridges. A typical ophiolite sequence is shown in the McHugh Complex section in Figure 43. The Resurrection ophiolite is correlative to other Tertiary ophiolitic rocks of south-central Alaska (Figure 44). Ophiolite sequences are usually topped by chert; however, the Tertiary ophiolite sequences of south-central Alaska are interbedded and overlain by clastic sedimentary rocks. Several hypotheses have been proposed for how these ophiolites formed, including: (1) subduction of a mid-oceanic spreading ridge (Moore et al. 1983; Bol et al. 1992; Bradley et al. 1993, 2003; Cowan 2003) (Figure 52); (2) "leaky" transform faults (Tysdal et al. 1977; Davidson and Garver 2015); or, (3) in a supra-subduction zone setting (Davidson and Garver, in press). In all cases, mantle derived magma reached the surface within a subduction zone to form the ophiolite sequence with interbedded and overlying clastic sedimentary rocks (turbidites).

Intrusive rocks

Map Units: Tgh Granitic rocks of the Harding Icefield region, TKd dikes (Plate 1)

The granitic rocks of the Harding Icefield region (**Tgh**) crop out along Resurrection Bay on Hive and Rugged Islands, on the Aialik Peninsula and Harding Icefield, and along McCarty Fjord (Plate 1). The rocks are granite and granodiorite (Tysdal and Case 1979; Bradley et al. 1999). Ages of the granitic rocks in the map area range from 61 to 50 MYA (Paleocene and Eocene) (Tysdal and Case 1979; Bradley et al. 1999, 2000a; Lytwyn et al. 2000;

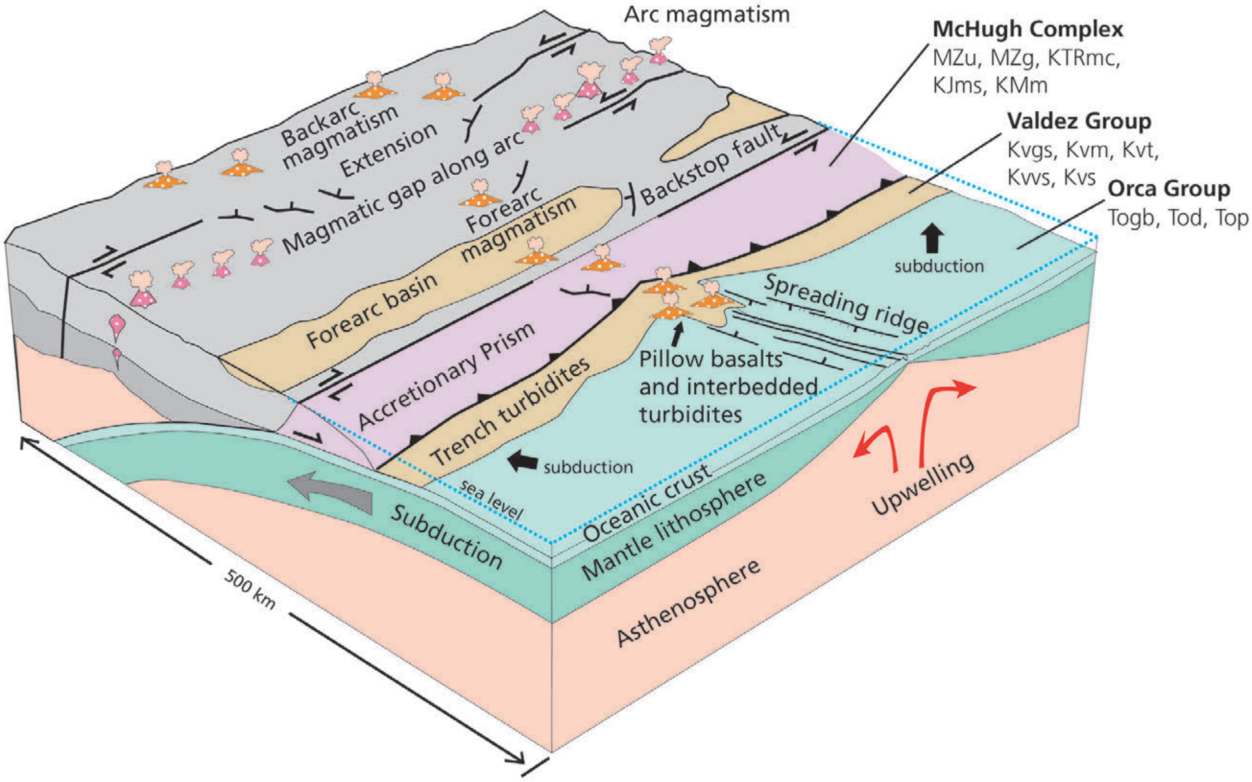


Figure 52. Diagram showing the effects on igneous activity during the subduction of a spreading ridge. The rocks of Kenai Fjords National Park represent the accretionary prism, trench turbidite and oceanic crust portions of the diagram. The spreading ridge opens fractures where upwelling mantle derived magma melts and reaches the surface where it cools to form pillow basalts. Turbidites are deposited while the pillow basalts form, interlayering the two units. Not shown are the near-trench plutons that formed within the accretionary prism, approximately 200 km (124 mi) outboard of typical subduction related arc magmatism. Beyond the accretionary prism, volcanism along the volcanic arc ceases, but new and different volcanism occurs (for more information see Bradley et al. 2003). Map units correspond to the map units on Plate 1. Figure modified from Bradley et al. (2003).

Davidson and Garver 2015). Dikes and sills (**TKd**) are present throughout the map area and are related to the plutons (Figure 53). They were formed by magma that escaped from the plutons through tabular weaknesses such as joints, fractures, and shear-zones.

These plutons in the accretionary prism are called near-trench plutons, because they formed near a subduction trench. The geologic setting of the plutons intruding an accretionary complex is unusual, because there is typically no source of heat to create melts. Subduction zones are where cold oceanic crust subducts, so there is actually a cooling mechanism. However, the process that formed the Resurrection ophiolite within the accretionary complex is a likely heat source to form the plutons. The age of the granitic rocks is essentially the same age as the Resurrection ophiolite. Heat from the upwelling magma caused the sedimentary rocks of the accretionary prism to melt, which is reflected in the similarity between the chemistry of the plutons and the turbidites.

The near-trench plutons are part of a belt of Paleocene–Eocene plutons that span from Sanak Island to Baranof Island (the Sanak-Baranof belt of Hudson et al. [1979]). Two hypotheses have been put forth to explain the formation of these near-trench plutons: (1) anatexis (melting in place) of the accretionary prism sedimentary rocks due to thickening and subsequent quiescence of subduction (Hudson et al. 1979); and (2) subduction of a mid-oceanic spreading ridge (Marshak and Karig 1977; Moore et al. 1983; Bradley et al. 1993, 2003; Cowan 2003; Figure 52).

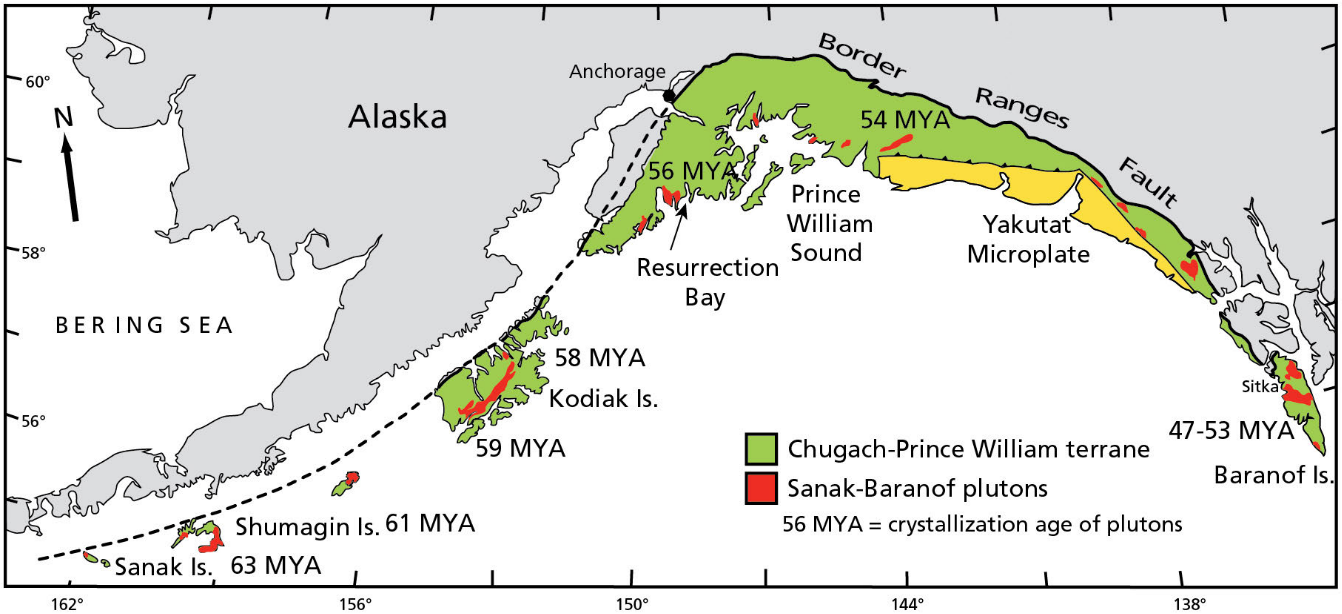


Figure 53. Map showing the location and extent of the near-trench plutons of the Sanak-Baranof belt. Modified from Davidson and Garver (2015).

Gold Deposits

Gold-bearing quartz veins occur throughout the Valdez Group and to a lesser extent in the Orca Group and McHugh Complex (Haeussler et al. 1995). In addition to gold, the quartz veins also contain silver, copper, and the sulphides pyrite, arsenopyrite, chalcopyrite, shalerite, galena, tetrahedrite, covellite, and chalcocite (Smith 1938). Radiometric ages from the gold-bearing

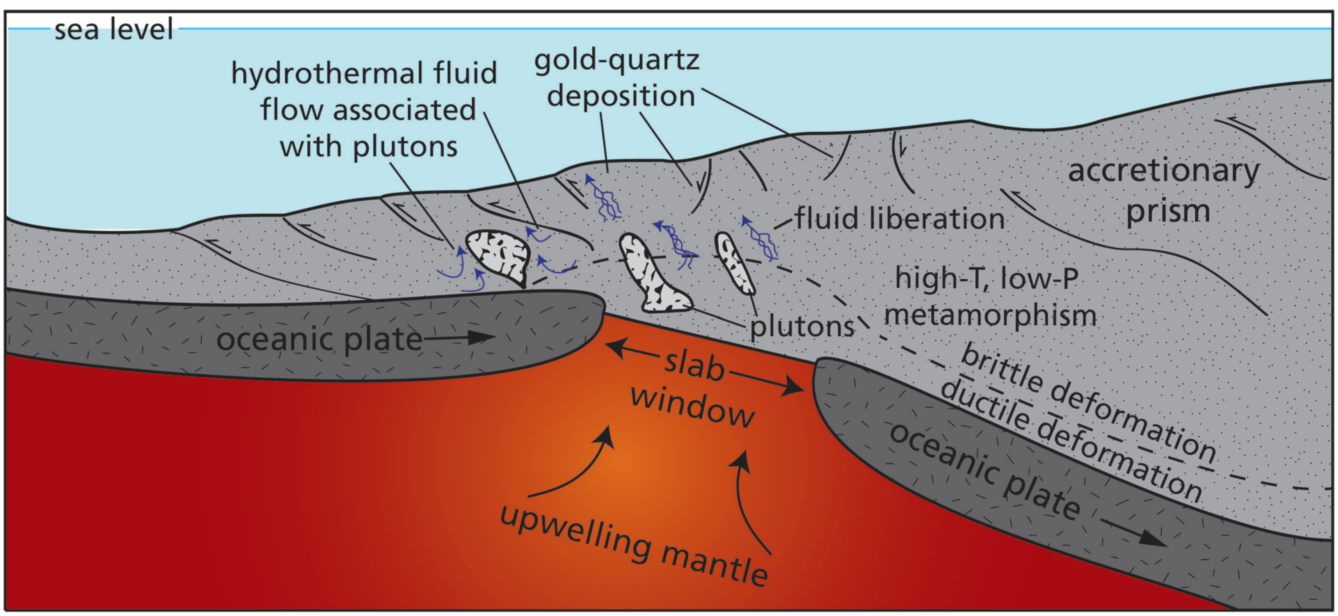


Figure 54. Diagram showing a cross-section of the hypothetical tectonic setting for gold mineralization on the Kenai Peninsula. Contact of hot, mantle material with the relatively cold accretionary prism via the slab window (former spreading ridge where mantle is pushed through oceanic crust) led to high temperature, low pressure metamorphism, partial melting of the accretionary prism sediments to form plutons and dikes, and the generation of gold-bearing hydrothermal fluids that migrated along fractures in the rock, and deposited gold-bearing quartz veins (Haeussler et al. 1995). Figure modified from Haeussler et al. (1995).

veins (including three ages obtained from mines in the park) range from 57.3 +/- 0.1 to 49.4 +/- 0.5 MYA, with a trend of older ages in the west and younger to the east (Haeussler et al. 1995). These ages are essentially identical to the cooling ages for nearby near-trench plutons (**Tgh**; Figure 53; Haeussler et al. 1995), which have been interpreted by some as evidence for spreading ridge subduction (see "Orca Group" section for more details). The subduction of a spreading ridge would have provided the heat source for the generation of gold-bearing hydrothermal fluids. These fluids flowed through fractures in the rock and deposited quartz veins rich in gold and other minerals (listed above, Figure 54).

Border Ranges Fault System

Part of the Border Ranges fault system runs through the southwestern portion of the park, between Petrof and Yalik glaciers (Plate 1; Wilson et al. 2015). This fault system has a long, complicated history of thrust and strike-slip motion, and can be traced from Baranof Island in the east (Plafker et al. 1976) to Kodiak Island in the west (MacKevett and Plafker 1974). The Border Ranges fault system is projected to continue westward beyond the Sanak Islands (Fisher and von Huene 1984), which gives a total traceable length of more than 2000 km (1243 mi; Figure 53). The Border Ranges fault system represents a Mesozoic plate boundary that separates inboard rocks of the Wrangellia Composite terrane from the more outboard rocks of the Chugach-Prince William accretionary complex (Figure 39; for more information see "Geologic and Plate Tectonic History"). Subsequent reactivation of the Border Ranges fault resulted in dextral strike-slip motion, but the magnitude of slip along this boundary remains unresolved (Pavlis and Roeske 2007). Recently, using detrital zircon ages, Garver and Davidson (2015) suggest that strike-slip motion on the Border Ranges fault could be over 2000 km (1243 mi) because some of the rocks from the Chugach-Prince William accretionary complex appear to have origins as far south as California.

On the southern Kenai Peninsula, the Border Ranges fault system is split into two segments: the North Kenai Peninsula segment and the South Kenai Peninsula segment (Wilson et al. 2015). The South Kenai Peninsula segment runs through the park and juxtaposes the Valdez Group (**Kvs**, **Kvm**) and McHugh Complex (**KMm**). The North Kenai Peninsula segment of the Border Ranges fault system runs to the west of the park and exposes the Seldovia blueschist, which is one of the oldest and most compressed portions of the Chugach-Prince William accretionary complex (Bradley et al. 1999; (Bradley et al. 2000b; Pavlis and Roeske 2007; Lopez-Carmona et al. 2011). Blueschists are indicative of subduction because they contain minerals that form under high-pressure and low-temperature conditions. Similar blueschists are exposed by the Border Ranges fault system on Kodiak Island (e.g., Raspberry schist; Roeske et al. 1989) and northeast of Anchorage, along Liberty Creek (e.g., Liberty Creek blueschist; Lopez-Carmona et al. 2011).

Paleontological Resources

Map Units: KMm, Kvs (Plate 1)

Paleontological resources, or fossils, are any evidence of life preserved in a geologic context. Fossils have been found in two of the geologic units that occur within Kenai Fjords: the McHugh Complex (**KMm**) and the Valdez Group (**Kvs**). Significantly, the fossils found in the McHugh Complex are exotic with respect to North America, including a conodont species (Wardlaw and Harris 1994 unpublished report) and a bivalve genus (Blodgett and Isozaki 2013) that have not been found elsewhere in North America.

The McHugh Complex (**KMm**) contains rare fossiliferous limestone blocks fossils just outside the park boundary. Fossils collected from these blocks include Permian fusulinids (single-celled organisms that produce shells; Stevens et al. 1997), conodonts (microscopic tooth-like fossils), large bivalves belonging to the family Alatoconchidae (Blodgett and Isozaki 2013), and crinoids (echinoderms common to Paleozoic seas; Fiorillo et al. 2004). Many of these are species that are characteristically Tethyan, meaning they are more similar to species found in the Paleo-Tethys (an ancient ocean basin that existed on the other side of Pangea) than species found in western North America (Figure 55; Stevens et al. 1997; Blodgett and Isozaki 2013). In addition, these fossils are indicative of shallow, tropical water (Stevens et al. 1997).

The age of the fossils, Tethyan affinity, and environmental implications indicate that the limestone blocks represent the remains of Permian (298.9–251.9 MYA) seamounts (reefs accumulated around an oceanic volcano) that formed in the western portion of the

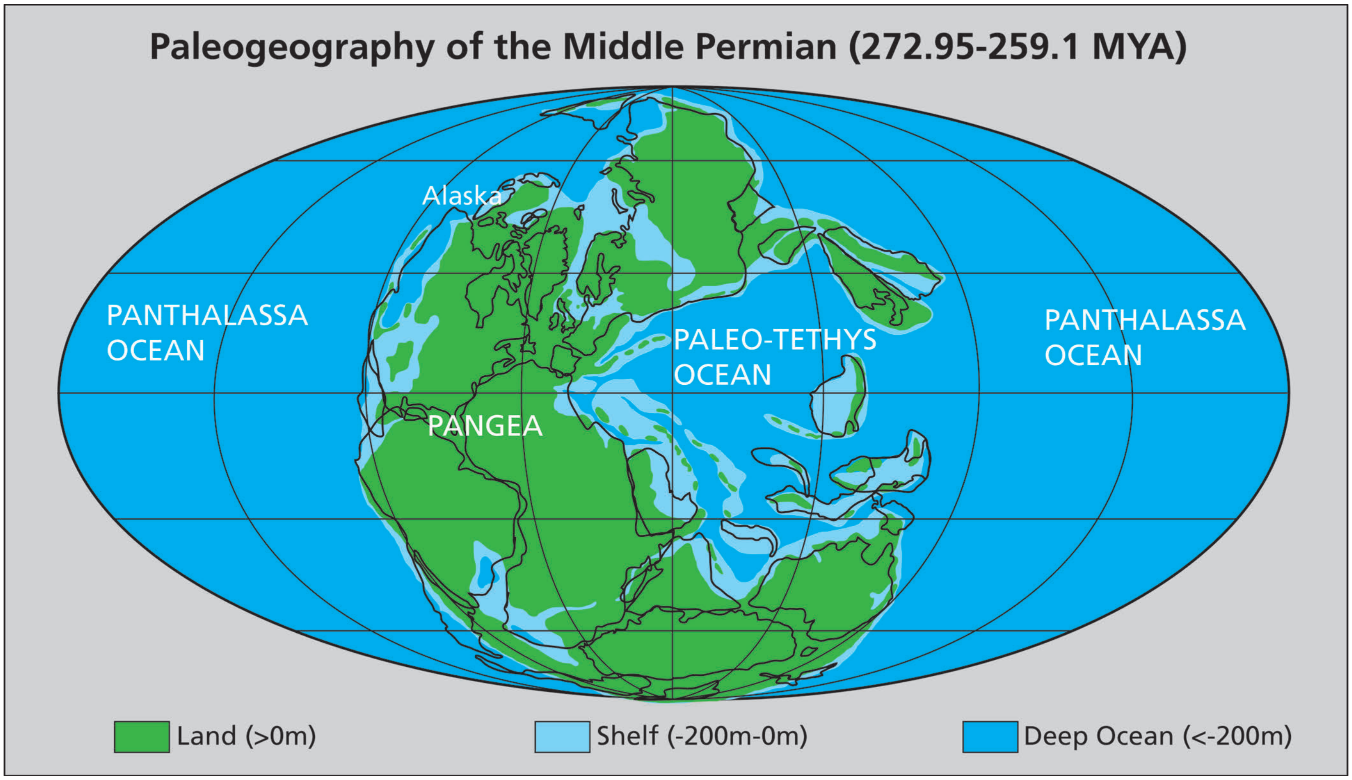


Figure 55. Map showing the paleogeography of the Middle Permian (272.95-259.1 MYA). The fossils from the McHugh Complex limestone are more similar to deposits that formed in and around the Paleo-Tethys Ocean (seen in the center of the figure). This suggests that the rocks those fossils are found in were formed near the Paleo-Tethys Ocean, and subsequently transported across the Panthalassa Ocean to Alaska by the movement of the oceanic plate. Map by Amanda Lanik (NPS Alaska Regional Office) using information from Hein (2004).

Panthalassa (proto-Pacific) Ocean (Figure 43; Stevens et al. 1997). The seamounts were transported thousands of miles by plate tectonics before being incorporated into the McHugh Complex. For more information about the formation of the McHugh Complex, see the "McHugh Complex" section of this report.

During the summer of 2016, a NPS field expedition collected similar McHugh Complex limestone from within Kenai Fjords. These limestone cobbles contained the first Paleozoic fossils documented from within the park, including alatoconchidid bivalves, crinoids, ostracods, uniserial foraminifera, and fusulinids (Figure 56). While the limestone cobbles were not found in-situ, it is very likely that the source outcrop is within park boundaries. Future field investigations will aim at finding the location of the source outcrop and possibly sampling it for fossils.

The McHugh Complex also contains fossiliferous chert (microcrystalline sedimentary rock composed of silica) and conglomerate clasts. Although the chert inside the park has not yet been studied, outside the park, chert collected from various portions of the McHugh Complex contains radiolarians (microscopic organisms with a skeleton made of silica; Nelson et al. 1986; Karl et al. 1979; Bradley and Miller 2006). These radiolarians have been used to date the McHugh Complex and understand its formation (see Kenworthy and Santucci [2003] for an overview). In addition, limestone clasts from conglomerate collected at the McHugh Complex type section (along the Seward Highway, south of Anchorage) contain Mississippian–Pennsylvanian (358.9–298.9 MYA) conodonts (Nelson et al. 1986).

Outside of the park, the Valdez Group contains the marine bivalve *Inoceramus* (Tysdal and Plafker 1978). Despite the Valdez Group being wide-spread in Kenai Fjords, no fossils from this unit have yet been reported from within park boundaries. This could be a result of the low abundance and scattered nature of bivalve fossils in the Valdez Group (Bradley et al. 1999).

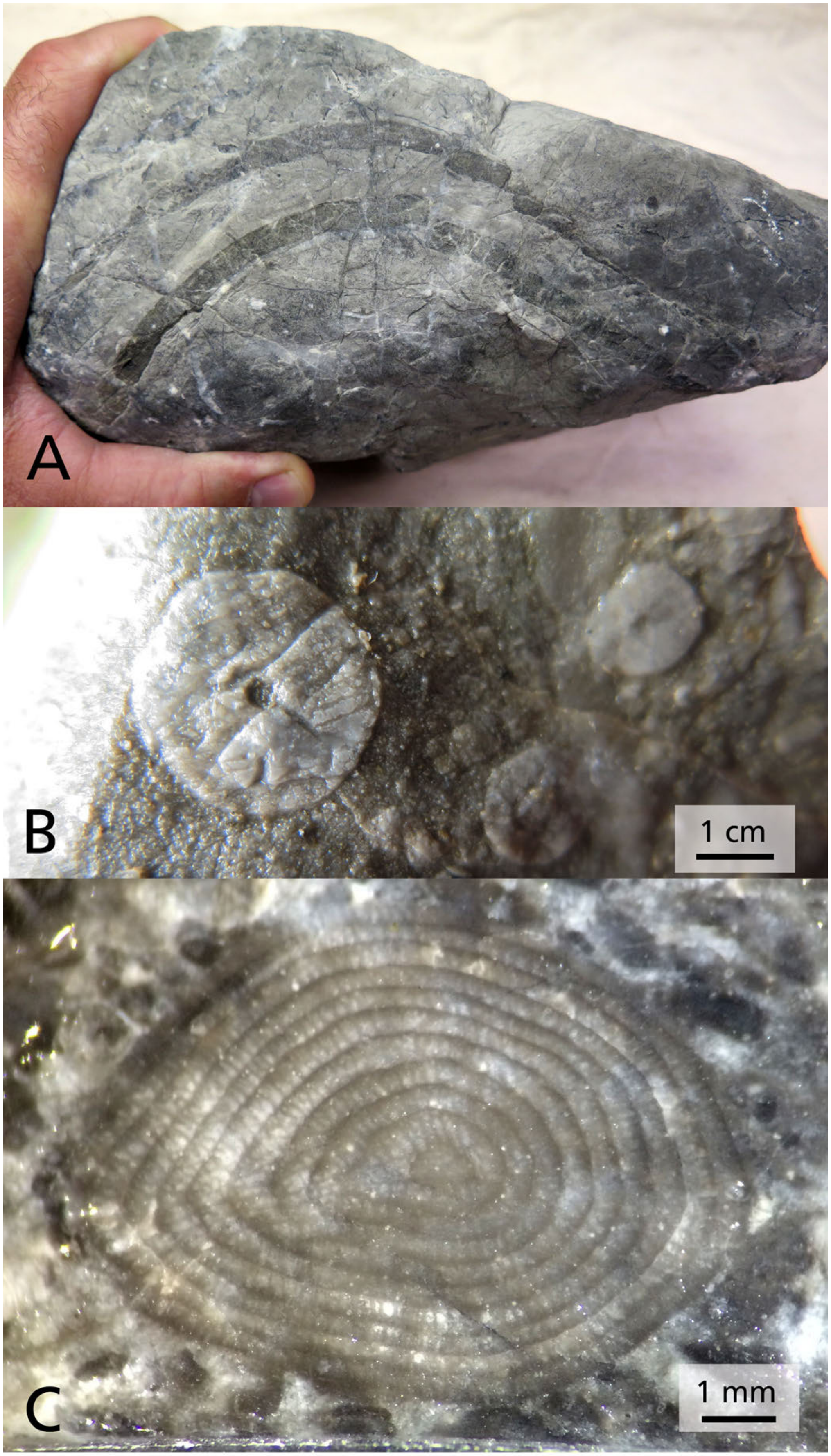


Figure 56. Photos of Permian invertebrate fossils collected from limestone cobbles of the McHugh (KMm) Complex. The fossils were collected during the summer of 2016 and are the first Paleozoic fossils confirmed from within park boundaries. A: Cross-section view of a large Permian bivalve belonging to the family Alatoconchidae. The McHugh Complex contains the only occurrence of alatoconchid bivalves in North America, with other reports of these fossils being primarily from Asia and the Middle East (Blodgett and Isozaki 2013);
B: Cross-section view of a portion of a crinoid stem;
C: Cross-section view of a fusulind (large, single-celled organism that created a chambered shell composed of calcite).
NPS photographs by Chad Hults.

Geologic and Plate Tectonic History

The following is a brief chronology of the events leading to the present landscape of the park. The Geologic Features and Processes chapter provides additional details for the geologic map units mentioned here.

Permian

298.9–251.9 MYA

Blocks of limestone in the McHugh Complex (**KMm**) represent the remains of seamounts that supported tropical, shallow-water marine ecosystems (Stevens et al. 1997). The geographic affinity of many of the fossils from the limestone indicate that these seamounts were located proximal to the Paleo-Tethys Ocean, likely in the western part of the Panthalassa (proto-Pacific) Ocean (Figure 55; Stevens et al. 1997; Fiorillo et al. 2004; Blodgett and Isozaki 2013).

Jurassic to Early Cretaceous

201.3–100.5 MYA

The oldest portion of the McHugh Complex (**KMm**) began to form as oceanic crust subducted underneath an island arc (Wrangellia composite terrane). Blocks from the subducting plate, including mafic igneous rocks (**KTRmc**, **MZg**), chert (**KTRmc**), and limestone, and blocks from the upper plate became chaotically mixed together and metamorphosed as they were moved down into the subduction trench.

Middle Cretaceous

Approximately 125–85 MYA
(informal time interval, useful in Alaska)

McHugh Complex (**KMm**) continued to form along the edge of Wrangellia. Collision of the Wrangellia composite terrane with North America increased sedimentation from the upper plate, which caused increased deposition of the greywacke and conglomerate portions of the McHugh Complex (**KJms**).

Late Cretaceous

100.5–66.0 MYA

As sediment continued to be shed from the upper plate, turbidites of the Valdez Group (**Kvgs**, **Kvm**, **Kvt**, **Kvvs**, **Kvs**) were deposited outboard and probably to the south of the older McHugh Complex.

Paleocene–Eocene

66.0–33.9 MYA

Subduction continued beneath the western margin of North America, and a mid-ocean ridge approached the subduction zone. Because of the proximity of the mid-ocean ridge to the subduction zone, rocks that typically form at mid-ocean ridges (e.g., pillow basalts of the Resurrection ophiolite [**Top**]) became interbedded with turbidites shed from North America. As the ridge subducted, oceanic rocks of the Resurrection ophiolite (**Top**, **Tod**, **Togb**) were accreted to North America while the rest of the oceanic crust was lost to the mantle. The subduction of a mid-ocean ridge, an area where hot mantle rises toward the surface of the earth, caused partial melting of the overlying sediments, and the formation of near-trench granitic plutons (**Tgh**) and associated gold-bearing quartz veins.

Quaternary (Pleistocene–Holocene)

2.58 MYA–present

Five major Pleistocene glaciations are recorded by glacial deposits on the Kenai Peninsula (Karlstrom 1964). Although these deposits are not preserved within the park boundaries, glacial deposits that correspond to the Naptowne (**Qgn**), Caribou Hills (**Qch**), and older glaciations (**Qogo**) occur to the north of the park (Plate 1). Excepting minor advances, glaciers have been in retreat since the end of the Pleistocene (**Qao**, **Qm**, **Qat**, **Qs**). The most recent glacial advance occurred during the Little Ice Age (1540s–1710s and 1810s–1880s). During this time many of the park's glaciers reached their most recent maximum extent, which is recorded by terminal moraines and other glacially-derived sediments. Active glacial, fluvial, and coastal processes are responsible for the modern deposition of beaches and other surficial deposits (**Qb**, **Qs**).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management to address visitor safety needs, and preservation of natural and cultural resources in Kenai Fjords National Park.

Two meetings were held to discuss the GRI products, geology of the park, and resource management issues. These meetings were held with NPS natural resources managers, NPS southwest network staff, NPS Alaska Region specialists, and geologists with experience in the park. A scoping meeting was held in 2005 (Graham 2005); a report kick-off meeting was held on November 20, 2015. Attendees of the scoping meeting and the report kick-off meeting are listed in Appendix A:

At these meetings, participants identified the following geologic resource management issue priorities:

- Glacier change and climate change
- Outburst floods
- Flood hazards (specifically with respect to Exit Creek)
- Coastal issues
- Geohazards
- Archeological/Geological connections
- Abandoned Mineral Lands issues

Geologic Resource Management

In addition to this document, the park's Foundation Statement (NPS 2013), Natural Resource Condition Assessment (Stark et al. 2015), and State of the Park report (NPS 2017) are all primary sources that provide more information concerning resource management within the park.

Resource managers may find the book *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs, which are measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

Geoscience-focused internship programs exist that may help parks carry out geologic resource-related projects. The Geoscientists-in-the-Parks and Mosaics in Science programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Past projects at Kenai Fjords have included (as of May 2017):

- Geology Interpretation and Education (2012)
- Climate Change Interpretation and Education (2012)
- Glacier Monitoring (2013)
- Paleontology Inventory (2016)
- Geology Interpretation and Education (2016)

Projects are listed on the GIP website: http://go.nps.gov/gip_products. Products created by the program participants may be available on that website or by contacting the Geologic Resources Division (http://go.nps.gov/grd). Refer to the programs' websites at http://go.nps.gov/gip and http://go.nps.gov/mosaics for more information.

Glacier Monitoring

Protecting the features and natural processes of the Harding Icefield and its outflowing glaciers is a main part of Kenai Fjords' mission (Alaska National Interest Lands Conservation Act 1980; NPS 1984; NPS 2013). Educating the public about these same features and processes is also at the core of the park mission. Unprecedented human-caused climate change is causing park glaciers to retreat, and diminishing the potential for visitor experience. Monitoring Kenai Fjord's glaciers allows park staff to better predict and respond to future glacier loss. This is important not only because glaciers themselves are a core resource for the park, but because glaciers have a profound impact on local ecosystems and communities.

The Gulf of Alaska, including the fjords of Kenai Fjords, represents one of the most productive marine ecosystems on Earth. This abundant ecosystem and scenic glacial landscape imparts benefits to the surrounding communities in terms of water, food, recreation, and economic opportunities. Glaciers

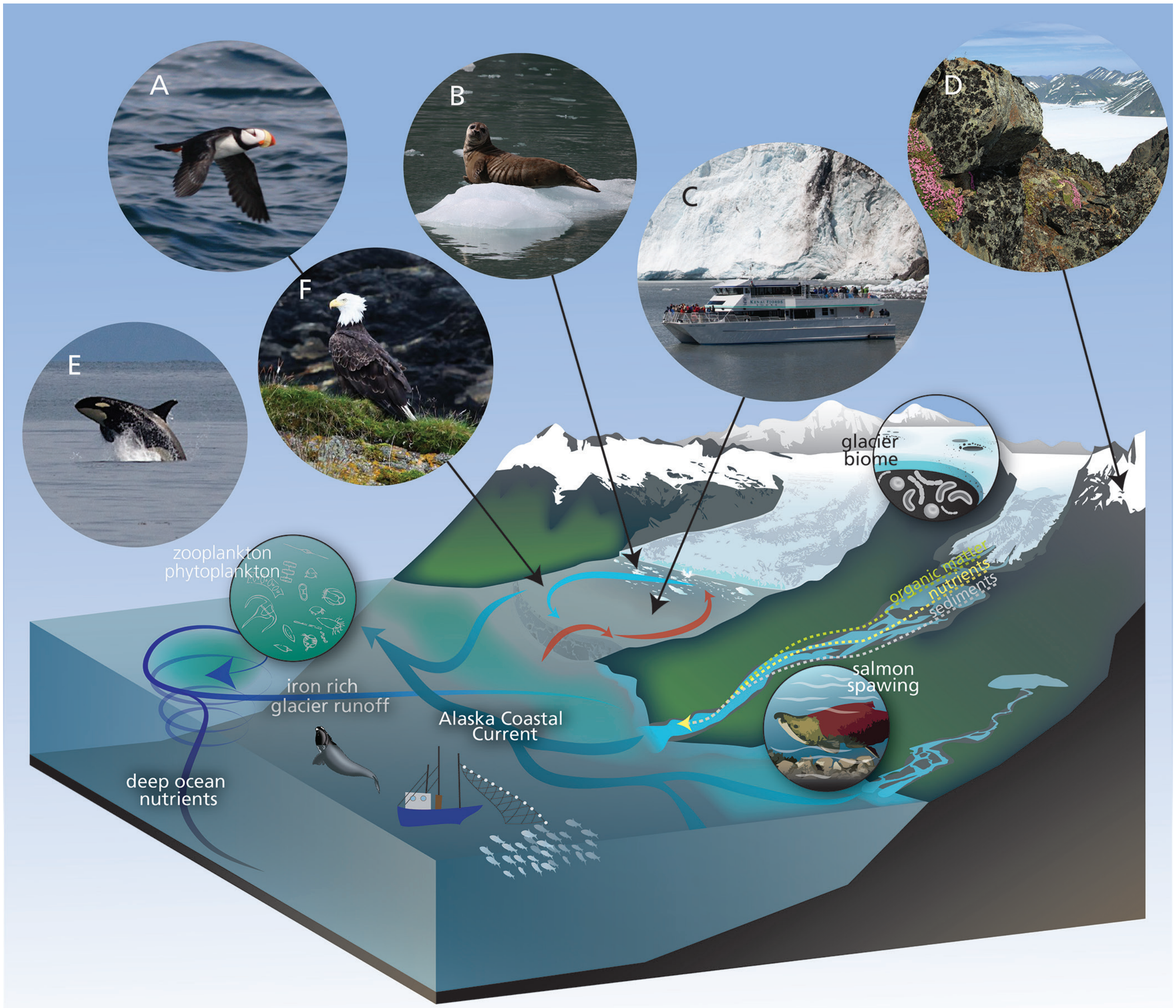


Figure 57. Diagram showing the connections among glaciers, fjord ecology, and the economic opportunities for local communities. The fjords contain a variety of organisms including fish, birds (A: Horned puffin; F: Bald eagle), and marine mammals (B: Harbor seal; E: Orca). Harbor seals raise their pups in the protected ice-clogged waters at the terminus of tidewater glaciers. Nunataks (rocky outcrops found within glaciers) support plant communities, including several endangered species of vascular plants (D: lichen and plant covered nunatak near the head of Skilak Glacier). The abundant organisms and stunning scenery of the fjords and glaciers draw visitors to the park (C: Kenai Fjords tour boat visiting Holgate Glacier). Diagram adapted from original design by K. Timm, Alaska Climate Science Center.

constitute a first-order control on the physical and biological landscape of the region, generating cascading impacts on downstream riverine and nearshore marine ecosystems (Figure 57). Water in the region is partly sourced from glacier melt. Glaciers regulate the timing and amount of water available throughout the year. Glacier meltwater inputs sediments, nutrients, and organic matter into surrounding ecosystems, and buoyant freshwater added directly into fjords via tidewater glacier melt causes water stratification and affects circulation. O'Neel et al. (2015) provided an overview of the links between glaciers and the northern Pacific ecosystem. Glaciers themselves host a variety of microorganisms that survive under extreme environmental conditions on, within, and under the ice (called the "glacier biome"). The reduction and loss of glaciers will alter the dynamics that currently exist between glaciers and the surrounding ecosystems, impacting these ecosystems and local communities.

The melting of Kenai Fjord's glaciers contributes to eustatic (global) sea level rise. Glaciers in Alaska, including those found in Kenai Fjords, have been among the most prolific sources of meltwater entering the oceans since the 1950s (Arendt et al. 2002; Gardner et al. 2013). Although eustatic sea level rise is not expected to outpace local, tectonically-driven uplift in Kenai Fjords (at least not until the next coseismic subsidence event), rising sea level constitutes a major threat to low-lying coastal areas in many other NPS units. Understanding glacier mass loss will aid scientists in predicting how much more meltwater the glaciers of Kenai Fjords will contribute to eustatic sea level rise under future climate regimes.

Glacier retreat and associated changes pose threats to many of the park's key resources, but it also presents the opportunity for outreach and education regarding the effects of climate change. For example, the rapid retreat of Exit Glacier has greatly reduced accessibility to the glacier, and makes maintenance of trails and facilities in the area a costly and constant challenge. However, the retreat also provides an important opportunity to educate the public about the impacts of dynamic landscapes, climate change, and natural hazards, and how we can interact with such environments to contribute towards solving the challenges presented by climate change.

There are many past and ongoing projects in Kenai Fjords that aim to better understand glacier dynamics and monitor glacier change (see Table 2). Glacial extent is identified as a vital sign for Kenai Fjords and is monitored by the Southwest Alaska Network Inventory

Table 2. Glacier management and monitoring activities in Kenai Fjords National Park.

Activity	Description	Study Area	Time frame	Reference
Mass balance	Measurements of the amount of snow and ice gained versus lost in a year determine if the glacier is growing or shrinking. For more information see the "Harding Icefield Mass Balance" section of this report.	Exit Glacier and "Glacier A"	1987–present	Kurtz (in draft)
Repeat Photography	Photographs repeatedly taken of a glacier from the same location visually show changes in glacier volume and extent. For more information see the "Terminus Positions" section of this report.	Many park glaciers	Early 1900s–present	Kurtz (in draft)
Terminus mapping	Annual mapping of terminus position using a Global Positioning System unit documents terminus fluctuations on a yearly basis. For more information see the "Terminus Positions" section of this report.	Exit Glacier	2010–present	Kurtz and Baker (2016)
Surface elevation change	Calculating the change in a glacier's elevation between historic mapping and more recent imagery quantifies how much mass the glacier has gained or lost in that time period. For more information see the "Glacier Extent" section of this report.	All park glaciers	1950–2005	Loso et al. (2014)
Timelapse Photography	Photographs taken of a glacier's terminus at a specified interval throughout the melt-season visually show how, when, and how much ice is lost. For more information see the "Terminus Positions" section of this report.	Exit Glacier	2010–present	See Paul Burger, Alaska Regional Office
Thickness measurements	Using ice-penetrating radar to measure the ice thickness provides insight into future melt and glacier geometry. For more information see the "Glacier Extent" section of this report.	Harding Icefield and outflowing glaciers	2010, 2012	Truffer (2014)
Aerial extent mapping	The Southwest Alaska Network Inventory and Monitoring division uses Landsat imagery to map decadal changes in glacier extent.	All park glaciers	1973, 1986, 2000	Giffen et al. (2014)
Glacier flow rates	Flow rates are measured by depositing a radio transmitter in a crevasse during the summer and recording how the location of this transmitter changes with time. Glacier surface velocities were derived using SAR (Synthetic-aperture radar) image pairs acquired between 2007 and 2010.	Exit Glacier All park glaciers	1995–2007 2007–2010	Klasner (2008) Burgess et al. (2013)

and Monitoring program (Bennett et al. 2006). For more information, visit the Inventory and Monitoring website at https://science.nature.nps.gov/im/units/swan/monitor/landscape.cfm.

Current trends of glacier reduction and retreat in Kenai Fjords are projected to continue into the future (for more information on the current glacier trends, see "Past Glaciations and Modern Glacier Change"). Loso et al. (2014) recently used data from the Scenarios Network for Alaska and Arctic Planning to model future climate for Alaska's parks. In every global climate model and emission scenario examined, Loso et al. (2014) found that the trend of warmer summers and wetter winters that prevailed in Alaska over the last 50 years will continue and accelerate in the next 50 years. Similarly, recent glacier trends of negative mass balance, diminished ice cover, and reduced ice volume are predicted to intensify as climate changes (Loso et al. 2014).

Exit Creek Flooding

Located in the northeastern portion of the park, Exit Glacier is one of the park's biggest attractions, offering activities such as ranger-led walks and talks, opportunities to view wildlife, and an up-close view of an active glacier. This area is highly visited, accounting for about half of the park's annual visitation (Stark et al. 2015). Access to the Exit Glacier area is provided by the Herman Leirer Road, an 13.5 km- (8.4 mile-) long paved road that parallels the northern bank of the Resurrection River for the majority of its length, but for the last 2.4 km (1.5 miles) crosses over the Resurrection River and runs west towards Exit Glacier (Figure 58). In addition to the part of the road in the park, the park maintains infrastructure in the area, including a network of hiking trails, a nature center, and a 12-site campground (Figure 58). The Exit Glacier area has a history of flooding that has affected the Herman Leirer Road and the trail system around the nature center.

An unnamed drainage system emanating from the slopes north of Exit Glacier was identified as the main flooding threat to the Nature Center and surrounding trails during the Nature Center's construction (Martin 2006). In response, a small dike was installed to divert flow of the unnamed drainage away from the Nature Center (Martin 2006). Stark et al. (2015) observed

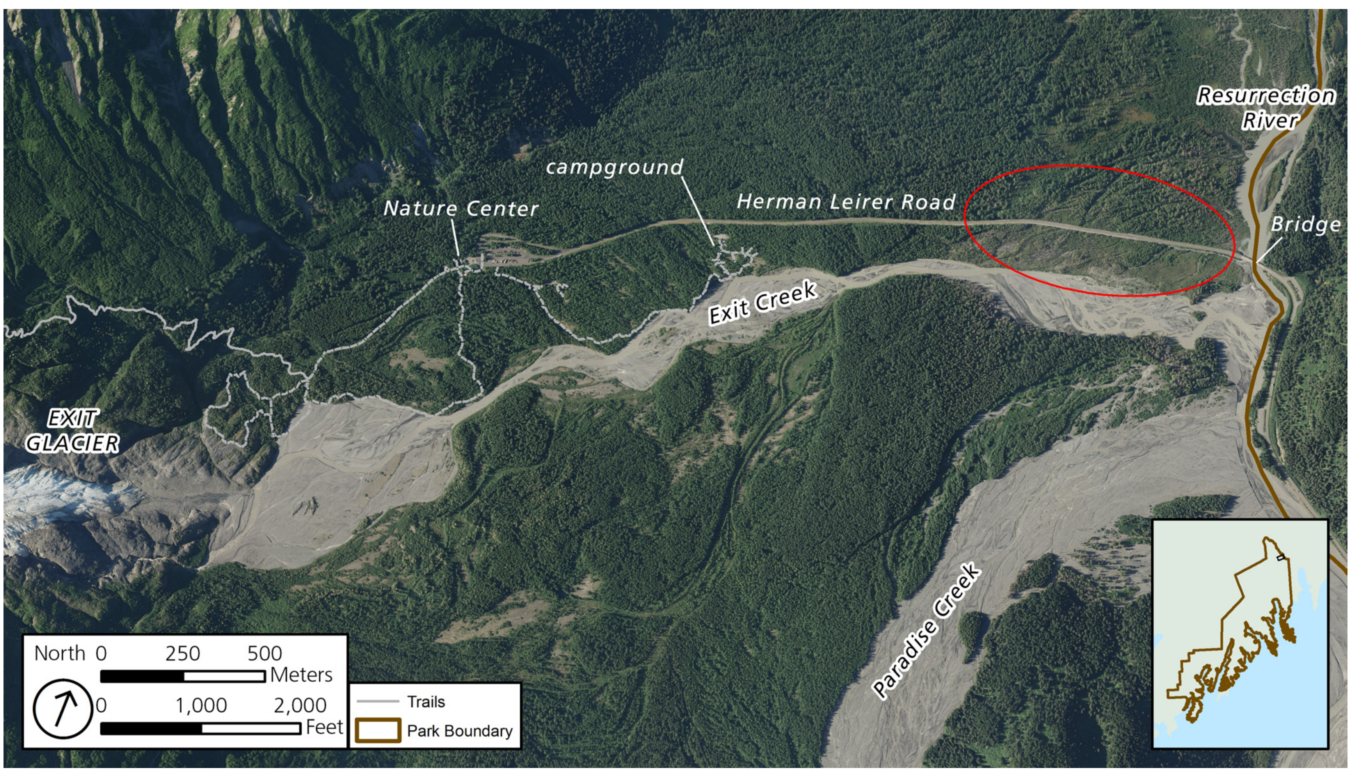


Figure 58. Map of the Exit Glacier area with Exit Creek and the surrounding infrastructure labeled. Circled in red is approximately the portion of the Herman Leirer Road that has experienced repeated inundation from Exit Creek floodwaters. This area corresponds to the location of active channels in 1950 (see "Exit Creek Geomorphology" for more information). Aerial photo date: 2015.

that the installation of the dike may have rerouted the unnamed drainage, causing it to flow into Exit Creek further upstream. Consequently, flooding from the unnamed drainage has been minimized, and more recent damage to the trail systems has stemmed from flooding of Exit Creek (Figure 59; Stark et al. 2015).

Prior to 2009, flooding of the Herman Leirer road only occurred on a few isolated occasions. However, the frequency of road flooding increased substantially between 2009 and 2014, during which time flooding occurred one to three times per year (Curran et al. 2017). Negative results of the flooding are damage to the road and road closure if water levels on the road exceed 15 cm (6 in) (NPS 2015). The Herman Leirer road is a dead end that provides the only automobile access to the park. Closure of the road interrupts visitor access to one of the park's most frequented destinations and poses the threat of stranding visitors and staff in the Exit Glacier area until the road can be reopened.

The portion of the road that is typically affected by floodwater (circled in red on Figure 58) is located just upstream of the Resurrection River Bridge. As recently as 1950, active channels of Exit Creek alluvial fan extended into the area where the road now experiences regular flooding (see "Exit Creek Geomorphology" for more information). A construction project to raise the problem portion of the road 1.5 m (5 ft) and install four box culverts to allow conveyance of floodwaters to the north side of the road was completed in 2016 (NPS 2015). This project aims to reduce the damage caused by flooding and the frequency of road closures by situating the box culverts in areas where flood channels already intersect the road (NPS 2015).

Figure 59. Photographs of flooding in the Exit Glacier area. A and B show flooding of the Herman Leirer road in 2008 and 2011 respectively. C and D show flooding along the trails in the Exit Glacier area, with C showing water running along a trail after a 2012 flood and D showing the deposition of ice on a footbridge after a 2006 flood. NPS photographs.

The Resurrection River Bridge has not incurred any damage from high waters of the Resurrection River thus far, but aggregation (building up of sediment) beneath the bridge is increasing (Stark et al. 2015). Aggregation has decreased the clearance of high water under the bridge since its construction and if this trend continues, it could prove to be an issue in the future (Stark et al. 2015).

Coastal Issues

Kenai Fjords contains 877 km (545 mi) of shoreline (Figure 1; Curdts 2011), and protection of the coastal fjords and islands is a core part of the park's enabling legislation (Alaska National Interest Lands Conservation Act 1980). The coast of Kenai Fjords is dynamic; geological processes, such as glacial advance and retreat, erosion, deposition, tsunamis, and landslides, have shaped and continue to shape the coast. Beach deposits (**Qb**) occur in the park, and abundant coastal geologic features such as sea caves, arches, and stacks are found all along the coastline (see the "Coastal Features" section for more information).

Sea caves, arches, and stacks are rocky erosional features that provide important habitat for many of the park's birds and marine organisms. These features are popular destinations for boaters and kayakers, but rockfall within and near sea caves or arches pose a potential visitor safety concern. Sea caves are protected under the Federal Cave Resources Protection Act of 1988, which requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request (also see Appendix B). The Geologic Monitoring chapter about caves provides more information about inventorying and monitoring cave-related vital signs (Toomey 2009) and the "Coastal Features" section of this report summarizes the findings from a recent inventory of coastal features in Kenai Fjords (Markus and Kurtz 2015).

Climate change is predicted to increase storm strength and cause storms to travel further north in the Northern hemisphere, so an increase in erosion from storms can be expected in the future. Geomorphic coastal change is identified as a vital sign for Kenai Fjords and is monitored by the NPS Southwest Alaska Network Inventory and Monitoring program (Bennett et al. 2006). Refer to the marine nearshore monitoring website for additional information (https://science.nature.nps.gov/im/units/swan/monitor/nearshore.cfm, accessed 30 March 2017).

Climate change is also expected to increase ocean acidification, which is monitored in nearby Resurrection Bay by the University of Alaska Fairbank's Ocean Acidification Research Center (Janzen 2016) and the Aluutiq Pride Shellfish Hatchery (Evans et al. 2015). Ocean acidification will affect the production of zooplankton, the development of shellfish, and reduce the overall food supply for the fjord ecosystems (Jones 2014). To monitor ocean acidification, NPS researchers are collecting baseline oceanographic data in Aialik Bay in 2017, including continuous sampling at two sites, monthly point data collected along a glacier-marine gradient, and mapping of the bathymetry and ocean currents. The continuous sampling sites are located at the head of Aialik bay (more glacially influenced) and at the mouth of Aialik bay (more marine influenced). Measurements at these sites include conductivity (as a proxy for salinity), temperature, pH, dissolved oxygen, turbidity, and total chlorophyll.

Kenai Fjords is one of the 118 parks servicewide that have been identified as potentially vulnerable to sea level change. Relative sea level changes in response to a number of factors: regional tectonic strain, isostatic rebound, earthquakes, and eustatic (global) sea level fluctuations. Current trends show that relative sea level is decreasing in the park, with tide gauge records from Seward showing a decrease of about 2.53 mm (0.10 in) per year since 1964 (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html, accessed 20 September 2017) . On a longer timescale, submergence since the last ice age is evident from the "drowned" coastline geomorphology in the region (Plafker 1969). Global, climate-driven sea level rise combined with current regional coastline uplift rates from Seward predicts that sea level in Kenai Fjords will change by -10 cm to +28 cm (-0.33 ft to +0.92 ft) by 2050 and by -19 cm to +113 cm (-0.62 ft to +3.71 ft) by 2100 (http://www.corpsclimate.us/ccaceslcurves.cfm, accessed 29 March 2017). Note, the Kenai Fjords coast is projected to rise on the higher end of both scenarios, because both scenarios have high ranges of global sea level rise that outpace current coastal uplift. However, a major earthquake could result in unpredicted, rapid subsidence of the coast similar to that seen during the 1964 Great Alaska Earthquake.

Although the current trend in the park is that of modest coastal uplift, the potential for large-scale, earthquake-driven subsidence poses a greater threat to park infrastructure and resources. During the 1964 Great Alaska Earthquake, Kenai Fjords subsided 1–2.5 m (3–8 ft; Figure 33; Plafker 1969). This subsidence caused rapid changes in shoreline processes and beach morphology that is comparable to fluctuations seen over hundreds of years of sea level change (Stanley 1968). A similar amount of subsidence today could increase the rate of tidewater glacier retreat, dramatically alter coastline dynamics and processes, and endanger park-maintained cabins and campsites along the coast.

The NPS Coastal Adaptation Handbook (Beavers et al. 2016) provides climate change adaptation guidance to coastal park managers in the 118 parks, including Kenai Fjords, which are potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts. Case studies of the many ways that park managers are implementing adaptation strategies for threatened resources, including Alaska parks, are available in Schupp et al. (2015). An additional reference manual that guide coastal resource management is NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction, which can provide insight for managers in parks with boundaries that may shift with changing shorelines (available at https://home.nps.gov/applications/npspolicy/DOrders.cfm). In the *Geological Monitoring* chapter on coastal resources, Bush and Young (2009) listed the following vital signs for inventorying and monitoring coasts: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. The NPS Water Resources Division, Ocean and Coastal Resources Branch website (https://www.nps.gov/orgs/1439/ocrb.htm) has additional information about servicewide programs and resources.

Geohazards

This section describes the potential geologic hazards ("geohazards") in the Kenai Fjords area. The area overlies the tectonically active Aleutian megathrust fault, and movement on this thrust causes large earthquakes. Steep slopes throughout the park are susceptible to landslides, rockfall, and avalanches. Coastal areas are vulnerable to tsunamis originating from earthquakes and submarine landslides. Glacier hazards are also present in the form of calving ice and glacier lake outburst floods.

There is a potential for geohazards such as earthquakes, landslides, tsunamis, and glacier outburst floods to occur in or around the park. As such, a vulnerability assessment could be conducted for these various hazards to identify areas that would be affected and determine the possible impacts to park resources, infrastructure, or visitor safety. This would be a first step towards developing an informed mitigation and response strategy for geohazards in the park.

Earthquakes

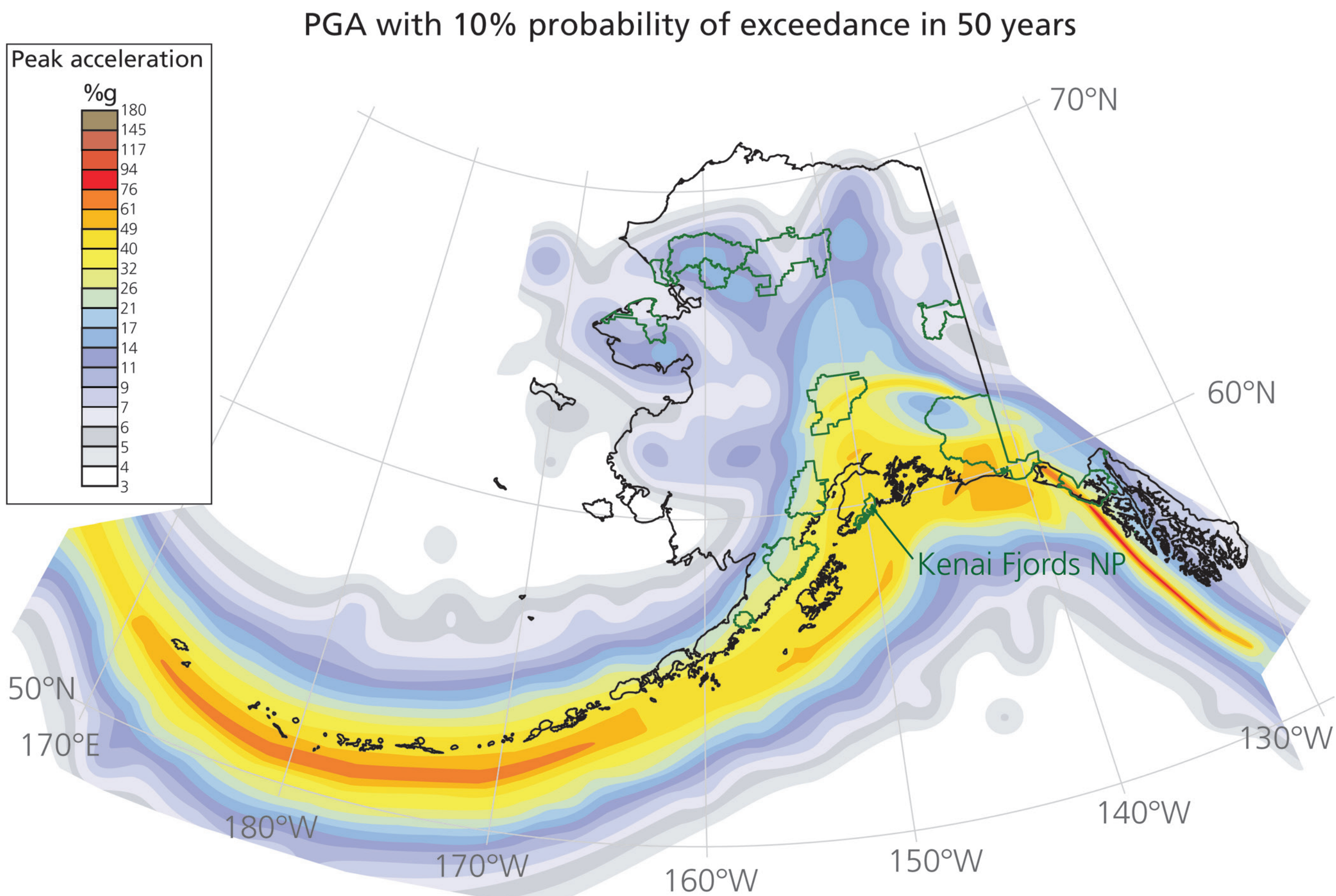
Earthquakes are common in the Kenai Fjords area because it lies over the Aleutian megathrust. Subduction megathrusts generate the largest earthquakes of any type of plate boundary, thus very large earthquakes can occur in the Kenai Fjords area. The 1964 Great Alaska Earthquake was a subduction earthquake and registered a magnitude 9.2, the most powerful earthquake recorded in North American history. In nearby Seward, where Kenai Fjords' headquarters and visitor center are now located, the earthquake caused thirteen deaths, five injuries, approximately 22 million dollars in property damage (Lemke 1967). The 1964 Great Alaska Earthquake caused widespread subsidence on the southern Kenai Peninsula (Figure 33), affecting coastline and glacier dynamics (Stanley 1968; Post 1967). For more information see the "Earthquake Features and Active Margin Tectonics" section of this report. A USGS video about the 1964 Great Alaska Earthquake and the geology behind it is available at https://www.youtube.com/watch?v=lE2j10xyOgI (accessed 3 April 2017).

The direct effects of an earthquake can cause great damage to infrastructure; the shaking may make it difficult to stand. But it is the indirect effects of an earthquake, such as landslides and tsunamis, that pose a higher risk (see those sections below). Earthquakes also have the potential to alter glacier dynamics in the park. Post (1967) cited evidence that the subsidence from the

1964 Great Alaska Earthquake caused increased erosion of the terminus of tidewater glaciers. The Serpentine and Harriman Glaciers, northeast of the park, in Prince William Sound, had larger embayments in the terminal ice cliffs that appeared to be a result of the lowering of the glaciers, which exposed them to stronger waves in the deeper water. Although not documented in Kenai Fjords, the tidewater glaciers probably had similar effects and would be expected for future earthquakes that cause significant subsidence.

Smaller, local earthquakes also have the potential to cause impacts to park resources. A magnitude 6.3 earthquake occurred approximately 193 km (120 mi) west of Bear Glacier on 28 July 2015 (NPS 2017). This earthquake caused landslides along the coast and triggered a significant calving event at the terminus of Bear Glacier.

The Alaska Earthquake Center maintains seismic monitoring stations in the Kenai Fjords area and actively monitors earthquake hazards in conjunction with the USGS (http://earthquake.alaska.edu/). According to the USGS 2007 seismic hazard map of Alaska (Figure 60), Kenai Fjords has a 10% probability for an earthquake to cause peak ground acceleration of between 40% and 49% the acceleration of gravity (9.8 m/s^2; 32 ft/s^2) in the next 50 years (Wesson et al. 2007). This amount



Peak acc. (%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very Light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

Figure 60. Earthquake hazard map of Alaska showing the peak ground acceleration (PGA) with 10% probability of exceedance in 50 years. This means the map is showing the greatest amount of ground acceleration (as a percentage of the acceleration of gravity) produced by an earthquake that has a probability of 10% to occur in the next 50 years. Green outlines are National Park System units. Map modified from Wesson et al. (2007). Table values from Wald et al. (1999) and were developed for Southern California earthquakes but provide a general sense of perceived shaking and damage for earthquakes elsewhere.

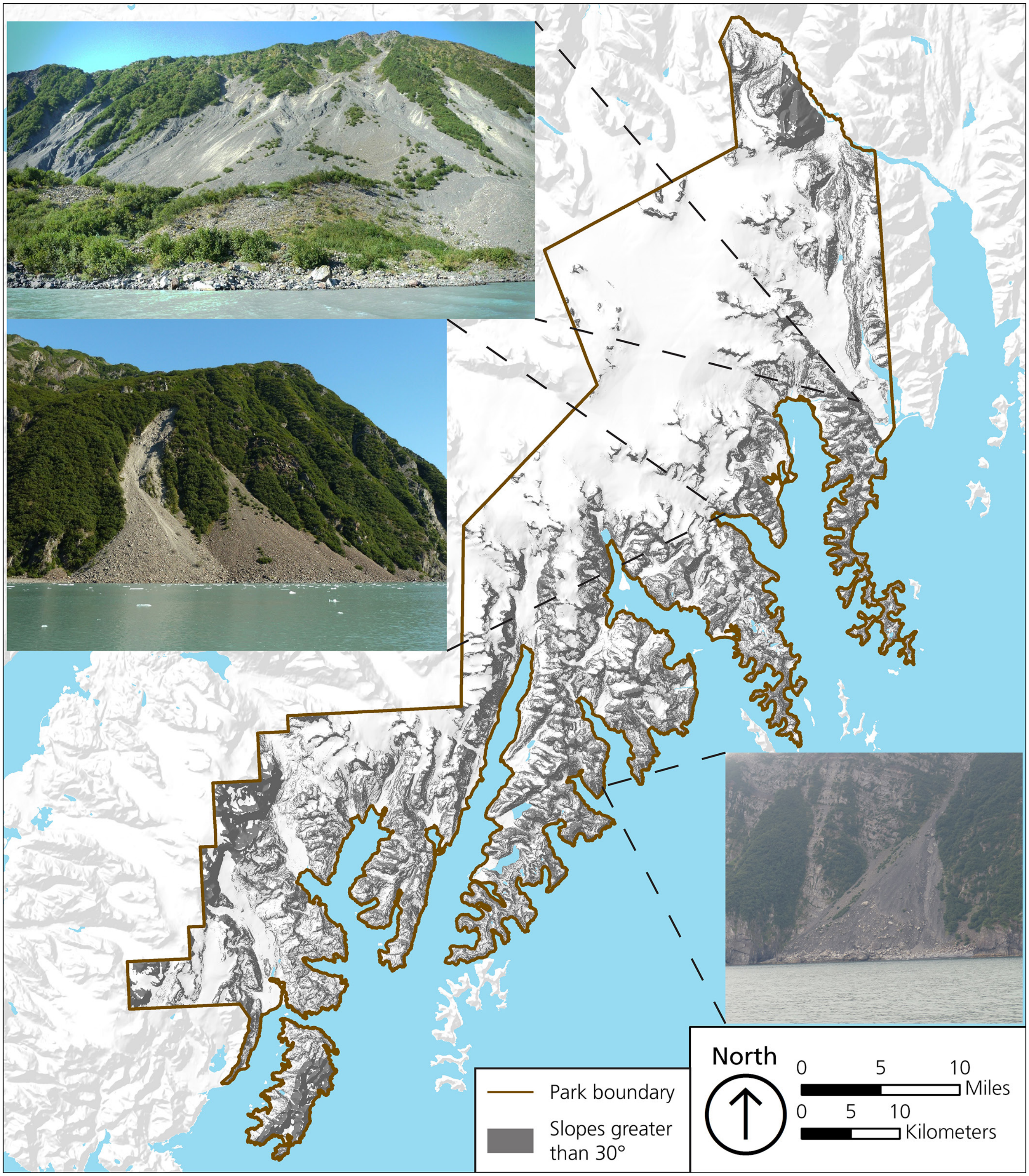


Figure 61. Map showing slopes greater than 30° that are prone to landslides, with pictures of landslides along the coast that correspond to these steep slopes (location of each photograph marked with dotted line). Park boundary outlined in brown. Slope map was derived from a digital elevation model (DEM) created from aerial imagery collected Mark Laker (US Fish and Wildlife Service) in 2016. The aerial imagery was converted to a DEM using the technique structure from motion (SfM). NPS photographs by Deborah Kurtz (top left, center left) and Chad Hults (bottom right).

of peak horizontal acceleration would be perceived as severe shaking, and could potentially cause moderate to heavy damage. Additional information is available in the *Geological Monitoring* chapter where Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (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.

Landslides and Avalanches

Kenai Fjords is characterized by steep slopes that are prone to landslides and avalanches; Wells et al. (2014) identified 38.6% of the park as vulnerable to these processes. Landslides and rockfall occur on steep slopes, particularly those greater than 30° (Figure 61). Steep, unvegetated slopes can be exposed when glaciers retreat rapidly, in a process known as glacial debuttressing (Figure 28). This process is occurring on the south side of Bear Glacier's proglacial lake, where the recent retreat of Bear Glacier has exposed steep slopes prone to mass movement (see photograph in upper left of Figure 61). Mass movement can be triggered by periods of elevated rainfall or earthquakes, and have the potential to generate dangerous tsunamis when they occur in coastal areas or underwater.

Avalanches may occur along steep slopes. The top third of the Harding Icefield Trail traverses numerous avalanche paths that continue to be active with wet slides in the late spring to early summer, when early season visitors hike the trail (NPS 2017). Warmer winter temperatures and heavier, wet snow at higher elevations could increase avalanche frequency and associated risks.

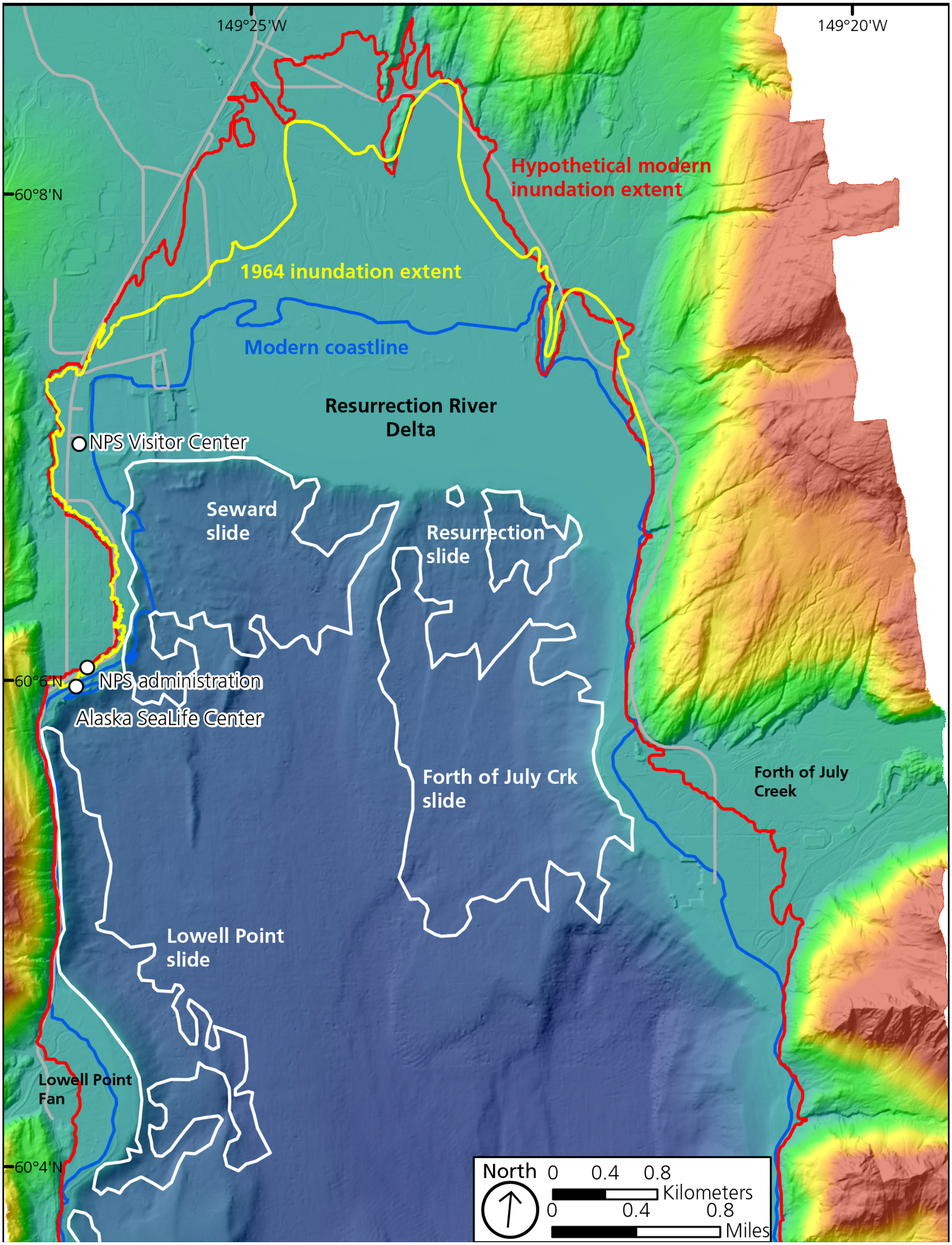
One relatively easy way to start accumulating baseline data for landslides would be to take photographs and GPS points for any landslides observed by staff while performing other duties. This opportunistic method would improve upon anecdotal evidence and the photographs would ensure documentation of the same slide multiple times would be easily recognizable. Remote sensing methods like aerial photography, satellite imagery, structure from motion (SfM), light detection and ranging (LiDAR), and interferometric synthetic aperture radar (IfSAR) could also be repeated to identify new landslides. For more information about assessing slope movements, hazards, and risks, see the *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009). Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Tsunamis

Tsunamis can be generated by earthquakes or submarine landslides (see "1964 Great Alaska Earthquake and Tsunamis" for more details). Figure 62 shows the modeled inundation extent from an earthquake similar to the 1964 Great Alaska Earthquake with similar submarine landslides (Suleimani et al. 2010). Park buildings located in Seward are at risk of tsunami inundation in the event of a major earthquake (Figure 62) and public use cabins located on the park coast may also face a similar tsunami risk. Park visitors or people working in low-lying, coastal areas of the park may also be at risk from a tsunami generated either by an earthquake itself or submarine landslide triggered by an earthquake.

No tsunami inundation modeling has been conducted for the Kenai Fjords coast. However, tsunamis can occur very shortly after an earthquake, so visitors and staff on the coast should seek higher ground immediately in the event of a large earthquake. Visitors who are Alaska residents may be cognizant of the tsunami threat associated with large earthquakes; however, many visitors to the park are unfamiliar with the earthquake and tsunami risk in southern Alaska, and will likely not be aware of this danger. The National Oceanic Atmospheric Administration Pacific Tsunami Warning Center (based in Palmer, Alaska) monitors global earthquakes and tsunami potential for the coast of North America and publishes real-time watches, warnings, and advisories on its website (http://ptwc.weather.gov/).

Figure 62 (facing page). Map showing the bathymetry and elevation of the north end of Resurrection Bay, and the extent of tsunami inundation in the Seward area from the 1964 Great Alaska Earthquake, and a hypothetical tsunami inundation extent if the 1964 Great Alaska Earthquake happened again (Suleimani et al. 2010). White lines show the extent of submarine landslides identified by Haeussler et al. (2007).


149°25'W
149°20'W
60°8'N
60°6'N
60°4'N
Hypothetical modern inundation extent
1964 inundation extent
Modern coastline
Resurrection River Delta
NPS Visitor Center
Seward slide
Resurrection slide
NPS administration
Alaska SeaLife Center
Forth of July Crk slide
Forth of July Creek
Lowell Point slide
Lowell Point Fan
North
0 0.4 0.8 Kilometers
0 0.4 0.8 Miles

Glacial Hazards

The abundant glaciers in the park are extremely dynamic and can be hazardous. Hazards associated with glaciers include down-glacier flooding caused by the rapid drainage of ice-dammed lakes (glacier lake outburst floods), and ice fall and calving (breaking off) from the terminus of a glacier.

Glacier lake outburst floods are known to occur in the park at Bear Glacier (for more information see "Glacier Lake Outburst Flooding"). These floods occurred when an ice-dammed lake, approximately 12 km (7.5 mi) up-glacier from the terminus drained into Bear Glacier's proglacial lake. The mechanism that caused the lake to drain is not understood. During an outburst flood, water levels in Bear Glacier's proglacial lake increase rapidly and can inundate visitors' camps and float away unsecured gear including camping gear, kayaks, and other water vessels. The largest outburst flood observed at Bear Glacier occurred in 2014 and resulted in a breach of the spit separating the proglacial lake from the mouth of Resurrection Bay. The outflow from the proglacial lake into marine waters resulted in a series of standing waves extending from the moraine almost two miles out to Callisto Head and sent a plume of silt water nearly eight miles out to Rugged Island (Plate 1). Water exiting the proglacial lake was rerouted through the newly breached outlet, leaving the previous outlet dry and dropping the water level 0.3–0.6 m (1–2 ft) below normal levels. The drop in water levels prompted an increase in calving activity at the terminus of Bear Glacier. The spit was rebuilt during storms the following winter; by the next summer there was little evidence that the breach ever occurred.

Past monitoring of Bear Glacier's outburst floods included the installation of pressure transducers to document water-level changes, and remote sensing techniques (Wilcox et al. 2013). Wilcox et al. (2013) observed that in recent years, the source lake drained every year or two in late summer or fall (August–October), but there is currently not enough data to determine trends in the frequency of flooding. More recent monitoring efforts included the installation a time-lapse cameras and pressure transducers in the ice-dammed lake and proglacial lake. In the summer of

Figure 63. Photograph of ice calving off the front of a tidewater glacier in Kenai Fjords National Park. Calving ice has the potential to fall on visitors, or create dangerous waves that can capsize boaters or swamp campsites. NPS photo by Jim Pfeiffenberger.

2015, these monitoring devises detected no drainage of the ice-dammed lake. In 2017, park staff redeployed a time-lapse camera at the ice-dammed lake and one at the proglacial lake, but an abundance of ice in the ice-dammed lake prevented the installation of a pressure transducer. NPS and State of Alaska investigators are considering other methods, such as structure from motion (SfM) data, to calculate changes in water volume and glacier surface elevation that occur when the ice-dammed lake releases.

Ice calving, or breaking off the front of a glacier, is a common occurrence in the park and the primary mechanism of mass loss for tidewater glaciers (Figure 63; Molnia 2008). Calving ice poses a risk to staff and visitors in two ways: falling ice can land directly atop a person, or ice can land in the water and produce potentially dangerous waves. In 1986, a park visitor died after half a ton of ice broke off the face of Exit Glacier and crushed her. Subsequent retreat and deflation of Exit Glacier has greatly reduced the relief of the toe, lessening the possibility for ice to fall from above. Additionally, the toe and area around it has been designated an "ice fall hazard zone" and entry to this zone is prohibited.

Another, less obvious ice fall hazard occurs when hanging glaciers terminate on steep cliffs. Ice can break off the front of these glaciers and fall from far above to the beach or waters below. Glaciers that present such a risk occur in Northwestern Fiord and Holgate Arm. There is an account of a fatality occurring in Blackstone Bay (Prince William Sound) from an ice fall event of this nature.

Ice calving into water can produce large waves that have the potential to capsize boats or inundate campsites. Kayakers are advised to stay at least half a mile away from the terminus of tidewater glaciers, give icebergs a wide berth, remain in deep water in the event that a large wave is generated, and camp at least 3.2 km (2 mi) from the glacier, well above the waterline (Kenai Fjords website, https://www.nps.gov/kefj/planyourvisit/kayak-and-boat-safety.htm).

Abandoned Mineral Lands Mitigation and Mineral Development Potential

According to the NPS Abandoned Mineral Lands (AML) database and Burghardt et al. (2014), Kenai Fjords contains 50 AML features at 14 sites. Abandoned mineral lands are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. The NPS takes action under various authorities to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources. According to Burghardt et al. (2014), of the 50 AML features in Kenai Fjords, 12 have already been mitigated and seven additional features (four high priority and three medium priority) at four sites are in need of mitigation. However, work since 2014 addressed many of these issues, and current possible mitigation needs include several non-historic collapsing structures. A Cultural Landscape report is planned for 2018, which will identify management needs at abandoned mine sites.

Abandoned mines and associated features in Kenai Fjords are mainly clustered in the Nuka Bay historic mining district, which consists of lode gold prospects situated in the Valdez Group (**Kvs**; see "Gold Deposits" more information about the geologic setting). Mineral resources were discovered in the area in 1918 and peak mining activity was reached during the early 1930s, when at least four mines and corresponding mills were actively producing gold (Kinney/Sonny Fox Mine, Nukalaska Mine, Alaska Hills Mine, Glass-Heifner Mine; Richter 1970). The principal producing mine in the district during this period was the Kinney Mine (formerly Sonny Fox Mine; Huber 1999). Mining in the region primarily targeted gold deposits, but minor quantities of other sulfides (silver, copper, lead, and zinc) were also extracted (Cook and Norris 1998). Mining activity ceased during World War II, but in the 1950s and 1960s activity resumed at the Kinney, Glass-Heifner, and Waterfield-Goyne mines (Venator 2016). By 2009, all claims at these mines had lapsed.

In the 1990s, mitigation projects included adit (passageway to underground mine) closures at the Kinney Mine and the capping of arsenic-rich tailings with concrete at the Glass-Heifner Mine (Figure 64; Venator 2016). Currently, there are unmonitored tailings present at the Kinney Mine that could potentially contain contaminants (NPS 2017). Adit closures in 2008 and 2010 at the Harrington Mine, Glass-Heifner Mine, Rosness-larson Mine, and Waterfield-Goyne Mine mitigated the last known easily accessible hazardous underground mine workings on NPS land in the park, excepting one inaccessible adit at the Alaska Hills

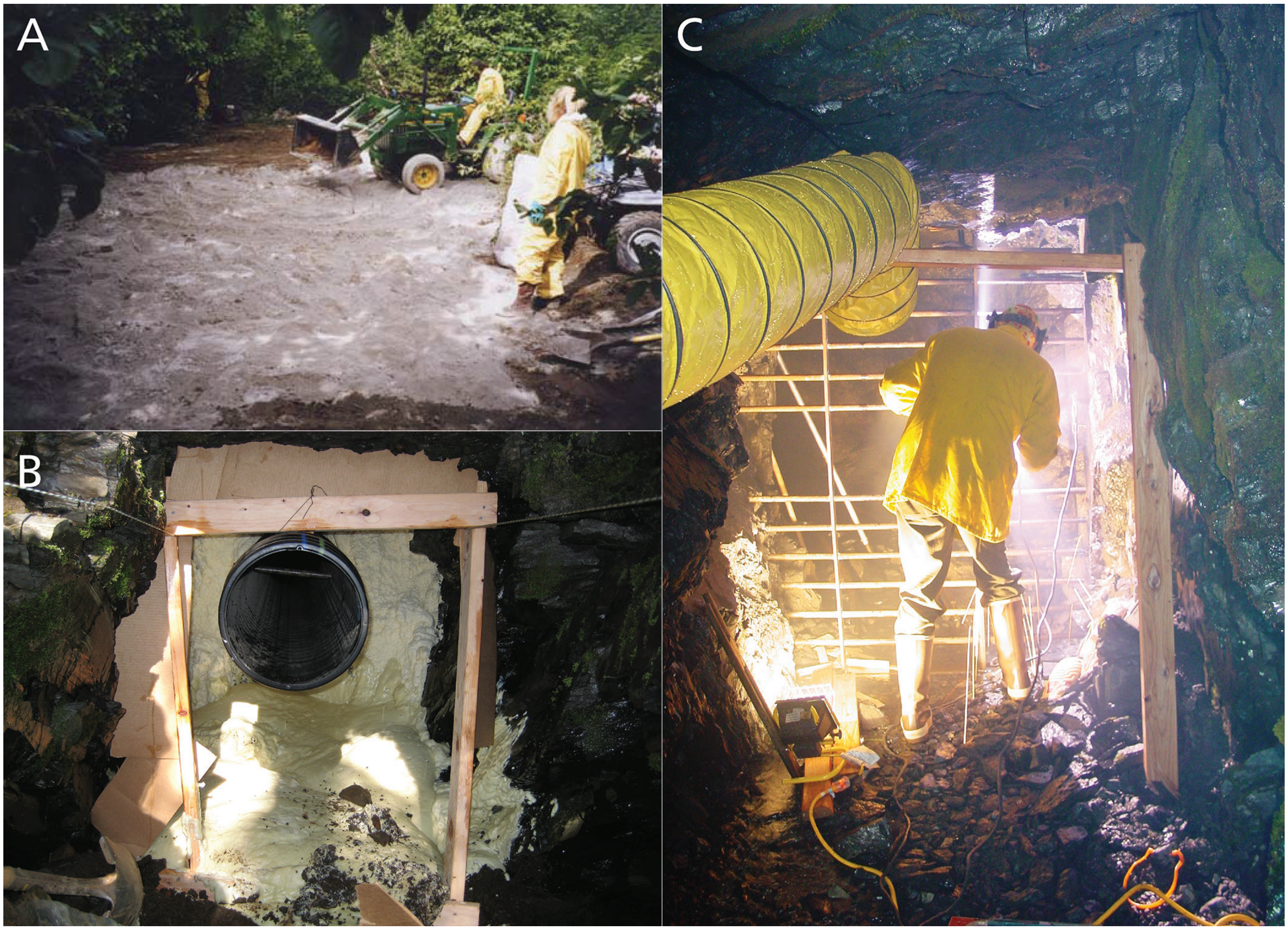


Figure 64. Photographs of abandoned mineral lands mitigation activities in the park. A: Photograph taken in 1998 showing workers capping arsenic-rich tailings with cement at the Glass Heifner Mine. Prior to the installation of the cement cap, these tailings were thought to have caused the death of a moose calf that was found in the area along with hoof prints and nose marks in the tailings. B: Photograph taken in 2010 showing the closure of an adit at the Rosness-Larson Mine using polyurethane foam, a material commonly used to seal abandoned adits. C: Photograph taken in 2010 showing a worker installing a metal gate that bars entrance to an adit at the Waterfield-Goyne mine. NPS photographs.

Mine that poses little threat to public safety (Venator 2016). All other underground mining features in the park that remain open are located on land owned by Native Corporations. In 2016, a condition assessment was conducted of previously mitigated AML features in the Nuka Bay historic mining district; two of the sites (Harrington Mine and Rosness-Larson Mine) were found to be in good condition, while further mitigation recommendations were made for the other three sites (Waterfield-Goyne Mine, Kinney Mine, and Glass-Heifner Mine; see Venator [2016] for more information).

Future mining could potentially occur on lands that are within the boundaries of Kenai Fjords, and are either entirely nonfederally owned or the subsurface is nonfederally owned (Figure 65). In May 2016, the park received a request for subsurface mineral testing by subsurface owners (NPS 2017). In cases where only the subsurface is nonfederally owned, the owner has a right to access and develop minerals in the subsurface. However, the park can require that these activities pose as minimal a disturbance to park resources as possible. These nonfederal lands encompass previously mined areas, including the majority of the Nuka Bay historic mining district (grey dotted line on Figure 65). For more information, see the NPS Energy and Minerals Management website, http://go.nps.gov/energyandminerals.

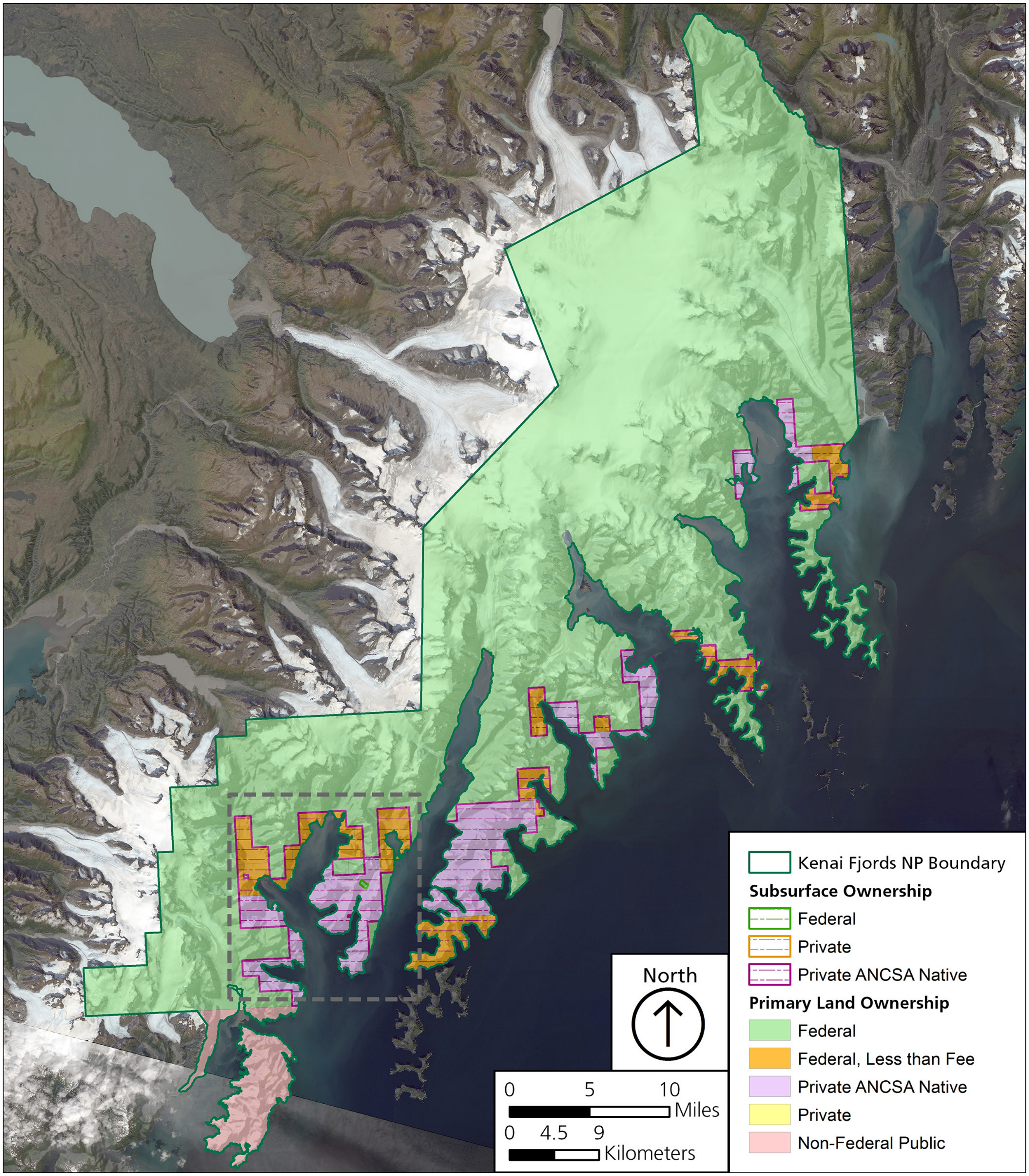


Figure 65. Map of Kenai Fjords showing land ownership, with the grey dashed line outlining the Nuka Bay historic mining district. The colors indicate the primary land ownership, with "Federal, Less than Fee" meaning that the land is not entirely federally owned. Horizontal line color indicates subsurface ownership. ANCSA stands for the Alaska Native Claims Settlement Act (1971) and indicates lands claimed by Alaska Native corporations under that act. Base map: 2013 Landsat satellite imagery, overlain by hillshade derived from the National Elevation Dataset.

Paleontological Resources Inventory, Monitoring, and Protection

Kenai Fjords has geologic units that contain fossils outside of park boundaries, and recently Paleozoic fossils from within the park were collected for the first time. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) outlines five methods and vital signs for monitoring in-situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

A paleontological resource summary for Kenai Fjords was completed by Kenworthy and Santucci (2003), and in 2016 a paleontological field-survey discovered the first Paleozoic fossils from within the park. Permian invertebrates were found in limestone cobbles collected from the lateral and medial moraines of a park glacier (Figure 56). While the fossils collected were not in-situ, the source is likely from a portion of the McHugh Complex within park boundaries. The fossils collected are very similar to fossils from limestone blocks of the McHugh Complex just outside of park boundaries described by Stevens et al. (1997), Fiorillo et al. (2004), and Blodgett and Isozaki (2013) (see "Paleontological Resources" section for more details). Some of the fossil species found are either rare or found nowhere else in North America.

Fossils sourced from the limestone in the McHugh Complex are relatively small, moderately to poorly preserved, marine invertebrates that are probably not at a great risk of loss via unauthorized collection. The threat of unauthorized collection is further reduced by the remote location of the fossils. However, the discovery of fossils in moraine material indicates that the source outcrop is being actively eroded and could possibly pose a management concern. Unlike most fossil-bearing limestone units, the limestone in the McHugh Complex does not occur in large, regionally extensive units. Rather, limestone in the McHugh Complex occurs in the form of smaller isolated blocks. Depending on the size of the limestone blocks and aggressiveness of erosion, the complete loss of fossil bearing rock through erosion could be a realistic possibility. Further surveys to locate and map the limestone blocks that sourced fossils collected in 2016 will enable staff to determine the abundance of paleontological resources in the area and identify any management concerns.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. A poster (in pocket) displays the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs. NPS employees can also obtain GRI GIS data via the Alaska Region NPS Theme Manager, under the KEFJ Themes folder, in the Geological Resources Inventory folder.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface. Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see Figure 4) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or 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 on the basis of age and/or rock type. GRI produced a bedrock map for Kenai Fjords.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following source to produce the GRI GIS data set for Kenai Fjords National Park:

Wilson, F. H., and C. P. Hults. 2012. Geology of the Prince William Sound and Kenai Peninsula region, Alaska (scale 1:350,000). Scientific Investigations Map 3110. US Geological Survey, Anchorage, Alaska. https://pubs.usgs.gov/sim/3110/.

The Wilson and Hults (2012) compilation was based on the following geologic maps:

Bradley, D. C., and M. L. Miller. 2006. Field guide to south-central Alaska's accretionary complex Anchorage to Seward. Alaska Geological Society, Anchorage, Alaska.

Bradley, D. C., and F. H. Wilson. 2000. Reconnaissance bedrock geology of the southeastern part of the Kenai quadrangle, Alaska. Pages 59–64 in K. D. Kelley, and L. P. Gough, editors. Geologic Studies in Alaska by the US Geological Survey, 1998. Professional Paper 1615. US Geological Survey, Denver, Colorado. https://pubs.er.usgs.gov/publication/70180441.

Bradley, D.C., T. M. Kusky, P. J. Haeussler, S. M. Karl, and D. T. Donley. 1999. Geology of the Seldovia quadrangle (scale: 1:250,000). Open-File Report 99-18. US Geological Survey, Anchorage, Alaska. https://pubs.usgs.gov/of/1999/of99-018/.

Karlstrom, T. N. V. 1964. Quaternary geology of the Kenai lowland and glacial history of the Cook Inlet region, Alaska. Professional Paper 443. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp443.

Magoon, L. B. W. L. Adkison, and R. M. Egbert. 1976. Map showing geology, wildcat wells, Tertiary plant localities, K-Ar age dates, and petroleum operations, Cook Inlet area, Alaska (scale: 1:250,000). Miscellaneous Investigations Series Map I-1019. US Geological Survey, Anchorage, Alaska.

Nelson, S. W., J. A. Dumoulin, and M. L. Miller. 1985. Geologic map of the Chugach National Forest (scale 1:250,000). Miscellaneous Field Studies Map MF-1645B. US Geological Survey, Anchorage, Alaska. https://pubs.er.usgs.gov/publication/mf1645B.

Tysdal, R. G., and J. E. Case. 1979. Geologic map of the Seward and Blying Sound quadrangles, Alaska (scale 1:250,000). Miscellaneous Investigations Series Map I-1150. US Geological Survey, Denver, Colorado.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Kenai Fjords was compiled using data model version 2.1, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (kefj_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 3);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (kefj_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- An ESRI map document (kefj_geology.mxd) that displays the GRI GIS data

GRI Map Poster

A poster of the GRI GIS draped over a shaded relief image of the park and surrounding area is included with this report as Plate 1. Not all GIS feature classes are included on the poster (table 3). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on Plate 1.

Table 3. GRI GIS data layers for Kenai Fjords National Park.

Data Layer	On Poster?
Age-Date Sample Localities	No
ARDF Geologic Sample Localities	No
ARDF Geologic Observation Localities	No
ARDF Mine Point Features	No
Geologic Lineament Line Features	Yes
Linear Dikes	Yes
Faults	Yes
Geologic Contacts	Yes
Geologic Units	Yes

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Additional References

These may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Selected Kenai Fjords National Park Natural Resource Management Guidance Documents

- Foundation Statement: NPS (2013)
- State of the Parks Report: NPS (2017)
- Natural Resources Condition Assessment: Stark et al. (2015)
- Southwest Alaska Network monitoring plan: Bennett et al. (2006)
- Network paleontology summary: Kenworthy and Santucci (2003)

Geology of National Park Service Areas

- NPS Geologic Resources Division—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/grd/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- 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://go.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
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- 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/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

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

- Alaska Division of Geological & Geophysical Surveys: http://dggs.alaska.gov/
- US Geological Survey: http://www.usgs.gov/
- USGS Publications: http://pubs.er.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- The Great M9.2 Alaska Earthquake and Tsunami of March 27, 1964: https://earthquake.usgs.gov/earthquakes/events/alaska1964/
- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- 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 "Find Maps")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

University of Alaska Fairbanks Alaska Earthquake Center Reference Tools

- Home page: http://earthquake.alaska.edu/
- Tsunami inundation mapping: http://earthquake.alaska.edu/tsunamis/atom

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 14-18 February 2005, or the follow-up report writing meeting, held on 20 November 2015. 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.

2005 Scoping Meeting Participants

Name	Affiliation	Position
Rebecca Beavers	NPS Geologic Resources Division	Coastal geologist
Alan Bennett	NPS Southwest Alaska Inventory and Monitoring Division	Network coordinator
Tom Bundtzen	NPS Geologic Resources Division	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Joel Cusick	NPS Alaska Regional Office	GIS specialist/LACL
George Dickson	NPS Alaska Regional Office	GIS team manager
Tony Fiorillo	Dallas Museum of Natural History	Curator
Bruce Giffen	NPS Alaska Regional Office	Geologist
John Graham	Colorado State University	Geologist
Lynn Griffiths	NPS Alaska Regional Office	Geological engineer
Peter Haeussler	US Geological Survey	Geologist
Shelley Hall	Kenai Fjords National Park	RM chief
Jim Halloran	NPS Alaska Region Natural Resources	Geologist
Patricia Heiser	University of Alaska Anchorage	Assistant professor – Geology
Janis Kozlowski	NPS Alaska Regional Office	RM specialist
Colleen Matt	Lake Clark National Park and Preserve	Natural Resources chief
Amy Miller	NPS Southwest Alaska Inventory and Monitoring Division	Ecologist
Joe Miller	NPS Southwest Alaska Inventory and Monitoring Division	Fishery biologist
Dorothy Mortenson	NPS Southwest Alaska Inventory and Monitoring Division	Data manager
Jeff Mow	Kenai Fjords National Park	Superintendent
Tina Neal	US Geological Survey, Alaska Volcano Observatory	Geologist
Joni Piercy	NPS Alaska Regional Office	GIS specialist
John Pinamont	NPS Alaska Regional Office	GIS specialist
Bud Rice	NPS RER	Environmental protection specialist
Janet Schaefer	Alaska Division of Geological & Geophysical Surveys, Alaska Volcano Observatory	Geologist
Linda Stromquist	NPS Alaska Regional Office	Geologist
Mike Tetreau	Kenai Fjords National Park	RMS
Richard VanderHoek	DNR/Parks Office of History & Archaeology/University of Illinois	Archaeologist
Sara Wesser	NPS Alaska Regional Office	Inventory and Monitoring coordinator
Frederic Wilson	US Geological Survey	Geologist

2015 Meeting Participants

Name	Affiliation	Position
Chad Hults	NPS Geologic Resources Inventory/Alaska Regional Office	Geologist
Sharron Kim	Kenai Fjords National Park	Natural Resource Manager
Christina Kriedeman	Kenai Fjords National Park	Biological Technician
Deborah Kurtz	Kenai Fjords National Park	Physical Science Program Manager
Rebecca Lasell	Kenai Fjords National Park	Superintendent
Kristy Sholly	Kenai Fjords National Park	Interpretation Manager
Laura Sturtz	Kenai Fjords National Park	Interpretation Supervisor

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 August 2017. 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. **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. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. DOI regulations in association with 2009 PRPA are being finalized (July 2017).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **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.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **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.
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.	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: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

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. **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]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **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. **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. **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. **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. **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. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include… erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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. **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 -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq**. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq**. allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq**. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: **16 USC § 230a** (Jean Lafitte NHP & Pres.) **16 USC §450kk** (Fort Union NM), **16 USC § 459d-3** (Padre Island NS), **16 USC § 459h-3** (Gulf Islands NS), **16 USC § 460ee** (Big South Fork NRRA), **16 USC § 460cc-2(i)** (Gateway NRA), **16 USC § 460m** (Ozark NSR), **16 USC§698c** (Big Thicket N Pres.), **16 USC §698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to -demonstrate bona fide title to mineral rights; -submit a plan of operations to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas (e.g., coal)	**NPS Organic Act, 54 USC §§ 100101 and 100751** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq**. prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	**No specific regulations, although applicable NPS policy memos include the following:** **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth in the NPS Coastal Adaptation Strategies Handbook (Beavers et al. 2016). **NPS Coastal Adaptation Strategies Handbook** (Beavers et al. 2016) provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq**. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **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. **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. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **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. **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. **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. **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. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

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

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U.S. Department of the Interior

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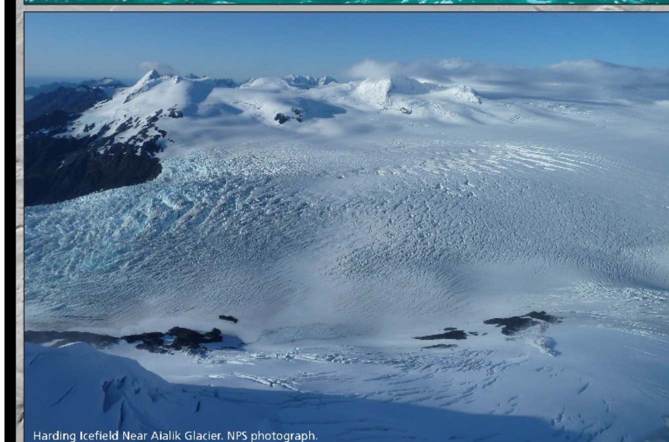
Geologic Map of Kenai Fjords National Park

Alaska

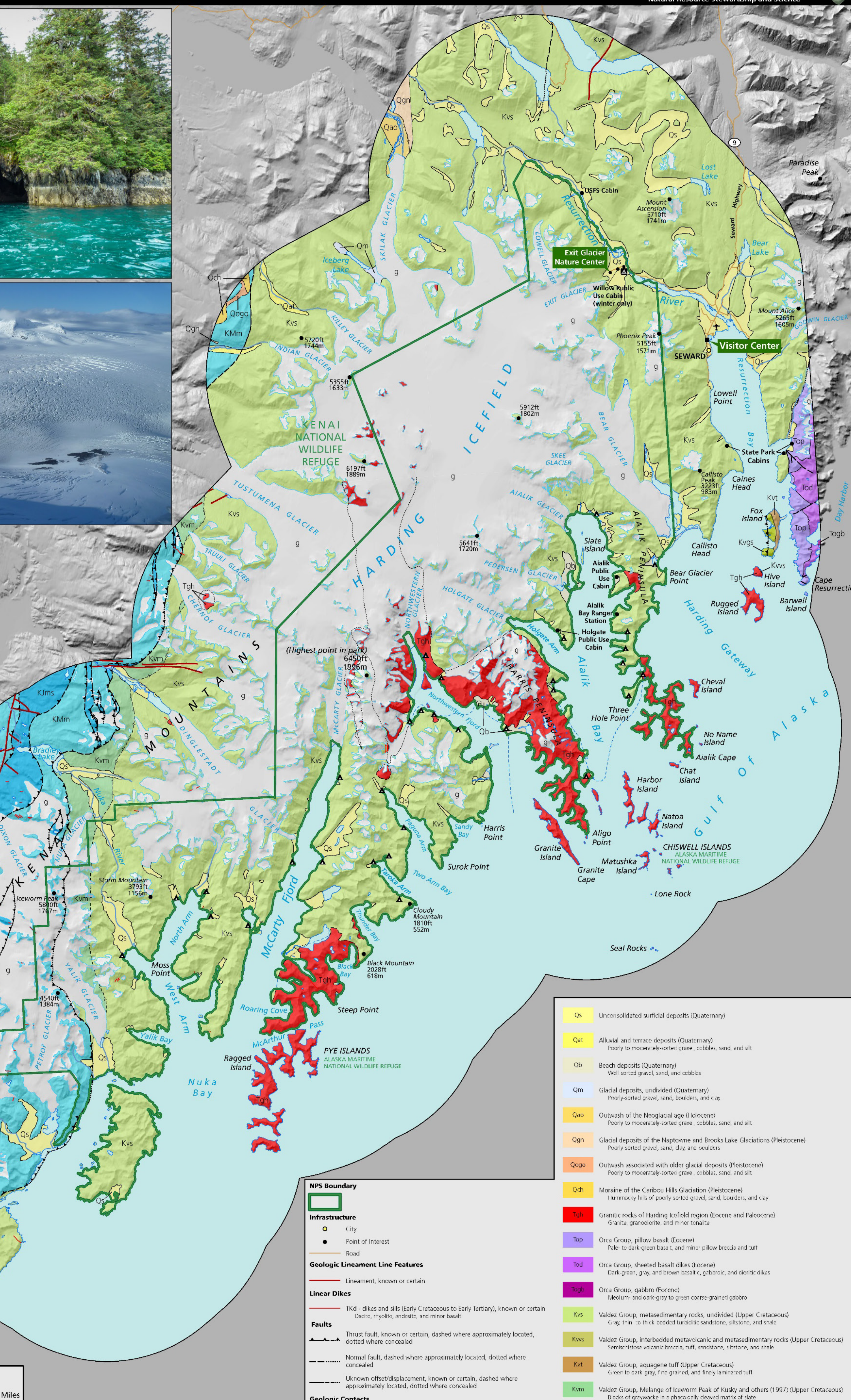
National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Cave in Nuka Bay. NPS photograph.



Harding Icefield Near Aialik Glacier. NPS photograph.



NPS Boundary

Infrastructure

- City
- Point of Interest
- Road

Geologic Lineament Line Features

- Lineament, known or certain

Linear Dikes

- TKd - dikes and sills (Early Cretaceous to Early Tertiary), known or certain
  Dacite, rhyolite, andesite, and minor basalt

Faults

- Thrust fault, known or certain, dashed where approximately located, dotted where concealed
- Normal fault, dashed where approximately located, dotted where concealed
- Uknown offset/displacement, known or certain, dashed where approximately located, dotted where concealed

Geologic Contacts

- Known or certain, dashed where approximately located, dotted where concealed
- Inferred and queried
- Water or shoreline, dashed where approximately located, dotted where inferred
- Ice or glacial, dashed where approximately located

Geologic Units

- Water - rivers, lakes, and Pacific Ocean (Quaternary)
- g — Ice fields or glaciers (Quaternary)
  Derived from glacial extents on 1950's USGS topographic maps.

Qs	Unconsolidated surficial deposits (Quaternary)
Qat	Alluvial and terrace deposits (Quaternary) Poorly to moderately-sorted gravel, cobbles, sand, and silt
Qb	Beach deposits (Quaternary) Well sorted gravel, sand, and cobbles
Qm	Glacial deposits, undivided (Quaternary) Poorly-sorted gravel, sand, boulders, and clay
Qao	Outwash of the Neoglacial age (Holocene) Poorly to moderately-sorted gravel, cobbles, sand, and silt
Qgn	Glacial deposits of the Naptowne and Brooks Lake Glaciations (Pleistocene) Poorly sorted gravel, sand, clay, and boulders
Qogo	Outwash associated with older glacial deposits (Pleistocene) Poorly to moderately-sorted gravel, cobbles, sand, and silt
Qch	Moraine of the Caribou Hills Glaciation (Pleistocene) Hummocky hills of poorly sorted gravel, sand, boulders, and clay
Tgh	Granitic rocks of Harding Icefield region (Eocene and Paleocene) Granite, granodiorite, and minor tonalite
Top	Orca Group, pillow basalt (Eocene) Pale- to dark-green basalt, and minor pillow breccia and tuff
Tod	Orca Group, sheeted basalt dikes (Eocene) Dark-green, gray, and brown basaltic, gabbroic, and dioritic dikes
Togb	Orca Group, gabbro (Eocene) Medium- and dark-gray to green coarse-grained gabbro
Kvs	Valdez Group, metasedimentary rocks, undivided (Upper Cretaceous) Gray, thin- to thick-bedded turbiditic sandstone, siltstone, and shale
Kvvs	Valdez Group, interbedded metavolcanic and metasedimentary rocks (Upper Cretaceous) Semischistose volcanic breccia, tuff, sandstone, siltstone, and shale
Kvt	Valdez Group, aquagene tuff (Upper Cretaceous) Green to dark gray, fine grained, and finely laminated tuff
Kvm	Valdez Group, Melange of Iceworm Peak of Kusky and others (1997) (Upper Cretaceous) Blocks of graywacke in a phacoidally cleaved matrix of slate
Kvgs	Valdez Group, schist (Upper Cretaceous) Schistose sandstone, siltstone, shale, and interbedded tuff
KMm	McHugh Complex, undivided (Mississippian to Cretaceous) Mélange of metasedimentary and metavolcanic rocks
KJms	McHugh Complex, graywacke and conglomerate (Early Jurassic to Early Cretaceous) Mélange of metamorphosed turbiditic conglomerate and graywacke
KTRmc	McHugh Complex, basalt and chert (Middle Triassic to Early Cretaceous) Fault bounded blocks in mélange
MZg	Gabbro (Mesozoic) Fault bounded blocks in mélange
MZu	Ultramafic plutonic rocks (Mesozoic) Fault bounded blocks in mélange

North
0 5 10 Kilometers
0 5 10 Miles

This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map
Wilson, F.H., C.P. Hults, K.A. Labay, and N. Shew. 2008. Digital data for the Reconnaissance geologic map for Prince William Sound and the Kenai Peninsula, Alaska (scale 1:250,000). Open File Report 2008-1002. US Geological Survey, Anchorage, Alaska. Primary source maps for the compilation are listed in the accompanying GRI Report.

Source Scale 1:250,000

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Source Map Date
2008

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.