



Wrangell-St. Elias National Park and Preserve

Geologic Resources Inventory Report



Coastal cliffs along Icy Bay with Mount St. Elias—the second-tallest peak in the United States—in the background. The cliffs consist of layered sedimentary rocks of the Yakataga Formation, which is part of a crustal block called the Yakutat terrane. The Yakutat terrane is colliding with the southern margin of Alaska, forming the highest coastal mountain range in the world, the St. Elias Mountains. Glaciers carve these mountains into steep peaks as they flow northward into the park's interior and southward into the Gulf of Alaska. The toe of Yahtse Glacier can be seen on the right side of the photograph.

NPS / NEAL HERBERT

Wrangell-St. Elias National Park and Preserve: Geologic Resources Inventory Report

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Abstract

Geologic Resources Inventory (GRI) reports provide geologic information and resources to help park managers make decisions for visitor safety, the planning and protection of infrastructure, and the preservation of natural and cultural resources. Information in GRI reports may also be useful for interpretation. The chapters of this report discuss the geologic heritage, geologic history, geologic features and processes, and geologic resource management issues of Wrangell-St. Elias National Park and Preserve. Guidance for resource management and information about the previously completed GRI GIS data and poster (separate products) are also provided.

Acknowledgments

We appreciate the many individuals who took the time to share their expertise and provide feedback that greatly increased the quality of this report. Firstly, we would like to thank our reviewers Matthew Brueseke (Kansas State University), Andrew Caruthers (University of Victoria), and Rebekah Levine (Wrangell-St. Elias National Park and Preserve). We would also like to thank those who provided information and reviewed portions of the report: Paul Burger (NPS Alaska Regional Office) for providing information for the caves sections; Tim Henderson (Colorado State University) for providing information and discussions for the stratotype section; Chad Hults (NPS Alaska Regional Office) for providing information and guidance for the mineral development section; Tim Orr (Alaska Volcano Observatory) for providing information and review for the mud volcanoes section; and Sarah Venator (NPS Alaska Regional Office) for providing information and review of the Abandoned Mineral Lands section. Thank you to Cullen Scheland (NPS Geologic Resources Division) for getting the ball rolling on the GRI poster, and Sarah Venator, Rebekah Levine, and Dan Wexler (NPS Alaska Regional Office) for providing feedback. We would also like to thank Trista Thornberry-Ehrlich (Colorado State University) for producing some of the graphics for this report, and Katie KellerLynn (Colorado State University) for developing standard report content and arrangement. Thank you to Suzanne McKetta (Colorado State University) for helping clarify and improve our writing through her wonderful editing skills. Finally, a huge thank you to the entire GRI team, particularly Rebecca Port (NPS Geologic Resources Division) and Victoria Crystal (Colorado State University), for providing consistent guidance, encouragement, and feedback throughout the writing process.

The GRI team thanks the participants of the 2004 scoping meeting for their assistance in this inventory. The lists of participants (below) reflect the names and affiliations of these participants at the time of the meeting and call. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the US Geological Survey for its maps of the area. This report and accompanying GIS data could not have been completed without them.

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Introduction

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the National Park Service (NPS) Natural Resource Stewardship and Science Directorate, 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 funded by the NPS Inventory and Monitoring Program.

Geologic Resources Inventory

GRI Products

The GRI team—which is primarily a collaboration between GRD staff and research associates at Colorado State University, Department of Geosciences, and University of Alaska Museum of the North—completed the following tasks as part of the GRI process for Wrangell-St. Elias National Park and Preserve (also referred to as “the park” throughout this report): (1) conducted a scoping meeting and provided a scoping summary, (2) provided geologic map data in a geographic information system (GIS) format, (3) created a poster to display the GRI GIS data, and (4) provided a GRI report (this document). GRI products are available on the “Geologic Resources Inventory—Products” website and on the NPS DataStore through the Integrated Resource Management Applications (IRMA) portal (see “Access to GRI Products”).

Information provided in GRI products is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided in GRI products. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data or on the poster.

Scoping Meeting

From 24–26 February 2004, the NPS held a scoping meeting at the NPS Alaska Regional Office in Anchorage, Alaska. The scoping meeting covered the three parks in the Central Alaska Inventory and Monitoring Network: Denali National Park and Preserve, Wrangell-St. Elias National Park and Preserve, and Yukon-Charley Rivers National Preserve. The scoping brought together NPS staff and geologic experts who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (GRI Team 2004) summarized the findings of that meeting.

GRI GIS Data

Following the scoping meeting, the GRI team compiled the GRI GIS data for the park. The data were compiled by the GRI team in 2022. The GRI GIS data may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format. These data are the principal deliverable of the GRI. The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (Figure 1). Scoping participants and the GRI team identified the best available source maps based on coverage (area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area.

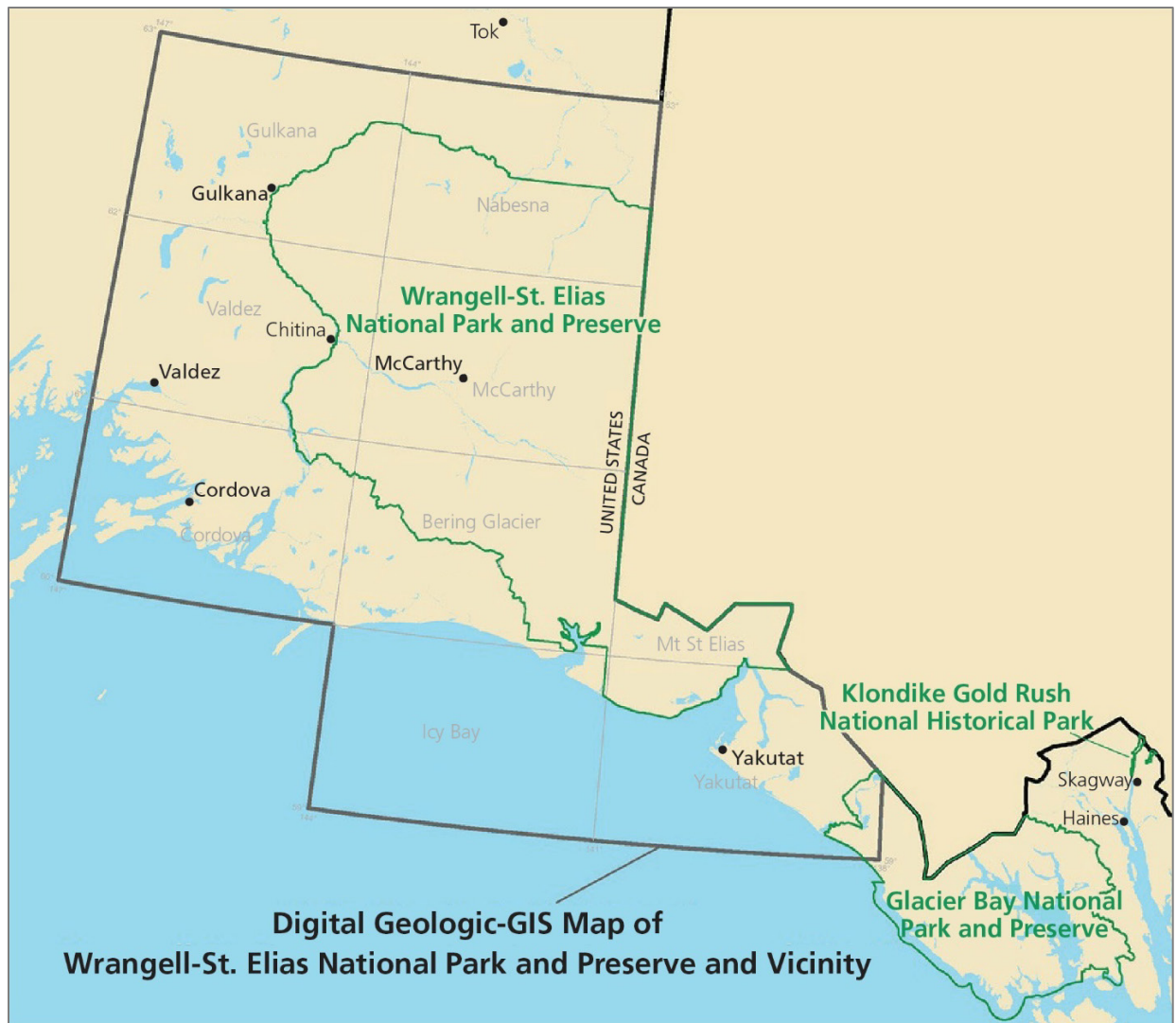


Figure 1. Index map for the GRI GIS data. The map displays the full extent of the GRI GIS data (dark gray line) and the quadrangles (boundaries in light gray) it covers. These include the Gulkana, Nabesna, Valdez, McCarthy, Cordova, Bering Glacier, and Icy Bay quadrangles, as well as part of the Mt. St. Elias and Yakutat quadrangles.

NPS / RON KARPILO (COLORADO STATE UNIVERSITY)

More information about the GRI GIS data can be found in the files accompanying the data. The “GIS readme file” explains the available file formats for the GRI GIS data, how to use the different file formats, and where to find more information about the GIS data model. The “ancillary map information document” lists the geologic maps or GIS data used to produce the GRI GIS data, the map units and map unit descriptions (including descriptions from all source maps), and additional information about the source maps.

The GRI GIS data for the park were compiled from the following two source maps:

- Geologic Map of the Wrangell-Saint Elias National Park and Preserve, Alaska (Richter et al. 2006)
- Geologic Map of Alaska (Wilson et al. 2015)

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the park and surrounding area is the primary figure referenced throughout this GRI report. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster, and geographic information and selected park features have been added. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

GRI Report

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2004, reviewers' comments in 2025, and additional geologic research. The selection of geologic features discussed in the report was guided by the previously completed GRI GIS data and discussions during the scoping meeting and discussions with park staff. Notably, the writing reflects the geologic interpretation provided by the authors of the source maps (see "GRI GIS Data").

Information from the park's foundation statement (NPS 2009), Natural Resource Condition Assessment (Draskowski et al. 2011), State of the Park Report (NPS 2016a), and Resource Stewardship Strategy (NPS 2024) has also been included as applicable to the park's geologic resources and resource management. Two primary references were used for the "Bedrock Geology" section of this report: (1) *A Geologic Guide to Wrangell-Saint Elias National Park and Preserve: A Tectonic Collage of Northbound Terranes* (Winkler et al. 2000); and (2) *Geologic Map of the Wrangell-Saint Elias National Park and Preserve, Alaska* (Richter et al. 2006).

The GRI report connects the GRI GIS data to the geologic features and processes discussed in the report using map unit symbols. Capital letters indicate age, and the following lowercase letters symbolize the unit name. For example, the Nikolai Greenstone mapped in the park has the map symbol **TRn**. "TR" represents the Triassic Period (251.9 million to 201.3 million years ago), and "n" represents Nikolai Greenstone. A geologic time scale, which displays the major divisions of geologic time and their numerical ages, is provided as a table in this report (see "Geologic Setting"). Additionally, map units discussed in each section of this report are listed at the beginning of the section, if applicable.

Park Background and Establishment

Wrangell-St. Elias National Park and Preserve (also referred to as "the park" throughout this report) was established in 1980 by the passage of the Alaska National Interest Lands Conservation Act (ANILCA 1980). The park was established for the following purposes: to maintain the natural scenic beauty of the diverse geologic, glacial, and riparian-dominated landscapes; to protect the attendant wildlife populations and their habitats; to ensure continued access for a wide range of wilderness-

based recreational opportunities; and to provide continued opportunities for subsistence use. The park was established on the traditional homelands of four Alaska Native peoples—the Upper Tanana, the Eyak, the Yakutat Tlingit, and the Ahtna—the traditional stewards of these lands.

The park protects a vast and wild landscape in southcentral Alaska (Figure 2; see GRI poster). At 53,400 km² (13.2 million acres), it is the largest national park unit in the United States. It stretches from the Copper River in the west to the Alaska-Yukon border in the east and from the Alaska Range in the north to the Gulf of Alaska in the south. The park contains the Wrangell-St. Elias Wilderness, which encompasses 38,000 km² (9.4 million acres) of designated wilderness and 10,000 km² (2.5 million acres) of eligible wilderness, making it the largest unit of the National Wilderness Preservation System (Figure 2A). The park is continuous with Kluane National Park and Reserve, Tatshenshini-Alsek Provincial Park, and Glacier Bay National Park (Figure 2B). Together, these units form a 24-million-acre World Heritage Site that is one of the largest internationally protected ecosystems on Earth.



Figure 2. Map of Wrangell-St. Elias National Park and Preserve. Wrangell-St. Elias National Park and Preserve (referred to as the “park” in this report) is the largest national park unit in the United States. It encompasses 53,400 km² (13.2 million acres) of wild and rugged landscape, stretching from the Copper River to the Alaska-Yukon border and from the Alaska Range to the Gulf of Alaska. The park includes four major mountain ranges: the eastern Alaska Range, the Wrangell Mountains, the Chugach Mountains, and the St. Elias Mountains. (A) Map of the Wrangell-St. Elias Wilderness. (B) Map of Wrangell-St. Elias National Park and Preserve, Kluane National Park and Reserve, Tatshenshini-Alsek Provincial Park, and Glacier Bay National Park, which together form a World Heritage Site. See the GRI poster for additional details regarding the park’s geography.

NPS / AMANDA LANIK (UNIVERSITY OF ALASKA MUSEUM OF THE NORTH)

The park's landscape is characterized by steep mountains, expansive glaciers, and braided rivers that provide habitat for many populations of Alaskan flora and fauna. Four major mountain ranges are found in the park: the Alaska Range (e.g., Mentasta Mountains), the Wrangell Mountains, the Chugach Mountains, and the St. Elias Mountains. Nine of the nation's 16 highest peaks occur within the park, including Mount St. Elias, which at 5,489 m (18,008 ft) is the second-highest peak in the United States. The park also contains Mount Wrangell, which is one of the largest active volcanoes in North America. Glaciers and icefields are found extensively in the mountainous regions and cover about 35% of the parklands. These glaciers provide meltwater and sediment to the park's river systems. The watersheds of two major drainages, the Copper River and the Yukon River, are within the park, along with numerous smaller watersheds along the Pacific Coast. The Copper River forms the western park boundary and is host to one of the most important populations of salmon in Alaska.

The park is approximately 240 km (150 mi) east of Alaska's largest city, Anchorage, and can be accessed by road, boat, or aircraft. The Richardson, Glenn, and Edgerton highways run parallel to the park's northwestern boundary, and two unpaved roads extend into the park: McCarthy Road and Nabesna Road. Communities adjacent to the park include Slana, Chistochina, Gakona, Gulkana, Glennallen, Tazlina, Copper Center, Kenny Lake, Chitina, and Yakutat. The park's headquarters and main visitor center are in Copper Center, and summer ranger stations are found in Slana and Chitina. The town of McCarthy is located within the park at the end of McCarthy Road and, according to the 2020 census, had a population of 107. The park maintains a summer-only visitor center north of McCarthy at the historic Kennecott mill town. Other communities within the park include Nabesna, at the end of Nabesna Road, and Chisana. In 2023, the park received 78,305 recreation visitors, making it the sixth most-visited national park unit in Alaska (Ziesler and Spalding 2024). Popular visitor activities include exploring the historic Kennecott mill town, day hiking, backpacking, mountaineering, floating and boating, sport hunting and fishing, and wildlife viewing.

Geologic Setting

The park is located astride an active tectonic boundary between the North American plate and the Pacific plate, specifically a crustal fragment moving with the Pacific plate known as the Yakutat terrane (also called the "Yakutat microplate" or "Yakutat block"; Figure 3). The Earth's crust is broken into tectonic plates that slowly shift relative to each other over time. Along the southern Alaskan margin, the denser Pacific plate is moving northwestward, sliding past and subducting (descending) beneath the less dense North American plate at a rate of 5–8 cm per year (2–3 in per year; Haeussler and Plafker 2003). In southeast Alaska, the Pacific plate is primarily sliding past the North American plate, creating a transform plate boundary, whereas in southcentral and southwest Alaska, the Yakutat terrane and Pacific plate are subducting beneath the North American plate, creating a convergent plate boundary. The park is located on the portion of the margin where plate motion transitions from transform (in the east) to subduction (in the west). This transitional zone is also where an overthickened oceanic plateau called the Yakutat terrane is colliding with and subducting beneath North America. This collision is resulting in significant deformation along the northern colliding edge of the Yakutat terrane and the overlying North American crust.

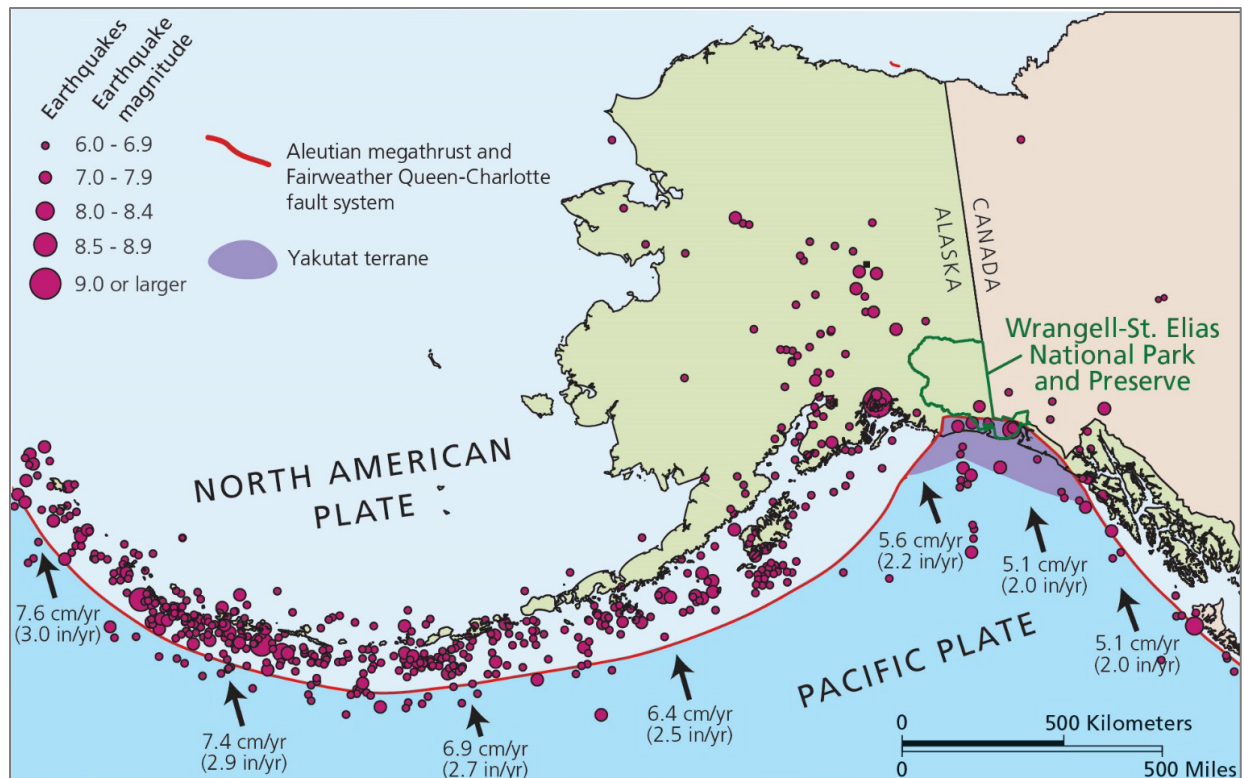


Figure 3. Tectonic map of Alaska. Alaska is on the edge of the North American plate (light blue). The Pacific plate (dark blue) is sliding past and subducting beneath the North American plate at a rate of 5–8 cm (2–3 in) per year. Additionally, the Yakutat terrane (purple) is a crustal fragment that is moving with the Pacific plate and subducting beneath the North American plate. Major faults form the boundaries between the North American plate, Pacific plate, and the Yakutat terrane (red lines). These faults generate frequent and sometimes large earthquakes (pink dots; earthquakes depicted on the map span 1899–2003). The park is situated where the Yakutat terrane is colliding with North America, and plate motion transitions from transform (in southeast Alaska) to subduction (in southcentral Alaska).

MODIFIED FROM CONTENT ORIGINALLY PUBLISHED BY USGS (HAEUSSLER AND PLAFKER 2003) / AMANDA LANIK (UNIVERSITY OF ALASKA MUSEUM OF THE NORTH)

The boundaries between the North American plate, Pacific plate, and Yakutat terrane are several tectonic faults that produce frequent and sometimes large earthquakes. The Fairweather-Queen Charlotte fault system accommodates most of the plate motion in southeast Alaska, and the Aleutian megathrust accommodates most of the subduction in southcentral and southwest Alaska. The Chugach-St. Elias fault system is located between the Fairweather fault and the Aleutian megathrust and forms the northern edge of the Yakutat terrane in and around the park. Tectonic pressure builds up and periodically releases along these major faults, producing earthquakes. Smaller earthquakes occur frequently, but these faults can also occasionally produce larger ones. For example, in 1964, a rupture of the Aleutian megathrust beneath Prince William Sound in southcentral Alaska caused a magnitude 9.2 earthquake. 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 the shaking itself, the 1964 earthquake produced a tectonic tsunami and many landslide-generated tsunamis.

create new crust; (2) plate accretion—crust from one plate can be transferred to another through collision; or (3) plate dismantle—crust can be lost when a plate subducts into the mantle. The western margin of the North American plate has received significant additions of crust since the Mesozoic Era (approximately 145 million years ago) through the process of accretion. This accreted crust makes up most of Alaska. The pieces of crust that have been added, known as “terranes,” have been transported from their original location and accreted onto the edge of North America through a complex tectonic history of collision, extension, and translation (see Figure 4; Figure 5).

Table 1. Geologic time scale. The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. Boundary ages are in millions of years ago (MYA) and follow the International Commission on Stratigraphy (2023). Items in parentheses include GRI map abbreviations for geologic time units. For example, “K” in a map unit symbol means that a map unit was deposited during the Cretaceous Period. “T” in a map unit symbol stands for Tertiary, which is a widely used but no longer formally recognized term for the geologic period from 66.0 million to 2.6 million years ago (Paleogene and Neogene Periods). Where no geologic time subdivision exists, “N/A” indicates not applicable.

Eon	Era(s)	Period(s)	Epoch(s)	MYA
Phanerozoic	Cenozoic	Quaternary (Q)	Holocene (H)	0.0117–today
	Cenozoic	Quaternary (Q)	Pleistocene (PE)	2.6–0.0117
	Cenozoic	Neogene (N)	Pliocene (PL)	5.3–2.6
	Cenozoic	Neogene (N)	Miocene (MI)	23.0–5.3
	Cenozoic	Paleogene (PG)	Oligocene (OL)	33.9–23.0
	Cenozoic	Paleogene (PG)	Eocene (E)	56.0–33.9
	Cenozoic	Paleogene (PG)	Paleocene (EP)	66.0–56.0
	Mesozoic	Cretaceous (K)	Upper, Lower	145.0–66.0
	Mesozoic	Jurassic (J)	Upper, Middle, Lower	201.3–145.0
	Mesozoic	Triassic (TR)	Upper, Middle, Lower	251.9–201.3
	Paleozoic	Permian (P)	Lopingian, Guadalupian, Cisuralian	298.9–251.9
	Paleozoic	Pennsylvanian (PN)	Upper, Middle, Lower	323.2–298.9
	Paleozoic	Mississippian (M)	Upper, Middle, Lower	358.9–323.2
	Paleozoic	Devonian (D)	Upper, Middle, Lower	419.2–358.9
	Paleozoic	Silurian (S)	Pridoli, Ludlow, Wenlock, Llandovery	443.8–419.2
	Paleozoic	Ordovician (O)	Upper, Middle, Lower	485.4–443.8
	Paleozoic	Cambrian (C)	Furongian, Miaolingian, Series 2, Terreneuvian	538.8–485.4
Proterozoic	Neoproterozoic (Z)	Ediacaran, Cryogenian, Tonian	N/A	1,000–538.8
	Mesoproterozoic (Y)	Stenian, Ectasian, Calymmian	N/A	1,600–1,000
	Paleoproterozoic (X)	Statherian, Orosirian, Rhyacian, Siderian	N/A	2,500–1,600
Archean	Neo-, Meso-, Paleo-, Eo-archean	N/A	N/A	4,000–2,500
Hadean	N/A	N/A	N/A	~4,600–4,000

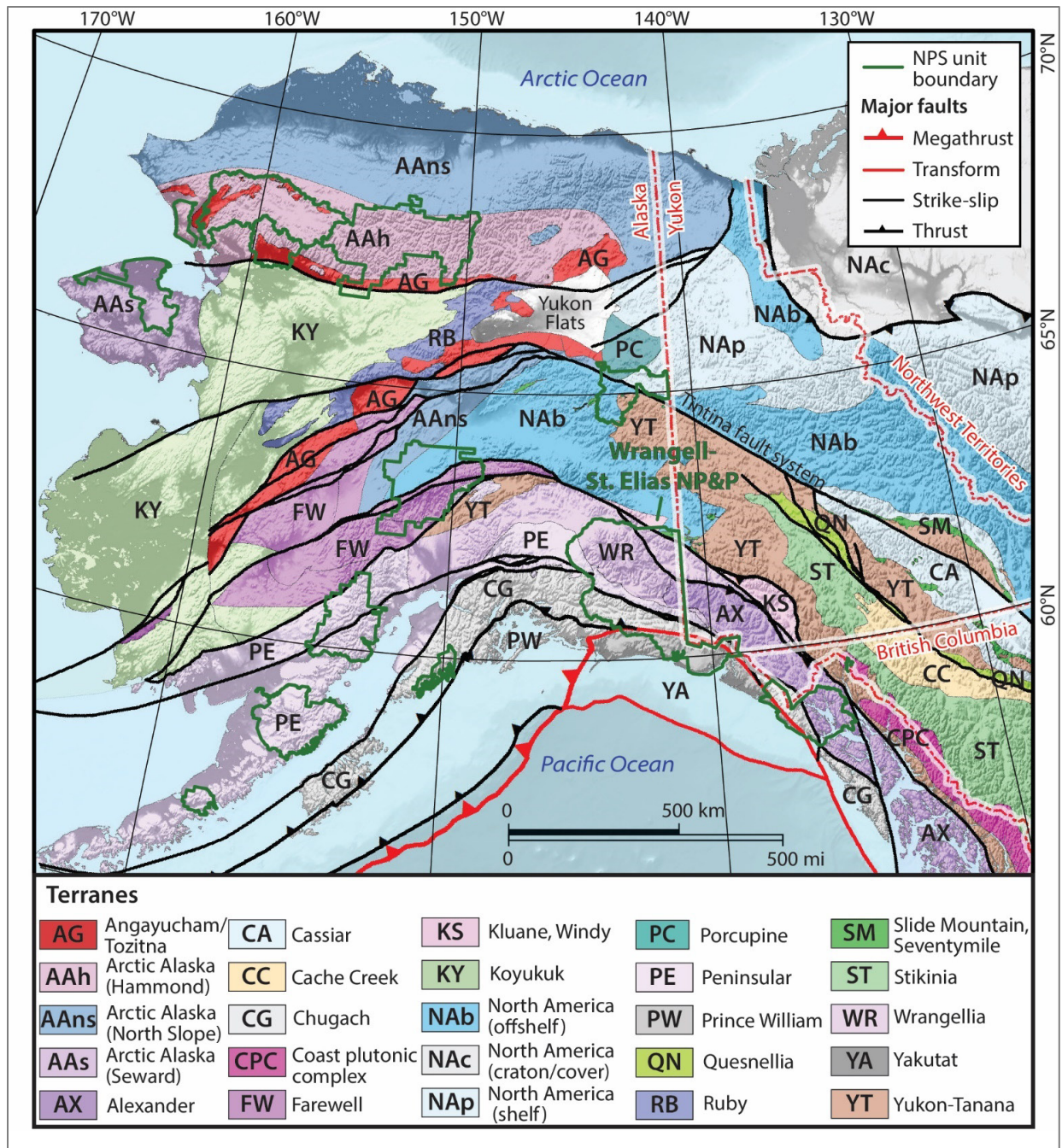


Figure 5. Terrane map of Alaska. Alaska is composed of displaced terranes separated by major faults. A terrane is a fault-bounded package of rocks that has a distinct geologic history when compared to adjacent rocks. Alaskan terranes have been transported by plate tectonics (i.e., translated) from where they originally formed and accreted together to the edge of the North American plate.

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Geologic Heritage

This chapter highlights geologic features, landforms, landscapes, and stories of the park valued for their geologic heritage qualities, including aesthetic, artistic, cultural, ecological, economic, educational, recreational, and scientific. It also draws connections between geologic resources and other park resources and stories.

Geologic heritage (also called “geoheritage”) evokes the idea that the geology of a place is an integral part of its history and cultural identity. It is the nexus of geology and human experience, encompassing the geologic features, sites, and stories preserved for the full range of values that society places on them. In 2015, in cooperation with the American Geosciences Institute, the NPS Geologic Resources Division published *America’s Geologic Heritage: An Invitation to Leadership* (NPS and AGI 2015). The booklet introduced the American experience of geologic heritage and outlined key principles and concepts, including five big ideas:

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

Geoheritage sites are conserved so that their lessons and beauty will remain as a legacy for future generations. Such areas generally have great potential for scientific studies, use as outdoor classrooms, and enhancing public understanding and enjoyment. Geoheritage sites are fundamental to understanding dynamic Earth systems, the succession and diversity of life, climatic change over time, the evolution of landforms, and the origin of mineral deposits. Currently, the United States does not have a comprehensive national registry of geoheritage sites. Although park units are not specifically established for geoheritage values, any geologic component included in a park’s enabling legislation or its planning and management documents can be regarded as a part of America’s geoheritage.

Wrangell-St. Elias National Park and Preserve’s significant geologic features, processes, and landscapes compose a rich geoheritage that is, in part, the reason for the park’s creation. The park’s foundation statement (a document that describes the park’s mission) identified maintaining the natural scenic beauty of the diverse geologic, glacial, and riparian-dominated landscapes as one of the park’s main purposes (NPS 2009). Many of the fundamental resources and values at the heart of the park’s mission are geologic in nature or closely tied to its geology. These resources include major

mountain ranges, the nation's largest protected active glacial complex, glacial river systems, and a cultural heritage that includes a significant history of mining (NPS 2009). More detail and information about these aspects of the park's geoheritage can be found in the sections of this report.

The park encompasses portions of four major mountain ranges that rise from sea level to over 5,500 m (18,000 ft), including nine of the 16 highest peaks in North America (see Figure 2; see the GRI poster; NPS 2009). These high mountains are a striking part of the superlative scenic beauty of the park (Figure 6). The four mountain ranges are the Alaska Range, Wrangell Mountains, Chugach Mountains, and St. Elias Mountains. All these mountains are a product of the park's tectonic setting. The tectonic forces associated with the subduction of the Pacific plate and Yakutat terrane beneath southern Alaska are causing deformation, crustal thickening, and rapid uplift of the rocks in the park, forming mountains. The uplifted region is being eroded by the park's many glaciers, which have carved the landscape into steep peaks and U-shaped valleys. The St. Elias Mountains are the highest coastal mountains in the world and contain the highest peak in Canada (Mount Logan) and the second-highest peak in Canada and the United States (Mount St. Elias, located directly on the international border). The exceptional elevation of the St. Elias Mountains is a result of the Yakutat terrane actively colliding with North America (see Figure 5; Elliot et al. 2013; Wech 2016). Additionally, the Wrangell Mountains are being formed by volcanic activity associated with the subduction of the Yakutat terrane. The Wrangell Mountains are composed of many volcanic centers that have been built up by repeated volcanic eruptions over the last 30 million years. The Wrangell Mountains include Mount Wrangell, which is one of the largest active volcanoes in North America, and Mount Churchill, which sourced one of the most widespread explosive eruptions (i.e., White River Ash) in the world during the last 2,000 years. Overall, Wrangell arc volcanoes are among the largest arc volcanoes on Earth (Richter et al. 1995; Brueseke et al. 2019).



Figure 6. Photograph of the St. Elias Mountains from Yakutat. The St. Elias Mountains are one of four major mountain ranges found within the park. They are the highest coastal mountains in the world, rising from sea level to over 5,500 m (18,000 ft). Their extreme relief is a product of the park's tectonic setting and erosional processes (e.g., glaciers).

NPS

The park has been the site of significant geologic research that advanced the way geologists understand the tectonics of Alaska and much of western North America. In the 1970s and 1980s, geologists developed the concept of “terrane” to explain major discrepancies observed in the bedrock that makes up western North America (see “Geologic Setting” and “Terranes” and Figure 5 for a terrane map of Alaska; Jones et al. 1972; Coney et al. 1980; Jones et al. 1983). Geologists proposed that Alaska, along with a significant portion of western North America, is composed of many different crustal blocks, or terranes, which did not originally form together but were instead juxtaposed later via plate tectonics. The Wrangellia terrane (named for the Wrangell Mountains where it was first described) was one of the first terranes identified and remains one of the most prominent examples of the terrane concept (Jones et al. 1977; Roeske and Pavlis 2024). In particular, paleomagnetic data collected from basalts near the town of McCarthy provided some of the first quantitative evidence that these rocks formed far away from the core of North America (known as the North American craton) and therefore had a distinctive geologic history (Hillhouse 1977; Jones et al. 1977). The terrane concept continues to be the main lens through which the geology of Alaska is understood, and the idea of terranes has since been applied to convergent tectonic boundaries worldwide. This transformative research is an important component of the park’s geoheritage. Indeed, the park’s foundation statement notes that the park’s mountains provide opportunities for geologic research and that research is a fundamental park value (NPS 2009).

The park contains the largest protected active glacial complex in the United States. As of 2014, the park had 3,121 glaciers that collectively covered 29,041 km² (11,212 mi²; Loso et al. 2014). That number not only dwarfs the collective glacier cover of the other 49 states (<580 km²) but also comprises one-third of all the glacier cover in Alaska and adjacent Canada. The park owes its prodigious glacier coverage not simply to being a large land mass, but also to the presence of many glaciers of globally significant size. For instance, three of the 10 largest glaciers in the world (not counting the Greenland and Antarctic ice sheets) are in the park: Malaspina Glacier (3,363 km² [1,289 mi²]; also known by its traditional Yakutat Tlingit name: Sít’ Tlein; Figure 7), Bering Glacier (3,025 km² [1,168 mi²]), and Hubbard Glacier (2,834 km² [1,094 mi²]). The park has the longest valley glacier (Nabesna Glacier is 85 km [53 mi] long), the largest piedmont glacier (Malaspina/Sít’ Tlein), and the largest tidewater glacier (Hubbard Glacier) in North America. Glacier cover is nearly continuous in the southern part of the park due to high levels of precipitation. Although the coastal region is not the coldest part of the park, it receives the most snow because of the movement of moist air from the Gulf of Alaska into the steep coastal Chugach and St. Elias mountains.



Figure 7. Photograph of Sit' Tlein, also known as Malaspina Glacier. Malaspina Glacier is one of the park's many spectacular glaciers. It is the world's largest piedmont glacier, a type of glacier that spills out of the mountains onto the flat foreland, forming a lobe.

NPS

The park protects over 1,500 km (1,000 mi) of scenic, free-flowing glacial rivers in their natural state (NPS 2009). Major river systems in the park include the Copper, Chitina, Bremner, Nabesna, White, and Chisana rivers. Most of the rivers are fed by water and sediment melting out of the park's many glaciers, which results in classic braided glacial river morphologies. The park's rivers and streams act as habitats for plants and animals, transportation corridors, supplies of food and water, and sources of recreation for residents and visitors alike. The Copper River provides freshwater habitat for a salmon population that is an internationally recognized fishery (NPS 2009). The park's foundation statement notes performing scientific research on glacial river systems is a fundamental park value (NPS 2009).

Historic copper and gold mining are a significant part of the cultural heritage the park protects and interprets today. Some of the richest copper deposits in the world existed at the contact between two of the park's geologic units: the Nikolai Greenstone (**TRn**) and Chitistone Limestone (**TRcn**). In 1900, an outcrop of nearly pure copper sulfide ore was discovered in the central part of the park, on Bonanza Ridge to the east of the Kennicott Glacier. The discovery of this and other rich copper deposits in the area prompted the construction of a 315 km (196 mi) railroad to access this remote part of Alaska, the creation of a new mining corporation called the Kennecott Copper Corporation (note the distinct spelling, which differs from that of the adjacent glacier), and the construction of

mines and a mill town (Kennecott; Figure 8) on the edge of the glacier. Kennecott was a self-contained company town that housed up to 300 people and included a hospital, general store, school, skating rink, tennis court, recreational hall, and dairy. Starting in 1911, the Kennecott Copper Corporation mined more than 536,000 metric tons of copper and an estimated 100 metric tons of silver from the Bonanza, Jumbo, Mother Lode, and Erie mines. Declining profits and increasing costs of railroad repairs caused the closure of the Kennecott operation and the abandonment of the town in 1938. In 1998, the NPS acquired many of the buildings and lands of the historic mining town. Kennecott was listed on the National Register of Historic Places in 1978 and designated as a National Historic Landmark in 1986. It is the best-preserved example of early 20th-century copper mining in the country and is one of the most popular places in the park to visit. Other, less extensive gold mining occurred in the northern portions of the park (e.g., Nabesna and Chisana areas), associated with Cretaceous plutons (**Kg**).



Figure 8. Photograph of the Kennecott machine shop (foreground) and mill building. Operated between 1911 and 1938, the Kennecott mines and mill town were among the nation's richest copper deposits, producing nearly \$200 million worth of copper (Thomson 2011). The historic mining town is now a National Historic Landmark that offers park visitors a rare glimpse into Alaska's early 1900s history.

NPS / MATTHEW YARBROUGH

Geologic Features and Processes

This chapter highlights geologic features and processes significant to the park's landscape and history. Selection of these features and processes was based on input from scoping participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more or less in order of geologic age (oldest to youngest).

At the beginning of each of the following sections, geologic map units corresponding to the GRI GIS data are listed; these indicate which map units are discussed in each section. Map units are referenced directly in the text as well. Some sections may not be directly related to a map unit on the poster, in which case no unit is listed at the start of the section. The map units can also be viewed in the GRI GIS data or on the GRI poster.

Bedrock Geology

Two publications discuss the bedrock of the park in detail: (1) *A Geologic Guide to Wrangell-Saint Elias National Park and Preserve: A Tectonic Collage of Northbound Terranes* (Winkler et al. 2000); and (2) *Geologic Map of the Wrangell-Saint Elias National Park and Preserve, Alaska* (Richter et al. 2006). Unless otherwise noted, the following discussion of bedrock geology is referencing these two publications. One major difference between the two publications is whether the Gravina-Nutzotin belt is included in the Wrangellia terrane. This report follows Winkler et al. (2000) and separates the Gravina-Nutzotin belt from the Wrangellia terrane.

Terranes

The bedrock of Alaska is composed of various crustal fragments, called “terranes,” that are the framework geologists use to understand Alaska's geology (Coney et al. 1980; Nokleberg et al. 1994; Yukon Geological Survey 2020; see Figure 5 for a terrane map of Alaska). A terrane is a fault-bounded fragment of crust that has a different geologic history when compared to adjacent rocks (Jones et al. 1983). While the terranes of Alaska are now part of the North American tectonic plate, they did not originate where they are found today. Instead, Alaskan terranes formed in different parts of the globe at different times and were transported to the edge of North America over millions of years by plate tectonics. As terranes reached the western edge of the North American plate, they were sequentially accreted (added) to North America, increasing the plate's size significantly. Those closer to the ancient core of North America (called the North American craton) are more “inboard,” and those further from the North American craton are more “outboard.” Almost all of Alaska is composed of terranes that have been accreted since the Mesozoic Era (approximately 145 million years ago). Rocks that formed during or after terrane accretion are called overlap assemblages. Overlap assemblages are sedimentary or igneous rocks deposited on or intruded into two or more adjacent terranes (Nokleberg et al. 1994).

Rocks in the park belong to several different terranes and overlap assemblages. From north to south, the park contains rocks that belong to the Windy terrane, Wrangellia terrane, Alexander terrane, Chugach terrane, Prince William terrane, and Yakutat terrane (Figure 9). Overlap assemblages in the park include rocks of the Gravina-Nutzotin belt and igneous rocks of the Wrangell arc (see “Wrangell

Arc”). Some of the terranes in the park evolved in tandem with other terranes and are grouped together as composite terranes. It has been argued that the Alexander and Wrangellia terranes make up part of the larger Wrangellia composite terrane. Under this hypothesis, these terranes are grouped together based on the presence of igneous rocks in the eastern part of the park that cross both terrane boundaries. The Chugach and Prince William terranes are sometimes grouped together to form the Southern Margin composite terrane or referred to collectively as the Chugach-Prince William terrane (Dumoulin 1988; Richter et al. 2006; Davidson and Garver 2017). This is because the Chugach and Prince William terranes are made up of rocks that formed in the same tectonic setting and are compositionally similar (Dumoulin 1988). Table 2 displays a correlation of the GRI GIS map units to terranes and overlap assemblages.

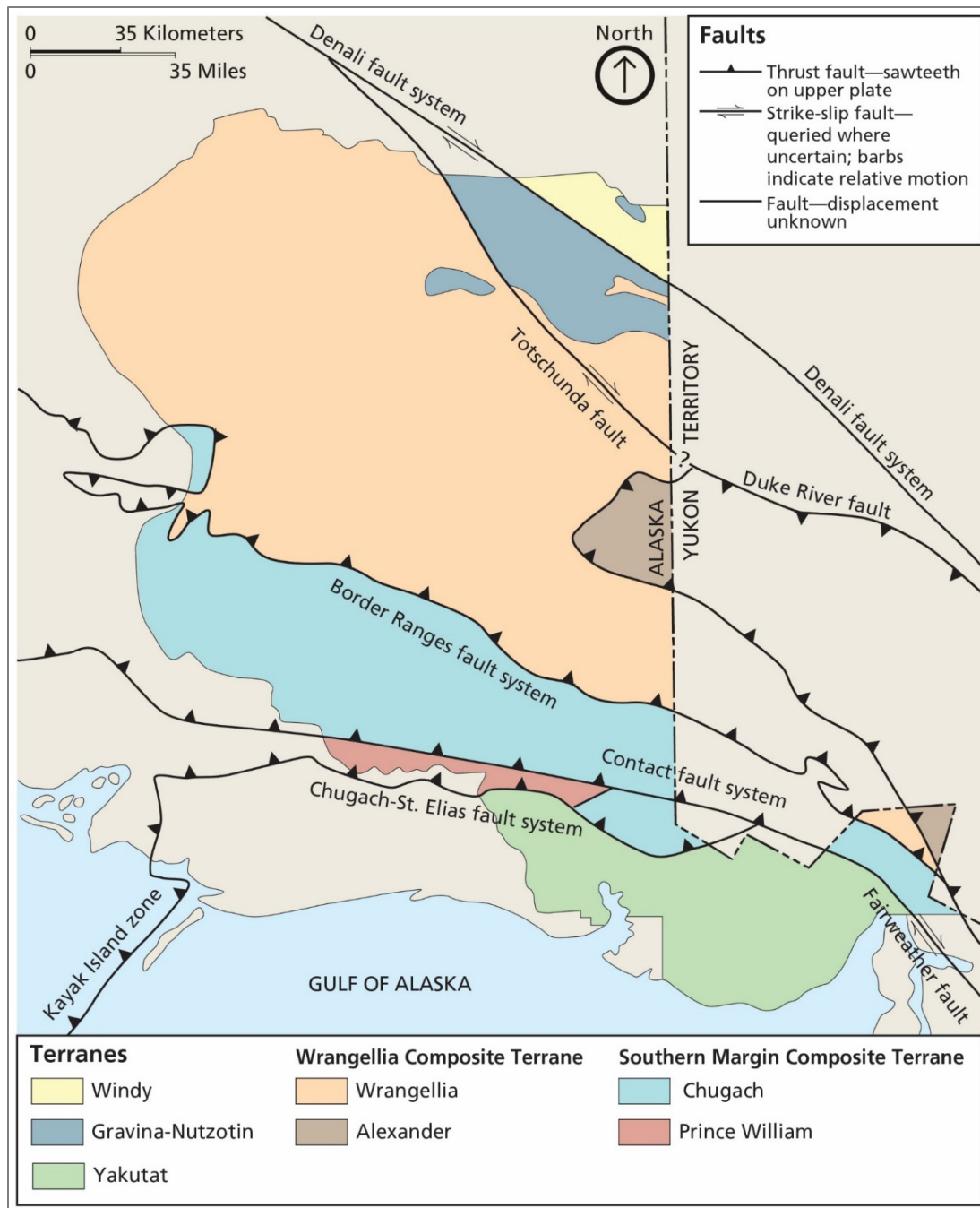


Figure 9. Terrane map of Wrangell-St. Elias National Park and Preserve. The park's bedrock belongs to several terranes that are separated by major fault systems. These include the Windy terrane, Wrangellia terrane, Alexander terrane, Chugach terrane, Prince William terrane, and Yakutat terrane. Some of these terranes have been grouped together in composite terranes. The Wrangellia and Alexander terranes are both part of the Wrangellia composite terrane, and the Chugach and Prince William terranes are part of the Southern Margin composite terrane. See Figure 5 for an Alaska-wide terrane map. The Windy terrane is included in the NAb terrane on Figure 5. The park also contains the Gravina-Nutzotin belt, which is an overlap assemblage.

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Table 2. Correlation of tectonic groups and GRI GIS map units. See the GRI poster for the geographic distribution of the map units.

Tectonic group	Map units (GRI)
Wrangell arc	Individual volcanic eruptive centers of the Wrangell arc (Qwws , Qwwv , Qwd , Qwdr , Qws , Qwsr , Qwc , Qwcr , Qwj , Qwjd , QTwt), other volcanic deposits (Qvd , Qpf , Qbc , QTw , QTwi , QTwr , Th , Tg , Tw , Twr , Twd)
Yakutat terrane	Yakutat Group (Kyf , Kym), Kulthieth Formation (Tk), Poul Creek Formation (Tps), volcanic and hypabyssal rocks (Tm), rhyolite porphyry and granite (Td), Yakataga Formation (QTy)
Prince William terrane (Southern Margin composite terrane)	Orca Group (Tos , Tov), granitic plutons (Tgp)
Chugach terrane (Southern Margin composite terrane)	Mélange units (KJm), Valdez Group (Kv , Kvv , Kvm , Kvg), granitic plutons (Tgp)
Alexander terrane (Wrangellia composite terrane)	Kaskels Group (PZk)
Wrangellia terrane (Wrangellia composite terrane)	Monzonite-granite complex (PNm), gabbro and orthogneiss (PNgo), diorite complex (PPNdm , PPNdp), Strelina Metamorphics (PPNm , PPNsm), Tetelna Volcanics (PPNt), Skolai Group (PPNs , PPNsc , Ph , PI), Mankomen Group (Pe , Pel , PPNss), Triassic limestone (TRI), Nikolai Greenstone (TRn), Chitistone and Nizina Limestones (TRcn), McCarthy Formation (JTRm), sedimentary rocks (Js), Kotsina Conglomerate (JK), Chitina Valley batholith (Jc), marine sedimentary rocks (Ku), shallow marine sedimentary rocks (KI), Mid-Cretaceous plutons (Kg), younger plutons (Tp)
Gravina-Nutzotin belt	Nutzotin Mountains sequence (KJs), Chisana Formation (Kc), nonmarine sedimentary rocks (Kun), Mid-Cretaceous plutons (Kg)
Windy terrane	Metasedimentary rocks (Dp), metamorphic rocks of the Carden Hills (PZv , PZvc), alpine-type ultramafic rocks and gabbro (MZPZu), conglomerate and sandstone (MZc), Snag pluton (Tsq), metamorphic complex of Cottonwood Creek (Tc)

The park's terranes sequentially accreted onto North America at various points in geologic time. The terranes that accreted earlier are further north and closer to the North American craton (inboard), while those that accreted later are further south and farther from the North American craton (outboard). This process progressively built the edge of North America outward as terranes arrived, collided with the continental edge, and became the new outermost part of the North American continent. The collision and accretion of crustal fragments often lead to the rocks undergoing metamorphism (alteration due to heat and pressure). The Windy terrane was the first to arrive; it accreted to the continent in the Triassic and Early Jurassic periods (225 million–180 million years ago; Richter et al. 2006). The Wrangellia terrane, Alexander terrane, and Peninsular terrane (found to the west of the park) were next and collided with North America in the Cretaceous Period (117 million–114 million years ago; Richter et al. 2006; Trop et al. 2020). These terranes have been transported northward along strike-slip faults, from latitudes coincident with modern California and Oregon, since accreting onto North America. Marine rocks of the Gravina-Nutzotin belt formed just

before and during the accretion of the Wrangellia, Alexander, and Peninsular terranes, and they essentially became the glue that attached these terranes to the North American continent (Richter et al. 2006; Manuszak et al. 2007; Trop et al. 2020). The Chugach and Prince William terranes were the next to arrive, apparently accreting between 67 million and 50 million years ago (Richter et al. 2006). Finally, the Yakutat terrane arrived about 30 million years ago and started subducting under southcentral Alaska (Brueseke et al. 2019). This terrane is actively colliding with the continent at a velocity of about 5 cm (2 in) per year (Elliott et al. 2010).

The following sections describe the park's bedrock geology and are organized by terrane or overlap assemblage. The sections are ordered from inboard to outboard: (1) the Windy terrane; (2) the Gravina-Nutzotin belt; (3) the Wrangellia composite terrane; (4) the Southern Margin composite terrane; and (5) the Yakutat terrane. The igneous rocks of the Wrangell arc are discussed in a separate section of this report called "Wrangell Arc." GRI GIS map units that correspond to the rocks discussed in each section can be viewed in Table 2 (organized by terrane/overlap assemblage).

Windy Terrane

Rocks assigned to the Windy terrane in the map area are fault-bounded sequences of primarily metamorphic rocks found to the north of the Denali fault system (see Figure 9 and the GRI poster). These rocks crop out in the very northeastern corner of the park, in the Carden Hills and Wellesley Mountain areas (see the GRI poster). The bedrock in the Carden Hills consists of mafic (iron-rich) volcanic lavas, tuffs (ash), and volcanoclastic rocks (composed of fragments of volcanic rocks and sediment) that erupted sometime during the Paleozoic Era (**PZv** and **PZvc**; 539 million–252 million years ago). These rocks were subsequently metamorphosed (altered by heat and pressure) to pressures and temperatures of the greenschist metamorphic facies (Figure 10). Mafic and ultramafic intrusive igneous rocks (**MZPZu**) are faulted against the metamorphic rocks of the Carden Hills. To the north, in the Wellesley Mountain area, Late Jurassic and Early Cretaceous (164 million–101 million years ago) sedimentary rocks (**MZc**) overlie the metamorphic rocks; however, there is an unconformity (gap in the rock record) between the older metamorphic rocks and the younger sedimentary rocks. During the Eocene Epoch (56 million–34 million years ago), the rocks of the Windy terrane were intruded by the Snag Creek pluton (**Tsq**), which is found on the southern flank of Wellesley Mountain. Rocks of the Windy terrane extend northwestward outside of the park, cropping out in the Black Hills and Mentasta Mountains (see GRI poster). These are metasedimentary (metamorphosed sedimentary) rocks (**Dp**) that contain poorly preserved Devonian (419 million–360 million years ago) fossils. Like the metamorphic rocks in the Carden Hills, they have undergone greenschist-facies metamorphism.

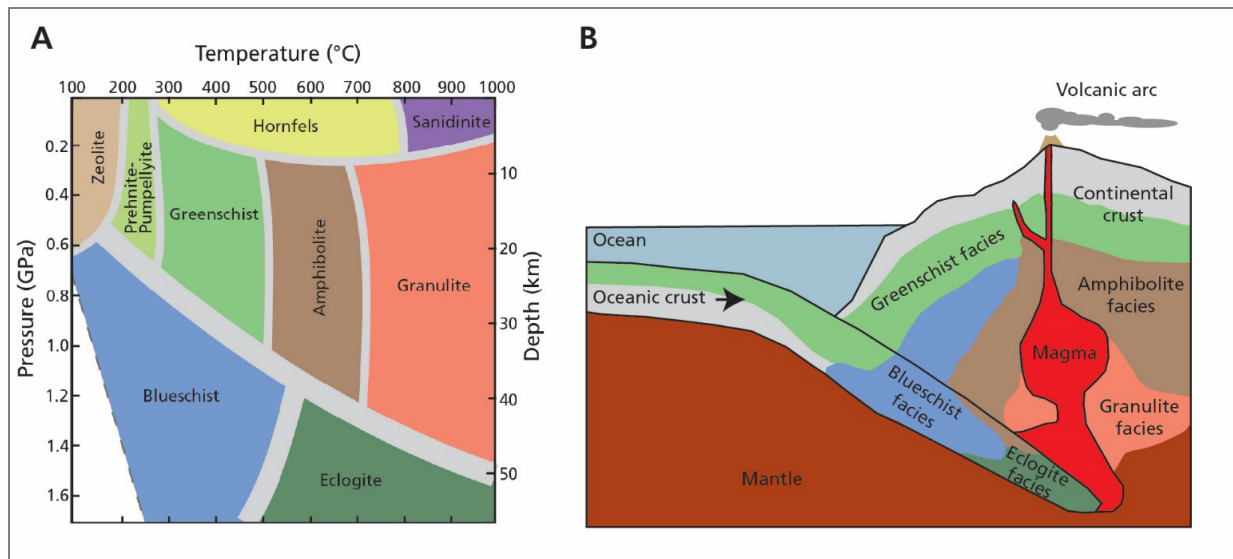


Figure 10. Pressure-temperature-depth diagram showing metamorphic facies and the generalized tectonic setting where they form. (A) Diagram showing metamorphic facies. Certain metamorphic minerals will develop depending on the original rock chemistry and the pressure and temperature during metamorphism. Metamorphic facies are characterized by mineral assemblages that form under similar pressure-temperature conditions. (B) Diagram showing the generalized tectonic settings where different metamorphic facies may form. Note that rocks that are more deeply buried correspond to metamorphic facies with higher pressures, and rocks that are close to heat sources such as magma correspond to metamorphic facies with high temperatures. Rocks in the park have undergone prehnite-pumpellyite-facies metamorphism (Nikolai Greenstone), greenschist-facies metamorphism (metamorphic rocks of the Carden Hills; Kaskawulsh Group; Valdez Group), and amphibolite-facies metamorphism (Valdez Group). *MODIFIED FROM CONTENT ORIGINALLY PUBLISHED IN WINTER (2001) / AMANDA LANIK (UNIVERSITY OF ALASKA MUSEUM OF THE NORTH)*

The Windy terrane is one of several narrow terranes found along the Denali fault system between the much larger Yukon-Tanana terrane to the north and the Wrangellia composite terrane to the south (see Figure 5). These terranes are the result of two major tectonic events: (1) the accretion of the Wrangellia composite terrane to North America and (2) the northward displacement of the Wrangellia composite terrane along the Denali fault system (Nokleberg and Richter 2007). The Windy terrane is a tectonic *mélange* (chaotic mixture of rocks) that contains rocks from the Gravina-Nutzotin belt and the North American continental margin (Nokleberg and Richter 2007).

Gravina-Nutzotin Belt

The Gravina-Nutzotin belt is an Upper Jurassic to Lower Cretaceous (164 million–117 million years ago) overlap assemblage composed of sedimentary and igneous rocks found south of the Denali fault system (see Figure 9). In the park, these rocks are found in the Nutzotin and Mentasta Mountains (see the GRI poster). The belt is composed of three distinct parts, which are (from oldest to youngest): (1) the predominately marine sedimentary rocks of the Nutzotin Mountains sequence (**KJs**), (2) volcanic and volcanoclastic rocks of the Chisana Formation (**Kc**) and associated mid-Cretaceous plutons (**Kg**), and (3) nonmarine sedimentary rocks described as the Beaver Lake formation by Trop et al. (2020; **Kun**; see the GRI poster). These rocks were deposited in the Nutzotin basin, which is a basin that

formed along the inboard (towards North American) edge of the Wrangellia composite terrane as it approached and collided with the North American continental margin in the Late Jurassic and Cretaceous periods (Trop et al. 2020).

The Nutzotin Mountains sequence is composed of marine sedimentary rocks such as mudstone, sandstone, and conglomerate (Manuszak et al. 2007). The base of the Nutzotin Mountains sequence sits unconformably (with a gap in the rock record) on older Triassic rocks of the Wrangellia Terrane. Fossils within the sequence indicate deposition started in Late Jurassic time (Oxfordian; 161.5 million years ago) and continued until Early Cretaceous time (Valanginian; 132.6 million years ago; Berg et al. 1972). The depositional environment of the Nutzotin Mountains sequence was a marine basin that transitioned from deep marine sand- and mud-rich submarine fan systems at the base to bivalve-rich muddy shelf deposits towards the top (Manuszak et al. 2007). The composition of the conglomerates and sandstones, as well as detrital zircon data, indicate the sediment of the Nutzotin Mountains sequence was sourced from progressively deeper erosion of the older, more outboard rocks that compose the Wrangellia terrane (Manuszak et al. 2007). Characteristics of the Nutzotin Mountains sequence (e.g., the basal unconformity, overall shallowing of depositional environment, and erosion of progressively deeper levels of the Wrangellia terrane) indicate that the sequence records the beginning stages of the collision of the Wrangell composite terrane with the North American margin (Manuszak et al. 2007).

The Chisana Formation conformably overlies (no gap in sedimentation) the upper part of the Nutzotin Mountains sequence. The Chisana Formation is composed of volcanic and volcanoclastic rocks with minor amounts of marine sedimentary rock in the lower part. Chisana volcanism occurred between 131 million and 117 million years ago based on reported lava ages and detrital U-Pb zircon ages from sandstones that underlie the lowest Chisana lavas (Manselle et al. 2020). In the map area, the Gravina-Nutzotin belt is intruded by mid-Cretaceous plutons, such as the Klein Creek and Chisana plutons, which were the source for the volcanic rocks of the Chisana Formation. The volcanic rocks of the Chisana Formation display textures and chemical signatures that indicate they formed in a volcanic island arc setting. The plutonic rocks represent the roots of the volcanic arc. This volcanic arc, called the Chisana arc, likely formed on the northern edge (present-day orientation) of the Wrangellia composite terrane as oceanic crust subducted beneath its southern edge (Manselle et al. 2020).

Directly overlying the Chisana Formation is the Beaver Lake formation, a package of nonmarine sedimentary rocks (e.g., conglomerates, sandstones, mudstones) deposited in and near rivers (Trop et al. 2020). The Beaver Lake formation is exposed near Chisana, as well as in scattered areas on the east side of the park (see the GRI poster). Beaver Lake formation sedimentary deposition occurred from 117 million to 98 million years ago (Trop et al. 2020). Beaver Lake sediments were derived from underlying Chisana and Gravina-Nutzotin belt strata, as well as from North America (e.g., Yukon-Tanana terrane), indicating deposition after Wrangellia accreted against North America (Trop et al. 2020).

Wrangellia Composite Terrane

The Wrangellia composite terrane (also referred to as the Insular composite terrane) includes the Alexander, Wrangellia, and Peninsular terranes. It is geographically extensive and underlies a large part of southern Alaska and western Canada (see Figure 5). In the park, rocks of the Wrangellia composite terrane are situated between the Gravina-Nutzotin belt to the north and the Chugach terrane to the south (see Figure 9). The Alexander terrane is the oldest and easternmost portion of the Wrangellia composite terrane; it extends from the park southeast into Yukon Territory, the Alaska Panhandle, and British Columbia (see Figure 5 and Figure 9). The Wrangellia terrane forms the central part of the Wrangellia composite terrane and is found extensively within the park (see Figure 9 and the GRI poster). The Peninsular terrane is the furthest west component of the Wrangellia composite terrane, extending from the Talkeetna Mountains to the Alaska Peninsula. Rocks of the Peninsular terrane are only found in one small area of the park but are more extensive in the western part of the map area (see the GRI poster).

The Alexander terrane is composed of Late Proterozoic to middle Paleozoic rocks. The park contains one geologic unit, the Kaskawulsh Group (**PZk**), that has been tentatively assigned to the Alexander terrane (see the GRI poster). The Kaskawulsh Group crops out in the park in the St. Elias Mountains, around the Barnard and Chitina glaciers. The Kaskawulsh Group consists of rocks that represent the remnants of oceanic crust and marine reefs that formed during the early and middle Paleozoic Era. These rocks have been metamorphosed to the upper greenschist metamorphic facies and at some localities, they are intensely folded (see Figure 10). The Kaskawulsh Group is at least several thousand feet thick and continues eastward into the Yukon Territory. In the Barnard Glacier area, a Middle Pennsylvanian pluton called the Barnard Glacier pluton (**PNm**) intrudes into both the Kaskawulsh Group (which has been tentatively assigned to the Alexander terrane) and Wrangellia terrane rocks to the west. The pluton intruding into both terranes supports the idea that the Alexander terrane and Wrangellia terrane were already adjacent to each other and evolving together by at least 310 million years ago. However, other stratigraphic, paleontological, and paleomagnetic data indicate marked differences between the Wrangellia and Alexander terranes later in geologic time (e.g., during the Triassic Period), which questions this interpretation that the Wrangellia composite terrane was formed as early as the Pennsylvanian (Jones et al. 1977; Hillhouse 1977; Caruthers and Stanley 2008).

The Wrangellia terrane, named after the Wrangell Mountains, where it was first described, is made up of late Paleozoic rocks associated with the Skolai-Tetelna volcanic arc, the Triassic Nikolai Greenstone, and overlying Triassic–Jurassic shallow marine sedimentary rocks (Jones et al. 1977). Rocks of the Wrangellia terrane are widespread within the park, underlying at least 50% of the area (see the GRI poster). The stratigraphy of the Wrangellia terrane differs between the northern part of the park (the eastern Alaska Range/northern Wrangell Mountains) and the southern part of the park (southern Wrangell Mountains/St. Elias Mountains). The boundary between these areas roughly correlates with the spine of the Wrangell Mountains. While most of the geologic units in these two areas differ, the rocks are generally equivalent and can be correlated between the north and south (Figure 11).

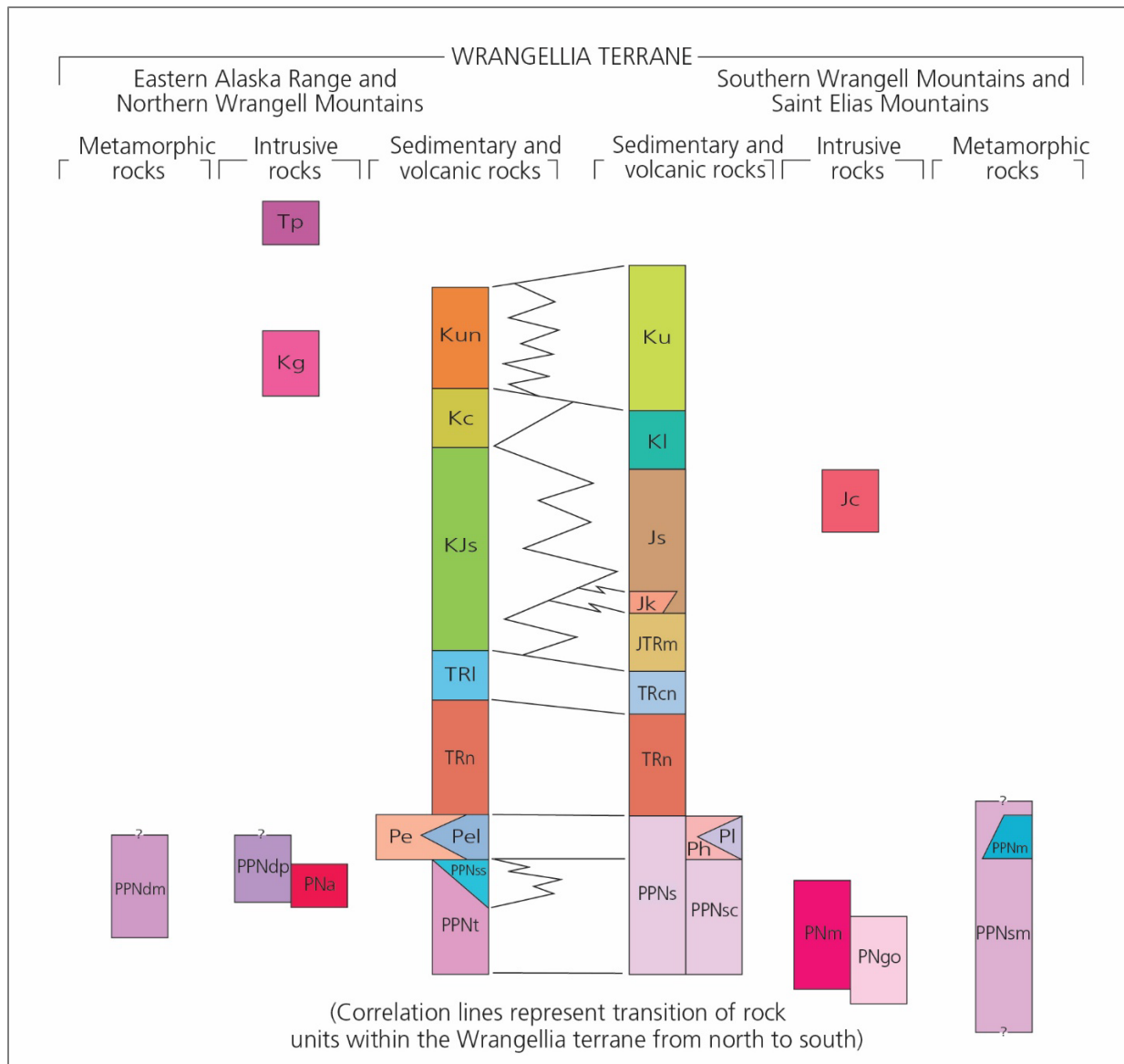


Figure 11. Stratigraphic column and correlation chart for the geologic units of the Wrangellia terrane. The rocks of the Wrangellia terrane include upper Paleozoic strata associated with the Skolai-Tetelna arc (PPNdm, PPNdp, PNa, Pe, Pel, PPNss, PPnt, PPNs, Ph, PI, PPNsc, PNm, PNgo, PPNsm, and PPNm), the Triassic Nikolai Greenstone (TRn), Late Triassic and Early Jurassic sedimentary rocks (TRcn, TRI, and JTRm), Jurassic sedimentary rocks (Jk and Js), Jurassic plutons (Jc), and Cretaceous sedimentary rocks (KI and Ku). Also included on this diagram are rocks of the Gravina-Nutzotin belt (KJs, Kc, Kun, and Kg).

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The base of the Wrangellia terrane is an upper Paleozoic assemblage of intrusive igneous, metamorphic, volcanic, and sedimentary rocks that formed along the Skolai-Tetelna volcanic arc. A volcanic arc is a chain of volcanoes that results from the subduction (downward movement) of oceanic crust beneath other crust, like the modern Wrangell and Aleutian arcs. The downgoing

tectonic plate melts the overlying rock (e.g., “mantle wedge”), creating magma that eventually rises to the surface and forms volcanoes. Remnants of the Skolai-Tetelna volcanic arc include rocks that formed deep underground in the roots of the arc, the magmatic core that fed the overlying volcanoes, and the volcanic edifice itself. Portions of oceanic crust and sedimentary rocks that flanked the arc are also found in the park. The Strelna Metamorphics (**PPNsm**, **PPNm**), a diorite complex (**PPNdm**, **PPNdp**), and gabbro and orthogneiss (**PNgo**) preserve the deepest roots of the Skolai-Tetelna arc and surrounding oceanic crust. These rocks are mostly found in a northwest-southeast trending band to the south of the Chitina River. The magmatic core of the Skolai-Tetelna volcanic arc is preserved by intrusive igneous rocks that include the Ahtell pluton (**PNa**), which is found in the Alaska Range just north of the park boundary, and the Barnard Glacier pluton (**PNm**), which is in the area surrounding Barnard Glacier. The Tetelna Volcanics (**PPnt**), the Station Creek Formation of the Skolai Group (**PPNsc**), and the Slana Spur Formation of the Mankomen Group (**PPNss**) all contain volcanic and volcanoclastic rocks that erupted out of the Skolai-Tetelna volcanic arc. Sedimentary rocks that formed around the Skolai-Tetelna volcanic arc make up the Eagle Creek Formation of the Mankomen Group (**Pe**, **Pel**) and the Hansen Creek Formation of the Skolai Group (**Ph**, **Pl**). These volcanic and sedimentary rocks associated with the Skolai-Tetelna volcanic arc are scattered within the park to the north of the Chitina River, occurring in the eastern Alaska Range, Wrangell Mountains, and St. Elias Mountains.

The Nikolai Greenstone (**TRn**) is a thick, widespread Triassic unit that overlies rocks of the Skolai-Tetelna arc (see the GRI poster). It is composed primarily of greenstone, which is basalt that has been metamorphosed. Although the Nikolai Greenstone has been metamorphosed to the prehnite-pumpellyite metamorphic facies (see Figure 10), the primary mineralogy and texture of the basalt are mostly preserved. The Nikolai Greenstone preserves the remains of a massive package of basalt lavas (e.g., flood basalt province) that erupted during a 7-million to 8-million-year interval in the Middle to Late Triassic. The basalts that constitute the Nikolai Greenstone have an aggregate thickness of nearly 3,000 m (10,000 ft) and occur widely on the north and south flanks of the Wrangell Mountains, on the south flank of the eastern Alaska Range, and in adjacent parts of Canada as far as Kluane Lake. The rocks of the Nikolai Greenstone are well exposed at Bonanza Ridge and Donoho Peak, as well as other areas around the town of Kennecott. Correlative Triassic basalts occur to the west on the Alaska Peninsula and to the east near Haines, Alaska. Additionally, another unit of Triassic basalt called the Karmutsen Formation occurs on Haida Gwaii and Vancouver Island in British Columbia. The Karmutsen Formation is likely part of the same volcanic field as the Nikolai Greenstone but was offset by faulting after the Triassic Period. Altogether, volumetric estimates for the Nikolai Greenstone exceed 250,000 km³ (60,000 mi³), which is enough to bury the entire state of Oregon with a quarter mile of basalt.

Paleomagnetic studies of the Nikolai Greenstone near McCarthy indicate that these rocks formed at least 27° further south than their predicted position in the Triassic, assuming they had been part of North America (Hillhouse 1977). Some rocks, such as the basalts of the Nikolai Greenstone, retain traces of the Earth’s magnetic field at the time they formed. These traces will correlate to the latitude at which the rocks formed and can be used to understand the paleogeography of far-traveled terranes like the Wrangellia terrane. Studies of the stratigraphy and molluscan fossils of the Wrangellia

terrane also support an exotic origin compared to other nearby rocks of a similar age (Jones et al. 1977). For example, the Chitistone Limestone that overlies the Nikolai Greenstone contains distinctive deposits that were interpreted to have formed near the equator in the Late Triassic; however, the part of North America where the Wrangellia terrane is now found was not located near the equator at that time. According to the paleomagnetic data, the Nikolai Greenstone has been displaced northward by at least 2,900 km (1,800 mi) by large-scale tectonism since the Triassic Period (252 million–201 million years ago).

A Late Triassic to Early Jurassic package of sedimentary rocks overlies the Nikolai Greenstone (see the GRI poster). In ascending order, the geologic units that make up this sedimentary package are the Chitistone Limestone (**TRcn**), Nizina Limestone (**TRcn**), and McCarthy Formation (**JTRm**; Figure 12). These rocks record a marine sequence that starts out shallow and becomes deeper over time. The lowermost part of the Chitistone Limestone is composed of shallow-water dolomite that formed in an intertidal-supratidal setting. In localized areas, it contains fossils and sedimentary features such as algal-mat chips, stromatolites, and evaporate relics that are indicative of a sabkha environment. A sabkha is a restricted, tidal mudflat characterized by high evaporation and the precipitation of evaporite-saline minerals. The lower Chitistone Limestone contains world-class Kennecott-type copper deposits that are the result of hydrothermal interactions between the underlying Nikolai Greenstone and the sabkha rocks (see “Mineral Resources”; Price et al. 2014). The upper part of the Chitistone Limestone is composed of dolomite and limestone that formed in shallow to moderately deep marine depositional environments. This deepening trend continues with the overlying Nizina Limestone, which is composed of limestones and sometimes cherty rocks, and culminates with the deposition of the deep-water rocks of the McCarthy Formation. The McCarthy Formation formed during the Late Triassic and Early Jurassic and is composed of sedimentary rocks such as spiculite, chert, and limestone.

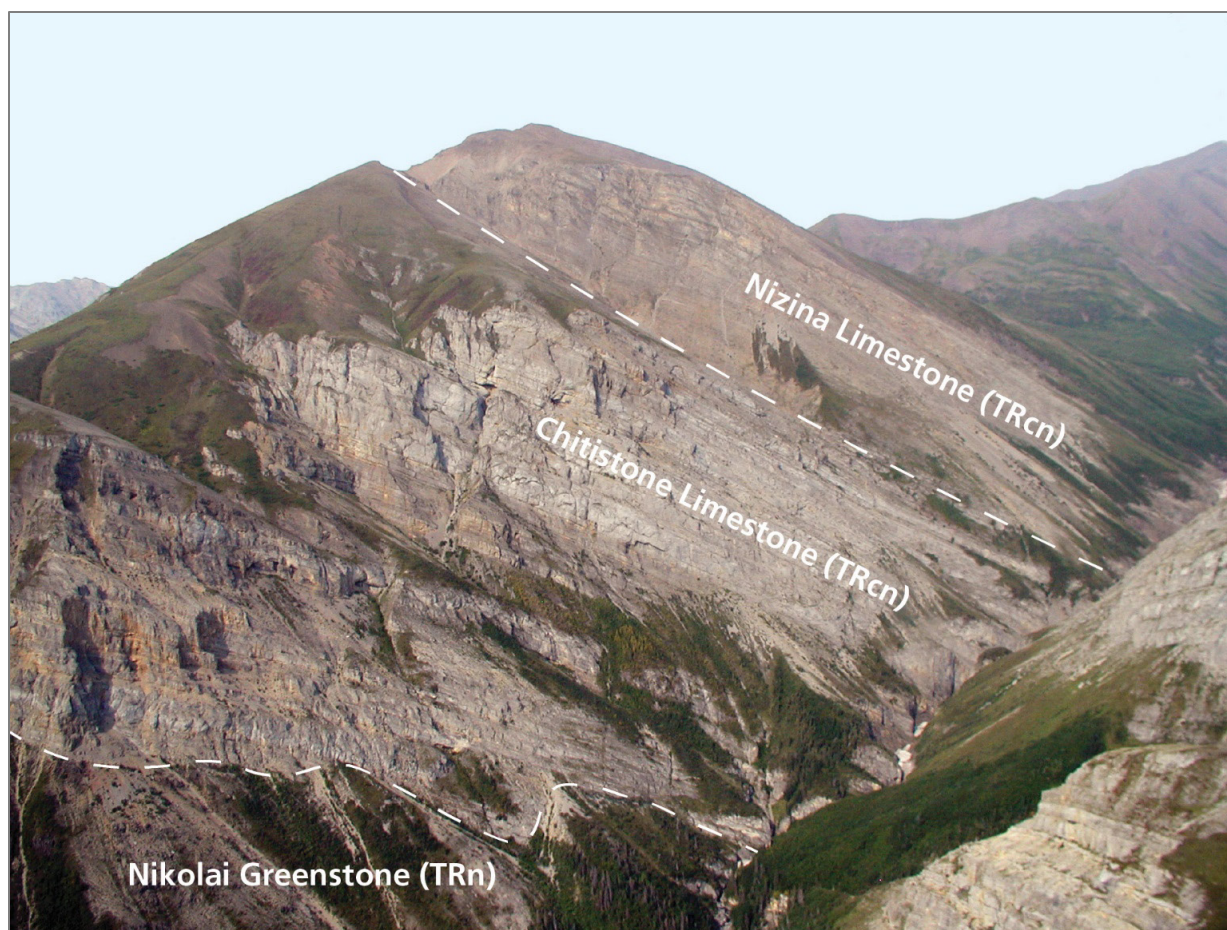


Figure 12. Photograph of the Nikolai Greenstone, Chitistone Limestone, and Nizina Limestone at Green Butte. The Nikolai Greenstone (bottom left) underlies the Chitistone Limestone, which in turn underlies the Nizina Limestone. This stratigraphy is exposed on Green Butte, located approximately 7.5 km (4.5 mi) east of the town of Kennecott. The contact between the Nikolai Greenstone and Chitistone Limestone is host to some of the richest copper deposits ever discovered. See the “Mineral Resources” section of this report for more information.

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A more than 1,500 m (5,200 ft) thick sequence of Jurassic sedimentary rocks (**Js**, **Jk**) overlies the McCarthy Formation (see the GRI poster). The complete sequence only occurs in the McCarthy area, indicating this area was the deepest part of the depositional basin. Geologic units that make up this succession are (in ascending order) the Lubbe Creek Formation, Nizina Mountain Formation, Kotsina Conglomerate, and Root Glacier Formation. In the GRI GIS data, all these formations are mapped together in unit **Js**, except for the Kotsina Conglomerate (**Jk**). Kotsina Conglomerate contains fossil-rich sedimentary rocks such as spiculite, greywacke, mudstone, and conglomerate that formed in a shallow marine and nearshore environment. Fossils from these rocks, including ammonites, range in age from Early to Late Jurassic (201 million–145 million years ago). The Middle and Upper Jurassic portions of the sedimentary succession are characterized by thin lavas, ash beds, and volcanic detritus, indicating volcanic arc activity from about 170 million to 150 million years ago. This volcanic arc is known as the Chitina arc. The upper part of the sequence has shallow-

water conglomerates and disconformities (gaps in sedimentation) that may be a result of the earliest collision of the Wrangellia composite terrane with North America.

Jurassic granitic plutons (**Jc**) formed the roots of the Chitina arc and are widespread along the southern margin of the Wrangellia terrane (see the GRI poster). These rocks are known as the Chitina Valley batholith, and they intrude into all the older rocks of the Wrangellia and Alexander terranes. Plutons can be classified based on the relative proportions of certain minerals (Figure 13). The composition indicates the plutons of the Chitina Valley batholith consist of tonalite, quartz diorite, and granodiorite. Radiometric dating indicates they formed between 175 million and 138 million years ago. The tectonic event that created the Chitina arc is believed to be east-dipping subduction along the outboard side of the Wrangellia composite terrane.

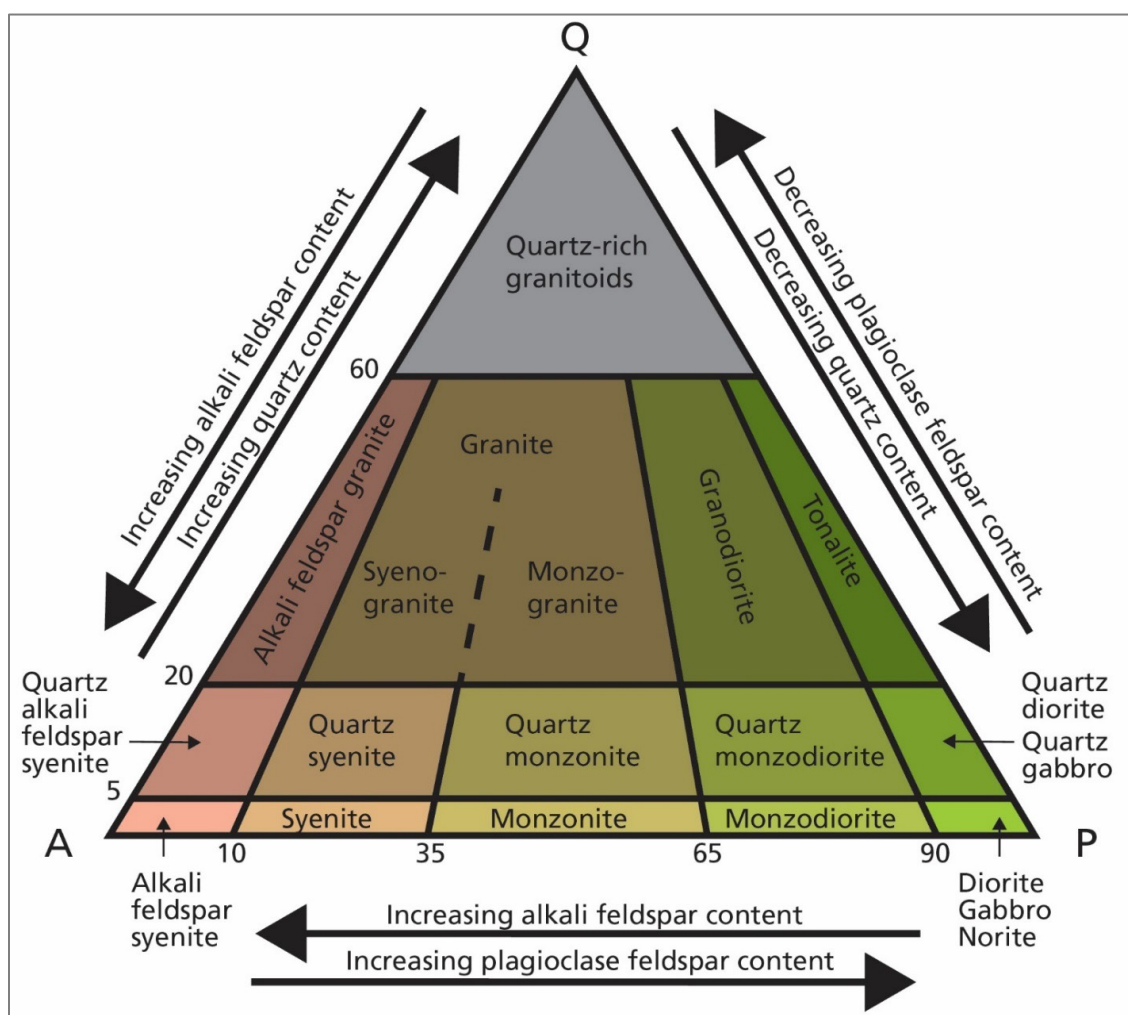


Figure 13. Diagram showing the classification of felsic intrusive igneous rocks. Classification is based on the relative percentages of the minerals quartz (Q), alkali feldspar (A), and plagioclase feldspar (P). The plutons of the Chitina Valley batholith are classified as tonalite, quartz diorite, and granodiorite based on their mineral composition.

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Cretaceous marine sedimentary rocks are widespread along the southern flank of the Wrangell Mountains (see the GRI poster). These rocks accumulated at roughly the same time as those of the Gravina-Nutzotin belt, but instead of forming on the north side of the Wrangellia terrane, they formed along the southern margin, adjacent to the Chisana arc (see Figure 11). Map units include the shallow marine sedimentary rocks of the Kennicott, Kuskulana Pass, and Berg Creek formations (**Kl**) and the shallow to moderately deep sedimentary rocks of the MacColl Ridge, Chititu, Schulz, and Moonshine Creek formations (**Ku**). These rocks are separated from the underlying Jurassic rocks by major unconformities (gaps in sedimentation). The unconformities are related to a mountain-building event that occurred as the Wrangellia composite terrane was being accreted to North America in the Cretaceous Period. This accretion happened no later than 85 million years ago.

Southern Margin Composite Terrane

The Southern Margin composite terrane encompasses the Chugach and Prince William terranes (see Figure 9). These terranes are also sometimes referred to collectively as the Chugach-Prince William terrane (Davidson and Garver 2017). The Southern Margin composite terrane is south of the Wrangellia composite terrane and is separated by the Border Ranges fault system. In the park, these rocks are found in a northwest-southeast trending band that extends through the Chugach and St. Elias Mountains. Both the Chugach and Prince William terranes are composed of deep-sea rocks that make up a Mesozoic-Cenozoic accretionary complex. An accretionary complex forms adjacent to a subduction trench, where sediments and rocks from the subducting (i.e., downgoing) plate, as well as a smaller proportion of sediment from the upper plate, are scraped off and accreted to the edge of the upper plate (see Figure 4). This accretionary complex is thought to have formed through the subduction of oceanic crust beneath the Wrangellia composite terrane. The Southern Margin composite terrane constitutes one of the thickest and most extensive subduction-related accretionary complexes in the world. It stretches 2,100 km (1,300 mi) along southern Alaska. The rocks that make up the Southern Margin composite terrane are up to 200 km (125 mi) thick and have a total estimated volume of over 800,000 mi³ (3,000,000 km³).

The oldest part of the Chugach terrane in the park includes Late Triassic (possibly), Jurassic, and mid-Cretaceous *mélange* units such as the McHugh Complex (**KJm**; see the GRI poster). The McHugh Complex is not widely distributed in the park, found between segments of the Border Ranges fault system to the east and west of the Tana River. “*Mélange*” is French for “mixture” and describes a geologic unit composed of many different deep-sea rocks that have been chaotically mixed and variably metamorphosed by the subduction process. Isolated and identifiable blocks range in size from centimeters to hundreds of meters. Rock types found within the *mélange* units include pillow basalts, altered volcanic ash beds, and deep-sea sedimentary rocks such as chert, greywacke, and argillite. These rocks were derived from oceanic crust subducting beneath the Wrangellia composite terrane, sediments eroded from the surrounding volcanic arcs, and fragments of older rocks from the southern margin of the Wrangellia composite terrane. Although microfossils are rarely preserved from this terrane, microfossils known as radiolarians (sourced from the chert of the *mélange* units) indicate a Middle Triassic to mid-Cretaceous age for these sediments, thereby indicating that the *mélange* formed over a long period of subduction beneath the Wrangellia composite terrane.

The Chugach terrane also includes the Late Cretaceous Valdez Group (**Kvu**, **Kvv**, **Kv**, **Kvm**, and **Kvg**; see the GRI poster). The Valdez Group is widely distributed in the park in the Chugach Mountains and in the St. Elias Mountains to the east of Malaspina Glacier. The Valdez Group is composed of metamorphosed basalt and clastic marine sedimentary rocks (which have been referred to as “flysch” in older publications). The basaltic rocks have chemistry indicative of an island arc setting, which has been referred to as the Kluane arc. As the Kluane arc approached the margin of the Wrangellia composite terrane (which by that time had accreted to North America), basalts and volcanic ash beds from the arc were mixed with marine sedimentary rocks derived from the continental margin. The sedimentary rocks are characterized by their thickness, fossil-poor nature, and repetitive bedding. The Valdez Group is thick (over 2.5 mi [4 km]) and was deposited rapidly over a span of about 5 million years (between 75 million and 70 million years ago). Studies focused on understanding the source of the Valdez Group sediments indicate it was probably derived from Upper Cretaceous magmatic rocks found in the Kluane Lake area of Yukon Territory. The rocks of the Valdez Group were metamorphosed about 50 million years ago during the Eocene Epoch to the greenschist and amphibolite metamorphic facies (see Figure 10). This high-temperature, low-pressure metamorphic event also affected rocks outside the park in southeast Alaska; rocks that were affected by this metamorphic event are collectively referred to as the Chugach metamorphic complex (Pavlis and Sisson 1995).

The Prince William terrane is composed of the late Paleocene and early Eocene Orca Group (**Tos**, **Tov**; see the GRI poster). The rocks of the Prince William terrane are separated from those of the Chugach terrane by the Contact fault system (see Figure 9). The Prince William terrane is only exposed in the park in high peaks surrounded by glacial ice of the Bagley Icefield and Yahtse Glacier; however, these rocks are found more broadly to the west of the park around the mouth of the Copper River and along the coast of Prince William Sound. Like the Valdez Group, the Orca Group is composed of clastic marine sedimentary rocks and basalt. The sedimentary rocks of the Orca Group were deposited in deep-sea fans that developed adjacent to the rapidly uplifting and eroding continental margin. The source of the Orca Group sediments was likely the Coast Mountains of British Columbia and southeast Alaska, which were uplifting during the Orca Group’s deposition between 60 million and 50 million years ago. Similar to the Valdez Group, the Orca Group is at least a few miles in total thickness and was formed by rapid deposition within a span of no more than 10 million years. The source of the volcanic rocks is likely seamounts or active ridges that existed on the oceanic crust as it subducted beneath the North American margin. The Orca Group is also part of the Chugach metamorphic complex, meaning it was affected by the same event approximately 50 million years ago that metamorphosed the Valdez Group. However, metamorphism of the Orca Group was weaker than that of the Valdez Group.

The rocks of the Southern Margin composite terrane were intruded by granitic plutons (**Tgp**) during the Eocene Epoch (56 million–34 million years ago; see the GRI poster). Within the park, the distribution of plutons is mostly restricted to a few areas in the Chugach Mountains. The plutons are compositionally granite, granodiorite, and diorite and date to about 50 million years ago (see Figure 13 for the classification of the intrusive rocks). Features of the plutons and their chemistry indicate they were derived by partial melting of the Southern Margin composite terrane accretionary

wedge. Tectonically, these plutons are located unusually close to the subduction trench, an area that would not usually experience magma intrusion. The near-trench plutons in the park are part of a larger belt of Paleocene–Eocene plutons that spans most of the southern Alaska margin, from Sanak Island to Baranof Island (the Sanak-Baranof belt of Hudson et al. 1979).

The emplacement of near-trench plutons and formation of the Chugach metamorphic complex have been interpreted as the result of subduction of an oceanic spreading ridge (area where magma from the mantle is forming new crust) beneath the southern Alaskan continental margin during the Eocene Epoch (Bradley et al. 1993; Pavlis and Sisson 1995; Davidson and Garver 2017). The Southern Margin composite terrane is an accretionary complex that formed adjacent to a subduction trench. This tectonic setting is usually not characterized by high-temperature metamorphism or magmatic activity (e.g., pluton emplacement). However, the presence of the high-temperature, low-pressure Chugach metamorphic complex and near-trench plutons indicate an unusual heat source along the subduction zone. These unusual characteristics have been attributed to the subduction of an oceanic spreading ridge under the Alaskan continental margin during Eocene time (Bradley et al. 1993; Pavlis and Sisson 1995; Davidson and Garver 2017). Additional evidence from outside the park that supports this hypothesis includes the presence of oceanic crust (e.g., the Resurrection Ophiolite just outside Kenai Fjords National Park) that accreted to southern Alaska during the same timeframe (Davidson and Garver 2017).

Yakutat Terrane

The Yakutat terrane (also referred to as the “Yakutat microplate” or “Yakutat block”) is the furthest south of the park’s terranes and underlies the southern coastal area (see Figure 9). It is bounded to the north and east by the Chugach-St. Elias and Fairweather fault systems, and the subducted part of the Yakutat terrane extends inboard beneath at least the central Alaska Range, south of Fairbanks. The Dangerous River structural zone separates two components within the Yakutat terrane. To the east, the lowermost rocks of the Yakutat terrane are Cretaceous rocks of the Yakutat Group (**Kyf**, **Kym**) and schist of Nunatak Fjord (**Kyn**). These rocks are absent to the west, and instead the basement rocks for the Yakutat terrane are Paleocene oceanic basalts. Unlike the other terranes found in the park, the Yakutat terrane is still moving with the Pacific plate and is in the process of accreting to North America. Movement of the Yakutat terrane is about 5 cm (2 in) per year toward the northwest (Haeussler and Plafker 2003). This active accretion involves major tectonic stress and is the driving force for the uplift of the highest coastal mountain range on Earth, the St. Elias Mountains.

The eastern part of the Yakutat terrane is composed of Cretaceous rocks of the Yakutat Group (**Kyf**, **Kym**) and schist of the Nunatak Fjord (**Kyn**; see the GRI poster). The Yakutat Group is made up of marine clastic sedimentary rocks (**Kyf**) and mélangé deposits (**Kym**) that have been intruded by Eocene plutons (**Tgp**). The Yakutat Group is located around Malaspina Glacier in the park. These rocks are similar in composition and age to those found in the Chugach terrane, suggesting that they represent displaced fragments of the Chugach terrane. The Yakutat Group was likely displaced by dextral (right-lateral) movement on the Fairweather-Queen Charlotte fault system during the late Cenozoic Era. Restoration of these rocks along this fault places their original position near the

present location of Haida Gwaii (an island archipelago off the coast of British Columbia, formerly known as the Queen Charlotte Islands).

The western part of the Yakutat terrane in the park includes the Paleocene and Eocene Kulthieth Formation (**Tk**), the Eocene–Miocene Poul Creek Formation (**Tps**), the Oligocene and Miocene igneous rocks (**Tm**), and the Miocene–Holocene Yakataga Formation (**QTy**; see the GRI poster). In the park, these rocks are found along the coast to the west of Malaspina Glacier. The Kulthieth Formation is composed of nonmarine to marine sedimentary rocks with minor coal beds. The rock characteristics and their fossils indicate that this formation developed in subtropical climatic conditions. Some of the siltstones of the Kulthieth Formation are organically rich and produce oil and gas seeps in the Samovar Hills area. Additionally, the Paleocene–Eocene basalts of the Hubbs Creek volcanics, the siltstone-rich Stillwater Formation, and the siltstone of Oily Lake are included in unit **Tk**. The Poul Creek Formation contains marine sedimentary rocks and minor volcanic ash. Parts of this formation are characterized by the mineral glauconite, which is indicative of restricted circulation and slow sedimentation rates. The Yakataga Formation is a thick sequence of sedimentary rocks that were sourced from erosion of the Chugach and St. Elias Mountains and deposited in a marine environment next to the continental shelf. Similar deposits accumulate along the northern Gulf of Alaska today that, when transformed into rock, will look just like the rocks of the Yakataga Formation (Figure 14). Some of the rocks in the Yakataga Formation show the influence of active tidal glaciers. For example, the formation contains diamictites (poorly sorted glacial deposits) and siltstones containing larger stones that were rafted to sea by ice.



Figure 14. Photograph of rocks of the Yakataga Formation (QTy) on the west coast of Icy Bay. The Yakataga Formation is the youngest unit of the Yakutat terrane and is composed of interbedded sedimentary rocks that formed along the continental shelf off the coast of Alaska and British Columbia. Although the Yakataga Formation formed in the ocean, it has been uplifted along with the other rocks that make up the St. Elias Mountains by tectonic forces associated with the collision of the Yakutat terrane with North America.

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The Yakutat terrane was displaced about 600 km (375 mi) northward along the Fairweather-Queen Charlotte fault system during the late Cenozoic time before colliding with and subducting beneath the southern margin of Alaska. The Yakutat terrane has a shared origin and early history with the Siletzia terrane, which is found today in Oregon and Washington (Donaghy et al. 2025). Based on similarities in age and composition of the older strata of the Yakutat and Siletzia terranes, they formed as conjugate oceanic plateaus on different sides of an Eocene spreading ridge offshore of the Pacific Northwest before colliding with the North American margin (Donaghy et al. 2025). While the Siletzia terrane accreted to the coast of Oregon and Washington, the Yakutat terrane was displaced about 600 km (375 mi) northward along the Fairweather-Queen Charlotte fault before colliding with and subducting beneath southern Alaska.

The Yakutat terrane is continuing to collide and subduct beneath Alaska today. Convergence of the Yakutat terrane with the southern Alaskan margin is causing uplift of the Chugach and St. Elias Mountains. Subduction of the Yakutat terrane beneath Alaska also formed the source for volcanism in the Wrangell arc, which began about 30 million years ago (Brueseke et al. 2019). Since this

subduction and related volcanism began, over half of the Yakutat terrane has been thrust under North America; the subducted portion of the terrane is believed to extend as far inland as the city of Talkeetna (Trop et al. 2012). This complex pattern of active deformation will continue until the remainder of the Yakutat terrane is either completely subducted or accreted to North America.

Wrangell Arc

Map units: Individual volcanic eruptive centers of the Wrangell arc (**Qwws, Qwwv, Qwd, Qwdr, Qws, Qwsr, Qwc, Qwcr, Qwj, Qwjd, QTwt**) and other volcanic deposits (**Qvd, Qpf, Qbc, QTw, QTwi, QTwr, Th, Tg, Tw, Twr, Twd**)

The Wrangell Mountains in the northern half of the park have been primarily built by volcanic eruptions associated with the Wrangell arc. The Wrangell arc is a group of igneous rocks and deposits in Alaska and Yukon that erupted over the past 30 million years (Figure 15; Richter et al. 1995; Brueseke et al. 2019). These volcanic deposits erupted on top of rocks of the accreted terranes (see “Bedrock Geology”) and therefore composed an overlap assemblage. Rocks of the Wrangell arc cover an area of about 9,200 km² (3,500 mi²) in the Wrangell and St. Elias Mountains in Alaska and northwest Yukon Territory, and similar volcanic rocks of the Wrangell volcanic belt continue to the southeast in Yukon Territory and British Columbia (Richter et al. 1995; Brueseke et al. 2019; Brueseke et al. 2023). The Wrangell arc is primarily characterized by the eruption of effusive (relatively fluid) lava that built broad shield volcanoes, although a few large stratovolcanoes are also present (Richter et al. 1995). Volcanoes of the Wrangell arc form many of the prominent peaks in the park, including Mount Wrangell (**Qwws, Qwwv**), Mount Drum (**Qwd, Qwdr**), Mount Sanford (**Qws, Qwsr**), Capital Mountain (**Qwc, Qwcr**), Tanada Peak (**QTwt**), Mount Jarvis (**Qwj, Qwjd**), Mount Churchill, and Mount Blackburn (Figure 15 and Figure 16; also see the GRI poster). The US Geological Survey report “Guide to the Volcanoes of the Western Wrangell Mountains, Alaska—Wrangell-St. Elias National Park and Preserve” by Richter et al. (1995) provides a comprehensive overview of the Wrangell arc, as well as detailed descriptions of individual volcanoes.

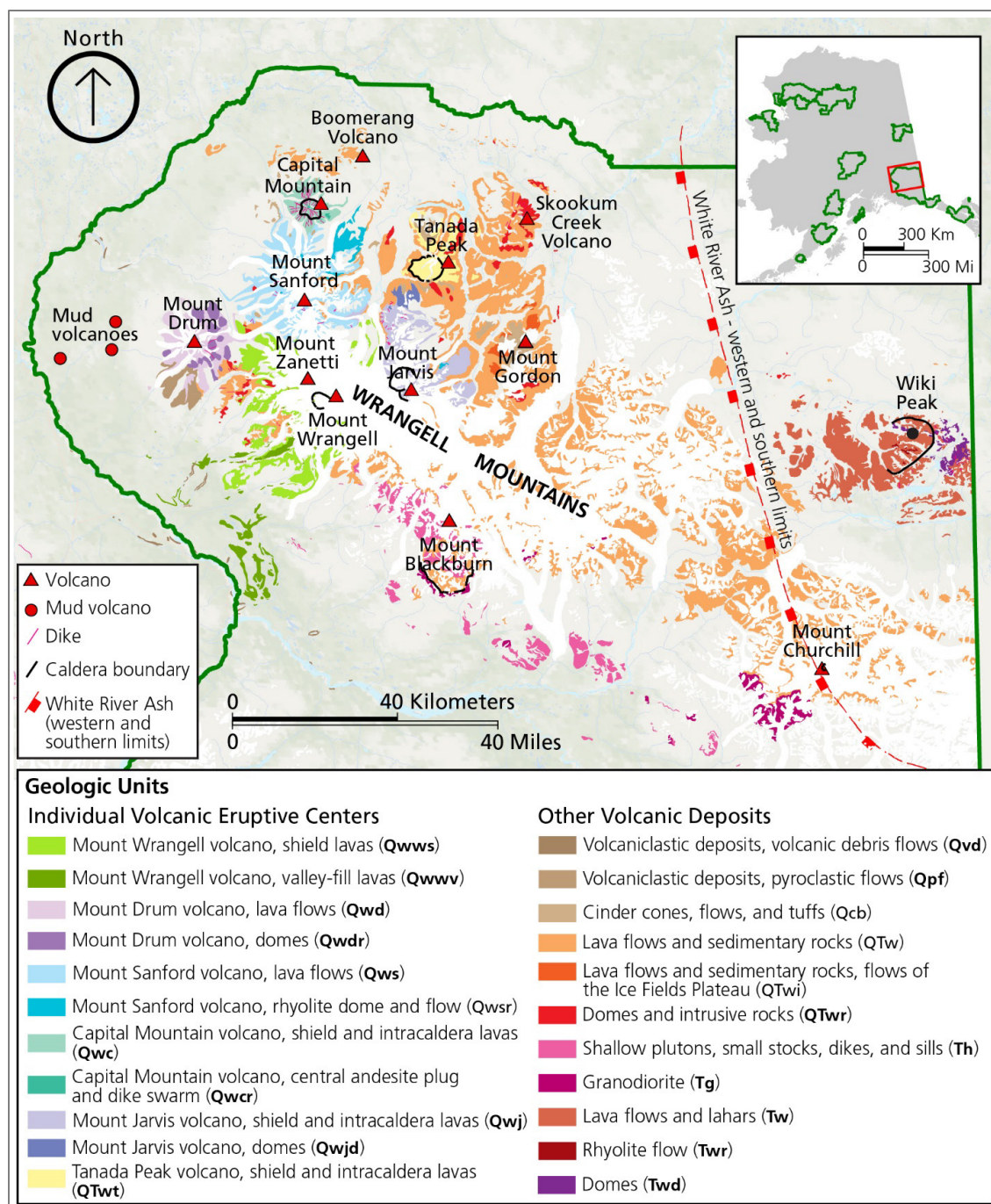


Figure 15. Geologic map of the Wrangell arc. The Wrangell arc is composed of igneous rocks that erupted over the past 30 million years and make up most of the Wrangell Mountains. Volcanic centers are labeled with red triangles, mud volcanoes are labeled with red circles (discussed in the “Geothermal Features” section of this report), and dikes are labeled with pink lines. Mapped caldera boundaries are outlined in black, and the western and southern limits of the White River Ash are marked with the dashed red line. Igneous geologic units of the Wrangell arc are depicted, including those that have been mapped based on individual volcanic eruptive centers and other volcanic deposits that have not been attributed to individual volcanoes.

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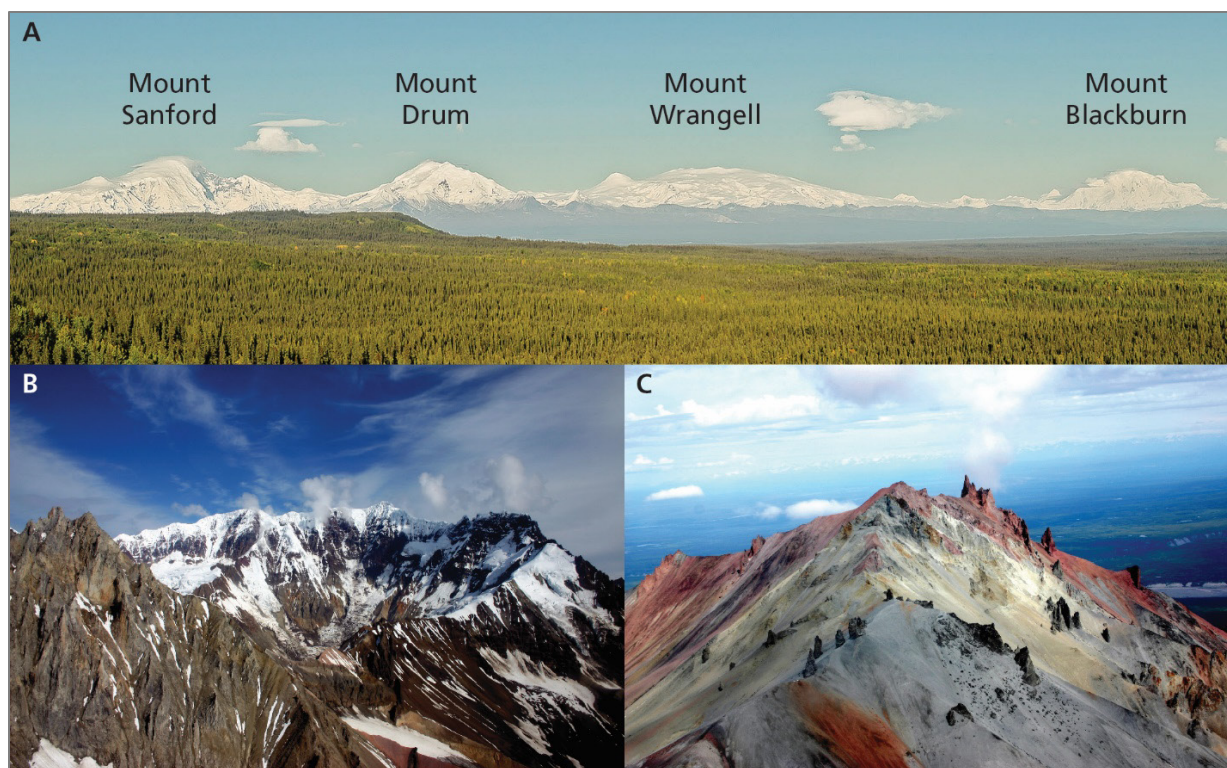


Figure 16. Photographs of volcanoes and volcanic features in the park. (A) Photograph of four major, <8-million-year-old volcanic peaks in the Wrangell Mountains: Mount Sanford, Mount Drum, Mount Wrangell, and Mount Blackburn. (B) Photograph of the summit of Mount Drum from the southeast. Mount Drum's most recent eruptive activity occurred between 250,000 and 150,000 years ago and entailed violently explosive eruptions that destroyed the top and much of the southwest face of the volcano. The resulting "crater," referred to as the "amphitheater" by Richter et al. (1995), can be seen in the central part of the photograph, surrounded by ridges that represent the sides of the summit that were not destroyed. (C) Photograph of igneous rocks and volcanic dikes in the Wrangell Mountains.

A) NPS / BRYAN PETRYL, B) NPS, C) NPS

Most of the volcanism in southern Alaska, including that of the Wrangell Arc, is the result of the Pacific plate and Yakutat terrane subducting (moving downward) beneath the North American plate (see Figure 4 for a diagram depicting the tectonic setting). In the southwest, the Pacific plate is subducting beneath Alaska in a typical manner, creating the volcanoes of the Aleutian volcanic arc (e.g., Redoubt and Iliamna volcanoes in Lake Clark National Park and Preserve). In southcentral Alaska, the plate margin transitions to the subduction of the Yakutat terrane, which is subducting at a shallower angle compared to the Pacific plate. The Wrangell arc is located along the edge of the subducting Yakutat block. The oldest rocks of the Wrangell arc coincide with the initiation of subduction of the Yakutat block (Enkelmann et al. 2008; Brueseke et al. 2019).

Igneous activity in the Wrangell arc began about 30 million years ago and has continued to this day (Brueseke et al. 2019). Between about 30 million and 17 million years ago, magmatism (magma-forming activity) occurred on the northern side of the Wrangell and St. Elias mountains, on both sides of the Totschunda fault (Trop et al. 2022), primarily around Wiki Peak and east of Chisana.

Magmatism then shifted southeast into Yukon Territory between about 17 million and 10 million years ago (Trop et al. 2022). Following that, magmatism shifted westward again into Alaska, along the southern flank of the Wrangell and St. Elias mountains, and finally into the western Wrangell Mountains (Trop et al. 2022). Many of the peaks in the western Wrangell Mountains were active within the last 2 million years, including Tanada Peak volcano (1.8 million–0.9 million years ago), Mount Jarvis volcanoes (1.7 million–1 million years ago), Capital Mountain volcano (1 million years ago), Mount Sanford volcano (0.9 million–0.5 million years ago), Mount Drum volcano (0.6 million–0.2 million years ago), and Mount Wrangell (0.64 million years ago–present; Richter et al. 2006; see the GRI poster). Although Mount Wrangell has no confirmed eruptions in historic times, it has active fumaroles (openings that release volcanic gas and steam) at the summit and is still considered an active volcano (see “Volcanic Hazards”; Richter et al. 1995).

The volcanic deposits of the Wrangell arc are chiefly andesitic lavas that emanated from multiple eruptive centers (Richter et al. 1995). While some explosively erupted pyroclastic deposits are found across the arc and have been linked to individual volcanoes, most of the Wrangell volcanoes were built by hundreds of effusive lavas. One rare example of an explosive volcanic mass-flow deposit is the Chetaslina volcanic mass-flow deposit that records a major flank collapse of Mount Wrangell during the Pleistocene (Waythomas and Wallace 2002). However, most of the volcanoes of the Wrangell volcanic arc are composed of effusive lavas that formed broad, gently sloping shield volcanoes (e.g., Mount Wrangell). Because of their broad nature and extremely high magma production rates, the Wrangell volcanoes are also much more voluminous than a typical stratovolcano and are some of the largest Quaternary volcanoes on Earth (Richter et al. 1995; Brueske et al. 2019; Trop et al. 2022). For example, Mount Wrangell is composed of about 1,000 km³ (250 mi³) of lava, making it one of the largest active volcanoes in North America.

Almost all the known Wrangell shield volcanoes have a caldera (collapsed area) at their summit (see the GRI poster). Most of these calderas formed nonexplosively by the withdrawal of magma following an eruption. One exception is the small caldera on Mount Churchill, which is the result of a series of explosive eruptions that produced the White River Ash Bed (Richter et al. 1995; Lerbekmo 2008; Preece et al. 2014). The White River Ash Bed is composed of two lobes that erupted 1,900 and 1,147 years ago, respectively (Richter et al. 1995). These ash plumes traveled north and west from Mount Churchill, covering more than 335,000 km² (130,000 mi²) in Alaska and Canada, and the ash has been found across Greenland and northern Europe (Jensen et al. 2014) (see Figure 15 for the extent of the White River Ash Bed in the park). It is a conspicuous light gray ash layer ranging in thickness from a few centimeters (inches) to 5 m (16 ft) thick, found just under the top organic-soil layer of the ground (Richter et al. 1995; Preece et al. 2014). In addition to the shield volcanoes, smaller cinder cones are scattered throughout the Wrangell arc, with the largest being Mount Gordon (Richter et al. 1995; Preece and Hart 2004).

Geothermal Features

Map units: Mineral spring deposits (**Qms**)

Three mud-rich mineral springs, referred to as “mud volcanoes,” occur on private land within the park’s outer boundary approximately 30 km (18 mi) west of Mount Drum (Figure 17; Richter et al. 1998; see the GRI poster). The mud volcanoes are called Shrub, Upper Klawasi, and Lower Klawasi and are collectively known as the Klawasi group (Richter et al. 1998). The springs discharge warm, muddy waters that are charged with carbon dioxide (CO_2) and contain high concentrations of sodium, chloride, and bicarbonate (Nichols and Yehle 1961; Motyka et al. 1986). Broad mounds that resemble small volcanoes have built up around the springs, standing 50–100 m (150–300 ft) above the surrounding landscape (**Qms**; Nichols and Yehle 1961).

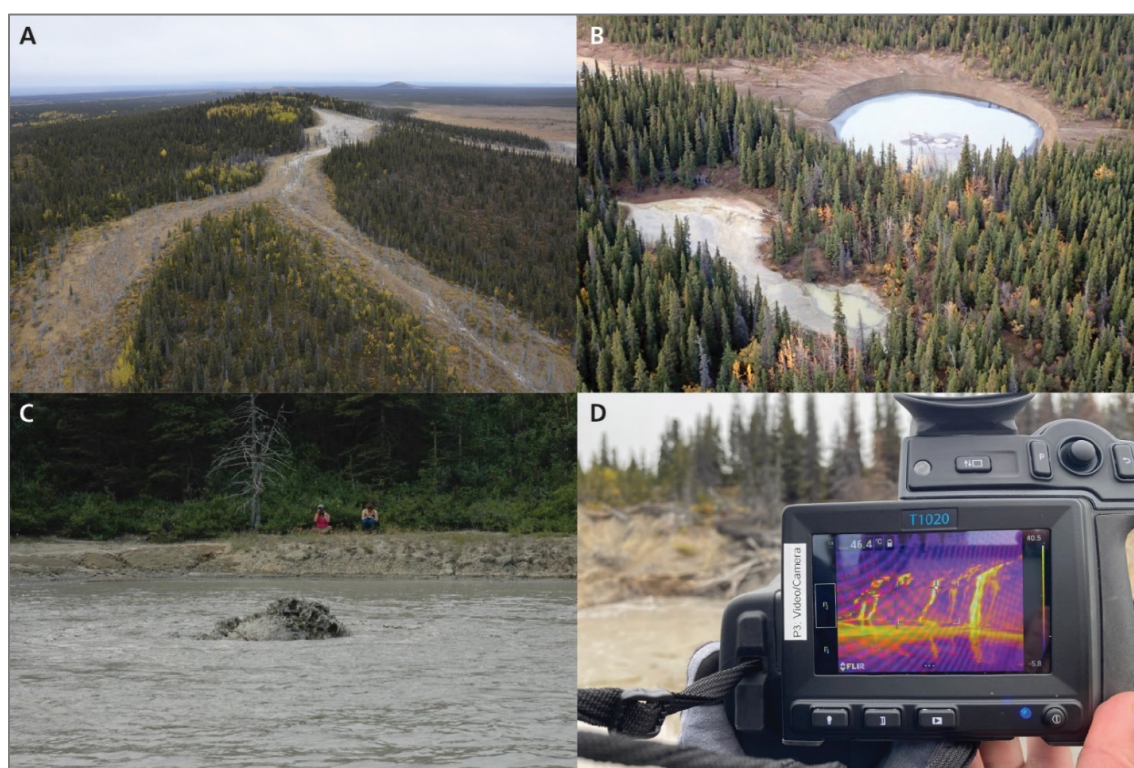


Figure 17. Photographs of the Klawasi mud volcanoes, found on the west side of the park between Mount Drum and Glennallen. The park contains three mud-rich warm springs atop hills that resemble small volcanoes, earning them the name “mud volcanoes.” (A) Photograph taken in 2021 (looking north) of Upper Klawasi mud volcano. Shrub mud volcano is visible on the skyline in the background. (B) Photograph taken in 2024 of the summit pond at Lower Klawasi mud volcano. (C) Photograph taken in 2009 of the central upwelling area (CO_2 gas) at Upper Klawasi mud volcano. The upwelling becomes significantly more vigorous on an interval that varies from minutes to 10s of minutes. The vigorous upwelling lasts for a few minutes and attains a height of as much as a meter (3 ft) above the pool level. (D) Infrared imagery taken in 2021 of the northeast wall of the main pool at the Shrub mud volcano. Measured temperatures of the flow into the main pool from vents on and above the northeast wall ranged from 49 to 54°C (120 to 130°F). The main pool is 26°C (80°F).

A) ALASKA VOLCANO OBSERVATORY (AVO)/USGS / TIM ORR, B) AVO/USGS / MAX KAUFMAN, C) AVO/UNIVERSITY OF ALASKA FAIRBANKS / GAME MCGIMSEY, D) AVO/USGS / GAME MCGIMSEY

Activity of the Klawasi mud volcanoes has varied since they were first described in the mid-1950s (Nichols and Yehle 1961; Richter et al. 1998; McGimsey et al. 2007). Since the 1950s, Upper Klawasi and Lower Klawasi have been continuously active, discharging low levels of mud-rich water and gas with temperatures typically ranging between 20°C and 25°C (68°F and 77°F; Richter et al. 1998). Shrub was thought to be virtually inactive between the 1950s and 1996; however, vigorous activity began at Shrub starting in 1996 (Richter et al. 1998). A 1997 survey noted numerous springs at the summit and on the flanks of the mud volcano with activity that ranged from quiet effusion of CO₂ to vigorous gushing of mud and gas with fountaining up to 10 m (33 ft) high (Richter et al. 1998; McGimsey and Wallace 1999). The activity observed at Shrub was more vigorous than at the other two mud volcanoes and hotter, with temperatures in 1997 measuring up to 47°C (116°F; Richter et al. 1998). Additionally, in some areas high CO₂ emissions killed vegetation up to heights of 2 m (6.6 ft) above the ground, as well as small mammals and birds (Richter et al. 1998; McGimsey and Wallace 1999). Discharge at Shrub has continued since the late 1990s, with recorded temperatures reaching as high as 57°C (135°F) in 2000 (McGimsey et al. 2007). In 2004 a large water-filled collapse pit formed near the summit, becoming the focus of activity, and springs on the flanks of Shrub dried up. The summit pool was the site of steady-state activity until 2017, when new activity began on the flanks of the mud volcano, and it was active sporadically until 2024. New springs also opened at the summit of Shrub in 2021, blanketing its summit and parts of its flank with mud. These springs were still active at the time of publication (Tim Orr, Alaska Volcano Observatory, written communication, 18 August 2025). More details about the history of activity at Shrub are available on the Alaska Volcano Observatory website (<https://avo.alaska.edu/volcano/klawasi-group>).

The mud volcanoes are being formed by warm saline water and CO₂-rich gases from within the crust moving upward and bubbling out at the Earth's surface. Analysis of the water and gas indicates that the springs are probably sourced from the interactions of a magmatic body and limestone beds at depth (Motyka et al. 1986; Sorey et al. 2000; McGimsey et al. 2007). The saline water itself is likely connate, which means that it was trapped within the pore space of the limestone when it formed in the ocean millions of years ago (Motyka et al. 1986). The CO₂ is generated by the deeply buried magma, as well as through metamorphism of the limestone as it contacts the hot magma (Motyka et al. 1986; Sorey et al. 2000). Despite the temperature measurements being higher at Shrub compared to Upper and Lower Klawasi, all three mud volcanoes are being sourced from a common, deeply buried reservoir (Sorey et al. 2000). Shrub's elevated temperatures and discharge rate are instead a product of faster delivery of the gas-rich waters from the reservoir to the surface (Sorey et al. 2000).

Mineral Resources

Mineral resources within the park primarily include copper, silver, and gold deposits, as well as less common occurrences of other minerals. The US Geological Survey Alaska Resource Data File (ARDF), which is a compilation of mineral resources in Alaska, includes 365 records for the park (<https://www.usgs.gov/centers/alaska-science-center/science/alaska-resource-data-file>, accessed 10 June 2024). Of these records, 31 are mines, 215 are prospects, 118 are mineral occurrences, and one is unspecified. In general, mines have had past production, prospects have had development work completed, and mineral occurrences include unexplored or incompletely explored mineral deposits. A map of mineral resource locations is not included in this report due to the sensitive nature of this

data, but park managers can access the locations of mines within the park by viewing the “Mine Point Features” layer within the “sensitive” GRI GIS dataset (available at <http://go.nps.gov/gripubs>). Additional detailed information about mineral resource sites can be found in the ARDF database (<https://mrdata.usgs.gov/ardf/>).

The mines within the park are distributed among five mining districts: the Nabesna, Chisana, Kotsina-Kuskulana, McCarthy-Nizina, and Bremner mining districts. Two gold mines are in the Nabesna mining district, which is found in the northern part of the park near the town of Nabesna. The Chisana mining district contains six mines, mostly placer gold mines located around the historic Chisana town in the northeast part of the park. Two silver-gold-copper mines are found in the Kotsina-Kuskulana mining district, which occurs north of the McCarthy Road near the Kotsina and Kuskulana Rivers. The McCarthy-Nizina mining district, which encompasses the area around the towns of McCarthy and Kennecott, contains 16 mines, including the famous Kennecott copper mines and a few placer gold mines (e.g., Dan Creek). The Bremner mining district encompasses five placer and lode gold mines in the Chugach Mountains, mostly in the vicinity of Golconda Creek.

The copper-silver deposits associated with the Kennecott mines are among the richest copper ore bodies ever discovered (Winkler et al. 2000). In 1900, an outcrop of nearly pure copper sulfide ore was discovered on Bonanza Ridge to the east of the Kennicott Glacier (Winkler et al. 2000). Three other rich lode deposits (Jumbo, Mother Lode, and Erie) were discovered soon after, prompting the construction of a 315-km (196-mi)-long railroad from Cordova on the coast to the west, the creation of a new mining corporation called the Kennecott Copper Corporation, and the construction of many buildings to support the mining and milling operations (see Figure 8; Winkler et al. 2000). Between 1911 and 1938, the Kennecott Copper Corporation mined more than 536,000 metric tons of copper and an estimated 100 metric tons of silver from the Bonanza, Jumbo, Mother Lode, and Erie mines (Figure 18; Winkler et al. 2000).

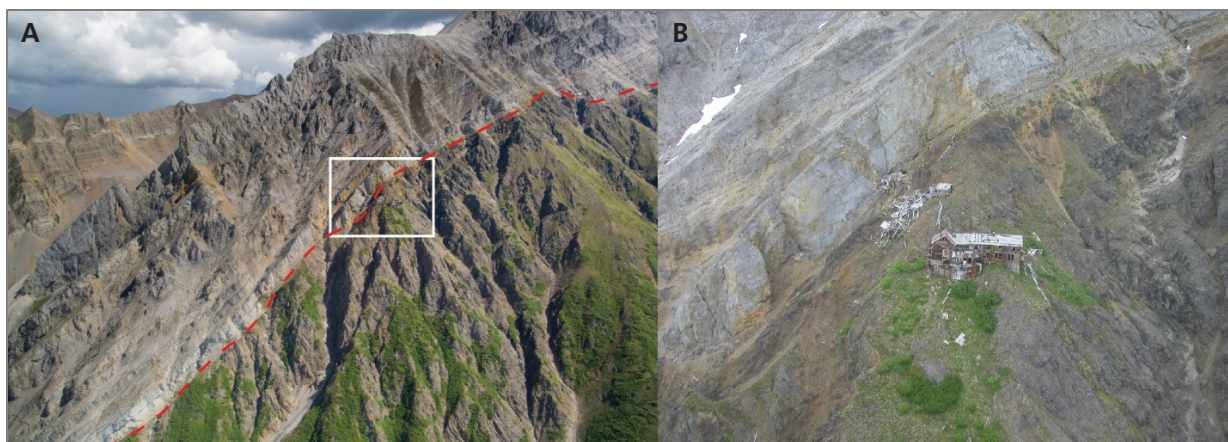


Figure 18. Photographs of the Erie mine, one of the copper mines operated by the Kennecott Copper Corporation in the early 20th century. The rich Kennecott copper deposits are located near the contact between the Nikolai Greenstone (TRn) and Chitistone Limestone (TRcn). The Nikolai Greenstone, composed of metamorphosed basalts, is the underlying dark rock unit, and the Chitistone Limestone is the lighter-colored overlying unit. (A) Photograph of the slope the Erie mine is located on, with the contact between the Nikolai Greenstone and Chitistone Limestone highlighted by a dotted red line and the approximate extent of B highlighted by the white box. (B) Zoomed-in view of the remains of the buildings associated with the Erie mine.

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The Kennecott copper deposits are located within the lower part of the Chitistone Limestone (**TRcn**), generally less than 100 m (330 ft) above the contact with the underlying Nikolai Greenstone (**TRn**; MacKevett 1976). They are known as Kennecott-type deposits, and these types of deposits have only been found along the southern flank of the Wrangell Mountains (Bateman and McLaughlin 1920; Winkler et al. 2000). The largest and richest of the deposits are the Bonanza, Jumbo, Mother Lode, and Erie veins; however, a few other smaller copper deposits exist in the Kennecott area (MacKevett 1976). The major deposits occurred as north-to-east plunging veins, exhibiting a triangular cross section. Jumbo was the largest of the ore bodies, measuring about 110 m (360 ft) high, between 0.6 m (2 ft) and 18.5 m (60 ft) wide, and extending for 460 m (1,500 ft; MacKevett 1976). The primary ore minerals are chalcocite (Cu_2S), native copper, and several other copper-bearing minerals (Figure 19; MacKevett 1976). The mineralized zone also contains low-grade carbonate ore (e.g., malachite and azurite), which was processed using techniques such as gravity separation and ammonia leaching (Figure 19; Winkler et al. 2000).

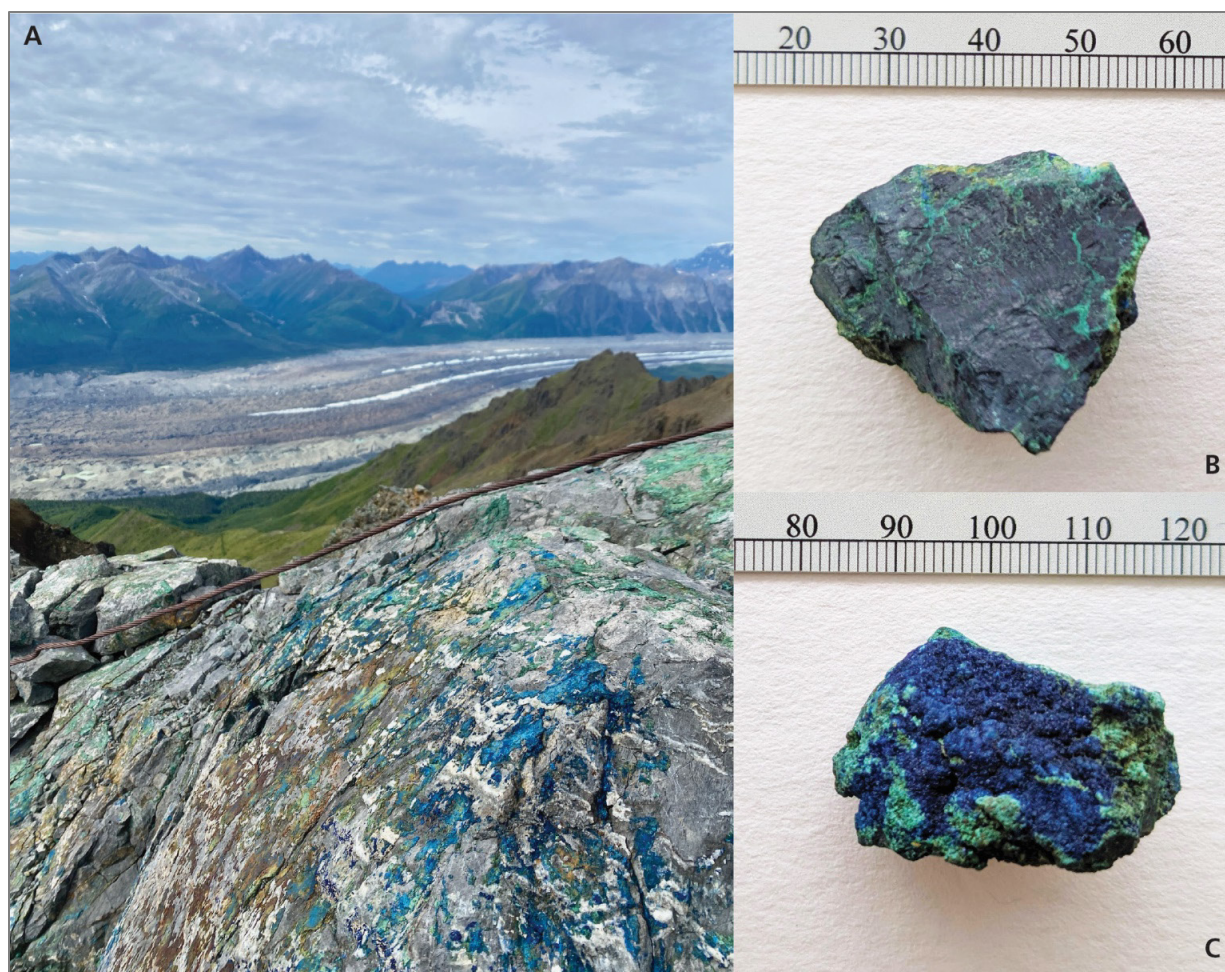


Figure 19. Photographs of copper ore minerals found at the Kennecott mines. (A) Photograph of azurite (blue mineral) and malachite (green mineral) within the bedrock at Bonanza Mine. Azurite and malachite are lower-grade carbonate minerals that were processed in the Kennecott mill. NPS photograph by Sarah Venator. (B) Photograph of chalcocite. Chalcocite was the dominant ore mineral at most of the Kennecott mines. Chalcocite is a dense, dark gray to black mineral with a metallic luster composed of copper and sulfur (Cu_2S ; scale is millimeters). (C) Photograph of azurite and malachite (scale is millimeters).

A) NPS / SARAH VANATOR, B) NPS / AMANDA LANIK, C) NPS / AMANDA LANIK

The geologic origins of Kennecott-type deposits are not completely understood but likely involved the movement of copper from the underlying Nikolai Greenstone into sabkha facies carbonate rocks of the lower Chitistone Limestone. The basalts of the Nikolai Greenstone are particularly high in copper, with estimates ranging from 92 ppm (Lassiter et al. 1995) to 143 ppm (MacKevett et al. 1997). The higher estimates are nearly twice as copper-rich as the worldwide average for basalts (75 ppm; Wedepohl 1978; Price et al. 2014). The lowest part of the Chitistone Limestone formed in a sabkha (Winkler et al. 2000). Sabkhas are characterized by high evaporation rates that produce sediments rich in sulfate minerals such as gypsum and anhydrite (Winkler et al. 2000). During the Cretaceous Period, the mineral deposits were formed by copper- and possibly S-bearing fluid from the Nikolai Greenstone moving upward and mixing with S-bearing fluid from the Chitistone

Limestone (Price et al. 2014). The system was likely driven by heat associated with the tectonic accretion of the Wrangellia composite terrane to North America (Price et al. 2014).

Paleontological Resources

Map units: see Table 3

The park contains paleontological resources, or fossils, which record a long history of ancient life that spans over 350 million years. Fossils are any evidence of life that has been preserved in a geologic context. Globally, this encompasses 3.7-billion-year-old microscopic cyanobacteria, 15,000-year-old woolly mammoths, and everything in between. The current geologic eon, known as the “Phanerozoic,” is divided into three eras that are dominated by different types of organisms and separated by major mass extinctions. The park contains fossils from all three eras, which are the Paleozoic Era (“old life” in Greek; 541 million–252 million years ago), Mesozoic Era (“middle life” in Greek; 252 million–66 million years ago), and Cenozoic Era (“new life” in Greek; 66 million years ago–today). The Paleozoic fossils in the park include marine fossils that were common in Paleozoic seas, such as corals, gastropods (snails), bivalves (clams), crinoids (sea lilies), brachiopods (two-shelled marine invertebrates), among others. The Mesozoic fossils in the park include marine organisms such as bivalves, ammonites (extinct nautilus-like cephalopods), and ichthyosaurs (marine reptiles), as well as terrestrial plants and dinosaur tracks. Cenozoic fossils in the park are not as numerous but include marine fossils such as bivalves, gastropods, foraminifera (shelled protists), and crustaceans, as well as plant fossils. Table 3 summarizes the general fossil types found within the park, organized by terrane and geologic unit. The following discussion of the park’s paleontological resources is summarized from the Central Alaska Network Paleontological Resource Inventory report (Santucci et al. 2011) unless otherwise noted.

Table 3. Fossils within Wrangell-St. Elias National Park and Preserve. Fossil information is summarized from Santucci et al. (2011). Santucci et al. (2011) provide more details about the fossil species found in each geologic unit, as well as primary references for the fossil occurrences. Rocks of the Gravina-Nutzotin belt are included in the Wrangellia terrane in Santucci et al. (2011).

Terrane	Age	Unit Name (Unit Symbol)	Fossils
Wrangellia terrane	Upper Mississippian to Lower Pennsylvanian	Strelina Metamorphics (PPNm, PPNsm)	Bryozoans, brachiopods, gastropods, and conodonts
Wrangellia terrane	Pennsylvanian to Lower Permian	Tetelna Volcanics (PPNt)	Ammonoids
Wrangellia terrane	Pennsylvanian to Lower Permian	Skolai Group (PPNs, PPNsc, Ph, PI)	Corals, bryozoans, brachiopods, gastropods, bivalves, and crinoids
Wrangellia terrane	Middle Pennsylvanian to Lower Permian	Mankomen Group (Pe, Pel, PPNss)	Corals

^A Reported fossil occurrences that have some degree of uncertainty.

Table 3 (continued). Fossils within Wrangell-St. Elias National Park and Preserve. Fossil information is summarized from Santucci et al. (2011). Santucci et al. (2011) provide more details about the fossil species found in each geologic unit, as well as primary references for the fossil occurrences. Rocks of the Gravina-Nutzotin belt are included in the Wrangellia terrane in Santucci et al. (2011).

Terrane	Age	Unit Name (Unit Symbol)	Fossils
Wrangellia terrane	Triassic	Unnamed Siltstone, Shale, and Chert (Ph, Pe)	Bivalves (<i>Daonella</i>)
Wrangellia terrane	Middle Triassic	Unnamed carbonaceous shale, calcareous argillite, and chert (Pe)	Bivalves (<i>Daonella</i>)
Wrangellia terrane	Upper Triassic	Triassic limestone (TRI)	Hydrozoans, brachiopods, and bivalves
Wrangellia terrane	Upper Triassic	Chitistone Limestone (TRcn)	Stromatolites, algal-mat fragments, spongiomorphs, corals, gastropods, nautiloids, ammonites, coleoids, bivalves, echinoids, crinoids, and calcareous worm tubes
Wrangellia terrane	Upper Triassic	Nizina Limestone (TRcn)	Brachiopods, gastropods, ammonites, bivalves, and ichthyosaurs
Wrangellia terrane	Upper Triassic to Lower Jurassic	McCarthy Formation (JTRm)	Ammonites, bivalves, conodonts, and hydrozoans.
Wrangellia terrane	Lower Jurassic	Lubbe Creek Formation (Js)	Brachiopods, ammonites, and bivalves
Wrangellia terrane	Middle to Upper Jurassic	Nizina Mountain Formation (Js)	Ammonites, belemnites, bivalves, a crustacean appendage, fish scales, and ichthyosaurs
Wrangellia terrane	Middle to Upper Jurassic	Kotsina Conglomerate (Jk)	Poorly preserved plants ^A
Wrangellia terrane	Upper Jurassic	Root Glacier Formation (Js)	Gastropods, ammonites, belemnites, bivalves, and wood fragments
Wrangellia terrane	Lower Cretaceous	Berg Creek Formation (KI)	Ammonites, belemnites, and bivalves
Wrangellia terrane	Lower Cretaceous	Kuskulana Pass Formation (KI)	Ammonites, belemnites, and bivalves
Wrangellia terrane	Lower Cretaceous	Kennicott Formation (KI)	Foraminifera, radiolarians, ammonites, bivalves, and plant macrofossils
Wrangellia terrane	Middle to Upper Cretaceous	Moonshine Creek Formation (Ku)	Gastropods, ammonites, and bivalves
Wrangellia terrane	Upper Cretaceous	Schulze Formation (Ku)	Foraminifera, radiolarians, ammonites, and bivalves
Wrangellia terrane	Upper Cretaceous	Chititu Formation (Ku)	Radiolarians, ammonites, and bivalves
Wrangellia terrane	Upper Cretaceous	MacColl Ridge Formation (Ku)	Ammonite fragments, bivalve fragments, and poorly preserved plants

^A Reported fossil occurrences that have some degree of uncertainty.

Table 3 (continued). Fossils within Wrangell-St. Elias National Park and Preserve. Fossil information is summarized from Santucci et al. (2011). Santucci et al. (2011) provide more details about the fossil species found in each geologic unit, as well as primary references for the fossil occurrences. Rocks of the Gravina-Nutzotin belt are included in the Wrangellia terrane in Santucci et al. (2011).

Terrane	Age	Unit Name (Unit Symbol)	Fossils
Gravina-Nutzotin belt	Upper Jurassic to Lower Cretaceous	Nutzotin Mountain Sequence (KJs)	Bivalves
Gravina-Nutzotin belt	Lower Cretaceous	Chisana Formation (Kc)	Ammonites, bivalves, and wood
Gravina-Nutzotin belt	Cretaceous	Unnamed Sedimentary rocks (Kun)	Ammonites
Gravina-Nutzotin belt	Cretaceous	Nonmarine Sedimentary rocks (Kun)	Plant macrofossils, trace fossils (dinosaur tracks ^A)
Alexander terrane	Devonian, Mississippian, Pennsylvanian, and older	Kaskawulsh Group (PZk)	Corals
Yakutat terrane	Miocene to Pleistocene	Yakataga Group (Kyf, Kym)	Foraminifera, scaphopods, gastropods, bivalves, barnacles, crustaceans, and trace fossils
Wrangell volcanic field	Lower to Middle Miocene	Frederika Formation (QTw)	Plants, and fish ^A

^A Reported fossil occurrences that have some degree of uncertainty.

The Wrangellia terrane contains late Paleozoic marine fossils and Mesozoic marine and terrestrial fossils. The late Paleozoic fossils are found in rocks that formed along the ancient Skolai-Tetelna volcanic arc (see “Bedrock Geology”). These rocks contain typical Paleozoic marine fossils such as corals, bryozoans, brachiopods, gastropods, ammonoids, bivalves, crinoids, and conodonts. While most of the Mesozoic fossils in the Wrangellia terrane are found in marine strata that overlie the Triassic Nikolai Greenstone, scattered occurrences of Middle Triassic fossiliferous sedimentary rocks intervene between the late Paleozoic rocks and the Nikolai Greenstone. These rocks were mapped by Richter et al. (2006) as part of the Mankomen and Skolai groups but contain distinctive Triassic bivalves of the genus *Daonella* (Richter 1973; Richter 1976; MacKevett 1978; Santucci et al. 2011). The sedimentary rocks that overlie the Nikolai Greenstone range in age from Triassic to Cretaceous (252 million–66 million years ago) and contain a diverse array of fossilized marine organisms (see Table 3). Of note, the stromatolites and algal-mat fragments found in the lower portion of the Chitstone Limestone have been interpreted to have formed in a sabkha environment (Winkler et al. 2000). This depositional environment supports paleomagnetic evidence from the underlying Nikolai Greenstone, indicating that the Wrangellia terrane was at a significantly lower latitude during the Triassic Period (Winkler et al. 2000). A few occurrences of plant fragments and wood have also been reported from the Mesozoic marine strata of the Wrangellia terrane (Santucci et al. 2011).

Recent paleontological research (2017–2020) in the park conducted by Andrew Caruthers and others focused on the McCarthy Formation exposed at Grotto Creek (Caruthers et al. 2022). The McCarthy Formation spans the Triassic–Jurassic boundary and records the end-Triassic mass extinction (one of the “big five” mass extinctions in Earth’s history). The rocks and fossils of the McCarthy Formation provide a rare glimpse into how the end-Triassic mass extinction played out in the tropical Panthalassa Ocean (ancient superocean that surrounded Pangea; Caruthers et al. 2022). The Late Triassic lower member of the McCarthy Formation is characterized by rocks and fossils made up of calcium carbonate; however, the overlying Early Jurassic upper member is dominated by fossils composed of silica (primarily sponges; Veenma et al. 2022). This transition from a carbonate-rich to carbonate-poor marine environment is documented over the same period elsewhere in the world and may reflect a global increase in oceanic silica concentrations associated with the end-Triassic mass extinction (Veenma et al. 2022). Ammonoid, bivalve, hydrozoan, and conodont fossils, along with geochemistry and radiometric dating, establish the timing and characteristics of the boundary between the last two stages of the Triassic Period (Norian and Rhaetian) and the end-Triassic mass extinction in the Grotto Creek section (Caruthers et al. 2022). Given the completeness of the record and the scarcity of sites that record the end-Triassic mass extinction in the Panthalassa Ocean, the Grotto Creek section is the best documentation of these events in the Wrangellia terrane (the only record from this portion of the Wrangellia composite terrane) and likely the entire western side of North America (Caruthers et al. 2022). Other records of this event are confined to the portions of the Wrangellia composite terrane on Haida Gwaii.

Ichthyosaur fossils have been discovered in the park in Triassic rocks of the Nizina Limestone. A partial ichthyosaur jaw was discovered and collected by David Whistler while mapping the Nizina Limestone in 1963 (Callaway and Massare 1989). This specimen is now housed in the University of California Museum of Paleontology in Berkeley. The locality was revisited in 2017, and ichthyosaur bone fragments were discovered that likely belonged to the same specimen as the previously collected jawbone (Figure 20; Druckenmiller and Loso 2017). Additionally, another ichthyosaur specimen was discovered near the location of the 1963 specimen (Druckenmiller and Loso 2017). Ichthyosaur fossils are rare in Alaska. Only a few discoveries have been published from across the state, including the 1963 discovery in the park (Tailleur et al. 1973; Callaway and Massare 1989; Adams 2009; Druckenmiller and Maxwell 2014; Druckenmiller et al. 2014). Furthermore, the park ichthyosaurs are likely Late Triassic in age, and, globally, ichthyosaurs from the Late Triassic are not very common (Druckenmiller and Loso 2017). The discovery of two ichthyosaur specimens in the Nizina Limestone during relatively short field visits indicates this unit may produce more ichthyosaurs and potentially other vertebrate fossils if the locality was studied further (Druckenmiller and Loso 2017).

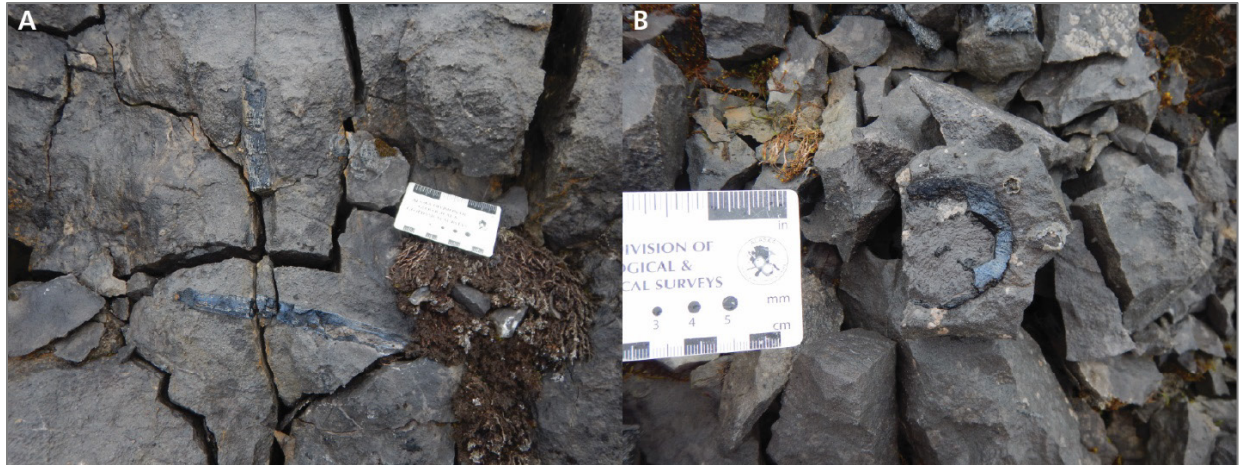


Figure 20. Photographs of ichthyosaur fossils in the park from the Nizina Limestone. (A) Photograph showing black fossilized bones within dark grey limestone. (B) Photograph of black bone fragments within dark grey limestone. A partial ichthyosaurus jaw was collected from the Nizina Limestone in the early 1960s, and in 2017 University of Alaska and NPS geologists revisited the site, discovering ichthyosaurus bone fragments that likely belonged to the same specimen as the previously collected jaw.
NPS / PATRICK DRUCKENMILLER (UNIVERSITY OF ALASKA MUSEUM)

The Gravina-Nutzotin belt is composed of Jurassic and Cretaceous rocks that, in the park, contain marine fossils such as bivalves and ammonites and terrestrial fossils such as plants and dinosaur tracks. Two dinosaur tracks, one attributed to a theropod (mostly carnivorous dinosaur group) and one attributed to an ornithomimid (herbivorous dinosaur group), were reported from Late Cretaceous nonmarine sedimentary rocks of the Gravina-Nutzotin belt (**Kun**; Beaver Lake formation of Trop et al. 2020; Fiorillo et al. 2012). This unit also locally contains well-preserved plant fossils (Fiorillo et al. 2012; Hults and Druckenmiller 2017; Trop et al. 2020; Matthew Brueseke, written communication, 22 May 2025). In 2017, a field team attempted to locate the dinosaur tracks described by Fiorillo et al. (2012); however, they were unable to access the original fossil site, and the characteristics of the rocks in the surrounding area were not conducive to track preservation (Hults and Druckenmiller 2017).

There are also reports of fossils in the Alexander terrane, Yakutat terrane, and Wrangell arc within the park. Rocks of the Alexander terrane are metamorphosed and not very fossiliferous but have been reported to contain poorly preserved tabulate corals of Devonian age. The Yakutat terrane contains the Miocene-Pleistocene Yakataga Formation. The Yakataga Formation contains trace fossils, foraminifera, mollusks, bivalves, gastropods, barnacles, crustaceans, and scaphopods. Recent research undertaken in 2017 was focused on finding Tertiary vertebrate fossils in this formation, but the only vertebrate fossil discovered was a fragment of a fish skull that was not collected. Rocks of the Wrangell arc in the park include the fossiliferous, extensional-basin fill deposits of the Frederika Formation. The Frederika Formation is Miocene in age and contains abundant and well-preserved plant fossils and potentially fish fossils.

Caves

Map units: Glaciers and permanent icefields (**g**), and Chitistone and Nizina Limestone (**TRcn**)

Three types of caves are found in the park: glacier caves (caves within glacier ice), frost pockets (small caves formed by freeze-thaw processes), and solution caves (caves formed by the dissolution of rock). Caves are naturally occurring underground voids in rock, soil, or ice. According to the 2016 State of the Park Report, 53 caves in the park have been explored and documented to some extent (NPS 2016a). Caves in the park include the longest known cave in Alaska, Whispering Cave, and potentially the deepest known cave in Alaska, Leprechaun Cave (both of which are solution caves; NPS 2016a).

Glacier caves form by water melting pathways through the ice, creating subglacial streams and rivers that typically emerge at or near a glacier toe or discharge into proglacial lakes (lakes in front of a glacier; Figure 21). These caves are ephemeral, and their morphology changes over time. Glacier caves tend to be unstable and hazardous due to melting and falling ice.

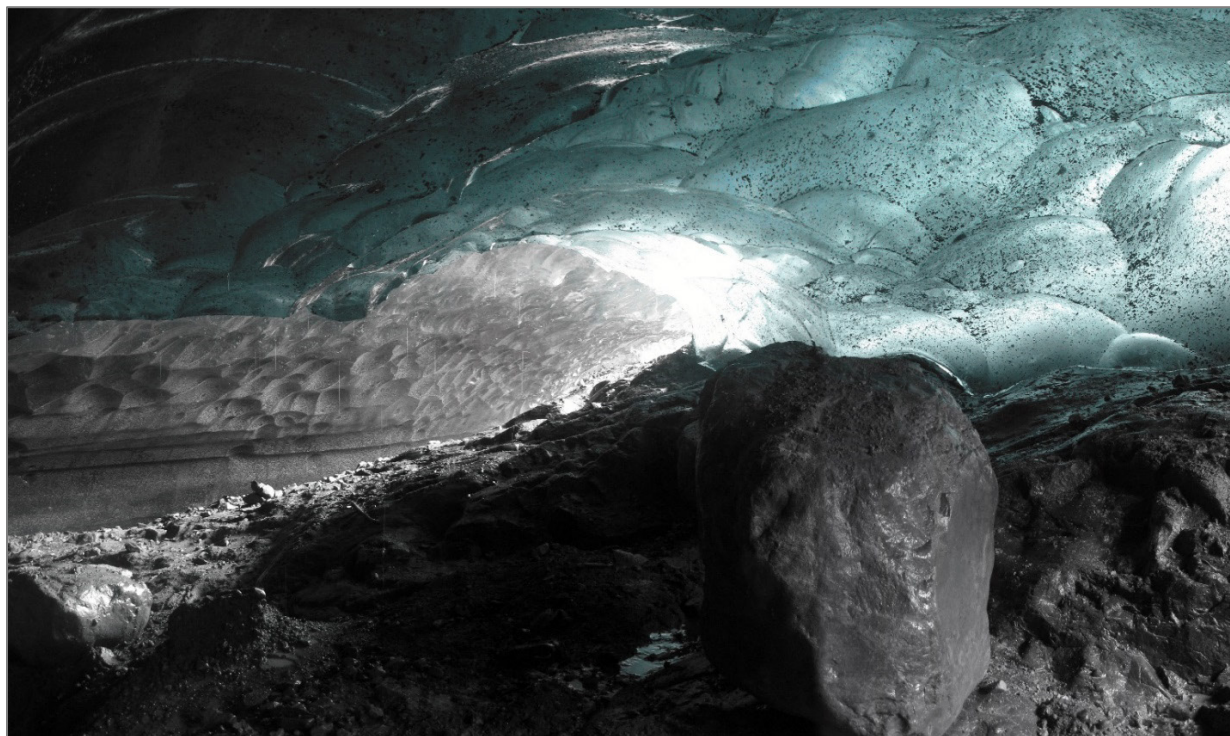


Figure 21. Photograph of the inside of a glacier cave in the park. Glacier caves form within glaciers by water melting pathways through the ice. Glacier caves are, by nature, ephemeral and change over time. This makes them unstable and potentially hazardous to enter.

NPS / DAN LEFLER

Frost pockets form by the mechanical breakup of bedrock by freeze-thaw action. The shattered material generally slides out of the entrance and forms piles of rock at the base of the cliff. Frost pockets frequently appear to be cave entrances on cliff faces and steep bedrock slopes but rarely

extend more than 50 ft (15 m) deep and typically slope upward from the entrance to the end. From a distance, they can be mistaken for solution caves, especially since the entrances of many solution caves have also been modified by freeze-thaw cycles.

The most extensive types of caves found in the park are solution caves and other smaller karst features. Solution caves form via karst processes, which are the dissolution of soluble rocks such as limestone or dolomite (Toomey 2009). Most of the known caves occur within the Chitistone and Nizina Limestones (**TRcn**), with most of the longest caves being entirely within the Chitistone Limestone. The caves appear as cliffside openings, open pits, and holes where subterranean water reappears onto the surface. They are concentrated along faults, folds, and fractures, and some are vertically controlled by bedding planes or other lithologic features. The caves appear to have formed under phreatic conditions (below the water table) and then subsequently modified by vadose (above the water table) processes. Some caves have been influenced by or partially re-exhumed by paleokarst that possibly developed during the Triassic Period (252 million–201 million years ago). Additionally, a few caves seem to have been influenced by hydrothermal activity during their early development stages but are no longer actively hydrothermal. While most of the known caves are in the Chitistone and Nizina Limestones, several other smaller limestone and marble units crop out in the park that may contain caves. Most of these outcrops have not been searched for caves, so there is potential to find more in the park.

Surficial Geology

Map units: Alluvium (**Qa**), Slope deposits, bluff colluvium (**Qcb**), Rock glacier deposits (**Qrg**), Drift of Alaskan glaciation (**Qag**), Supraglacial deposits (**Qsm**), Fine-grained deposits (**Qfl**), Eolian deposits (**Qe**), Beach and delta deposits (**Qb**), Slope deposits, landslide deposits (**Ql**), Slope deposits, undifferentiated (**Qu**), Swamp deposits (**Qs**), Ice-contact deposits (**Qic**), Older alluvium (**Qao**), Drift of older glaciations (**Qg**), Copper River deposits (**Qcr**), and Outwash deposits (**Qo**)

Geologic processes (e.g., erosion and deposition) that, over millions of years, formed the park's bedrock continue to be active today, producing younger, unconsolidated (or weakly consolidated) surficial deposits that mantle the park's bedrock (see the GRI poster). Surficial deposits are typically found everywhere except for the steepest terrain and can range from a thin veneer of sediment only centimeters (inches) deep to thick deposits many meters (yards) deep. Surficial deposits are the geologic layer closest to the ground's surface and therefore constitute the earth materials that plants and animals (including humans) are most likely to interact with. Surficial geology can be an important factor in many park management activities, such as planning and maintaining facilities, understanding the distribution of plants and animals, tracking landscape change, and studying geohazards. However, bedrock geology maps (e.g., the park's GRI map) often omit surficial deposits to show the underlying bedrock units, only depicting surficial deposits that are more substantial and obscure the underlying bedrock. A dedicated park-wide surficial map is not available; however, broad surficial units are included in the bedrock GRI GIS data (Richter et al. 2006; Wilson et al. 2015). More detailed surficial mapping may be available in geologic maps focused on the park's quadrangles (see Figure 1 for a map depicting the park's quadrangles), which can be found in the US Geological Survey's National Geologic Map Database

(https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html). Additionally, the NPS can map surficial geology in areas of high management concern. For example, park geologists recently remapped the surficial geology and proglacial lake change for Sít' Tlein (Malaspina Glacier; Thompson et al. 2024).

Surficial geologic units are mainly differentiated and mapped based on the dominant physical process involved in their creation but can also take into account factors such as age, physical characteristics (e.g., grain size), and location. The park's surficial geologic units have been formed by mineral springs, glaciers, rivers, mass wasting, lakes, wind, and coastal processes (Richter et al. 2006). Surficial deposits formed by mineral springs, glaciers, rivers, and mass wasting are discussed in detail in other sections of this report ("Geothermal Features," "Glacial Deposits," "Fluvial Features," and "Landslides," respectively). Additionally, the "Permafrost" section of this report discusses how perennially frozen ground can affect what surficial deposits form and how they behave. Below is a discussion of the surficial deposits not discussed in other areas of this report, which includes lacustrine deposits (formed in lakes), eolian deposits (formed by wind), and coastal deposits.

Lacustrine deposits formed in ancient lakes and are usually composed of fine-grained sediments due to the low-energy environment. Lacustrine deposits within the park include fine-grained deposits (**Qfl**) and Copper River deposits (**Qcr**). The fine-grained deposits are chiefly composed of silt, clay, fine sand, peat, and other organic material that accumulated in now-drained ponds, swamps, lagoons, and along low-gradient streams. The Copper River deposits are composed of glacial and alluvial (river) deposits that are interbedded with glacial lake deposits (glaciolacustrine deposits). Glacial lakes can form when ice from glaciers blocks water drainage. Ice-dammed lakes have had a tremendous influence over the park's surficial geology through the accumulation of fine-grained lake bottom sediments that were later exposed by lake drainage.

The largest and longest-lived ice-dammed lake in the park is known as Lake Atna. Lake Atna, along with an earlier iteration known as Lake Susitna, occupied a large fraction of the Copper River Basin from as early as 40,000 years ago to approximately 10,500 years ago (Smith 2019). The history of this large lake is complex and, although it is poorly understood, it is clear that it consisted of a series of ice-dammed lakes that occupied different levels at various times throughout the last and possibly the prior ice age. The lake owed its existence to large glaciers damming the lower Copper River. As the lake level rose, the lake sought additional higher outlets that were at various times open or dammed. As a consequence, Lake Susitna/Atna flowed various times into the Matanuska River, the Tok River, the Copper River, and the Susitna River. The long history of lake occupation left the modern landscape with a mantle—often deep and quite complicated—of glaciolacustrine sediments (**Qcr**). The generally flat and poorly drained soils of the Copper Basin today (including much of the lower terrain along the Chitina and Copper Rivers) are consequences of Lake Atna occupation, and their predisposition to forming permafrost-rich wetlands has had a profound influence on the development, infrastructure, and ecosystems of that region. Recent archaeological work also suggests that Lake Atna significantly influenced the locations and migration patterns of early Alaskans as far back as 13,000 years ago (White et al. 2022). Ice-dammed lakes are still present on the landscape; a recent inventory found 14 ice-dammed lakes in the park with a median size of 0.4 km² (0.2 mi²) and

a maximum size of 3.2 km² (1.2 mi²; Rick et al. 2022). These are clearly much smaller than Lake Atna and tend to be concentrated at slightly higher elevations in the park, but importantly, these modern ice-dammed lakes are a variable but cumulatively persistent part of the landscape. Individual lakes grow, shrink, appear, and disappear, but there is no evidence that the landscape has been free of ice-dammed lakes for any extended period over the last several thousand years. Glaciolacustrine sedimentation is thus widely but patchily distributed in the park outside the Copper River Basin.

The park contains eolian deposits, which are fine-grained sediments deposited by wind (**Qe**). Fine-grained sediment, such as silt and clay, is easily picked up by wind, and when redeposited in well-sorted laminar beds, it is called loess. Where winds are reliably strong enough to transport sand, eolian sand can build up deposits with dune-like morphologies. The spatial distribution of eolian deposits is driven by the park's wind climate. This phenomenon is complicated, but broad patterns are well known: the park's main north-south river corridors (Copper River and Tana River) bisect the coastal Chugach Mountains and serve as preferred corridors for winds between the interior and coastal pressure systems. One conspicuous and well-studied loess deposit in the Copper River corridor sits at the junction of the Copper, Chitina, and Kotsina Rivers where the McCarthy Road climbs eastward from the Copper River Bridge (Muhs et al. 2013). There (and throughout the less accessible river bluffs of the Chitina, Copper, and Tana lowlands) the sediments left behind by past glaciations are mantled by several meters of loess that has accumulated over the last ~10,000 years. Thinner layers of loess are found in the lowlands of virtually the entire park. In the Bremner River area (which connects the Copper and Tana Rivers), several extensive dunefields are found (Wiles et al. 2003). These are uncommon in the park broadly and are understood to be found in that area because of the combination of high winds and a uniquely high preponderance of sand in the glacial sediments of the area, driven largely by erosion of the Chugach Terrane rocks (Loso et al. 2004).

Surficial deposits formed through coastal processes are found along the park's coastline (**Qb**). Coastal beaches and dunefields are found along the outer coast near Sít Tlein/Malaspina Glacier and in Icy Bay. These features are somewhat unique in having been influenced by significant local uplift that results from a combination of ongoing isostatic uplift (due to glacier retreat) and occasional coseismic uplift (Elliott et al. 2010; see the "Earthquakes" section of this report for more information). This uplift has created raised beaches and river spits that influence coastal geomorphology and give rise to shoreline-parallel river mouths in some areas.

Glacial Deposits

Most of the park's surficial deposits are influenced by modern and past glaciations. Glaciers presently cover 35% of the park, and 22,000 years ago, during the Last Glacial Maximum (LGM), glaciers covered approximately 90% of the park (see "Glacial Features and Processes"; Kaufman and Manley 2004). Because glaciers are efficient erosional agents, they incorporate and transport large amounts of glacial till (unsorted sediment with grain sizes ranging from clay to boulders) in various ways: (1) supraglacially (as moraines on top of debris-covered glaciers), (2) englacially (within the ice matrix itself), and (3) subglacially (as a veneer of variable thickness underneath the sliding glacier). Over one third of the park is presently covered by glacier ice, and a significant amount of the remainder of the park is covered by glacially derived surficial deposits.

Glacial deposits in the park are generally categorized by their mechanism of deposition and include glacial till, glaciofluvial alluvium (river deposits), loess (wind-transported silt and clay) and eolian (wind-transported) sand, and glaciolacustrine (glacier lake) sediments. The GRI GIS map data use the older term “glacial drift” to encompass glacial till and some glaciofluvial deposits. Glacial till is transported by ice directly to its place of deposition and retains the primary characteristics of glacial transport, such as poor sorting, high content of fine-grained clay and silt, limited rounding, and abundant striations. It is most often described with terms that characterize the morphology of the final deposit (e.g., terminal and lateral moraines, drumlins, and lodgement till). Till that was subsequently transported by water, either as subglacial/supraglacial rivers or more extensively by downstream subaerial rivers, is referred to as a glaciofluvial deposit. As these deposits are transported by water, they gradually become better sorted and more rounded. Glaciofluvial alluvium occurs in kames (hills formed by glacial processes), braided riverbeds, terraces and floodplains, and deltas. Some of the fine-grained materials in till and alluvium are subject to wind transport and accumulate as loess and eolian sand. Where glacial rivers (which commonly carry heavy loads of suspended clay, silt, and sand) are impounded by glaciers, moraines, or other landscape features, they develop glacial lakes. These lakes commonly experience rapid deposition of silt and clay, along with ice-rafted debris and other materials, and following lake drainage, these glaciolacustrine materials are responsible for a substantial amount of the surficial character of some portions of the park.

Because of previously extensive glacial advances, glacial till is widely exposed throughout the park (**Qag, Qao, and Qg**). It is most obvious and exposed near the modern glaciers, where recent glacier retreat has left behind terminal and lateral moraines. The last significant and widespread glacier advance in the park was the Little Ice Age (LIA), which peaked about 200 years ago. Moraines associated with the LIA are generally close to the modern glacier margin, steep, poorly vegetated, and conspicuous in comparison with moraines deposited by older glacier advances (Figure 22). Though widespread, moraines have been mapped only in isolated portions of the park and so their total areal coverage remains unknown. That said, LIA moraines are reasonably obvious around the margins of almost all of the more than 3,000 glaciers in the park, and hence constitute one of the most evident surficial deposits parkwide. Of the older glacial till in the park, some is in well-vegetated and topographically subdued morainal landforms (Figure 23), but much of it mantles the ground surface in formerly glaciated valleys as a variably thick deposit of compact lodgement till. Lodgement till is material that was transported subglacially and abandoned in place when the glacier retreated. Sometimes such material is sculpted into distinctive cigar-shaped landforms known as drumlins, but more commonly it overlies the valley floor as a sheet of inconspicuous parent material upon which soils, wetlands, and forests have developed. Wherever glacial till occurs, it influences ecosystem and soil properties mostly through the abundance of clay. Clay makes glacial till fairly impermeable and also provides substantial cohesion, allowing some moraines to maintain steep slopes well beyond the angle of repose. The latter property poses risks in some areas, such as along the McCarthy Road, where high rainfall can saturate previously stable till slopes, giving rise to small or even large slumps and landslides that threaten infrastructure.



Figure 22. Photograph of a backpacker traveling along a glacial moraine. Moraines build up along the edges (lateral moraines) and at the toe (terminal moraine) of a glacier, marking the extent of that glacier in the past. As seen in the photograph, moraines formed during the LIA tend to be steep, poorly vegetated ridges that are conspicuous on the landscape.

NPS

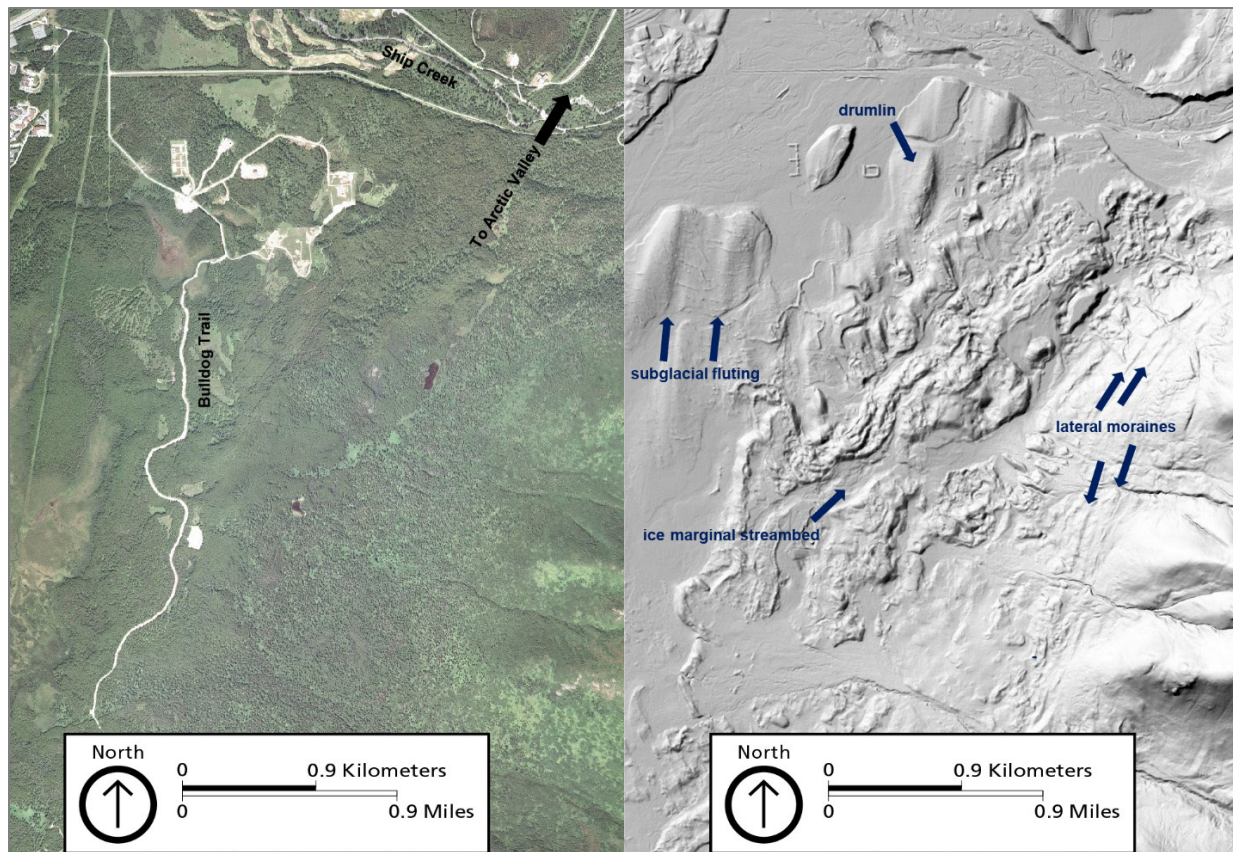


Figure 23. Aerial (left) and lidar-based bare-ground hillshade (right) images showing glacial landforms that underlie vegetated areas. Although this imagery is from an area just north of Anchorage, similar development of soils and vegetation atop older glacial landforms and deposits occurs in many areas of the park. In these cases, vegetation hides, but importantly, it is growing in response to the older glacial landforms. Annotations on the left provide landscape orientation, and on the right point out glacial features such as drumlins and moraines that are more than 14,000 years old.

NPS / MIKE LOSO

Glacial Features and Processes

The foundation statement for the park states that the park was set aside, in part, because it encompasses the nation's largest protected active glacial complex (NPS 2009). The number and scale of glaciers in the park are enormous by almost any standards. As of 2014, the park had 3,121 glaciers that collectively cover 29,041.0 km² (11,212.8 mi²; Figure 24; Loso et al. 2014). That number not only dwarfs the collective glacier cover of the other 49 states (<580 km² [220 mi²]) but also comprises a very significant one-third of all the glacier cover in Alaska and adjacent Canada. Even the other Alaskan national parks do not rival that level of glacier coverage. In fact, the park has more than twice as much glacier cover as the other eight glacierized Alaska national parks combined.

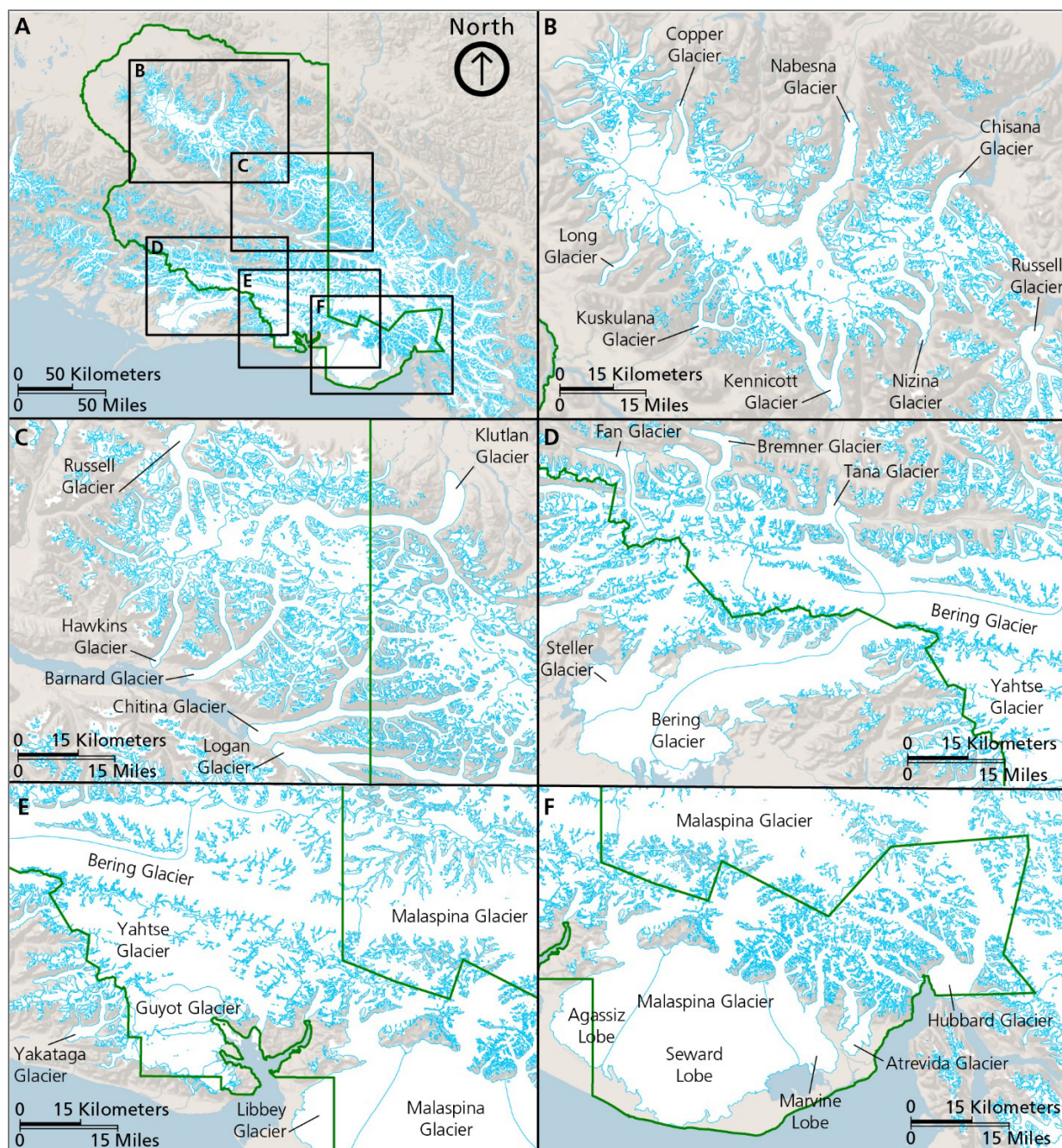


Figure 24. Glacier maps of the park. (A) Map of the park and surrounding area showing overall glacier coverage (in white) and the location of the zoomed-in maps. The park is covered extensively by glaciers, having twice as much glacier-covered area as the other eight glacierized Alaska national parks combined. (B) Glacier map of the northern part of the park. (C) Glacier map of the east-central part of the park. (D) Glacier map of the southwestern part of the park. (E) Glacier map of the southcentral part of the park. (F) Glacier map of the southeastern part of the park.

NPS / AMANDA LANIK (UNIVERSITY OF ALASKA MUSEUM OF THE NORTH, USING GLACIER OUTLINES FROM THE RANDOLPH GLACIER INVENTORY [RGI 7.0 CONSORTIUM 2023])

The park owes its prodigious glacier coverage not only to simply being a large land mass (the biggest park in the country) but also to the presence of many glaciers of globally significant size (Figure 25). For instance, three of the 10 largest glaciers in the world (not counting the Greenland and Antarctic ice sheets) are in the park: Malaspina ($3,363 \text{ km}^2$ [$1,289 \text{ mi}^2$]; also known by its traditional Yakutat Tlingit name: Sít' Tlein), Bering Glacier ($3,025 \text{ km}^2$ [$1,168 \text{ mi}^2$]), and Hubbard Glacier ($2,834 \text{ km}^2$ [$1,094 \text{ mi}^2$]; Windnagel et al. 2023). All three of those glaciers are so large that they spill outside the park boundary, in two cases (Malaspina and Hubbard) straddling the border with Canada. Other glacier superlatives deserve mention. By North American standards, the park has the longest valley glacier (Nabesna Glacier is 85 km long), the largest piedmont glacier (Malaspina/Sít' Tlein), and the largest tidewater glacier (Hubbard Glacier; Windnagel et al. 2023). To emphasize the point that glaciers are not mere ornaments on the landscape, but rather—for large portions of the park—they are the landscape, consider this: a glacier enthusiast could ski eastward and upward from the terminus of Miles Glacier (at the western edge of the park) across the Bagley Ice Field, down the Seward Glacier, over a divide onto the Hubbard Glacier, through a pass, and down the Tweedsmuir Glacier to its Canadian terminus, at which point one will have skied roughly 400 km, traversed the entire park, and done so without ever climbing above 2,133 m (7,000 ft) in elevation nor even once stepping off of glacier ice.

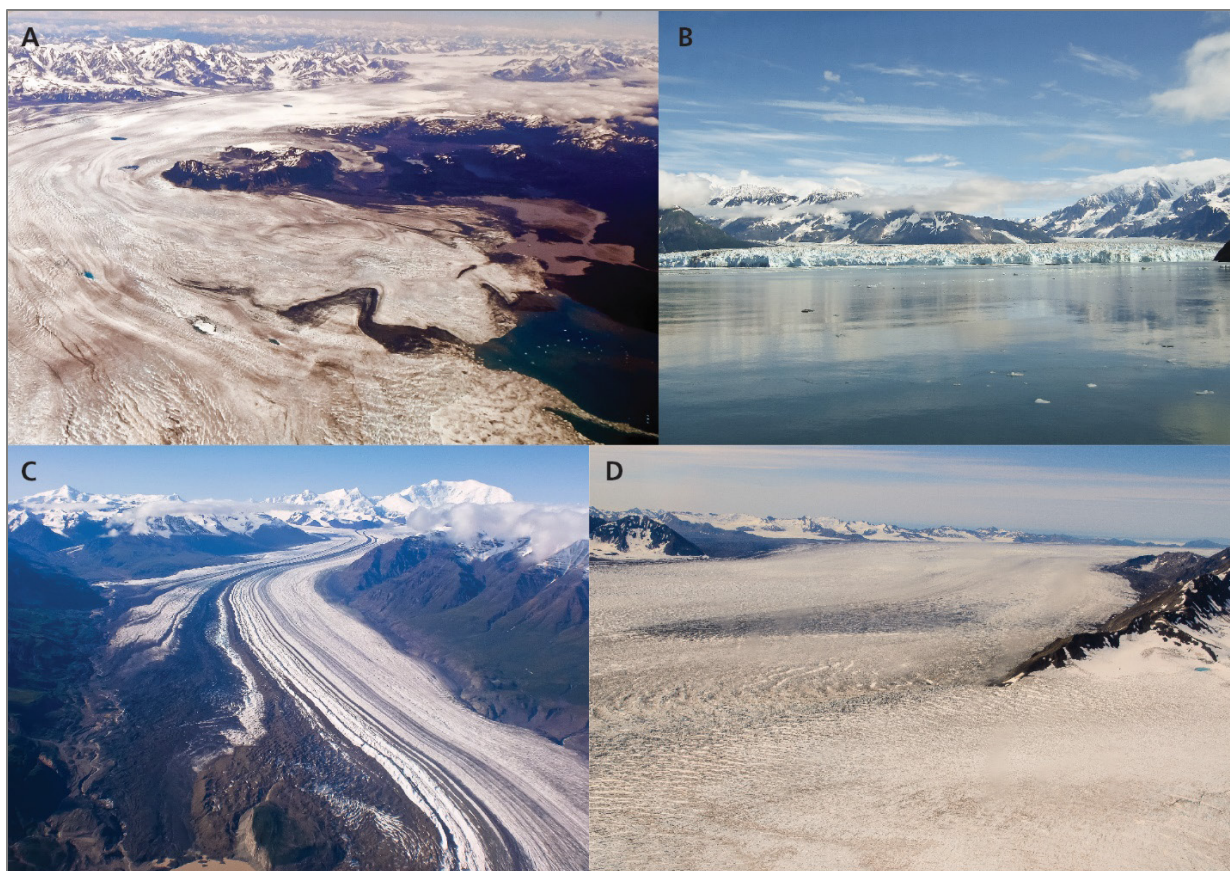


Figure 25. Photographs of glaciers in the park. (A) Photograph of Bering Glacier, which is one of the 10 largest glaciers in the world. (B) Photograph of the terminus (end) of Hubbard Glacier, which is also one of the 10 largest glaciers in the world. (C) Photograph of Nabesna Glacier, the longest valley glacier in the world. (D) Photograph of the Bagley Icefield, which is an extensive continuous mass of ice in the southern part of the park.

A) NPS, B) NPS, C) NPS / BEV GOAD, D) NPS / BRYAN PETRTYL

Glacier cover is largely determined by climate. Glaciers form in areas where snow accumulates faster than subsequent melt can remove it. The excess snow, which is gradually transformed by the pressure of additional overlying snow into glacier ice, then flows downhill toward a warmer microclimate (called the ablation zone), where melt exceeds accumulation. There, glaciers typically shrink as they continue downhill until the last ice melts away at the glacier terminus. Therefore, it is the balance between winter precipitation (snowfall) and summer temperatures (melting) that governs glacier distribution. Not coincidentally, most of the park's very largest glaciers originate on the southern, coastal side of the park and flow southwards toward the ocean. Though that coastal region is not the coldest part of the park, it is the wettest, and heavy snows from the Pacific Ocean blanket the coastal Chugach and St. Elias Mountains with many meters of snow each winter, especially near Mount St. Elias—the world's highest coastal mountain—rising 18,008 ft (5489 m) within just 16 km of tidewater to the north of Icy Bay and Malaspina/Sít' Tlein. In this southern part of the park, along with adjacent protected areas to the east and west, glacier cover is nearly continuous. Only isolated rocky ridgelines and nunataks (mountain peaks surrounded by glacier ice) break through the glaciers

and icefields, and many of the glaciers flow either directly into the ocean (tidewater glaciers) or spread out on the coastal plain as piedmont (foot of the mountain) glaciers. In comparison, glaciers in the colder and drier central and northern parts of the park, though in some cases still large, are generally more isolated and dependent on high, cold terrain to sustain them. Many of the largest interior glaciers originate on the high volcanoes of the Wrangell Mountains and then flow down long glacierized valleys into the otherwise heavily forested lowlands of the Chitina, Nabesna, White River, and other interior basins.

As the climate changes, so too do the glaciers. Modern glacier change is occurring against a backdrop of prior advances and retreats that have profoundly shaped the park landscape. Ninety percent of the park, including most presently non-glacierized areas, was under ice during the Last Glacial Maximum (LGM; approximately 22,000 years ago). The ice sheet that covered most of southern Alaska during the LGM took thousands of years to retreat to something approximating modern glacier extent by the start of the Holocene Epoch around 12,000 years ago. Small-scale glacier fluctuations have continued since then, culminating in the peak of the Little Ice Age (LIA) 200 years ago. Glacier moraines deposited during that most recent glacier advance remain quite distinctly visible today in most of the park's glacier valleys. These and other (often unknown) past glacier fluctuations have exerted substantial controls over plant colonization, proglacial lake development and drainage, fish and animal colonization patterns, and even human settlement and migration. Those processes continue today.

Since the peak advance of the LIA in the mid-1800s, the nearly ubiquitous pattern of glacier change in the park has been glacier retreat. The post-LIA retreat began as a response to predominantly natural climate variations, but starting in the 20th century, anthropogenic greenhouse gas emissions accelerated the pace of summer warming, forcing increased glacier melt and mass loss for almost all park glaciers (Loso et al. 2014). The most straightforward way to measure glacier retreat is through changes in glacier-covered areas. As a glacier shrinks, it does so primarily at the low-elevation terminus, where melt occurs more quickly. The glacier outline can be measured by field surveys or, more commonly, through aerial photography and satellite images. In the park, glacier perimeters have been mapped three times: (1) while making the first topographic maps in the 1950s; (2) through direct manual digitizing of satellite images in the 2010s; and (3) most recently, through automated digitizing of a series of satellite images that ranged from 1985 to 2020 (Loso et al. 2014; Roberts-Pierel et al. 2022). Over the period spanning from the 1950s topographic maps to the 2010-era satellite images, the park lost 5% (1,656 km²; [639.4 mi²]) of its glacier cover (Loso et al. 2014; Roberts-Pierel et al. 2022). Automated measurements from 1985 to 2020 partially overlap with the latter one-third of that earlier period and reveal net glacier area losses of 16% in coastal glaciers of the park and 8% in interior glaciers in the northern portion of the park (Roberts-Pierel et al. 2022). That inventory, completed using different techniques over a slightly different study area, confirms continuation and suggests acceleration of glacier loss since the 1950s.

Much of the change that occurs as a glacier shrinks is due to thinning, which makes the glacier appear to be deflating. This is harder to see than terminus retreat, but measurements of these volume changes are necessary to assess a glacier's contribution to river flow and sea level rise. Glacier

volume is estimated by repeatedly measuring the surface elevation of the ice over intervals of one to several years, typically either from an aircraft or a satellite. Volume change is typically reported in units of “meters water-equivalent” (meters w.e.) by converting variable snow and ice densities to the uniform density of water and then dividing the volume change by the area measured (typically the full area of the glacier to provide a glacier-wide average). Thinning rates (usually reported as meters w.e. per year) are generally greatest near the glacier terminus and much lower at high elevations. But the glacier-wide average volume change—in meters w.e.—allows for visualization of the volume lost on a thinning glacier as analogous to water drained out of a glacier-sized swimming pool. These units are directly pertinent to the rivers, lakes, and oceans experiencing enhanced flow downstream of these glaciers. To complement these thinning measurements, NPS also makes direct field measurements of elevation change, ice velocity, and snow depth/density at several sites on Kennicott Glacier each spring and fall. These measurements show the direct relationship between glacier thinning and the processes—snow accumulation, snow/ice melt, and glacier flow—that drive it.

Like the measurements of area change, volume change measurements from various glaciers in the park over the last half century confirm the ubiquitous pattern of glacier mass loss. Interior glaciers from the central Wrangell Mountains measured by satellite imagery experienced glacier-wide average thinning rates of 0.07 m (0.23 ft) w.e./yr from 1957 to 2000 and accelerated thinning of 0.24 m (0.79 ft) w.e./yr from 2000 to 2007 (Das et al. 2014). Using airborne lidar over multi-year epochs ranging from 1994 to 2013, measurements of several dozen large southern Alaska glaciers revealed that land-terminating glaciers were the most consistent in their response to climatic forcing. This result was presumably because the mass balance of lake- and tidewater-terminating glaciers is subject to an additional mass balance forcing related to their subaqueous or submarine tongues (Larsen et al. 2015). For the land-terminating glaciers, the derived median thinning rates from 1994 to 2013 were 0.88 m (2.9 ft) w.e./yr (interior glaciers, including those in the northern and central areas of the park) and -0.73 m/yr (-2.4 ft/yr; coastal glaciers, including those in the southern part of the park; Larsen et al. 2015). Mass balance measurements on the Kennicott Glacier confirm the close correspondence between thinning rates and summer temperatures, confirming that these patterns of volume change are driven primarily by warming summer temperatures. Observations of rapid warming in southern Alaska help explain why Alaskan glaciers are contributing disproportionately to sea level rise: since 2006, it is estimated that Alaskan glaciers are responsible for 22% of the total sea level rise attributable to the melt of mountain glaciers (this excludes the Greenland and Antarctic ice sheets) worldwide (Zemp et al. 2019).

Hidden within the broad patterns of regional glacier retreat described above are exceptional behaviors by a small number of anomalous glaciers. For example, the park is home to several surging glaciers. Surging is an uncommon characteristic of certain glaciers that leads them to periodically speed up, flowing much faster than they normally do during the longer, quiescent (non-surging) intervals. Surging glaciers have complicated patterns of terminus retreat and thinning because a surge rapidly delivers ice from higher elevations to lower elevations, typically causing the terminus to advance and the lower portion of the glacier to thicken, even though the total ice volume has not increased. Malaspina/Sit' Tlein, for example, surged in 2021. Portions of the glacier that had typically flowed at (still impressive) rates of 0.2 to 2 m (0.7 to 7 ft) per day surged to velocities of 10

to 12 m (33 to 39 ft) per day for close to a year, rapidly transferring a massive amount of ice down to the previously stagnant terminus. Roughly 2% of glaciers in the park surge; the most recent complete inventory of glaciers within the park lists two glaciers as possibly surge-type, 39 as probable, and 27 as having been directly observed surging. This list includes some of the largest glaciers in the park, including the coastal Malaspina/Sít' Tlein, Hubbard, and Bering glaciers; the Chitina, Ogilvie, and Logan glaciers at the head of the Chitina Valley; and the Klutlan, Russell, and Chisana glaciers along the active Totschunda fault. As modern satellite technology is used to examine glacier flow patterns more closely, it appears that new members will be added to the list of surging glaciers. One example is the Kennicott Glacier, which is not generally known as a surging glacier but was recently recognized (from satellite imagery) as having undergone a small and previously undetected surge of its terminus in 2019.

Another category of glacier that sometimes behaves unusually is tidewater/lake-terminating glaciers. These types of glaciers, which flow directly into either marine or freshwater bodies, respectively, lose mass not only through climatically driven surface melting forced by prevailing air temperatures but also through unique processes at the water interface. These include submarine or subaqueous melt (loss of ice below the waterline in response to water temperatures) and calving (loss of glacier ice by fracture and iceberg creation). Both these processes are governed by the geometry and dynamics of the glacier's interface with the water body and therefore can be both 1) highly variable in space and time as the glacier terminus evolves and 2) largely decoupled from the behavior of adjacent land-terminating glaciers that respond primarily to climate variations (Brinkerhoff et al. 2017). In the park, there are only a handful of tidewater glaciers: the Hubbard and Turner glaciers at the head of Disenchantment Bay; Yahtse Glacier and others in Icy Bay; and Malaspina/Sít' Tlein, which only breached its morainal banks and made direct contact with saltwater in the last decade or so (Thompson et al. 2024). All these glaciers have records of surface elevation changes that are unusual in comparison with other glaciers in the park. Yahtse and Hubbard are the only ones that have added glacier mass (though inconsistently) in recent decades. This change is consistent with the known tendency of tidewater glaciers, regardless of climatic conditions, to oscillate between periods of slow glacier growth and rapid glacier retreat (the “tidewater glacier cycle”). A recent inventory of freshwater proglacial lakes identified 24 in the park and showed the number and size of such lakes increasing since 1984 (Rick et al. 2022). This change impacts glacier behavior, as described previously, but also impacts access to—and recreational opportunities associated with—glaciers throughout the park. The large proglacial lakes forming and joining around the terminus of Kennicott Glacier, for example, have in the last decade-plus become a prime destination for locals and visitors on rafts, kayaks, and packrafts.

The pattern of ubiquitous and accelerating glacier retreat throughout Alaska has particularly significant consequences for a landscape, like the park, which is presently heavily glacierized. Almost every facet of the park is vulnerable to impact from glacier change. Some high-profile examples of landscape-level consequences from recent peer-reviewed literature include a predicted change in the course of a major river, impacts on the riverine habitat quality for Pacific salmon, a massive landslide and tsunami from recently deglaciated terrain, glacier collapses that buried an entire valley, enhanced flood hazards in abandoned fluvial channels, plant and animal succession in

glacier forelands, and the forecasted loss of thousands of square kilometers of park land as it transitions to open ocean (Curran et al. 2017; Higman et al. 2018; Jacquemart et al. 2020; Loso et al. 2021; Pitman et al. 2021; Sytsma et al. 2023; Brinkerhoff et al. 2024). Some of these impacts pose direct challenges to park management, residents, and visitors. More broadly and optimistically, glacier change provides the NPS with perhaps its most tangible and comprehensible opportunity to educate the public about climate change while also providing a laboratory to understand proglacial and deglaciating landscapes (e.g., Bollati et al. 2023).

Though the park's glaciers are changing rapidly, their size and distribution ensure that the park will remain the "glacier heavyweight" for a very long time. In fact, recent projections of glacier change in the Alaskan national parks show that other parks will likely lose glacier cover faster than this park. This trend stems most directly from the fact that this park has so many large, and hence thick, glaciers. Glacier thickness is not often measured, but fortuitously, good estimates of ice thickness at Malaspina/Sit' Tlein do exist. There, the ice reaches an incredible maximum thickness of over 900 m (2,953 ft). This is an extreme example from one of the park's largest glaciers, but it emphasizes the point that rapid glacier thinning, even in a continually warming climate, will take a very long time to "eradicate" large glaciers. As the smaller glaciers disappear, the park will eventually support a disproportionately large fraction of the glaciers in America's national parks. The massive "glacier complex" that led to the original establishment of the park will therefore become even more significant as glaciers elsewhere disappear and the park becomes an ever more dominant refuge for North America's remaining glacier legacy.

Fluvial Features

The park contains glacial and nonglacial streams and rivers that critically impact ecosystem health, infrastructure stability, and park operations (NPS 2024). Six major drainages are in the park: the Copper, Chitina, Bremner, White, Chisana, and Nabesna rivers (Simmons 2017). The Chitina and Bremner rivers flow into the Copper River, which drains into the Gulf of Alaska, and the White, Chisana, and Nabesna rivers flow into the Yukon River, which drains into the Bering Sea (Simmons 2017). In addition, many of the glaciers in the southern coastal portion of the park discharge large amounts of glacial meltwater directly into the ocean. The park's rivers and streams provide habitat for plants and animals, transportation corridors, supplies of food and water, and sources of recreation for both residents and tourists alike. The Copper River and its tributaries support significant populations of sockeye, coho, chum, and chinook salmon, as well as steelhead (Simmons 2017).

Rivers and streams in the park are dominantly glacier-sourced, though the few typically smaller clearwater nonglacial streams (e.g., the Gilahina River) are disproportionately important for salmon rearing and other ecosystem services. The dominance of glacial rivers means that surficial alluvial deposits (**Qa** and **Qao**) are largely glaciofluvial and sourced from braided riverbeds. Braided rivers transport large quantities of sand, gravel, and cobbles, and their many channels are highly mobile within a typically wide braidplain (Figure 26). Braidplains of some of the larger rivers in the park (e.g., Copper River, White River, Nabesna River) are commonly 1.5–3 km (1–2 mi) wide, and the Chitina River braidplain is, in places, over 5 km (3 mi) wide. Deposits of these rivers are coarser,

more permeable, and more stratigraphically complex than those of typical, nonglacial, meandering streams.



Figure 26. Photograph showing the braided morphology of the Chitina River braidplain. The park's many glaciers slowly carve away the bedrock of the park, feeding sediment and water into the river systems. These glacier-fed rivers and streams often display a braided morphology due to the high volume of sediment they transport. Braided rivers have many channels that are interwoven and frequently shift as sediment builds up and redirects the water.

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Glacial-fed braided rivers also mark the landscape with a signature landform of glacial landscapes: abandoned river channels. Within braidplains, individual braids migrate laterally on a subseasonal basis, but the park also has many examples of entire rivers abandoning their channels in favor of new hydraulically favorable settings. This most commonly occurs in the foreland of retreating glaciers, where channels emerging from either side of a glacier terminus favor a route along the ice edge towards the valley center and hence must continually form new channels as the ice edge retreats upvalley. Such behavior leaves the foreland riddled with abandoned channels that are sometimes subsequently occupied by smaller, underfit streams fed by springs or small tributaries. One conspicuous example of this behavior is occurring in the foreland of Kennicott Glacier, where a small spring-fed stream (Clear Creek) is occupying former channels of the Kennicott River. Clear Creek occasionally floods and impacts the town and roads of the McCarthy area. Another less common form of channel abandonment occurs when tributary streams are temporarily impounded by the

advances of valley glaciers. These streams form ice-dammed lakes that often drain subglacially in flood events known as jökulhlaups, but sometimes instead drain subaerially by incising the adjacent bedrock with overflow channels that allow continual lake drainage around the ice edge. Once the ice retreats, the dry channels are abandoned far from the modern river. Examples exist at Skolai Creek, Iceberg Lake, and Barclay Lake, but the most conspicuous example is just outside the park boundary near Chitina, where the Edgerton Highway travels for several miles through a deep, riverless, and lake-dotted canyon: the former course of the Copper River.

Although most rivers and streams in the park are in their natural state, global stressors such as climate change and local factors such as mining activities and culverts impact hydrologic regimes. Climate change is causing glaciers in the park to retreat and may alter precipitation. These changes have the potential to cause increasing summertime flows in glacier-fed streams (NPS 2016a). The park has a long history of placer mining, which has impaired some of the flowing waters in the Chisana and McCarthy districts (Simmons 2017). Finally, the park's Natural Resource Condition Assessment identified culverts as a stressor to hydrology (Drazkowski et al. 2011). As of 2011, 28 culverts were known on the McCarthy Road, and 33 were known on the Nabesna Road (Drazkowski et al. 2011). Although the culverts alter the flow of water, no research has been conducted to quantify their impact on flow regimes in the park (Drazkowski et al. 2011).

River and stream flow are one of the vital signs monitored by the NPS Central Alaska Inventory and Monitoring program (MacCluskie et al. 2005; Simmons 2017). The park's rivers have been minimally studied, so hydrologic information, including flow measurements and flood frequency, is limited (Drazkowski et al. 2011; NPS 2016a). Over the past 50 years, the US Geological Survey has maintained stream gaging stations in the Wrangell-St. Elias area, but few of them have been within park boundaries, and the data records tend to be short (Simmons 2017). The only current stream gages in the park are temporary stream gages on National Creek and the Kennicott River. The Resource Stewardship Strategy identified supporting natural hydrologic processes and regimes as one of the park's stewardship goals (NPS 2024). Potential management activities that would support this goal include improving hydrological monitoring (including maintaining current stream gages and seeking opportunities for new gages), scenario planning to identify changes in recreational use of rivers and streams, and developing maps that predict how the changing glacial landscape will impact fluvial systems (NPS 2024).

Permafrost

Map units: Rock glacier deposits (**Qrg**)

Large areas of the park are underlain by permafrost, which is ground (soil, sediment, or rock plus any ice or organic material) that remains below 0°C (32°F) for at least two consecutive years, often frozen for much longer. The upper portion of the ground that thaws each summer and refreezes each winter is known as the active layer. Permafrost exists between the active layer and the depth at which the geothermal gradient increases ground temperatures to above freezing. Models predict that permafrost is continuous (underlying over 90% of the landscape) at higher elevations in the northern part of the park, discontinuous (underlying 50–90% of the landscape) in the lowlands in the northern

part of the park, sporadic (underlying 10–50% of the landscape) or isolated (underlying 1–10% of the landscape) along some of the park’s river corridors, and mostly absent in the southern part of the park (Figure 27; Jorgenson et al. 2008a).

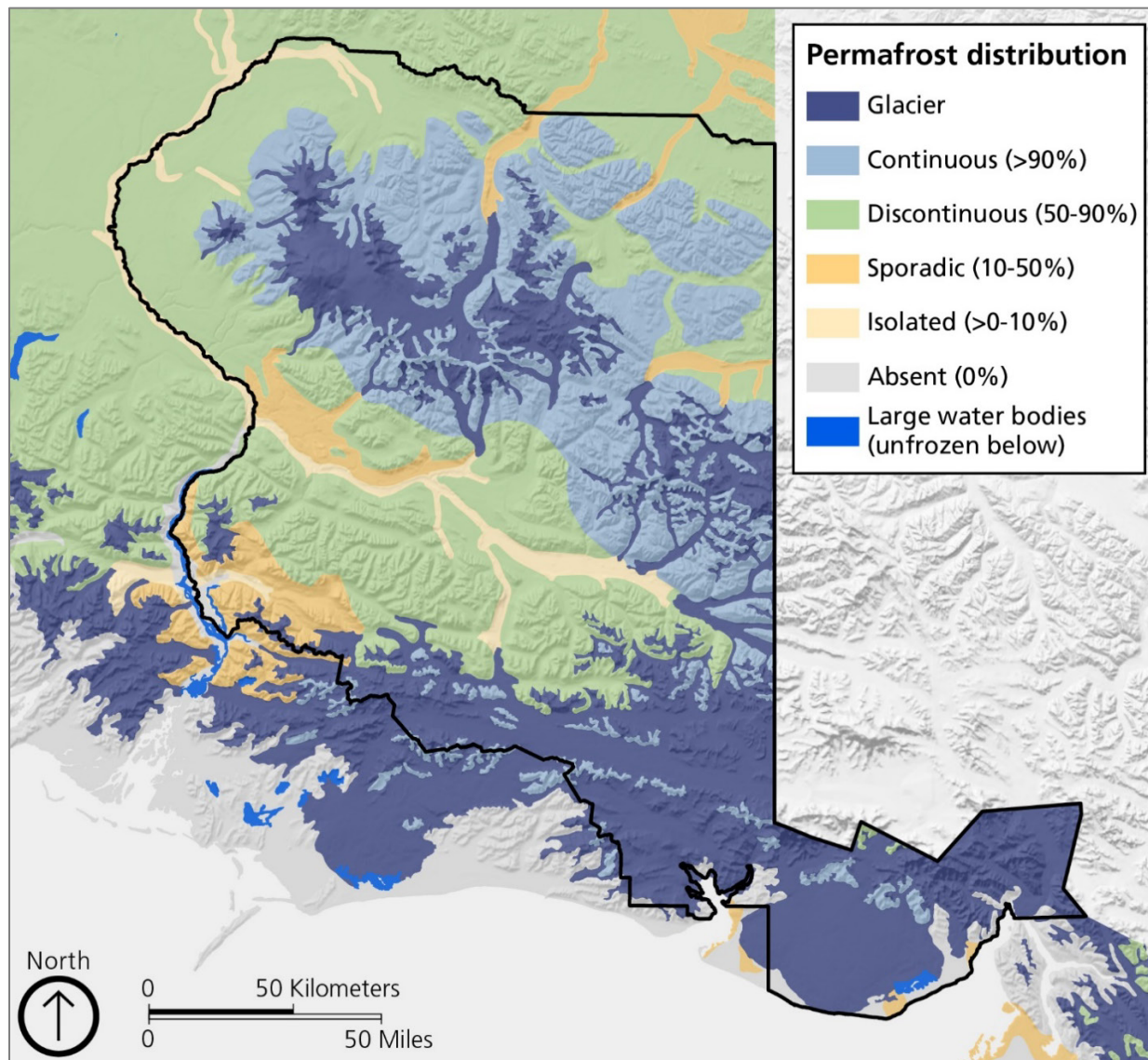


Figure 27. Permafrost map of the park. Permafrost is ground that remains frozen for at least two consecutive years. The park contains areas of continuous permafrost (underlying over 90% of the landscape), discontinuous permafrost (underlying 50–90% of the landscape), sporadic permafrost (underlying 10–50% of the landscape), or isolated permafrost (underlying 1–10% of the landscape). Small areas in the southern area of the park are absent of permafrost.

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Various physical and ecological factors determine if permafrost will form or persist in a given area (Shur and Jorgenson 2007). Climate is one of the most important and obvious factors that affects ground temperature and, therefore, permafrost. For permafrost to exist, mean annual air temperatures

generally need to be below freezing. Between 2001 and 2010, the mean annual air temperatures in the park ranged from about -24.7°C to 5.2°C (-12.5°F to 41.4°F ; Panda et al. 2014). Given the air temperature distribution, permafrost is modeled to have existed across 80% of the park during that period (Panda et al. 2014). Other factors, such as snow cover, soil saturation, and vegetation, can influence permafrost. Snow can insulate the ground during the winter, causing mean ground temperatures to be warmer compared to mean annual air temperatures. In contrast, wet soil and thick vegetation can cause ground temperatures to be colder than air temperatures, preserving permafrost that formed when the climate was colder (Shur and Jorgenson 2007). An example of this occurs near Anchorage, where patches of permafrost exist in black spruce bogs despite the mean annual air temperature being approximately 2.2°C (36°F ; Kanevskiy et al. 2013).

Permafrost creates distinctive landscape features, some of which can be found within the park. When permafrost thaws with high amounts of ground ice, it can lead to landscape subsidence called thermokarst. Permafrost in the Copper River Basin is generally ice-rich, and thermokarst lakes (lakes formed by melting permafrost) occur in the lowlands in the northern part of the park, particularly near the communities of Gakona and Slana, and in the northeast corner of the park (Jorgenson et al. 2008b). The ice-rich nature of the ground and ubiquity of thermokarst in the Copper River Basin are connected to the widespread glacial lake surficial deposits from the ancient Lake Ahtna (see “Surficial Geology”). In contrast, permafrost in the upland areas has little ground ice and thus does not display thermokarst features (Jorgenson et al. 2008b).

Rock glaciers are another type of landscape feature associated with permafrost that occur abundantly in the park, particularly in the central Wrangell Mountains (**Org**; Loso 2018). Rock glaciers provide cold and stable habitats for biodiversity and are less susceptible to climate change-driven melt because of the insulation provided by debris cover (Brighenti et al. 2020). Therefore, rock glaciers may act as future refuges for cold-adapted species in mountain ecosystems (Brighenti et al. 2020). The Sourdough Rock Glacier, located east of McCarthy, has been selected by the NPS Central Alaska Inventory and Monitoring Network for monitoring to understand permafrost thaw and the loss of permafrost-related features (Figure 28; Loso 2018). For more information about projected future permafrost thaw and monitoring of permafrost in the park, see the “Permafrost Thaw and Monitoring” section of this report.



Figure 28. Photograph of the Sourdough Rock Glacier. Rock glaciers are flowing masses of ice that are mantled with a thick layer of rock and debris that helps insulate the ice from melting. The Sourdough Rock Glacier is an informal name given to a large rock glacier on the south side of Sourdough Mountain, in the central Wrangell Mountains. The extent, elevation, and velocity of the Sourdough Rock Glacier are monitored by the NPS Central Alaska Inventory and Monitoring Network to understand the park's permafrost features and how they will change with a warming climate and permafrost thaw.

NPS

Geologic Resource Management Issues

This chapter highlights issues (geologic features, geologic processes, and human activities affecting or affected by geology) that may require management for human safety, protection of infrastructure, or preservation of natural and cultural resources. The GRD provides technical and policy assistance for these issues (see “Guidance for Resource Management”).

Geohazards

The dynamic landscape of the park presents a variety of geologic hazards (“geohazards”) that may pose a risk to NPS resources, facilities, staff, and visitors. Geohazards are active geologic processes, such as landslides, earthquakes, and floods that have the potential to cause damage to structures, facilities, or the loss of life. Management plans to address geohazards could include (1) identifying and mapping potential geohazards; (2) understanding the processes that lead to geohazards; (3) quantifying the frequency and magnitude of geohazards; (4) developing monitoring or detection tools; (5) conducting vulnerability assessments of populated areas or infrastructure; (6) creating plans to avoid or respond to geohazards; and (7) educating employees and visitors (Hults et al. 2019). NPS Policy Memorandum 15-01 (Jarvis 2015) directs NPS managers and their teams to proactively identify and document facility vulnerabilities to climate change and other natural hazards (including geohazards). Geohazards with the potential to impact the park include volcanoes, earthquakes, landslides, tsunamis, glacial lake outburst floods, river breakup, river erosion, and coastal erosion (Hults et al. 2019). Some of these hazards occur more frequently and have a relatively small impact on park infrastructure and visitor safety (e.g., smaller earthquakes and landslides in remote areas), while other hazards are less likely to occur but could potentially have a larger impact (e.g., large earthquakes, explosive volcanic eruptions, landslides in areas of the park that are heavily used, or significant tsunamis).

Earthquakes

Earthquake risk in southern Alaska is particularly high because of its proximity to a tectonically active plate boundary, where the Pacific plate is sliding past and subducting beneath the North American plate (Figure 29; Petersen et al. 2024). The tectonic forces associated with the interaction of multiple plates and pieces of crust at the edge of North America have caused the park’s rocks to deform, producing structural features called faults (planes along which rocks slip past one another). Faults can be inactive, meaning they formed in the past and displacement is no longer occurring, or active, meaning they are currently accommodating motion through periodic ruptures that cause earthquakes. Active faults in the park include (from north to south) the Denali fault system, Totschunda fault, Contact fault system, Chugach-St. Elias fault system, and the Fairweather fault (see Figure 9; US Geological Survey Quaternary Faults database, <https://www.arcgis.com/apps/webappviewer/index.html?id=5a6038b3a1684561a9b0aadf88412fcf>, accessed 6 August 2025).

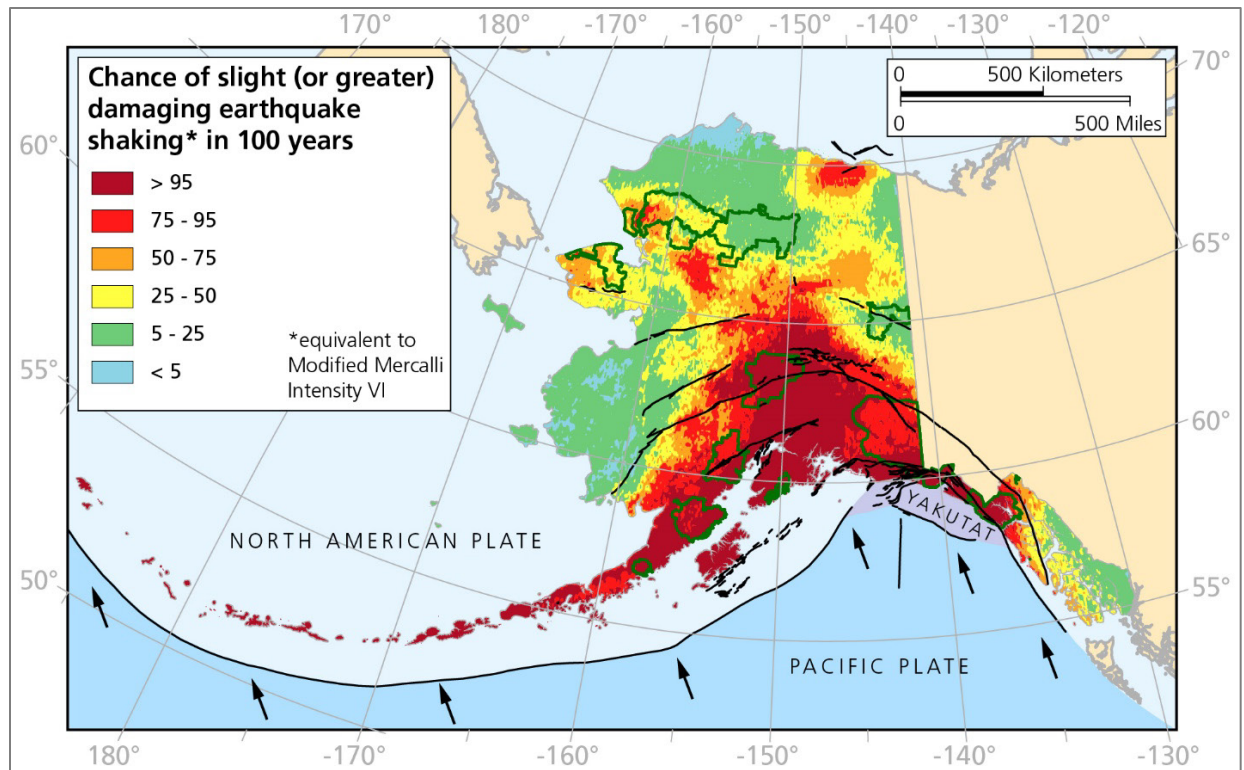


Figure 29. Seismic hazard map of Alaska. The map shows the chance of slight or greater damaging shaking in 100 years from the US Geological Survey 2023 50-State National Seismic Hazard Model. The shaking is equivalent to MMI VI, which is defined as felt by all, many frightened; some heavy furniture moved; a few instances of fallen plaster; slight damage. Green outlines are National Park System units, and black lines are Quaternary faults. The park has areas with a 75–95% (bright red) and greater than 95% (dark red) chance of experiencing a damaging earthquake in 100 years.

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Several major (magnitude 7 and greater) earthquakes have occurred in and around the park in historic times (US Geological Survey earthquake catalog, <https://earthquake.usgs.gov/earthquakes/search/>, accessed 1 March 2024). Most of these earthquakes affected the southern part of the park, resulting from ruptures on the Aleutian megathrust (magnitude 9.2 in 1964), the Fairweather fault system (magnitude 7.8 in 1958), and the complex series of faults between these major features (magnitudes 8.1 and 8.2 in 1899; magnitude 7.1 in 1979). The central part of the park has not experienced many strong earthquakes, mainly due to a lack of active faults in the area. The northern part of the park, however, is cut by the strike-slip Denali and Totschunda faults that produced one major earthquake in 2002 (magnitude 7.9).

The southern part of the park has a history of large earthquakes because of its proximity to major, plate-bounding faults. In 1899, a series of earthquakes occurred within the Yakutat terrane in the vicinity of the park's southern coastline (Tarr and Martin 1912; Plafker and Thatcher 2008). The two largest of these earthquakes (magnitudes 8.1 and 8.2) caused tectonic uplift along the coast of about 1 m (3 ft) near Cape Yakataga and up to 14.4 m (47.2 ft) in Yakutat Bay (Plafker and Thatcher 2008).

Additionally, the earthquakes triggered landslides, avalanches, and changes to glaciers in the Yakutat Bay region (Tarr and Martin 1912). While the 1899 earthquakes were strongly felt throughout the Gulf of Alaska region, they caused no loss of life and only minor property damage due to the low population and infrastructure in the area (Plafker and Thatcher 2008). To the southeast of the park, a magnitude 7.7 earthquake ruptured the Fairweather fault near Lituya Bay (Glacier Bay National Park and Preserve) in 1958 (Tocher 1960). The shaking resulted in a massive landslide and associated tsunami in Lituya Bay (Tocher 1960). In 1964, the largest earthquake in US history occurred along the Aleutian megathrust about 150 miles west of the park in Prince William Sound (Brocher et al. 2014). The magnitude 9.2 Great Alaska Earthquake was felt throughout most of Alaska and triggered widespread tsunamis, landslides, and lesser aftershocks (Plafker 1969). In 1979, the magnitude 7.1 St. Elias earthquake occurred in the southern part of the park, about 50 km northwest of Mount St. Elias (Perez and Jacob 1980). Damage caused by the earthquake was minor given the remoteness of the epicenter (Stover and Coffman 1993). It was most strongly felt at a lumber camp near Icy Bay, where trees and bushes were strongly shaken, a truck was bounced across a road, and people had difficulty standing (Stover and Coffman 1993).

The northern part of the park is characterized by the active Denali and Totschunda faults. While these faults do not produce as many large earthquakes as those in southern Alaska, in 2002, a rupture on the Denali fault triggered the largest strike-slip earthquake in North America in almost 150 years (Eberhart-Phillips et al. 2003). The epicenter of the magnitude 7.9 Denali fault earthquake is located on the Susitna Glacier fault, about 170 km (100 mi) northwest of the park, but the rupture propagated along the Denali and Totschunda faults into the northern part of the park (Eberhart-Phillips et al. 2003; Haeussler et al. 2004). The 2002 Denali fault earthquake resulted in one injury and extensive damage to roads and bridges (US Geological Survey earthquake catalog, <https://earthquake.usgs.gov/earthquakes/eventpage/ak002e435qpj/impact>, accessed 19 March 2024). It also caused landslides, rockslides, ground cracks, and snow avalanches near the fault rupture.

According to the US Geological Survey 2023 National Seismic Hazard Model, the park has areas with a 75–95% chance and over a 95% chance of a Modified Mercalli Intensity (MMI) VI or greater earthquake within 100 years (see Figure 29; Petersen et al. 2024). The MMI scale is a qualitative scale used to describe the effects of an earthquake at a given location, in contrast to the Richter scale, which measures earthquake magnitude. An MMI VI earthquake frightens many people, causes many objects to fall from shelves, does minor damage to buildings, causes some tree limbs to fall, and triggers isolated rockfalls, landslides, and liquefaction (when water-saturated soil or sediment loses strength and behaves like a liquid). A larger earthquake could cause more damage. Seismicity across Alaska is monitored by the Alaska Earthquake Center (see <https://earthquake.alaska.edu/>). Many seismic monitoring stations are within and near the park, including near Glennallen, in Nabesna, in McCarthy, and on the Bagley Icefield. A map of all the seismic monitoring stations in Alaska is available on the Alaska Earthquake Center website (earthquake.alaska.edu/network).

Ground shaking from an earthquake can damage infrastructure and natural resources, which in turn may directly threaten human safety. Indirect effects, such as soil failure, slumping, landslides, avalanches, and tsunamis, are also hazardous. Emergency planning can include measures to reduce

risk prior to the occurrence of an earthquake and to develop resiliency in response to an earthquake (West et al. 2019). Assessing facilities for potential dangers and seeking ways to reduce them are examples of reducing risk before an earthquake (West et al. 2019). Resilience planning strategies can include developing written plans for responding to earthquakes, creating inspection checklists, training staff, and educating visitors (West et al. 2019). More information about addressing earthquake hazards in Alaska's national parks can be found in West et al. (2019).

Landslides

Landslides are a natural geologic phenomenon that have the potential to be hazardous to people, resources, and infrastructure. Here, the term “landslide” is used as an all-inclusive term that includes various types of slope movement such as fast-moving rockfalls, rock avalanches, debris flows, slow-moving debris slides, ridge spreading, and earth flows (Varnes 1978). Landslides occur when down-slope forces (primarily gravity) exceed the strength of the slope material. Steep slopes, particularly those greater than 30°, are more likely to produce landslides because these slopes have already increased down-slope force. Factors that either increase the effects of down-slope forces or reduce the strength of slope material can trigger landslides. Usually, multiple factors contribute to a landslide; these factors can include gradual changes to the condition of a slope, such as stream erosion at the toe of the slope or thawing permafrost, and discrete events such as heavy rainfall and earthquakes. Heavy rainfall can alter the hydraulics of the sediments on a slope, leading to an increase in pore pressure that reduces their overall cohesion. Additionally, human activities such as vegetation removal, mining, construction, and other ground-disturbing actions can contribute to the likelihood of slope failure.

Many areas of the park have steep slopes that have generated landslides in the past and appear as surficial deposits with distinctive features. A handful of landslide deposits (**QI**) are mapped in the park's GRI geologic map, primarily in the Wrangell Mountains (see GRI poster). More landslides have been mapped by the US Geological Survey landslide inventory (<https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=ae120962f459434b8c904b456c82669d>; accessed 1 May 2024). The US Geological Survey landslide inventory landslides are primarily concentrated along the McCarthy and Nabesna roads, as well as in the St. Elias Mountains near Malaspina Glacier (Bessette-Kirton and Coe 2020). A more comprehensive park-wide inventory has not yet been completed. Detailed studies have been conducted on three recent landslides within the park: the 2015 Taan Fiord landslide, a series of ice-rich debris flows in the Flat Creek drainage between 2013 and 2016, and the 1994 Nelson Mountain landslide.

On 17 October 2015, a massive landslide and tsunami occurred near the head of Taan Fiord, in Icy Bay (see “Tsunamis”). The Taan Fiord landslide was one of the largest non-volcanic landslides in decades, unleashing 180 billion kg (340 billion lbs) of debris onto the toe of Tyndall Glacier, into Taan Fiord, and 105 m (344 ft) up the opposite side of the fjord (Higman et al. 2018). The ultimate trigger of the landslide is unclear, but slumping along the fjord wall can be seen in satellite imagery as early as 1995 (Higman et al. 2018). Factors that likely contributed to the slope instability include ongoing rapid uplift of the St. Elias Mountains and recent deglaciation (Higman et al. 2018). The landslide occurred at a time when no one was close enough to be affected; however, if a similar

landslide and tsunami were to happen when visitors were in Taan Fiord, the consequences could be devastating (see “Tsunamis”).

The Flat Creek drainage in the interior portion of the park has experienced three large, ice-rich debris flows over the past 15 years (Jacquemart and Loso 2019). The debris flows occurred in August 2013, July 2015, and August 2016 (Jacquemart and Loso 2019). The first two flows were heard and felt by nearby resident Tom Vaden, and he later observed the ice- and mud-rich deposits overrunning the forest in Flat Creek (Jacquemart and Loso 2019). Remarkably, the 2016 flow was by coincidence captured on video by NPS rangers flying a routine hunting patrol in the area (Jacquemart and Loso 2019). Although the 2016 flow was an impressive spectacle, remote sensing data indicates the 2013 and 2015 events were much larger, moving up to 11 million m³ (395 million ft³) and 27 million m³ (965 million ft³) of debris downstream, respectively (Jacquemart and Loso 2019). All three debris flows contained an unusual amount of ice because they involved the collapse of significant portions of an unnamed glacier in the upper Flat Creek drainage (Jacquemart and Loso 2019). The areas where the glacier collapsed were not steep enough to characterize the flow as an ice avalanche, and only a few similar events involving low-angle glacier collapse have been described worldwide (Jacquemart and Loso 2019). More research would help better characterize the Flat Creek debris flows and help scientists understand if, given the worldwide trend of glacial retreat, these events may be occurring more often (Jacquemart and Loso 2019).

Climate change will likely result in increased landslide activity, particularly in high latitude areas like Alaska (Coe 2016). Consequences of climate change that could increase landslides in the park include glacial retreat, permafrost thaw, and changes in precipitation. Glaciers across the park are retreating, and the newly exposed slopes are often unstable and prone to landslides. This is because recently deglaciated slopes have been over-steepened by glacial erosion and no longer have ice providing lateral support. A warming climate is also causing the park’s permafrost to thaw, which in turn increases hillslope susceptibility to landslides (Patton et al. 2020). This is because permafrost thaw alters the hydrology and physical properties of hillslopes in such a way that it decreases the strength of the underlying slope materials (Patton et al. 2020). Finally, precipitation events are often a trigger for landslides, so changes in precipitation will affect landslide risk. Lader et al. (2023) used climate model projections for the park to assess future landslide risk along the McCarthy Road corridor. They projected elevated landslide hazards along the McCarthy Road related to a rise in mean annual air temperature and permafrost thaw, as well as increases in summer precipitation.

Landslides can pose a threat to park resources, infrastructure, staff, and visitors. Most of the park is characterized by physical conditions conducive to landslides, which include steep terrain, active tectonic uplift, recent deglaciation, and permafrost thaw. The park is also in a seismically active region that experiences many earthquakes that could potentially trigger landslides. Although many areas of the park may be prone to landslides, landslide risk is limited due to the rarity of major infrastructure and relatively low visitation throughout most of the park. Landslides have a higher potential to cause damage if they occur in areas with infrastructure, if they occur in areas frequented by people such as along trails, if they occur in areas with important nonrenewable resources, or if they enter a body of water and generate a tsunami. Most park infrastructure exists within the

Kennicott valley and along the McCarthy and Nabesna roads. The McCarthy Road, for example, is subject to routine blockage by small slumps at its western (“Kotsina Bluffs”) and eastern (“Mile 58”) ends (Figure 30). If slumps in either of these areas grow in size or frequency, they could pose a substantial risk for visitors and communities along the road. Targeted monitoring for potential landslides in high-risk areas could help park staff identify and prepare for hazards.

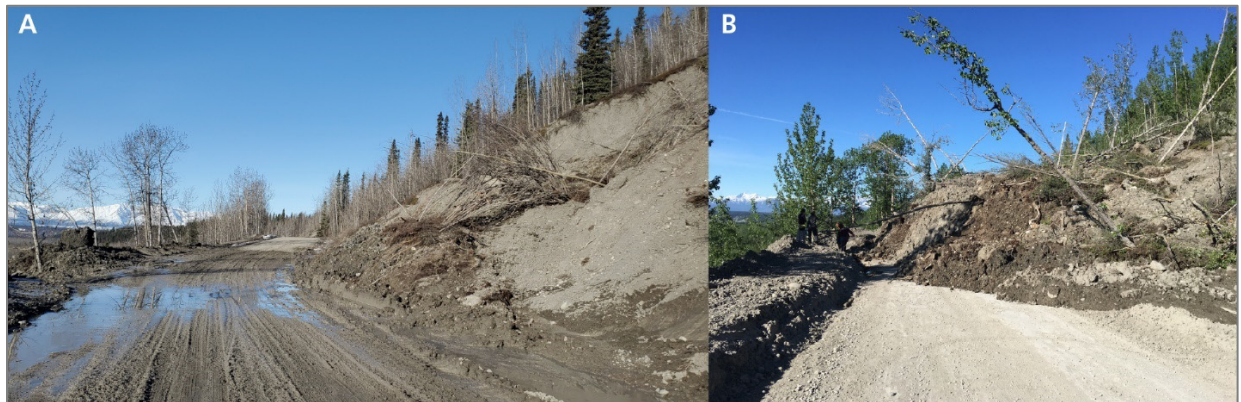


Figure 30. Photographs of landslides along the McCarthy Road around mile 58. The McCarthy Road is routinely blocked by small slumps of surficial sediments moving downslope. A recent study by Lader et al. (2023) projected landslide hazard along the McCarthy Road will rise in the future due to consequences of climate change such as permafrost thaw and increased summer precipitation.

NPS / MIKE LOSO

Tsunamis

Coastal areas throughout southern Alaska are vulnerable to tsunamis. Table 4 lists historic tsunamic activity with water height over 0.3 m (1 ft) that affected the park’s coast and surrounding area. A tsunami is a series of waves caused by a large, sudden displacement of the ocean (NTHMP 2019). Tsunamis can be triggered by earthquakes, landslides, glacial ice collapse, volcanic activity, certain types of weather, and near-Earth object impacts (e.g., asteroid, comet; NTHMP 2019; Higman et al. 2018). Because the coast of the park is characterized by frequent earthquakes and high probability for landslides, tsunamis that affect the park are likely to be caused by earthquakes or landslides (see “Earthquakes” and “Landslides”). Earthquake-induced tsunamis typically are long-period waves that rise and fall gradually, can affect large areas, and have shorter runups (they only inundate low elevations; Higman et al. 2018). In contrast, tsunamis caused by landslides typically are short-period waves that can rise and fall quickly, reach heights of several hundred meters, and affect a smaller geographic area (Higman et al. 2018).

Table 4. Historic tsunamis with maximum water height above 0.3 m (1 ft) that affected the coast in and around the park. Information is from the National Oceanic and Atmospheric Administration’s Global Historical Tsunami Database (accessed 13 March 2024).

Year	Cause	Runup location	Max water height (m)	Notes
1845	Glacier collapse	Haenke Island (Disenchantment Bay)	Unknown	A hanging glacier (Fallen Glacier) collapsed into Disenchantment Bay, causing a hundred fatalities at a sealing camp a few miles south of Haenke Island. This event was described by locals after a similar event occurred in 1905. Date is approximate.
1899	Earthquake and landslide	Cape Yakataga, Logan Coast, Yakutat Bay, Yakutat, Disenchantment Bay, Russell Fjord, Kwik River Delta	3–12.19	Series of earthquakes up to M 8.2 between Yakutat Bay and Cape Yakataga.
1905	Glacier collapse	Disenchantment Bay, Russell Fjord, Haenke Island, Turner Glacier	6.1–33.53	A hanging glacier (Fallen Glacier) slid in its entirety into Disenchantment Bay.
1946	Earthquake and landslide	Yakutat	0.37	M 8.6 earthquake near Umiak Island (Aleutian Islands, Alaska)
1957	Earthquake	Yakutat	0.34	M 8.6 earthquake south of the Andreanof Islands (Aleutian Islands, Alaska)
1958	Earthquake and landslide	Disenchantment Bay, Yakutat, Khantaak Island	0.9–6.1	M 7.8 earthquake near Palma Bay (southeast Alaska)
1960	Earthquake	Yakutat	0.76	M 9.5 earthquake in Chile
1964	Earthquake and landslide	Cape Yakataga, Yakutat, Disenchantment Bay, Yakutat	1.2–4.8	M 9.2 Great Alaska earthquake in Prince William Sound (southcentral Alaska)
1985	Earthquake	Yakutat	Unknown	M 8 earthquake in Chile
1987	Earthquakes	Yakutat	0.06–0.43	M 7.9 earthquake south of Cape Yakataga
2010	Earthquake	Yakutat	0.36	M 8.8 earthquake in Chile
2011	Earthquake	Yakutat	0.35	M 9.1 earthquake in Japan
2015	Landslide	Taan Fiord, Yakutat	0.18–193	Landslide in Taan Fiord
2022	Volcanic	Yakutat	0.48	Volcanic eruption in Tonga

On 17 October 2015, a massive landslide slid into Taan Fiord, an arm of Icy Bay, generating the fourth-highest tsunami ever recorded (Higman et al. 2018). The tsunami reached 193 m (633 ft) near the head of the fjord where the landslide entered the water (Higman et al. 2018). The wave gradually diminished as it moved down-fjord, reaching 15 m (50 ft) at the mouth of the fjord and 11 m (36 ft) directly across from the fjord outlet (Higman et al. 2018). Tide gages 130 km (80 mi) and 400 km

(250 mi) away recorded 40-minute-long oscillations of several inches in the water level due to the Taan Fiord tsunami (Higman et al. 2018). The wave inundated 20 km² (8 mi²) of forest in the park and surrounding private property (Higman et al. 2018). Additional onshore impacts included transporting boulders up to 5 m (16 ft) in diameter, depositing loose sediment ranging in size from sand to boulders, and scouring vegetation from intertidal areas (Higman et al. 2018). Luckily, no one was harmed by the Taan Fiord tsunami (Higman et al. 2018). Higman et al. (2018) provide more detailed information on the 2015 Taan Fiord tsunami, highlighting the importance of rapid glacial retreat for precipitating the landslide and discussing the potential for future similar events in Icy Bay.

As demonstrated by the 2015 Taan Fiord event, tsunamis have the potential to be extremely destructive. If a similar tsunami happens at a busier time of year or in an area with more human activity, it could have devastating impacts on people, vessels, and infrastructure. The coast of the park encompasses Icy Bay (including Taan Fiord), Malaspina Glacier, and the northern side of Yakutat Bay (including Disenchantment Bay; see the GRI poster). Additionally, the park maintains a hangar in the town of Yakutat, on the southern side of Yakutat Bay. Icy Bay, Yakutat Bay, and Yakutat all have a history of tsunamis (see Table 4). The main mechanisms for triggering past tsunamis—earthquakes and landslides—will continue to occur or, in the case of landslides, potentially increase in the future (see “Landslides”). Although visitation to the park’s southern coastline is low compared to other areas of the park, a small and growing number of kayakers, anglers, hunters, and ships spend time in the offshore waters. Even cruise ships visit, with growing numbers of large cruise ships making Disenchantment Bay a regular destination and mostly smaller ships making occasional forays into Icy Bay.

The park’s vulnerability to tsunamis, particularly large tsunamis like the 2015 Taan Fiord event, combined with the presence of visitors and infrastructure along the coast, produces a potentially hazardous situation. While not on NPS land, the community of Yakutat is vulnerable to tsunami inundation. The Alaska Division of Geological and Geophysical Surveys (DGGS) evaluated tsunami hazards for the nearby town of Yakutat (Suleimani et al. 2016). This study provided maps that show the extent of inundation from potential tsunami waves generated by tectonic and landslide sources (Suleimani et al. 2016). Similar mapping to evaluate at-risk areas along the park’s coast has not been completed. The NPS could take preparatory actions that could include, but are not limited to, mapping areas of potential coastal landslides, monitoring potential landslide areas periodically for precursory movement, modeling impacts of tsunamis, identifying areas of high tsunami risk, and developing planning and education efforts to reduce risk (Higman et al. 2018). A collaborative NPS-US Geological Survey project is underway to identify areas that may present landslide-generated tsunami hazards in Glacier Bay National Park and Preserve (Hults et al. 2023). Given the similarities between the coasts of Glacier Bay National Park and Preserve and Wrangell-St. Elias National Park and Preserve, this study may be a useful model for addressing tsunami hazards in the park.

Volcanic Hazards

The park has many volcanoes that formed within the last 30 million years; however, only one of these volcanoes (Mount Wrangell) is considered active (see “Wrangell Arc”; Richter et al. 1995). Mount Wrangell has had no confirmed eruptions in historic times (since about 1760 CE), but the

summit contains three craters with active fumaroles (volcanic vents that emit vapor and gas; Richter et al. 1995). Two of the summit craters also display sporadic phreatic activity (steam explosion caused by the interaction of hot volcanic rock or magma and groundwater) that can blanket the surrounding area with a thin layer of ash (Richter et al. 1995). Since the 1700s, there have been over 20 reports of non-eruptive activity and questionable eruptions at Mount Wrangell (<https://avo.alaska.edu/volcano/wrangell>, accessed 30 May 2024). The last confirmed eruption producing lava occurred about 80,000 years before present (Richter et al. 1990). Additionally, although Mount Churchill is considered dormant, it is classified as a higher threat volcano than Mount Wrangell (e.g., high threat vs. moderate threat) by the US Geological Survey (Ewert et al. 2018). This classification puts Mount Churchill into the same threat category as Iliamna Volcano in Lake Clark National Park and Preserve and the volcanoes of Katmai National Park and Preserve (Ewert et al. 2018). The chances of either volcano erupting are low, but they should be considered threats, especially given the status imparted by the US Geological Survey (Ewert et al. 2018).

Major earthquakes can alter the plumbing system beneath a volcano and either cause an increase or a decrease in volcanic activity (Richter et al. 1995; Sánchez and McNutt 2004). Ash falls on Mount Wrangell were reportedly common following a series of large earthquakes in 1899 in the vicinity of Yakutat Bay (see “Earthquakes”; Richter et al. 1995). Similarly, thermal activity increased markedly at the summit following the 1964 Great Alaska Earthquake (Richter et al. 1995). The 1964 earthquake may have shifted the focus of fumarole activity from the western summit crater to the northern crater (Richter et al. 1995). In contrast, studies of volcanic-related seismic activity at Mount Wrangell before and after the 2002 Denali fault earthquake showed about a 50% decrease in seismic activity following the earthquake (Sánchez and McNutt 2004). In both cases, where volcanic activity increased and decreased following major earthquakes, the changes have been hypothesized to be a result of seismic activity altering the plumbing system beneath the volcano (Richter et al. 1995; Sánchez and McNutt 2004).

Volcanic hazards in the park include proximal hazards that can affect the area around the vent and distal hazards that are capable of impacting areas at the regional, national, or international scale (Mulliken et al. 2019). Potential proximal volcanic hazards include ballistics, lahars, pyroclastic flows, lavas and domes, rockfalls, landslides, debris avalanches, and volcanic gases (Mulliken et al. 2019). Mount Wrangell was built by the eruption of large volumes of lava, and a future eruption could produce similar flows. Lavas are generally slow-moving, avoidable hazards, but when they interact with water or ice, additional hazards may include explosions and ballistic projectiles (Mulliken et al. 2019). In the past, Mount Wrangell has also produced a significant volcanic landslide (mass-flow; Waythomas and Wallace 2002). During the Pleistocene Epoch, a major flank collapse occurred on the southwest side of Mount Wrangell, producing an extensive volcanic mass-flow that is recorded by deposits now found in the Copper, Tonsina, and Chitina river valleys (Waythomas and Wallace 2002). If visitors were to get close enough to the active fumaroles, volcanic gases could pose a risk at Mount Wrangell even when it is not erupting. Another explosive eruption from Mt. Churchill will also pose widespread regional (and likely global) hazards, given how widely the White River ash was deposited. Additionally, the mud volcanoes located about 29 km (18 mi) west of Mount Drum produce gases that could be hazardous to visitors (Winkler et al. 2000). Distal volcanic hazards are

primarily related to volcanic ash expelled during an eruption, which can be carried by wind a significant distance from the source vent. Depending on the accumulation of ash, impacts can range from eye and respiratory irritation to heavy infrastructure damage and loss of plants and animals (Table 5; <https://avo.alaska.edu/volcano/hazards>, accessed 31 May 2024). Additionally, ash is highly abrasive and can severely damage aircraft (Mulliken et al. 2019).

Table 5. Impacts of volcanic ash fallout. Table modified from the Alaska Volcano Observatory (<https://www.avo.alaska.edu/volcanoes/hazards.php>).

Term	Accumulation	Key Impact Thresholds (cumulative)
Trace or dusting	<0.08 mm (0.031 in)	Eye and respiratory irritant, very low level impacts for most people.
Minor	0.8–6.4 mm (0.031–0.25 in)	Possible crop, animal equipment, and infrastructure problems; widespread cleanup likely.
Moderate	6.4–25.4 mm (0.25–1.0 in)	Ash removal efforts significant.
Heavy	25.4–100 mm (1.0–4.0 in)	Weaker roofs can fail at about 10–12 cm (4–5 in) of compacted, wet ash accumulation ~200 kg/m ² (~40 lb/ft ²).
Very Heavy	100–300 mm (4.0–12.0 in)	Danger of roof collapse increases, damage to trees occurs, essential services are interrupted.
Severe	>300 mm (>12 in)	Roads impassable, severe infrastructure damage, heavy plant and animal loss.

The Alaska Volcano Observatory (AVO) monitors and conducts research on volcanoes in Alaska to better understand volcanic processes and determine the likelihood of future volcanic hazards (Mulliken et al. 2019). Generally, volcanic eruptions are preceded by earthquakes that can be detected by the AVO seismic network. AVO monitors Mount Wrangell using seismic sensors and webcams at Chistochina and Tazlina. Mount Churchill is currently not instrumented by AVO and was identified in a 2005 US Geological Survey report as one of the “11 high-threat volcanoes that are significantly under-monitored” (Ewert et al. 2005). In addition to the seismic network and webcam monitoring, the following methods are used to detect volcanic unrest at Alaska volcanoes:

- Daily satellite analysis of images from space to look for signs of elevated surface temperatures or airborne volcanic ash.
- Regional infrasound capability that may be able to detect explosions, with potentially hours of delay.
- Permanent GPS stations and space-based radar interferometry (InSAR) are used to detect ground deformation (uplift or subsidence) that may occur prior to eruptions, though these are not real-time techniques.
- Pilot reports and other direct observations of changes at a volcano.

For more information on the hazards associated with volcanoes in the park and monitoring updates, see the AVO website (<http://avo.alaska.edu>). Additional information on volcanic hazards in Alaska's national parks can be found in Mulliken et al. (2019).

Stratotype Inventory, Monitoring, and Protection

Map units: **QTw, Ku, Kun, Kc, Kl, Js, JTRm, TRcn, TRn, PPNs, Ph, Pl**

The park contains 25 stratotypes, which are exposures of rock that form the basis for defining a geologic unit (Figure 31; Henderson et al. 2022). Geologic units, such as those displayed in the GRI GIS data and discussed throughout this report, form the framework through which the geology of an area is studied and understood. When geologists map, describe, and name a new geologic unit, they will designate a specific section or area, called a stratotype, that is a representative example of the new unit. Typically, formalized geologic units are named after geographic locations that coincide with the original stratotype designation; an example would be the Nizina Limestone, named after its type locality exposure along the Nizina River. See Table 6 for a summary of the stratotypes designated within the park. Additionally, an unnamed Cretaceous nonmarine sedimentary unit (**Kun**) has recently been informally named the Beaver Lake formation by Trop et al. (2020). A formal designation of the Beaver Lake formation would bring the park's stratotype number up to 26.

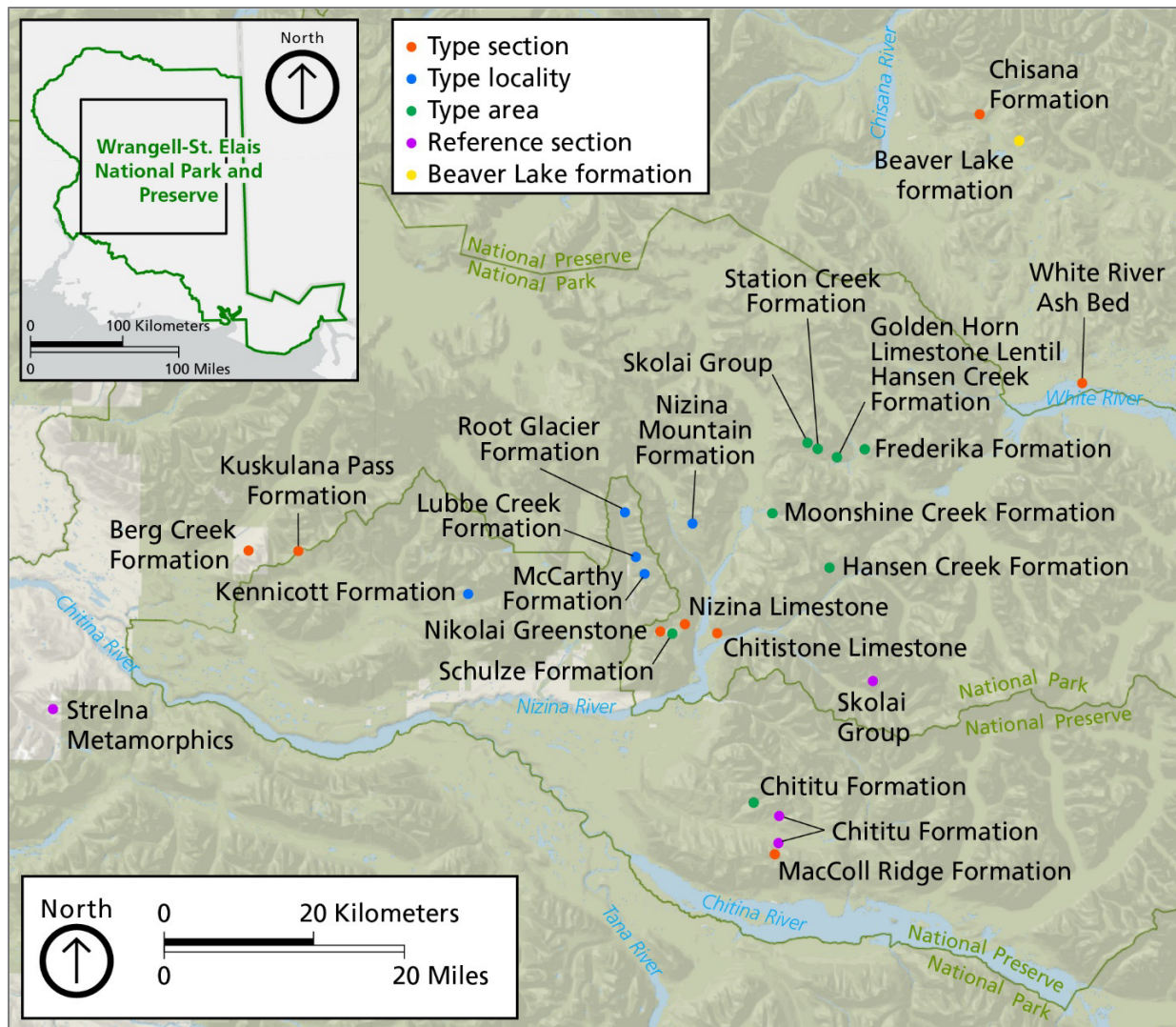


Figure 31. Stratotype map for Wrangell-St. Elias National Park and Preserve. The park contains 25 stratotypes, including type sections, type localities, type areas, and references sections. Additionally, an unnamed Cretaceous sedimentary unit (Kun) has been informally named the Beaver Lake formation by Trop et al. (2020). These rock exposures contain the diagnostic criteria that define geologic units and are therefore important to protect from development and make available for scientific research. See Henderson et al. (2022) for more information about the park's stratotypes.

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Table 6. Stratotypes in Wrangell-St. Elias National Park and Preserve. Stratotypes are sorted by age with associated reference publications and locations. In some cases, the GRI geologic units (and unit symbols) have grouped multiple formations together. See the original publications for the distribution of individual units. Table is sourced from Henderson et al. (2022).

Age	Unit Name	GRI Unit Symbol(s)	Stratotype Description	Reference(s)
Holocene	White River Ash Bed	N/A	Type section: on the north side of the White River, about 13 km (8 mi) downstream from the source of the river in Russell Glacier and about 50 km (31 mi) west of the Alaska-Canada border, McCarthy D-2 Quadrangle	Péwé 1975
middle Miocene	Frederika Formation	QTw	Type area: in sec. 5, T. 2 S., R. 18 E., McCarthy C-4 Quadrangle, southern Alaska	MacKevett 1970
Late Cretaceous	MacColl Ridge Formation	Ku	Type section: about 4.8 km (3 mi) east of western boundary of McCarthy A-4 Quadrangle and trends southward from the contact with the Chititu Formation to near the crest of MacColl Ridge, McCarthy A-4 Quadrangle, southern Alaska	Jones and MacKevett 1969
late Early to early Late Cretaceous	Moonshine Creek Formation	Ku	Type area: Moonshine Creek in McCarthy C-4 Quadrangle, southern Wrangell Mountains, southern Alaska	Jones and MacKevett 1969
late Early to early Late Cretaceous	Schulze Formation	Ku	Type area: upland north of Sourdough Peak east of upper reaches of Nikolai Creek, McCarthy B-5 Quadrangle, southern Alaska	Jones and MacKevett 1969
Late Cretaceous	Chititu Formation	Ku	Type area: exposures north and south of Young Creek, in northwestern part of McCarthy A-4 Quadrangle, and south of latitude of Copper Creek, in southern part of McCarthy B-4 Quadrangle, southeastern Alaska. Reference sections (2): exposures that extend north and south of Young Creek about 6.4 km (4 mi) east of the western border of the McCarthy A-4 Quadrangle	Jones and MacKevett 1969
Early Cretaceous	Chisana Formation	Kc	Type section: lower part in valley of Bonanza Creek, in secs. 25, 35, and 36, T. 4 N., R. 19 E.; upper part in valley of Toby Creek, in secs. 28, 33, and 34, T. 4 N., R. 20 E., Nabesna A-2 Quadrangle, southern Alaska	Richter and Jones 1973; more description of facies is available in Manselle et al. (2020).

Table 6 (continued). Stratotypes in Wrangell-St. Elias National Park and Preserve. Stratotypes are sorted by age with associated reference publications and locations. In some cases, the GRI geologic units (and unit symbols) have grouped multiple formations together. See the original publications for the distribution of individual units. Table is sourced from Henderson et al. (2022).

Age	Unit Name	GRI Unit Symbol(s)	Stratotype Description	Reference(s)
Early Cretaceous	Kennicott Formation	KI	Type locality: at Kennicott Pass (now known as Fourth of July Pass) Type locality (redefined): hillsides east of Fohlin Creek and north of Bear Creek, mainly in the southwestern part of the McCarthy C-6 Quadrangle, but to a lesser extent in the northwestern part of the adjoining McCarthy B-6 Quadrangle	Martin 1926; Jones and MacKevett 1969
Early Cretaceous	Kuskulana Pass Formation	KI	Type section: exposures in upper drainage basin of Trail and Slatka Creeks near Kuskulana Pass, extending south from NE/4 SE/4 sec. 32, T. 3 S., R. 10 E., to NE/4 SW/4 NW/4 sec. 5, T. 4 S., R. 10 E., McCarthy C-8 Quadrangle, Wrangell Mountains, Alaska	MacKevett et al. 1978
Early Cretaceous	Berg Creek Formation	KI	Type section: from west of Berg Creek to 1.8 km (1.1 mi) south of Kuskulana Pass; exposures from SE/4 SW/4 sec. 34, T. 3 S., R. 9 E. southward to south part of SE/4 NW/4 sec. 3, T. 4 S., R. 9 E., McCarthy C-8 Quadrangle, Wrangell Mountains, Alaska	MacKevett et al. 1978
Late Jurassic	Root Glacier Formation	Js	Type locality: designated as hillside east of upper part of McCarthy Creek, McCarthy C-5 Quadrangle, southern Alaska	MacKevett 1969
Middle Jurassic	Nizina Mountain Formation	Js	Type locality: outcrops that partly girdle the ridge that extends southward from Nizina Mountain, McCarthy C-5 Quadrangle, southern Alaska	MacKevett 1969
Late Triassic to Early Jurassic	McCarthy Formation	JTRm	Type locality: between McCarthy Creek and Nizina River, Nizina–Tanana region, southern Alaska	Moffit and Capps 1911
Late Triassic	Nizina Limestone	TRcn	Type section: cliffs on west side of Nizina River opposite mouth of Chitistone River, Nizina–Tanana region, southern Alaska	Martin 1916
Late Triassic	Chitistone Limestone	TRcn	Type section: in Nizina Valley, at junction of Nizina and Chitistone Rivers	Moffit and Capps 1911; Martin 1916
Middle to Late Triassic	Nikolai Greenstone	TRn	Type section: in the Wrangell Mountains	Glen et al. 2011

Table 6 (continued). Stratotypes in Wrangell-St. Elias National Park and Preserve. Stratotypes are sorted by age with associated reference publications and locations. In some cases, the GRI geologic units (and unit symbols) have grouped multiple formations together. See the original publications for the distribution of individual units. Table is sourced from Henderson et al. (2022).

Age	Unit Name	GRI Unit Symbol(s)	Stratotype Description	Reference(s)
Pennsylvanian to early Permian	Skolai Group	PPNs	Type area: extending southeastward from SW/4 sec. 15, T. 2 S., R. 17 E., to terminal moraine of Frederika Glacier, McCarthy C-4 Quadrangle, southern Alaska. Reference section: designated in secs. 26, 27, 33, 34, and 35, T. 5 S., R. 18 E. along upper Glacier Creek near the eastern border of the McCarthy B-4 Quadrangle	Smith and MacKevett 1970
Early Permian	Hansen Creek Formation	Ph, PI	Type area: valley walls of Hansen Creek, in secs. 11 and 12, T. 4 S., R. 17 E., McCarthy Quadrangle, southern Alaska	Smith and MacKevett 1970
Early Permian	Golden Horn Limestone Lentic, Hansen Creek Formation	PI	Type area: north side of Skolai Creek extending west from peak of Golden Horn to Tinplate Hill, in sec. 23, T. 2 S., R. 17 E., McCarthy C-4 Quadrangle, southern Alaska	Smith and MacKevett 1970
Pennsylvanian to early Permian	Station Creek Formation	PPNsc	Type area: extends 5.6 km (3.5 mi) west from point 1.6 km (1 mi) south of Station Creek, a tributary of Frederika Creek, southern Wrangell Mountains, northeastern McCarthy C-4 Quadrangle, southern Alaska	Smith and MacKevett 1970
Middle Pennsylvanian to early Permian	Strelina Metamorphics	PPNm	Reference section: headwaters of Canyon Creek, in SW/4 sec. 12, T. 6 S., R. 6 E., Valdez B-1 Quadrangle, southern Alaska	Plafker et al. 1989

Several variations of stratotypes exist, including type sections, type areas, type localities, reference sections, and Global Boundary Stratotype Sections and Points (GSSPs). Of the 25 stratotypes within the preserve, eight are type sections, five are type localities, eight are type areas, and four are reference sections (Table 6; Henderson et al. 2022). A type section (used for a stratified unit) or type area (used for a non-stratified unit) serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2021). A type locality is the geographic territory encompassing a formally recognized type section or area (North American Commission on Stratigraphic Nomenclature 2021). A reference section is another exposure that supplements the type section in some way. The designation of a reference section may be necessary for well-established geologic units that were never assigned a formal type section; when a type section has been destroyed, covered, or is otherwise inaccessible; or when multiple exposures are needed to illustrate heterogeneity or a key feature not found in the type section (North American Commission on Stratigraphic Nomenclature 2021).

Several prominent rock units within the park have never been formally named or they lack a formal stratotype. The currently unnamed Cretaceous nonmarine sedimentary unit (**Kun**) was recently described and informally named the Beaver Lake formation by Trop et al. (2020); however, this unit has not yet been formally named, nor has a type section been designated. Additionally, several rock units within the park have been named, but a formal stratotype was never designated. These include the Triassic Kuskulana Formation, the Jurassic Kotsina Conglomerate, the Jurassic–Cretaceous Yakutat Group, and the Miocene–Holocene Wrangell Lava (Henderson et al. 2022). Designating stratotypes, and in some cases also formally naming the unit, would provide these geologic units with a standard reference for scientific research, educate park staff and visitors about their geoheritage value, and help safeguard important exposures (Henderson et al. 2022). Information about the process of formally proposing new geologic names and designating stratotypes is available in Stamm (2023).

Stratotypes are unique geologic reference exposures that contain most (if not all) of the diagnostic criteria that define a geologic unit. Due to their scientific value, it is important to protect stratotypes in such a way that safeguards exposures from development but does not limit availability for future scientific research. A literature-based inventory of the stratotypes within the preserve has been completed (Henderson et al. 2022). Further work that would support the protection of these resources includes visiting stratotype sites (some of which were designated almost 100 years ago), collecting representative photographs and field samples, assessing their condition and vulnerability to threats, and developing outreach and educational material. More information on management recommendations can be found in the Central Alaska Inventory and Monitoring Network Geologic Type Section Inventory (Henderson et al. 2022).

Mineral Development

Unlike some other national parks, active mining is permitted under some circumstances within the original legislative outer boundary of Wrangell-St. Elias National Park and Preserve. Mining can occur on private inholdings with patented mining claims, as well as on NPS land with unpatented mining claims. Mining claims are a type of mineral right authorized by the General Mining Law of 1872. This law allows a US citizen to stake a mining claim on federal public domain lands (lands that have continuously remained in federal ownership) to prospect, explore, and develop minerals. A mining claim starts out as an “unpatented” claim, which is a parcel of land to which the government retains ownership of the surface rights while the claimant has a right to develop a mine and extract minerals. A legal interest in a properly recorded mining claim can be transferred to another party. Each year, the claimant must either pay a fee or file a waiver with the Bureau of Land Management (BLM) to maintain the claim. An unpatented mining claim can become “patented” when the federal government conveys title to the claimant, making it private land. Mining on patented claims within the outer boundary of the park is not subject to NPS regulation or oversight, and such lands are abundant: approximately 1 million of the 13 million acres of land within the park’s boundaries are non-federally owned, belonging to Native Corporations, other private owners, and the State of Alaska. Mining claims that were patented before the creation of the park in 1980 are one type of private property within the park. Active mining is currently taking place on several patented mining claims located in and around Dan Creek, on the south side of the Nizina River, and it is possible that

additional mining on patented claims will occur in the future. Additionally, park staff have detected signs of mining in the northeast part of the park, near Baultoff Creek; however, no more information is currently known about these activities.

Mining of unpatented claims on NPS lands is governed by the Mining in the Parks Act of 1976. NPS lands are now closed to the establishment of new mining claims, so the number of unpatented claims subject to mining under that law is limited to those that were present and valid when the park was created in 1980. A “valid” claim must contain mineral deposits of sufficient value to economically justify a commercial mining operation. Active mining is presently taking place on only a handful of those claims in the Gold Hill area, east of Chisana. Some claims have been validated, while others await final validity determinations from the BLM, who are responsible for such determinations. To conduct mining operations on unpatented mining claims in a park, the claimant must submit a proposed Mining Plan of Operations (MPO). The NPS then evaluates the proposed MPO, usually through an Environmental Assessment that contains information on the mining claims, impacted resources, environmental consequences, potential actions, and mitigation measures (NPS 2012, 2013, 2016b, 2017). If the NPS approves the MPO, it then issues stipulations aimed at conserving NPS resources and monitors subsequent mining activities for the duration of the MPO.

There are presently three claim groups (clusters of multiple mining claims) being mined under active MPOs in the Gold Hill area: Gold Run, Little Eldorado/Bonanza, and Shamrock. These are all small-scale placer gold mines, operated mostly in the summer months with suction dredges, hand tools, and some limited machinery like ATVs and mini excavators. The claimants mostly utilize stabilized historic buildings to support their operations and typically access their claims via ATV trails that link the claims to a small nearby airstrip. The potential exists for these and other presently inactive, unpatented claims to expand their operations via the submission of newly proposed MPOs. Planning documents and current MPOs associated with active mining in the park are available at the NPS Planning, Environmental, and Public Comment (PEPC) website (<https://parkplanning.nps.gov/>). More information about NPS regulations relating to mining and mining claims can be found in the “Geologic Resource Laws, Regulations, and Policies” section of this report and in Title 36 of the Code of Federal Regulations, Part 9, Subpart A.

In 1990, the NPS completed an Environmental Impact Statement on the Cumulative Impacts of Mining within the park. That document records a decision to implement a strategy of acquiring, from willing sellers, all patented and valid unpatented mining claims in the park (NPS 1990). This decision stemmed from a 1985 lawsuit that halted the approval of MPOs in Alaska until the NPS fully complied with its mining regulations (36 CFR Subpart 9A) and prepared environmental documents in compliance with the National Environmental Policy Act (NPS 1990). The resulting Environmental Impact Statement (NPS 1990) found that past mining had major impacts on park resources, including aquatic resources and moose habitat; furthermore, future mining could result in major cumulative impacts on these resources as well as grizzly bear and caribou habitat. The preferred alternative to acquire all mining claims was chosen because it provides the most protection to park resources and causes the least damage to the environment (NPS 1990). Until the NPS can acquire all the mining

claims, the park is instructed to conduct MPO reviews and evaluations in accordance with the “Interim Operations” section of the EIS (NPS 1990).

Mineral resource exploration and mining can also potentially occur on private land within the preserve’s original legislative outer boundary. An examination of the records of mines, prospects, and mineral occurrences from the Alaska Resource Data File (<https://mrdata.usgs.gov/ardf/>) shows that mineral resources are found on some of the private lands within the park (see “Mineral Resources”). No active exploration or mining is currently occurring on these private lands, except for patented claims in the Dan Creek vicinity mentioned earlier. Nonetheless, the potential for additional future mining activities heightens the importance of proactive strategic land acquisitions. Park managers can contact the Alaska Regional Natural Resources Team or the GRD Energy and Minerals Team for information and assistance regarding mineral development in the park (see “Guidance for Resource Management”).

Abandoned Mineral Lands

The park has a long history of mining that has left its mark on the landscape in the form of abandoned mineral land (AML) sites and features (see “Geoheritage”). AML sites contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. Examples of AML features found at sites can include (but are not limited to) shafts, surface mines, tailings, wells, roads, buildings, and equipment (Figure 32). In some cases, AML sites and features may be cultural resources that are an integral part of the park’s cultural landscape. The most prominent examples of AML sites in the park are those associated with the Kennecott Mines National Historic Landmark, which include the Kennecott mill and related copper mines. Additionally, the park contains many other AML sites outside the Kennecott area that are associated with historic mineral extraction, coal mining, and oil and gas exploration. More background on abandoned mineral lands in the NPS can be found in Burghardt et al. (2014).



Figure 32. Photographs of AML features found in the Bremner historic mining district. The Bremner mining district contains several lode and placer gold mines located within the park in the Chugach Mountains. Past mining activity at these mines, such as the Yellow Band mine, left behind historic objects and structures that can still be seen by park visitors today. (A) Yellow Band Mining Camp mess hall and bunkhouse. (B) 27.5-gallon wheelbarrow at Yellow Band Mining Camp. (C) Yellow Band Mining Camp outhouse.

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According to the internal NPS AML database, the park contains 323 AML features at 96 AML sites (<https://irma.nps.gov/AML/>, accessed 16 July 2024 [only available on Department of the Interior [DOI] network computers]). A map of AML sites is not included here due to the sensitive nature of this data, but park managers can see a map of sites in the NPS AML database. The park's AML sites are concentrated in the same areas where mineral deposits exist and past mining occurred (see "Mineral Resources"). Most of the park's AML sites are on the southern flank of the Wrangell Mountains, in the vicinity of the Kotsina-Kuskulana and McCarthy-Nizina mining districts. A handful of AML sites are found to the north of the Wrangell Mountains in the vicinity of the Chisana and Nabesna mining districts. Several other AML sites are scattered throughout the park: for example, five AML sites associated with gold mining are found in the Bremner mining district; a former oil and gas exploration site and a coal-related site are near the toe of Malaspina Glacier; one silver prospect is near the toe of Chitina Glacier; one silver prospect is on the south side of the Chitina River near Nelson Mountain; and two sites are north of the Nabesna Road in the Mentasta Mountains. About two dozen AML sites are located on patented mining claims (private property) within the park boundaries, but these sites are not managed by NPS.

Park managers can find information about the location, history, and status of the park's AML sites in several sources. The internal NPS AML database provides a summary of AML sites and features that may pose a risk to physical safety or threaten park resources, as well as previously mitigated features. The database contains information about the park's AML sites that is updated periodically after site visits. Examples of information found in the database include site name, latitude and longitude, site type, ownership, natural resource mitigation needs, features, and more. More detailed information about the park's AML sites (e.g., NPS trip reports and reports of previous site assessments or mitigation work; copies of relevant US Geological Survey or other government reports; US Mineral

Survey plats and BLM mining claim case abstracts) can be found in internal NPS files and the Mining and Minerals collection of the NPS archives (contact the NPS Alaska Region Natural Resources Team or the GRD Energy and Minerals Team for more information). Additionally, the internal cultural resources databases and cultural landscape inventories and reports provide more information on culturally significant AML features such as structures (Sarah Venator, AKRO AML Coordinator, written communication, 16 July 2024).

Abandoned mineral lands can present numerous hazards to human safety and the natural environment. Human safety hazards associated with abandoned mines include drowning in water-filled quarries and pits, falling into vertical features such as shafts, exposure to deadly gases and radioactive air trapped underground, unstable structures prone to collapse, steep and unstable pit walls, explosives, and other hazardous chemicals discarded during mining operations (Burghardt et al. 2014). AML features can also have detrimental effects on the natural environment. Contaminants released from mined materials may affect air, soil, and water quality, as well as plant and animal health (Burghardt et al. 2014). Excavations or the emplacement of tailings piles may interrupt natural drainages and potentially lead to increased erosion and destabilization of slopes (Burghardt et al. 2014). Additionally, AML features may affect the scenic values or “viewshed” of an area (Burghardt et al. 2014).

The NPS acts under various authorities to mitigate, reclaim, or restore AML features to reduce hazards and impacts on resources. The park contains 46 features that have already been mitigated and three high-priority features that require mitigation. For more information on the high-priority features, contact the NPS Alaska Region Natural Resources Team or the GRD Energy and Minerals Team. Assessment work is regularly conducted on AML features to re-evaluate the physical hazards that may be present. The physical condition of AML features often changes over time, and periodic monitoring is recommended.

AML sites associated with past milling are often contaminated because of those activities. Soils may contain elevated concentrations of metals that are harmful to human health, such as arsenic, lead, cadmium, and mercury. This is because of their presence in the milled ore, the use of mercury amalgamation or other chemicals in the milling process, or both. The NPS is authorized under the Comprehensive Environmental Response, Compensation, and Liabilities Act (CERCLA) to respond as the lead agency to a release or threatened release of harmful substances and/or a release of any pollutant or contaminant that may present an imminent and substantial danger to public health or welfare on or from land under the authority, custody, or control of the NPS. The NPS is currently engaged in environmental investigations under CERCLA at two AML sites in the park: the Kennecott mill town and the Nabesna Gold Mine. Once a CERCLA investigation is completed, NPS will release a public comment document that compares cleanup alternatives and recommends an alternative (Sarah Venator, AKRO AML Coordinator, written communication, 16 July 2024).

The GRD is the lead NPS office for AML management and reclamation. GRD is responsible for the funding, coordination, and oversight of AML projects for both mine sites and oil and gas sites. The Environmental Compliance and Cleanup Division (ECCD) is the lead NPS office for management of

contaminated sites, including contamination at AML sites. The Alaska Region has a designated Regional Environmental Coordinator who interfaces between Alaska national parks and the GRD and ECCD regarding the management of AML sites. See the “Guidance for Resource Management” section of this report for information on requesting assistance from the Alaska Regional Office Natural Resources Team, the GRD, and the ECCD.

Paleontological Resource Inventory, Monitoring, and Protection

The park contains a diverse paleontological record that spans over 350 million years (see “Paleontological Resources”). Paleontological resources, or fossils, are important because they are the record of life on our planet. The fossil record shows how life has responded to major global events such as climate change, meteorite impacts, tectonic reorganizations, and mass extinctions. Additionally, fossils often provide essential context for understanding a region’s geology, including information such as the age of a rock (biostratigraphy), the geographic location where the rock formed (paleobiogeography), and the environment in which the rock was deposited. Paleontological resources are nonrenewable; once a fossil is destroyed, it can never be replaced, and that piece of Earth’s history is lost forever. As such, the NPS is mandated by federal law (Paleontological Resources Preservation Act 2009), regulation (36 CFR Part 2), and NPS policy to protect, preserve, and manage fossils on park service lands for public education, interpretation, and scientific research. It is illegal to collect fossils on both NPS land and Alaska state land without a research permit.

Baseline documentation of paleontological resources is an important first step toward effective management. An inventory of fossils in the park was completed by Santucci et al. (2011). The NPS Alaska Region has a regional paleontological resource database; however, fossil sites from the park have not yet been entered into the database. This work has not yet been completed, but future projects could focus on compiling fossil data from existing sources into the database. This would allow park managers to more easily query fossil sites within the park and aid in addressing various questions, such as understanding the location of fossil sites prior to construction projects or identifying fossil sites that are proximal to highly visited areas that may be vulnerable to disturbance.

Field-based fossil inventories are also important, both for gaining deeper understanding of known fossils in the preserve and for providing opportunities for new discoveries. A field-based survey of select fossil-bearing rocks was undertaken in 2017 (Druckenmiller and Loso 2017; Hults and Druckenmiller 2017). This project focused on revisiting known, important fossil sites to assess their condition and potential management concerns. The sites selected were an ichthyosaur site in the Nizina Limestone and Beaver Lake formation Cretaceous rocks that had previously been reported to contain dinosaur tracks (see “Paleontological Resources”). Notable management considerations identified by this study include the potential vulnerability of well-preserved plant fossils in the Beaver Lake formation and the recommendation to collect the loose cobbles that contain ichthyosaur bones in the Nizina Limestone (Druckenmiller and Loso 2017; Hults and Druckenmiller 2017).

Both natural processes and human activities have the potential to damage and destroy fossils (Santucci et al. 2009). Natural processes, primarily weathering and erosion, are responsible for exposing fossils at Earth’s surface, enabling their discovery and study. However, the progression of

these same processes leads to the eventual destruction of fossils. Fossil sites that are especially vulnerable to destructive erosional events are located along streams or rivers, lakeshores, the coast, or on slopes prone to mass movements. Anthropogenic threats to paleontological resources include unauthorized disturbance, removal, and destruction of fossils, or an increase in erosion rates because of visitor traffic. Fossil sites especially prone to human disturbance are those easiest to access or near areas frequented by visitors. These include fossils exposed along riverbanks, coastal bluffs, or near roads and trails. Additionally, new construction projects cutting through fossil-rich rock units could also pose a threat to paleontological resources; therefore, fossils should be considered when these types of projects are in their planning phase.

Caves and Associated Landscape Management

Caves, or naturally occurring underground voids, exist within the park's glaciers (glacier caves), carbonate rocks (solution caves), and other bedrock (frost pockets; see the "Caves" section of this report for more information). Caves are nonrenewable resources that, in addition to their intrinsic value, can contain other important park resources (e.g., paleontological resources, archaeological resources, sediment records, and speleothems) and be habitat for wildlife such as bats and sheep. Most of the caves in the park do not seem to indicate usage by humans in the past because they recently emerged from glacier ice (NPS 2016a).

The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and the inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or its resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request. According to the 2016 State of the Park Report, the park's caves are well known in Alaskan caving groups and are gaining popularity as destinations (NPS 2016a). Although most of the park's caves are difficult to access, some receive regular use, often from large groups (NPS 2016a). Cave management actions could include documenting and mapping known caves, exploring areas with the potential for new caves, identifying natural and cultural resources within caves, and assessing cave vulnerability. Toomey (2009) provides additional information about inventorying and monitoring cave-related vital signs.

Permafrost Thaw and Monitoring

Large parts of the park are underlain by perennially frozen ground called permafrost; however, climate change will cause permafrost to become unstable and thaw in many places over the coming decades (see "Permafrost"). Focused modeling to predict permafrost thaw has been completed for the park (see Panda et al. 2014). Between 2001 and 2010, permafrost is modeled to have existed across 80% of the park, with 24% of this permafrost being within 2°C (4°F) of thawing (Panda et al. 2014). Due to projected rising mean annual air temperatures, the area of the park predicted to contain permafrost drops to 42% between 2051 and 2060 and to 15% by the 2091–2100 decade (Panda et al. 2014; Figure 33). The widespread thaw of permafrost will have various impacts, which may include the loss of permafrost landscape features (such as rock glaciers), the development of thermokarst, increased landslides and slumping, changes to hydrology and vegetation, and enhanced release of

greenhouse gases (Loso 2018). See Loso (2018) for more information about these potential impacts, and see the “Landslides” section of this report for more information about the interaction of permafrost thaw and landslides.

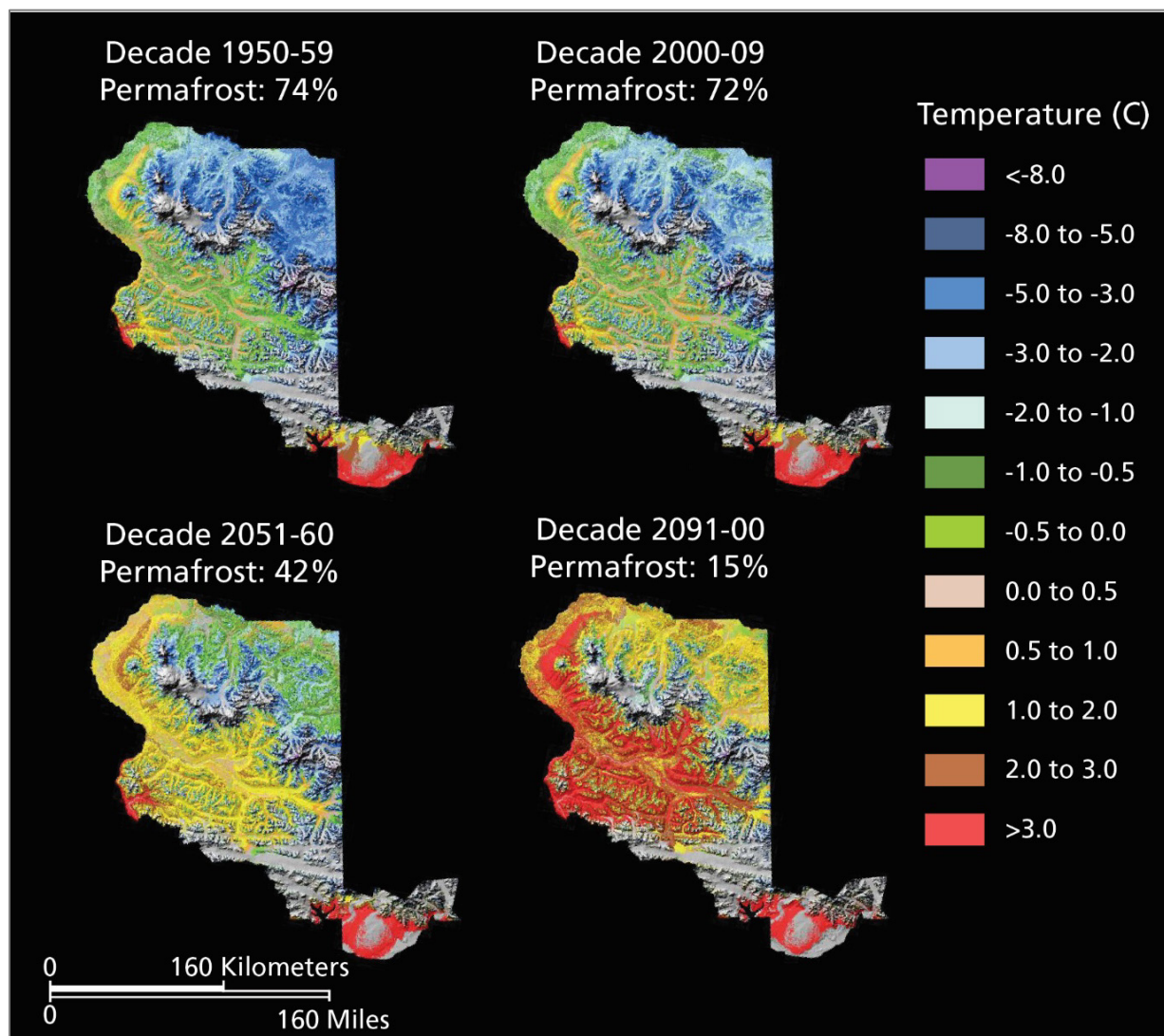


Figure 33. Permafrost modeling maps for 1950–1959, 2000–2009, 2051–2060, and 2091–2100 (Panda et al. 2014). The maps show the modeled decadal ground temperature at the bottom of the seasonal freeze-thaw layer in the park. Between 1950 and 1959, permafrost is modeled to have underlain 74% of the park. Between 2000 and 2009, permafrost is modeled to have underlain 72% of the park. Between 2051 and 2060, permafrost is modeled to underlie 42% of the park. And between 2091 and 2100, permafrost is modeled to decrease to just 15% of the park.

NPS

Permafrost is one of the vital signs monitored by the NPS Central Alaska Inventory and Monitoring Network (MacCluskie et al. 2005). The Inventory and Monitoring Network’s permafrost protocols focus on the thermal and physical state of permafrost in the preserve (Loso 2018). Measurements of

shallow and deep ground temperatures keep track of the permafrost's thermal state. At 10 sites, temperature measurements are made regularly at shallow depths (1–2.0 m [3.3–6.5 ft]), and at one site, a single deep (70 m [230 ft]) cased borehole records the ground temperature profile once per year (Loso 2018). The physical state of permafrost is monitored by measuring active layer thickness and soil surface elevation at five sites every three years (Loso 2018). These measurements track changes in the depth of the perennially frozen layer and the extent of associated soil surface subsidence (Loso 2018). In addition, the extent, surface elevation, and surface velocities of Sourdough Rock Glacier, located west of McCarthy, are measured every six years (Loso 2018).

Guidance for Resource Management

This chapter provides information to assist resource managers in addressing geologic resource management issues and applying NPS policy. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Access to GRI Products

- GRI Products (scoping summaries, GIS data, posters, and reports): <http://go.nps.gov/gripubs>
- GRI products are also available on the NPS DataStore through the Integrated Resource Management Applications (IRMA) portal: <https://irma.nps.gov/DataStore/Search/Quick>. Enter “GRI” as the search text and select a park from the unit list.
- GRI GIS data model: <http://go.nps.gov/gridatamodel>
- Additional information regarding the GRI, including contact information: <https://www.nps.gov/subjects/geology/gri.htm>

Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Alaska Regional Natural Resources Team (<https://www.nps.gov/orgs/1349/whatwedo.htm>). Alaska Regional Natural Resources Team staff members provide support for geologic resource management issues related to climate change, geographic information systems, geology and geological processes, hydrology and stream restoration, and ocean and coastal science. Information about the Alaska Regional Natural Resources Team members can be found at <https://www.nps.gov/orgs/1349/whoweare.htm>.
- Contact the NPS GRD (<https://www.nps.gov/orgs/1088/contactus.htm>). GRD staff members provide coordination, support, and guidance for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, regulations, and compliance; resource management planning; and data and information management.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: <https://irma.nps.gov/Star/> (only available on Department of the Interior [DOI] network computers). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Submit a proposal to receive geologic expertise through the Scientists in Parks (SIP) program (see <https://www.nps.gov/subjects/science/scientists-in-parks.htm>). Formerly the

Geoscientists-in-the-Parks program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects that may address resource management issues. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring. The GRD can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program. Visit the internal SIP website to submit a proposal at <https://doimspp.sharepoint.com/sites/nps-scientistsinparks> (only available on DOI network computers).

Geological Monitoring

Geological Monitoring (Young and Norby 2009) provides guidance for monitoring vital signs (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. Chapters are available online at <https://www.nps.gov/subjects/geology/geological-monitoring.htm>.

Park-Specific Documents

The park's Foundation Statement (NPS 2009), Natural Resource Condition Assessment (Drazkowski et al. 2011), State of the Park Report (NPS 2016a), and Resource Stewardship Strategy (NPS 2024) are primary sources of information for resource management within the park. These documents guided the writing of this GRI report.

NPS Natural Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): <https://www.nps.gov/subjects/policy/management-policies.htm>
- National Parks Omnibus Management Act of 1998: <https://www.congress.gov/bill/105th-congress/senate-bill/1693>
- Natural Resources Inventory and Monitoring Guideline (NPS-75): <https://irma.nps.gov/DataStore/Reference/Profile/622933>
- Natural Resource Management Reference Manual #77 (NPS-77): <https://irma.nps.gov/DataStore/Reference/Profile/572379>
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: <https://doi.org/10.36967/nrr-2283597>

Geologic Resource Laws, Regulations, and Policies

The following sections, which were developed by the GRD, summarize laws, regulations, and policies that specifically apply to NPS geologic resources, geologic processes, energy, and minerals. The first section summarizes law and policy for geoheritage resources, which includes caves, paleontological resources, and geothermal resources. The energy and minerals section includes abandoned mineral lands, mining, rock and mineral collection, and oil and gas operations. Active processes include geologic hazards (e.g., landslides), coastal processes, soils, and upland and fluvial

processes (e.g., erosion). Laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, NEPA, or the National Historic Preservation Act) are not included, but the NPS Organic Act is listed when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

Geoheritage Resource Laws, Regulations, and Policies

Caves and Karst Systems

Resource-Specific Laws:

- **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.

Resource-Specific Regulations:

- **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.

NPS Management Policies 2006:

- **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 the 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.

Geothermal

Resource-Specific Laws:

- **Geothermal Steam Act of 1970, 30 USC. § 1001 et seq.** as amended in 1988, states:

- No geothermal leasing is allowed in parks.
- “Significant” thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead).
- NPS is required to monitor those features.
- Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects.
- **Geothermal Steam Act Amendments of 1988, Public Law 100-443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.

Resource-Specific Regulations:

- **43 CFR Part 3200** requires BLM to include stipulations when issuing, extending, renewing, or modifying leases or permits to protect significant thermal features in NPS-administered areas (see 43 CFR §3201.10), prohibit the bureau from issuing leases in areas where geothermal operations are reasonably likely to result in significant adverse effects on significant thermal features in NPS-administered areas (see 43 CFR §3201.11 and §3206.11), and prohibit BLM from issuing leases in park units.

NPS Management Policies 2006:

- **Section 4.8.2.3** requires NPS to:
 - Preserve/maintain integrity of all thermal resources in parks.
 - Work closely with outside agencies.
 - Monitor significant thermal features.

Paleontological Resources

Resource-Specific Laws:

- **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1)**
Archaeological Resource—nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law.
- **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5)**
Cave Resource—the term “cave resource” includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.

- **National Parks Omnibus Management Act of 1998, 54 USC § 100701** 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.

Resource-Specific Regulations:

- **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.
- **43 CFR Part 49** contains the DOI regulations implementing the Paleontological Resources Preservation Act, which apply to the NPS.

NPS Management Policies 2006:

- **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.

Energy and Minerals Laws, Regulations, and Policies

Abandoned Mineral Lands and Orphaned Oil and Gas Wells

Resource-Specific Laws:

- **The Bipartisan Infrastructure Law, Inflation Reduction Act, and NPS Line Item Construction** program all provide funding for the reclamation of abandoned mineral lands and the plugging of orphaned oil and gas wells.

Resource-Specific Regulations:

- None applicable.

NPS Management Policies 2006:

- None applicable.

Coal

Resource-Specific Laws:

- **Surface Mining Control and Reclamation Act (SMCRA) 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.

Resource-Specific Regulations:

- **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.

NPS Management Policies 2006:

- None applicable.

Common Variety Mineral Materials (Sand, Gravel, Pumice, Etc.)

Resource-Specific Laws:

- **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.
- **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas.
- **16 USC §90c-1(b)** authorizes sand, rock, and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.

Resource-Specific Regulations:

- None applicable.

NPS Management Policies 2006:

- **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 the 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.

Federal Mineral Leasing (Oil, Gas, and Solid Minerals)

Resource-Specific Laws:

- **The Mineral Leasing Act, 30 USC § 181** et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq. do not authorize the BLM to lease federally owned minerals in NPS units.
- **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in Glen Canyon National Recreation Area, which is the only park unit that contains a STSA.
- **Exceptions:** Glen Canyon National Recreation Area (NRA) (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.) authorize the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration.
- **American Indian Lands** Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108, all minerals on American Indian trust lands within NPS units are subject to leasing.
- **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.

Resource-Specific Regulations:

- **36 CFR § 5.14** states prospecting, mining, and...leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law.
- **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing.
- Regulations re: Native American Lands within NPS Units:
 - **25 CFR Part 211** governs leasing of tribal lands for mineral development.
 - **25 CFR Part 212** governs leasing of allotted lands for mineral development.
 - **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development.
 - **25 CFR Part 224** governs tribal energy resource agreements.

- **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108).
- **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases.
- **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases.
- **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases.
- **30 CFR § 1206.450** governs the valuation of coal from Indian Tribal and Allotted leases.
- **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.

NPS Management Policies 2006:

- **Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Mining Claims (Locatable Minerals)

Resource-Specific Laws:

- **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.

Resource-Specific Regulations:

- **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.

NPS Management Policies 2006:

- **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 Minerals Other Than Oil and Gas

Resource-Specific Laws:

- NPS Organic Act, 54 USC §§ 100101 and 100751

Resource-Specific Regulations:

- **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 business operation (§ 5.3) or for construction of buildings or other facilities (§ 5.7), and to comply with the solid waste regulations at Part 6.

NPS Management Policies 2006:

- **Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

Nonfederal Oil and Gas

Resource-Specific Laws:

- **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 NRR)

- 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.)

Resource-Specific Regulations:

- **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 in parks outside of Alaska to:
 - Demonstrate valid right to develop mineral rights;
 - Submit an Operations Permit Application to NPS describing where, when, and how they intend to conduct operations;
 - Prepare/submit a reclamation plan; and
 - Submit financial assurance 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.

NPS Management Policies 2006:

- **Section 8.7.3** requires operators to comply with 9B regulations.

Recreational Collection of Rocks and Minerals

Resource-Specific Laws:

- **NPS Organic Act, 54 USC. § 100101** et seq. directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law.
- **Exception: 16 USC. § 445c (c)** – Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).

Resource-Specific Regulations:

- **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources...in park units.
- **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown National Recreation Area.
- **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and 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.

NPS Management Policies 2006:

- **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Transpark Petroleum Product Pipelines

Resource-Specific Laws:

- The **Mineral Leasing Act, 30 USC § 181** et seq., and the **Mineral Leasing Act for Acquired Lands, 30 USC § 351** et seq. authorize new rights of way across some federal lands for pipelines, excluding NPS areas.
- The only parks with the legal authority to grant new rights of way for petroleum product pipelines are:
 - Natchez Trace Parkway (16 USC §460a)
 - Blue Ridge Parkway (16 USC §460a-8)
 - Great Smoky Mountains National Park (P.L. 107-223 – 16 U.S.C. §403 notes)
 - Klondike Gold Rush National Historical Park (16 USC §410bb(c) (limited authority for the White Pass Trail unit)
 - Gulf Islands National Seashore: enabling act authorizes rights-of-way for pipelines for oil and gas transported across the seashore from outside the unit (16 USC §459h-3)
 - Gateway National Recreation Area: enabling act authorizes rights-of-way for gas pipelines in connection with the development of methane gas owned by the City of New York within the unit (16 USC §460cc-2(i))
 - Denali National Park: 2013 legislation allows for issuance of right-of-way permits for a natural gas pipeline within, along, or near the approximately 7-mile segment of the George Parks Highway that runs through the park (Public Law 113–33)

Resource-Specific Regulations:

- NPS regulations at **36 CFR Part 14 Rights of Way**

NPS Management Policies 2006:

- **Section 8.6.4** states that new rights of way through, under, and across NPS units may be issued only if there is specific statutory authority and there is no practicable alternative.

Uranium

Resource-Specific Laws:

- **Atomic Energy Act of 1954** allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.

Resource-Specific Regulations:

- None applicable.

NPS Management Policies 2006:

- None applicable.

Active Processes and Geohazards Laws, Regulations, and Policies

Coastal Features and Processes

Resource-Specific Laws:

- **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.

Resource-Specific Regulations:

- **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.

NPS Management Policies 2006:

- **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.

Geologic Hazards

Resource-Specific Laws:

- **National Landslide Preparedness Act, 43 USC §§ 3101–3104** strengthens the mandate to identify landslide hazards and reduce losses from landslides. Established the National Landslide Hazards Reduction Program. “...the United States Geological Survey and other Federal agencies, shall – identify, map, assess, and research landslide hazards;” Reduce landslide losses, respond to landslide events.

Resource-Specific Regulations:

- None applicable.

NPS Management Policies 2006:

- **Section 4.8.1.3**, Geologic Hazards
- **Section 9.1.1.5**, Siting Facilities to Avoid Natural Hazards
- **Section 8.2.5.1**, Visitor Safety
- **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.

Soils

Resource-Specific Laws:

- **Soil and Water Resources Conservation Act, 16 USC §§ 2001–2009** 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 ensure 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).

Resource-Specific Regulations:

- **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.

NPS Management Policies 2006:

- **Section 4.8.2.4** requires NPS to (1) prevent unnatural erosion, removal, and contamination; (2) conduct soil surveys; (3) minimize unavoidable excavation; and (4) develop/follow written prescriptions (instructions).

Upland and Fluvial Processes

Resource-Specific Laws:

- **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**).

Resource-Specific Regulations:

- None applicable.

NPS Management Policies 2006:

- **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.

Additional References, Resources, and Websites

Abandoned Mineral Lands

- NPS AML: <https://www.nps.gov/subjects/abandonedminerallands/index.htm>
- NPS AML Database: <https://irma.nps.gov/AML/> (only available on Department of the Interior [DOI] network computers)
- NPS AML, reclamation and restoration: <https://www.nps.gov/subjects/abandonedminerallands/reclamation-and-restoration.htm>

Caves and Karst

- Cave Research Foundation: <https://www.cave-research.org/>
- Caves and Karst Laws, Regulations, and Policies (NPS webpage): <https://www.nps.gov/subjects/caves/cave-karst-protection.htm>
- National Cave and Karst Research Institute: <https://www.nckri.org/>
- NPS Caves and Karst: <https://www.nps.gov/subjects/caves/index.htm>

- National Speleological Society: <https://caves.org/>

Climate Change Resources

- Intergovernmental Panel on Climate Change: <http://www.ipcc.ch/>
- NPS Climate Change Response Program Resources: <https://www.nps.gov/subjects/climatechange/resources.htm>
- NPS Climate Change, Sea Level Change website: <https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm>
- NPS Policy Memorandum 12-02—Applying NPS Management Policies in the Context of Climate Change: <https://www.nps.gov/subjects/policy/policy-memos.htm>
- NPS Policy Memorandum 15-01—Addressing Climate Change and Natural Hazards for Facilities: <https://www.nps.gov/subjects/policy/policy-memos.htm>
- US Global Change Research Program: <https://www.congress.gov/crs-product/R48478>

Coastal Geology

- National Oceanic and Atmospheric Administration ShoreZone (images, videos, and maps of Alaska’s coastline): <https://www.fisheries.noaa.gov/alaska/habitat-conservation/alaska-shorezone>
- National Oceanic and Atmospheric Administration Tide Gauges: <https://tidesandcurrents.noaa.gov/>
- NPS Coastal Geology: <https://www.nps.gov/subjects/geology/coastal-geology.htm>

Days to Celebrate Geology

- Geologist Day—the first Sunday in April (marks the end of the winter and beginning of preparation for summer field work; formally celebrated in Ukraine, Kazakhstan, Belarus, Kyrgyzstan, and Russia)
- National Cave and Karst Day—6 June, also known as International Day of Caves and Subterranean World
- International Geodiversity Day—6 October: <https://www.geodiversityday.org/>
- Earth Science Week—typically the second full week of October: <https://www.earthsciweek.org/>
- National Fossil Day—the Wednesday of Earth Science Week: <https://www.nps.gov/subjects/fossilday/index.htm>

Disturbed Lands Restoration

- Geoconservation—Disturbed Lands Restoration: <https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm>

Geohazards

- Alaska Earthquake Center: <https://earthquake.alaska.edu/>
- Alaska Park Science Understanding and Preparing for Alaska's Geohazards: <https://www.nps.gov/subjects/aknatureandscience/geohazards.htm>
- Alaska Volcano Observatory: <https://avo.alaska.edu/>
- NPS Geohazards: <https://www.nps.gov/subjects/geohazards/index.htm>
- NPS Volcanoes: <https://www.nps.gov/subjects/volcanoes/index.htm>
- Taan Fiord Landslide and Tsunami Web Article: <https://www.nps.gov/articles/taanfjord.htm>
- Taan Fiord Landslide and Tsunami Video: <https://www.youtube.com/watch?v=QwjOP6FApsA>
- Tsunamis in Alaska: <https://earthquake.alaska.edu/about-tsunamis-alaska>
- US Geological Survey Earthquake Hazards Program unified hazard tool: <https://earthquake.usgs.gov/hazards/interactive/>
- Unstable Slope Management Program for transportation corridor risk reduction: <https://usmp.info/client/credits.php>
- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): <http://go.nps.gov/geomonitoring>
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): <http://pubs.usgs.gov/circ/1325/>
- Smithsonian Institution Global Volcanism Program: <https://volcano.si.edu/>

Geologic Heritage

- National Register of Historic Places: <https://www.nps.gov/subjects/nationalregister/index.htm>
- NPS America's Geologic Heritage: <https://www.nps.gov/subjects/geology/americas-geoheritage.htm>
- NPS Geoheritage Sites-Examples on Public Lands, Natural Landmarks, Heritage Areas, and The National Register of Historic Places: <https://www.nps.gov/subjects/geology/geoheritage-sites-listing-element.htm>
- NPS Museum Collection (searchable online database): <https://museum.nps.gov/ParkPList.aspx>
- UNESCO Global Geoparks: <https://www.unesco.org/en/igpp/geoparks/about>
- US Geological Survey Geoheritage Sites of the Nation: <https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/geoheritage-sites-nation#data>

Geologic Maps

- Geologic Map of Alaska: <https://doi.org/10.3133/sim3340>
- Alaska Digital Geologic Map and Geologic Data Online Viewer: <https://mrdata.usgs.gov/geology/>
- Alaska Division of Geological & Geophysical Surveys interactive maps: <https://dggs.alaska.gov/maps-data/interactive-maps.html>
- American Geosciences Institute (provides information about geologic maps and their uses): <http://www.americangeosciences.org/>
- General Standards for Geologic Maps (Evans 2016)
- National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Geological Surveys and Societies

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

Glaciers

- Alaska's Shrinking Glaciers Storymap: <https://www.nps.gov/maps/stories/alaskas-shrinking-glaciers.html>
- NPS Glaciers: <https://www.nps.gov/subjects/glaciers/index.htm>
- Randolph Glacier Inventory: <https://www.glims.org/RGI/>

Hydrology

- US Geological Survey National Hydrography Products <https://www.usgs.gov/national-hydrography>
- US Geological Survey National Water Dashboard: <https://dashboard.waterdata.usgs.gov/app/nwd/en/>
- NPS Aquarius WebPortal: <https://irma.nps.gov/aqwebportal/>

Mineral Resources

- Alaska (Minerals) Resource Data File: <https://www.usgs.gov/centers/alaska-science-center/science/alaska-resource-data-file>
- NPS Energy and Minerals Management: <https://www.nps.gov/subjects/energyminerals/index.htm>

NPS Geology

- NPS Alaska Regional Office Active Geology Website: <https://www.nps.gov/subjects/aknatureandscience/activegeology.htm>
- Alaska National Parks Geology Sketchfab Website (3D models of geologic resources): https://sketchfab.com/alaska_nps_geology
- NPS America's Geologic Legacy: <http://go.nps.gov/geology>. This is the primary site for information about NPS geology and includes a geologic tour, news and other information about geology in the NPS, and resources for educators and park interpreters.
- NPS Geodiversity Atlas: <https://www.nps.gov/articles/geodiversity-atlas-map.htm>. The NPS Geodiversity Atlas is a collection of park-specific webpages containing information about the park's geology and links to additional resources.
- NPS Geologic Resources Inventory: <http://go.nps.gov/gri>
- NPS Geology subject sites:
 - Caves and Karst: <https://www.nps.gov/subjects/caves/index.htm>
 - Coastal Geology: <https://www.nps.gov/subjects/geology/coastal-geology.htm>
 - Energy and Minerals Management: <https://www.nps.gov/subjects/energyminerals/index.htm>
 - Fossils and Paleontology: <https://www.nps.gov/subjects/fossils/index.htm>
 - Geohazards: <https://www.nps.gov/subjects/geohazards/index.htm>
 - Geothermal Features/Hot Springs: <https://www.nps.gov/subjects/geology/hot-springs.htm>
 - Glaciers: <https://www.nps.gov/subjects/glaciers/index.htm>
 - Mountains—Geology and Physical Processes: <https://www.nps.gov/subjects/mountains/geology.htm>
 - Volcanoes, Craters, and Lava Flows: <https://www.nps.gov/subjects/volcanoes/index.htm>

NPS Reference Tools

- NPS Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loans): <https://www.nps.gov/orgs/1804/dsctic.htm>
- GeoRef. The GRI team collaborates with TIC to maintain an NPS subscription to GeoRef (the premier online geologic citation database) via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records. Park staff can contact the GRI team or GRD for access.
- NPS Integrated Resource Management Applications (IRMA) portal: <https://irma.nps.gov/>.
Note: The GRI team uploads scoping summaries, maps, and reports to IRMA. Enter “GRI” as the search text and select a park from the unit list.

Soils

- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS): <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>
- WSS_four_steps (PDF/guide for how to use WSS):
<https://irma.nps.gov/DataStore/Reference/Profile/2305342>.

US Geological Survey Reference Tools

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary):
<http://ngmdb.usgs.gov/Geolex>
- Geographic Names Information System (GNIS; official listing of place names and geographic features): <https://www.usgs.gov/tools/geographic-names-information-system-gnis>
- US Geological Survey Store (find maps by location or by purpose): <http://store.usgs.gov>
- National Geologic Map Database (NGMDB):
http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- US Geological Survey Publications Warehouse: <http://pubs.er.usgs.gov>

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These references are cited in this report. Contact the GRD for assistance in obtaining them.

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