National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

# Yukon-Charley Rivers National Preserve

## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2023/2600

**ON THE COVER**
**Photograph of canoers in front of Calico Bluff. Calico Bluff is about 12 km (8 mi) north of Eagle on the Yukon River, in the southeast corner of the preserve. The rocks that make up Calico Bluff are part of the Calico Bluff Formation (PNMDf), which is a geologic unit composed of interbedded limestone (light-colored layers) and shale (dark-colored layers). The folding and faulting of the beds is the result of soft-sediment deformation shortly after the rocks were deposited during the Pennsylvanian and Mississippian Periods (358.9–298.9 million years ago).**
**National Park Service photograph by Stephen Lias.**

**THIS PAGE**
**Photograph the Coal Creek Dredge, about a mile off the Yukon River in the historic Coal Creek Mining District. The Coal Creek Dredge is a remnant of the preserve's more than 100 years of mining history. The dredge arrived in the Coal Creek drainage in the 1930s and ran on and off for about 20 years, during which time it recovered 3.2 tons of gold. The gold targeted by the Coal Creek Dredge and other mining efforts is found within alluvial sediments that either overlie or are downstream of Cretaceous and Tertiary sedimentary rocks (TKs). The natural function of some of the preserve's streams, including Coal Creek, has been disturbed by past mining activities.**
**National Park Service photograph by Anna O'Brien.**

# Yukon-Charley Rivers National Preserve

## *Geologic Resources Inventory Report*

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National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible and technically accurate.



This report is available from the Geologic Resources Inventory publications site and the Natural Resource Report publication series site. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov

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# Executive Summary

*Comprehensive park management to fulfill the National Park Service (NPS) mission requires an accurate inventory of the geologic features of a park unit, but park managers may not have the needed information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.*

Yukon-Charley Rivers National Preserve (also referred to as "the preserve" throughout this report) is in east-central Alaska, near the Alaska-Yukon border. It encompasses land along the Yukon River corridor between the towns of Eagle and Circle, as well as the entire Charley Wild and Scenic River. The preserve was established in 1980 to "maintain the environmental integrity of the undeveloped Charley River Basin, and to protect the natural and cultural history of the upper Yukon River corridor for public enjoyment and scientific study" (National Park Service 2012, p. 4). Many of the resources at the heart of the preserve's mission are geologic or are in some way tied to the preserve's geology. This report draws connections between geologic resources and the preserve's other resources and stories. It is the only report that provides a comprehensive compilation of preserve-specific geologic information for NPS staff.

This report—which is the culmination of the GRI process—contains the following chapters:

Introduction—This chapter is divided into two sections: "Introduction to the Park" and "Introduction to the Geologic Resources Inventory." It orients readers to the location and geography of the preserve and provides a brief overview of the preserve's history. Additionally, the chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators. The GRI provides NPS units with four products: (1) a scoping meeting and summary; (2) geologic map data in a geographic information system (GIS) format (referred to as the "GRI GIS data" in this report); (3) a poster to display the GRI GIS data; and (4) a GRI report (this document). Geologic map units in the GRI GIS data are referenced in this report using map unit symbols, and the GRI poster, which displays the GRI GIS data, is referenced throughout the report as a primary figure.

Geologic Heritage— Geologic heritage exists at the overlap of geology and human experiences and values. This chapter draws connections between geology and the significant resources and stories that led to the establishment of the preserve. The preserve is one of the few locations in the world where rocks in a relatively small geographic area record approximately 900 million years of geologic history. Fossils from the oldest rocks provide a rare glimpse into early eukaryotic (organisms that have cells with a nucleus) evolution. In addition to the deep history found within bedrock, the preserve contains remnants of more recent human activity, including evidence of gold mining that peaked during the 1896–1899 Klondike Gold Rush.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance for the preserve. The features and processes discussed are bedrock geology, the Tintina fault system, paleontological resources, mineral resources, caves, glacial history, Quaternary surficial deposits, fluvial features, possible geothermal features, and permafrost.

Geologic History—This chapter describes the chronology of geologic events that led to the modern landscape. The geology in the preserve spans approximately 900 million years, starting in the Neoproterozoic Era (1000–538.8 million years ago) with the formation of the Tindir Group and ending with modern active geologic processes. Prior to the Cretaceous Period (approximately 145–66 million years ago), the geologic history can be divided into events that occurred north and south of the Tintina fault system.

Geologic Resource Management Issues—This chapter discusses management issues related to the preserve's geologic resources (features and processes). Issues discussed are geohazards (earthquakes, landslides, ice jam flooding, and river erosion), stratotype protection, paleontological resource protection, mineral development potential, abandoned mineral lands, cave management, placer-mined stream evaluation, and permafrost monitoring.

Guidance for Resource Management—This chapter provides resource managers with a variety of ways to find and receive management assistance for the issues discussed in the "Geologic Resource Management Issues" chapter or other geologic issues. The chapter includes a table citing laws, regulations, and policies relevant to managing NPS geologic resources as well as a list of additional references, resources, and websites applicable to the preserve's geologic resource management issues.

In addition to these chapters, "Literature Cited" provides a bibliography of all the references cited in this GRI report. It serves as a source of preserve-specific geologic information applicable to the protection, management, and interpretation of the preserve's geologic resources.

# Introduction

*The purpose of this report is to familiarize readers with the geologic features, processes, history, and best practices for managing geologic resources for Yukon-Charley Rivers National Preserve (also referred to as "the preserve" throughout this report). 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.*

## Park Background and Establishment

Yukon-Charley Rivers National Preserve encompasses 10,000 km$^2$ (2.5 million acres) of land along the Yukon River corridor near the United States-Canada border in east-central Alaska (Figure 1). The preserve derives its name from the Yukon River, which flows from southeast to northwest through the preserve, and the Charley River, which is entirely contained within the western part of the preserve. The Alaska National Interest Lands Conservation Act (ANILCA), which became law in 1980, established the preserve along with many other NPS units in Alaska. The purpose of the preserve is to "maintain the environmental integrity of the undeveloped Charley River Basin, and to protect the natural and cultural history of the upper Yukon River corridor for public enjoyment and scientific study" (National Park Service 2012, p.4).

The Yukon River is one of the most prominent geographic features in both the preserve and Alaska as a whole. Stretching over 3,000 km (1,900 mi) from northwestern British Columbia in Canada to the Bering Sea in western Alaska, the Yukon River is the longest river in Alaska and the fourth largest drainage basin in North America. The Yukon River is a major artery that serves as a transportation corridor and source of food and water for humans and animals alike. The preserve encompasses about 200 km (130 mi) of the Yukon River between the towns of Eagle and Circle. The river flows through a narrow river valley flanked by bluffs and forested hills. The areas north and south of the Yukon River are mountainous, with the Ogilvie Mountains lying to the north and the Yukon-Tanana uplands to the south. The tallest peak in the preserve is Cut Mountain, at 1,961 m (6,435 ft). The preserve contains many tributary creeks and rivers that feed into the Yukon River; the rivers include the Charley River, Kandik River, Nation River, Seventymile River, and Tatonduk River. The entire 4,500 km$^2$ (1.1-million-acre) Charley River watershed is within the preserve, and this designated Wild and Scenic River is a fundamental preserve resource (National Park Service 2012).

The preserve is located on the western side of the North American tectonic plate, at the edge of mountain chain system called the North American Cordillera. Although Alaska is part of the North American plate today, most of the rocks in Alaska did not form in their current location relative to the ancient geologic core of North America (called "Laurentia"). The Earth's crust is broken into tectonic plates that have shifted relative to each other over the billions of years of geologic history (see Table 1 for a geologic time scale). Tectonic plates can change in size over time through several processes: magma from the mantle can move upward and solidify to create new crust; crust from one plate can be transferred to another (a process called accretion); or crust can be lost when a plate subducts (descends) into the mantle. The western margin of Laurentia has received significant additions of crust since the Mesozoic Era, including almost all of Alaska. These pieces of crust, known as "terranes," have moved from where they originally formed and accreted to the edge of Laurentia through a complex tectonic history of collision, extension, and translation. The mountains along the western side of North America, known collectively as the Cordillera, are a product of terrane accretion.

The discovery of gold in the late 1800s brought thousands of people north to Alaska and the adjacent Canadian Yukon Territory, resulting in changes to the demographics, culture, and environment of these regions. Before the dramatic influx associated with the 1896–1899 Klondike Gold Rush, smaller numbers of prospectors were mining along the Yukon River on both sides of the Alaska-Yukon border. The town of Circle (named for its proximity to the Arctic Circle) was founded in 1893 to supply miners working in the area around the preserve (Figure 2). Circle was known as the "largest log-cabin city in the world" and grew to have a population of over 1,000 people. However, many of its residents flocked upriver to the Klondike region of Yukon, Canada, when gold was discovered there in 1896. A steamboat trip up the Yukon River, including through the stretch of river now within the preserve,

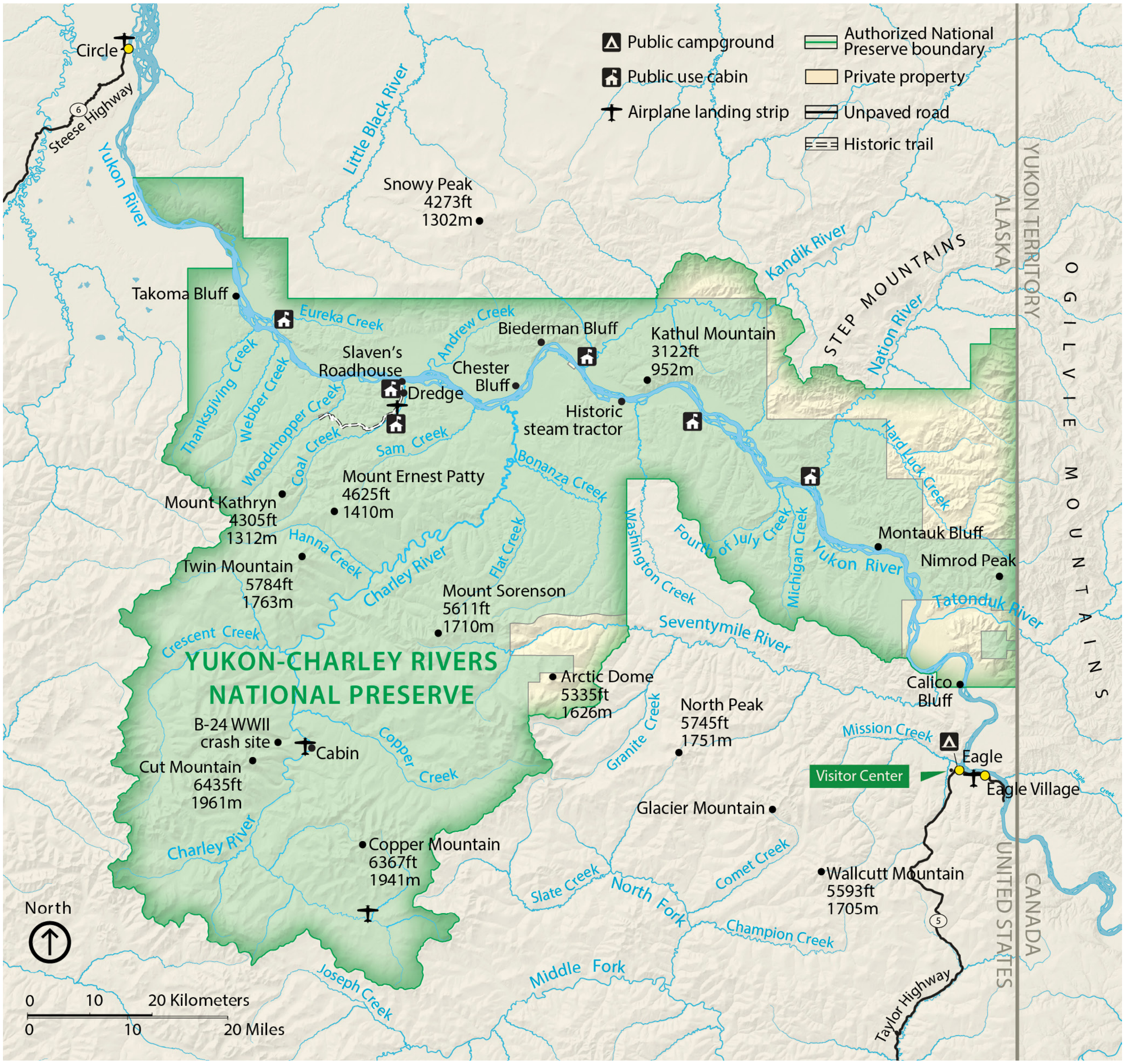


**Figure 1. Map of Yukon-Charley Rivers National Preserve.**
**The preserve is located along the Alaska-Yukon border in east-central Alaska. It encompasses 200 km (130 mi) of the Yukon River corridor between the towns of Eagle and Circle, as well as the entire Charley River Basin. No roads extend into the preserve, but the nearby town of Eagle can be accessed via the Taylor Highway and the town of Circle can be accessed via the Steese Highway. Map modified from the Yukon-Charley Rivers National Preserve brochure map.**

was a popular way for eager gold miners (called "stampeders") to access the Klondike. As the gold rush progressed, some miners were dissatisfied with the regulations imposed by the Canadian government and crossed the border back into Alaska. The town of Eagle was established in 1898, just 13 km (8 mi) from the Alaska-Yukon border, to support prospecting on the Alaskan side. Mining occurred along many of the rivers and creeks within the preserve during the gold rush era, but by the early 1900s, most stampeders had moved on. The preserve and surrounding area never again reached the population and activity seen during the boom of the gold rush. The population of both Eagle and Circle declined to less than 100 people by 1920. The stampeders who stayed either continued to mine, adopting more mechanized methods over time, or settled into a subsistence lifestyle that had been the norm in the area for hundreds of years prior to the gold rush.

**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. GRI map abbreviations for each time division and map unit symbols are in parentheses. The Paleogene and Neogene have been collectively referred to as the Tertiary in older publications. Since the GRI GIS data uses the term Tertiary, the term will be used within this report. Ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (https://stratigraphy.org/timescale/, accessed 12 April 2022).

| Eon | Era | Period | Epoch | MYA |
|---|---|---|---|---|
| Phanerozoic | Cenozoic | Quaternary (Q) | Holocene (H) | 0.0117 (11,700 years)–today |
| Phanerozoic | Cenozoic | Quaternary (Q) | Pleistocene (PE) | 2.6–0.0117 |
| Phanerozoic | Cenozoic | Neogene (N) | Pliocene (PL) | 5.3–2.6 |
| Phanerozoic | Cenozoic | Neogene (N) | Miocene (MI) | 23.0–5.3 |
| Phanerozoic | Cenozoic | Paleogene (PG) | Oligocene (OL) | 33.9–23.0 |
| Phanerozoic | Cenozoic | Paleogene (PG) | Eocene (E) | 56.0–33.9 |
| Phanerozoic | Cenozoic | Paleogene (PG) | Paleocene (EP) | 66.0–56.0 |
| Phanerozoic | Mesozoic | Cretaceous (K) | Upper, Lower | 145.0–66.0 |
| Phanerozoic | Mesozoic | Jurassic (J) | Upper, Middle, Lower | 201.3–145.0 |
| Phanerozoic | Mesozoic | Triassic (TR) | Upper, Middle, Lower | 251.9–201.3 |
| Phanerozoic | Paleozoic | Permian (P) | Lopingian, Guadalupian, Cisuralian | 298.9–251.9 |
| Phanerozoic | Paleozoic | Pennsylvanian (PN) | Upper, Middle, Lower | 323.2–298.9 |
| Phanerozoic | Paleozoic | Mississippian (M) | Upper, Middle, Lower | 358.9–323.2 |
| Phanerozoic | Paleozoic | Devonian (D) | Upper, Middle, Lower | 419.2–358.9 |
| Phanerozoic | Paleozoic | Silurian (S) | Pridoli, Ludlow, Wenlock, Llandovery | 443.8–419.2 |
| Phanerozoic | Paleozoic | Ordovician (O) | Upper, Middle, Lower | 485.4–443.8 |
| Phanerozoic | Paleozoic | Cambrian (C) | Furongian, Miaolingian, Series 2, Terreneuvian | 538.8–485.4 |
| Proterozoic | Neoproterozoic (Z) | Ediacaran, Cryogenian, Tonian | n/a | 1,000–538.8 |
| Proterozoic | Mesoproterozoic (Y) | Stenian, Ectasian, Calymmian | n/a | 1,600–1,000 |
| Proterozoic | 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 2. Photograph of Circle City in 1899.**
**The view of Circle City (now known as just Circle) is seen from a steamboat docked on the Yukon River. Circle was founded in 1893 along the Yukon River, about 25 km (15 mi) north of what is now the preserve's boundary. During its heyday, Circle was a regular stop for steamboats and boasted a music hall, two theaters, eight dance halls, six saloons, and a population of over 1,000 people. This photograph is part of the Arthur C. Pillsbury Collection, which includes photographs taken by Arthur Clarence Pillsbury during his 1899 trip down the Yukon River from Skagway to Nome, Alaska.**

Today, visitors to the preserve can explore Alaska's natural and cultural history, view a variety of wildlife, and travel through remote country by boat or on foot. While the towns of Eagle and Circle can be accessed by highway, no roads extend into the preserve. Most visitors travel into the preserve via the Yukon River or aircraft. Popular activities include floating the Yukon or Charley Rivers, visiting historic sites, hiking, skiing, camping, fishing, hunting, and dog mushing. Points of interest within the preserve include public use cabins (some of which are historic structures), historic mining equipment such as the steam tractor near Washington Creek or the dredge on Coal Creek, and a B-24 WWII crash site in the Charley River basin (see poster; see Figure 1). Each year, the Yukon Quest International Sled Dog Race runs through the preserve, and Slaven's Roadhouse acts as a dog drop-off station. In 2022, the preserve received 744 recreational visitors, making it the third least-visited NPS unit in Alaska behind Alagnak Wild River and Aniakchak National Monument and Preserve (Ziesler and Spalding 2023). Prior to 2020, recreation visits in the preserve were typically above 1,000, but in 2020 and 2021, visitation dropped to around 600 visitors. The 744 visitors recorded in 2022 is a 18.3% increase over the 629 visitors recorded in 2021 (Ziesler and Spalding 2022; Ziesler and Spalding 2023).

## Geologic Resources Inventory

The Geologic Resources Inventory was established in 1998 by the NPS Geologic Resources Division and the NPS Inventory and Monitoring Program [Division] to meet the NPS need for geologic mapping and related information. Geologic maps were identified as one of 12 natural resource data sets critical for long term science-informed park management. From the beginning, the GRI has worked with long-time NPS partner Colorado State University to ensure products are scientifically accurate and utilize the latest in GIS technology. Because Alaskan NPS units have unique scale and resource management challenges, the GRI partnered with the NPS Alaska Regional Office and, starting in 2021, the University of Alaska Museum of the North to develop GRI products. For additional information regarding the genesis of the program and its early focus, refer to National Park Service (1992, 1998, 2009).

### *GRI Products*

The GRI team—which is a collaboration among the NPS Geologic Resources Division, Colorado State University's Department of Geosciences, and the University of Alaska Museum of the North—completed the following tasks as part of the GRI process for Yukon-Charley Rivers National Preserve: (1) conducted a scoping meeting and provided a scoping summary (GRI Team 2004); (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 GRI publications website (http://go.nps.gov/gripubs) and through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/). Enter "GRI" as the search text and select a park unit from the unit list. Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The GRI GIS data can also be accessed through the Alaska Region Theme Manager ArcGIS plugin.

Information provided in GRI products is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based on the information provided in GRI products. 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 meeting 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 reports. A scoping summary (GRI Team 2004) summarizes the findings of that meeting and is available online (https://irma.nps.gov/DataStore/Reference/Profile/2250142).

### GRI GIS Data

Following the scoping meeting, the GRI team compiled the GRI GIS data for the preserve (Figure 3). 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. 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 with the current geologic interpretation of an area.

The GRI GIS data for Yukon-Charley Rivers National Preserve was compiled from the U.S. Geological Survey Alaska state map:

- Wilson, F. H., C. P. Hults, C. G. Mull, and S. M. Karl. 2015. Geologic Map of Alaska: U.S. Geological Survey, Scientific Investigations Map SIM-3340, scale 1:1,584,000.

The GRI GIS data also includes mineral locality information from five Alaska Resource Data File reports:

- Cameron, C. E. 2000. Alaska Resource Data File, Charley River Quadrangle, Alaska: U.S. Geological Survey, Open-File Report OF-2000-290, scale 1:250,000.
- Freeman, C. J., and J. Schaefer. 1998. Alaska Resource Data File, Circle Quadrangle, Alaska: U.S. Geological Survey, Open-File Report OF-98-783, scale 1:250,000.
- Rombach, C. 1999. Alaska Resource Data File, Big Delta Quadrangle, Alaska: U.S. Geological Survey: Open-File Report OF-99-354, scale 1:250,000.
- U.S. Geological Survey. 2008. Alaska Resource Data File, New and Revised Records Version 1.6: U.S. Geological Survey, Open-File Report OF-2008-1225, scale 1:250,000.
- Werdon, M. B., R. L. Flynn, and D. J. Szumigala. 2004. Alaska Resource Data File, Eagle Quadrangle, Alaska: U.S. Geological Survey, Open-File Report OF-2004-1056, scale 1:250,000.

For additional information, see the Yukon-Charley Rivers National Preserve GRI Ancillary Map Information Document pertaining to the source maps for the GRI GIS data.

### GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the preserve and its 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

On 22 November 2021, the GRI team hosted a follow-up meeting for NPS staff and interested geologic experts. The meeting provided an opportunity to get back in touch with park staff, introduce new (since the 2004 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

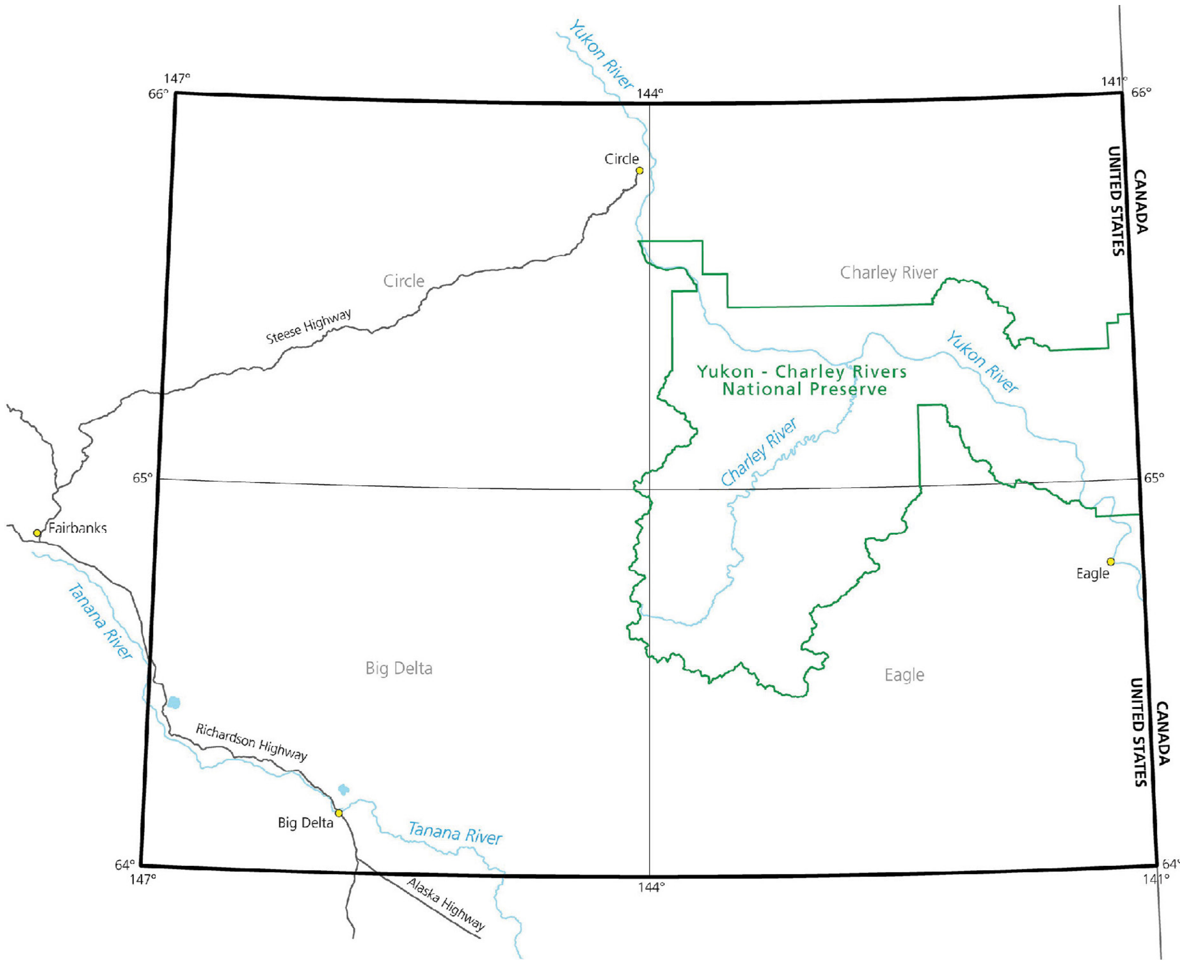


**Figure 3. Index map for the GRI GIS data.**
**The map displays the extent (quadrangle boundaries in black) of the GRI GIS data. The GRI GIS data extends beyond the boundary of the preserve (outlined in green) and covers the Big Delta, Charley River, Circe, and Eagle quadrangles (labeled in grey). Index map by James Winter (Colorado State University).**

The GRI report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2004, the follow-up meeting in 2021, and additional geologic research. The selection of geologic features and processes highlighted in this report was guided by the previously completed GRI map data, and the writing reflects the data and interpretation of the source map authors. Information from the preserve's Foundation Statement (National Park Service 2012) and Natural Resource Condition Assessment (Stark et al. 2012) has also been included as applicable to Yukon-Charley Rivers National Preserve's geologic resources and resource management.

The GRI report links the GRI GIS data to geologic features and processes using map unit symbols; for example, the Funnel Creek Limestone has the map symbol **Cf**. Capital letters indicate age, and the following lowercase letters symbolize the unit name. "**C**" represents the Cambrian Period (538.8 to 485.4 million years ago), and "**f**" represents Funnel Creek Limestone. A geologic time scale showing the distributions of the geologic periods is provided as a table in this report (see Table 1).

The primary audience of GRI reports is park resource managers, but the GRI team hopes that these reports will appeal to and be useful for other audiences such as park interpreters and the public. To that end, we try to keep the writing accessible to readers who do not specialize in geology. Geology is a science full of jargon and based on complex concepts that have changed over time with more information and greater understanding. Thus, GRI reports use geologic terminology. Some of the uncommon geologic terms are defined at first instance, usually in parentheses following the term. Readers can visit the GRI Glossary of Geologic Terms webpage (https://www.nps.gov/subjects/geology/gri-glossary-of-geologic-terms.htm) for more term definitions.

## Acknowledgements

I am very appreciative to the many individuals who took the time to share their knowledge and provide feedback that greatly increased the quality of this report. I would like to thank my reviewers Jamey Jones (U.S. Geological Survey Alaska Science Center), Jeff Rasic (Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve), and Justin Strauss (Dartmouth College). I would also like to thank those who provided review of portions of the report: Paul Burger (NPS Alaska Regional Office) for reviewing the stream restoration section; Tim Henderson (Colorado State University) for reviewing many of the sections, particularly the stratotype sections; Kyle Hinds (NPS Geologic Resources Division) for reviewing the abandoned mineral lands section; Chad Hults (NPS Alaska Regional Office) for reviewing the mineral and mining related sections; Vince Santucci (NPS Geologic Resources Division) for reviewing the paleontology sections; David Swanson (NPS Arctic Inventory and Monitoring Network) for reviewing the permafrost sections; and Jack Wood (NPS Geologic Resources Division) for reviewing the geohazards section. Thank you to Suzanne McKetta (Colorado State University) for helping clarify and improve my writing through her wonderful editing skills. Thank you to Katie KellerLynn (Colorado State University) for developing standard report content and arrangement. Finally, a huge thank you to the entire GRI team, particularly Jason Kenworthy (NPS Geologic Resources Division) and Rebecca Port (NPS Geologic Resources Division), for providing consistent guidance, encouragement, and feedback throughout the writing process.

The GRI team thanks the participants of the 2004 scoping meeting and 2021 follow-up 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 U.S. Geological Survey for its maps of the area. This report and accompanying GIS data could not have been completed without them.

### *2004 Scoping Participants*

Guy Adema (Denali National Park and Preserve)
Robert Blodgett (U.S. Geological Survey)
Phil Brease (Denali National Park and Preserve)
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Tim Connors (NPS Geologic Resources Division)
George Dickison (NPS Alaska Support Office)
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### *2021 Follow-up Meeting Participants*

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Ken Hill (Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve)
Chad Hults (NPS Alaska Regional Office)
Jason Kenworthy (NPS Geologic Resources Division)
Maggie MacCluskie (NPS Central Alaska Inventory and Monitoring Network)
Rebecca Port (NPS Geologic Resources Division)
Jeff Rasic (Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve)
Jillian Richie (Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve)
David Swanson (NPS Arctic Inventory and Monitoring Network)

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Ron Karpilo (Colorado State University)
James Chappell (Colorado State University)
Stephanie O'Meara (Colorado State University)

*GRI Poster Design*

Thom Curdts (Colorado State University)
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# Geologic Heritage

*Geologic heritage, also referred to as "geoheritage," encompasses the significant geologic features, landforms, landscapes, and stories characteristic of our nation that are preserved for the full range of values that society places on them, including scientific, aesthetic, cultural, ecosystem, educational, recreational, tourism, and other values. This chapter highlights the preserve's geoheritage and draws connections between geologic resources and other resources and stories.*

The preserve's significant geologic features, landforms, and landscapes are part of a rich geologic heritage that is, in part, the reason for the preserve's creation. Geologic heritage (or "geoheritage") is the nexus of geology and human experience; it encompasses the features, sites, and stories preserved for the full range of values that society places on them. The preserve was created to protect the Charley River Basin and the natural and cultural history of the upper Yukon River corridor (National Park Service 2012). From the way the course of the Yukon River mirrors the underlying geologic structure, to the over 900 million years of geologic history preserved within the rocks, to the gold deposits that attracted thousands of miners in the late 1800s, geology plays a significant role in the fundamental resources at the core of the preserve's mission.

The geology that underlies a landscape is a fundamental factor that influences what geographic features will develop in an area. The Yukon River flows from Canada to the west coast of Alaska in a broad arc that mirrors the distribution of geologic blocks called terranes. Alaska and western Canada are composed of many terranes that have been sliding past and colliding with each other for millions of years, resulting in the formation of many major geographic features such as mountain ranges and sedimentary basins. Within the preserve, the Yukon River runs parallel to a terrane-bounding fault (fracture in the bedrock) called the Tintina fault system. Geographic features will often follow the path of faults because, as rocks move along a fault, they will weaken, break, and become more susceptible to erosion. Examples from other parks in Alaska include the alignment of Lake Clark (in Lake Clark National Park and Preserve) with the Lake Clark fault (see Lanik et al. 2021 for more details) and the Taiya Inlet (near Klondike Gold Rush National Historical Park) with the Taiya Inlet fault (see Lanik 2022 for more details).

The preserve is one of the few locations in the world where rocks in a relatively small geographic area record approximately 900 million years of geologic history (National Park Service 2012). The rocks in the preserve north of the Tintina fault system are made up of a thick sequence of mostly sedimentary rocks that started to form in the Proterozoic Eon and continued to form with few breaks until the Cenozoic Era (see Table 1 for the position and dates of the time scale units referenced throughout this report). Additionally, many of these rocks contain fossils that record the evolution of life on Earth. The oldest rocks contain early forms of single-celled eukaryotes and multicellular animals that provide a rare glimpse into the evolution of eukaryotes, including the oldest known occurrence of biologically controlled mineralization (Cohen et al. 2017). The scientific and educational value of this succession of rocks is acknowledged in the preserve's enabling legislation, which states the preserve shall be managed to protect and interpret the geological and paleontological history of the area (ANILCA 1980). The preserve is one of eighteen NPS areas that have specific references to paleontological resources in the enabling legislation.

The preserve's bedrock forms bluffs along the Yukon River that are a striking part of the scenic beauty enjoyed by many visitors (Figure 4). Traveling along the Yukon River, either by boat in summer or dogsled or snowmachine in winter, is one of main ways visitors move through the preserve. The bluffs along the river display the long geologic history recorded in the preserve's bedrock and surficial deposits. Perhaps the most striking example is Calico Bluff (see front cover), which is the first bluff encountered when visitors enter the preserve from the south (coming from Eagle). This imposing outcrop is composed of alternating light and dark layers of rock that are thoroughly folded and faulted. Other notable bluffs on the Yukon River include Montauk Bluff (formed by exposures of the Nation River Formation), Biederman Bluff (formed by exposures of the Biederman Argillite), and Chester Bluff (formed by Quaternary surficial deposits; see Figure 1 for bluff locations).

The geologic history of the preserve produced gold deposits that have drawn people to the region since the 1800s. Most of the gold deposits occur within Cretaceous (145–66 million years ago) and Cenozoic (66 million years ago–present) sedimentary rocks that are found along the trace of the Tintina fault system (see the "Mineral Resources" section of this report for more details). These gold deposits have been

**Figure 4. Photograph of the Tahkandit Limestone along the Yukon River.**
**This photograph was taken near the mouth of the Nation River and shows resistant cliffs formed by the Permian Tahkandit Limestone. NPS photograph by Matthew Harrington.**

targeted by miners for over 100 years, including (1) early prospectors prior to the 1890s gold rush; (2) a significant influx of miners, people, and infrastructure associated with the gold rush; and (3) a handful of increasingly industrialized mining efforts that stayed on after the frenzy of the gold rush faded. Artifacts, structures, and environmental changes associated with this long mining history can still be seen throughout the preserve today (Figure 5). The gold mining history is a fundamental resource that the preserve protects and interprets (National Park Service 2012).

Geoheritage sites are conserved in order to protect these landscapes, resources, histories, and scenic values as a legacy for future generations. Typically, these areas have great potential for scientific research, use as outdoor classrooms, and enhancing the public's comprehension and enjoyment. Geoheritage sites are fundamental to understanding dynamic Earth systems, the succession and diversity of life, climatic changes over time, the evolution of landforms, and the origin of mineral deposits. Currently, there is no comprehensive national registry that includes all geoheritage sites in the United States. More information on geoheritage can be found in the 2015 booklet titled "America's Geologic Heritage: An Invitation to Leadership," which was published as a collaborative effort between the GRD and the American Geosciences Institute. This publication introduces key principles and concepts of America's geoheritage, which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States.

**Figure 5. Photograph of a steam boiler at Coal Creek.**
**This steam boiler is one of several obsolete mining machines that can be found in the Coal Creek Historic Mining District. The steam boiler was used by miners to thaw out sediment before sifting through it for gold. This step was necessary because the area is underlain by permafrost, meaning the ground stays frozen all year. NPS photograph by Chris Allan.**

# Geologic Features and Processes

*The geologic features and processes highlighted in this chapter are significant to the preserve's landscape and history. At the beginning of each of the following sections, map units corresponding to the GRI GIS data and poster are listed; these indicate which map units are discussed in each section. Map units are referenced directly in 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 selection of these features and processes was based on input from scoping and follow-up meeting participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. Based on these information sources, the following geologic features and processes are discussed in this chapter:

- Bedrock Geology
- Tintina Fault System
- Paleontological Resources
- Mineral Resources
- Caves
- Glacial History
- Quaternary Surficial Deposits
- Fluvial Features
- Possible Geothermal Features
- Permafrost

## Bedrock Geology

### *Terrane Translation and Accretion*

Alaska is composed of a network of displaced blocks of crust grouped into terranes (Figure 6; Coney et al. 1980; Nokleberg et al. 1994; Yukon Geological Survey 2020). A terrane is a fault-bounded package of rocks with a distinct geologic history that differs from adjacent rocks (Jones et al. 1983). Alaskan terranes have been transported by plate tectonics (i.e., translated) from where they originally formed and accreted together to the edge of Laurentia (the ancient geologic core of North America). Only a small portion of Alaska, along the eastern side of the preserve, is a relatively in-place part of Laurentia. The rest of Alaska consists of displaced terranes and overlap assemblages that formed after terrane accretion. Overlap assemblages are sedimentary or igneous rocks deposited on or intruded into two or more adjacent terranes (Nokleberg et al. 1994).

The bedrock in the preserve includes rocks that formed along Laurentia, parts of several terranes, and overlap assemblages. Rocks that developed along the margin of Laurentia include a triangular block (called the "Tatonduk block") to the north of the Tintina fault system in the eastern part of the preserve (NAp on Figure 6). While the rocks of the Tatonduk block have been thrust eastward, they are relatively in-place compared to the rest of the terranes of Alaska. Rocks south of the Tintina fault system in the southwestern part of the preserve also formed along the Laurentian margin but have been displaced by movement on the Tintina fault system (NAb on Figure 6). Terranes within the preserve include the Yukon-Tanana and Seventymile terranes to the south of the Tintina fault system (YT and SM on Figure 6) and the Porcupine and Angayucham/Tozitna terranes to the north of the Tintina fault system (PC and AG on Figure 6). Overlap assemblages, which formed during or after terranes accreted together, include the Kandik River assemblage, Cretaceous and Tertiary igneous rocks, sedimentary rocks of the Tintina fault system and Nation River Basin, and Quaternary surficial deposits (see Table 1 for the position and dates of the time scale units referenced throughout this report). Table 2 displays a correlation of these tectonic groups with the GRI GIS map units.

The following discussion of the preserve's bedrock geologic units is organized by the tectonic groups of Table 2. This report presents the general characteristics of each group and information about how they formed. Detailed unit descriptions for each unit, including descriptions from multiple different source maps and the Alaska state geologic map (Wilson et al. 2015), are available in the GRI GIS Ancillary Map Information Document. The Ancillary Map Information Document can be downloaded on IRMA alongside the GRI GIS data.

### *Laurentian Shelf/Tatonduk Block*

Map units: see Table 2

A thick succession of relatively unmetamorphosed rocks that formed on the western margin of Laurentia crop out in a triangular area called the Tatonduk block. The Tatonduk block is located between the Alaska-Yukon border, the Yukon River, and the Kandik River in the eastern part of the preserve (see Figure 6). Equivalent rocks extend eastward into the Ogilivie Mountains of Yukon, Canada. These rocks record the breakup of the supercontinent Rodinia at the end of the Proterozoic and the development of the early Paleozoic Laurentian passive margin (continental boundary

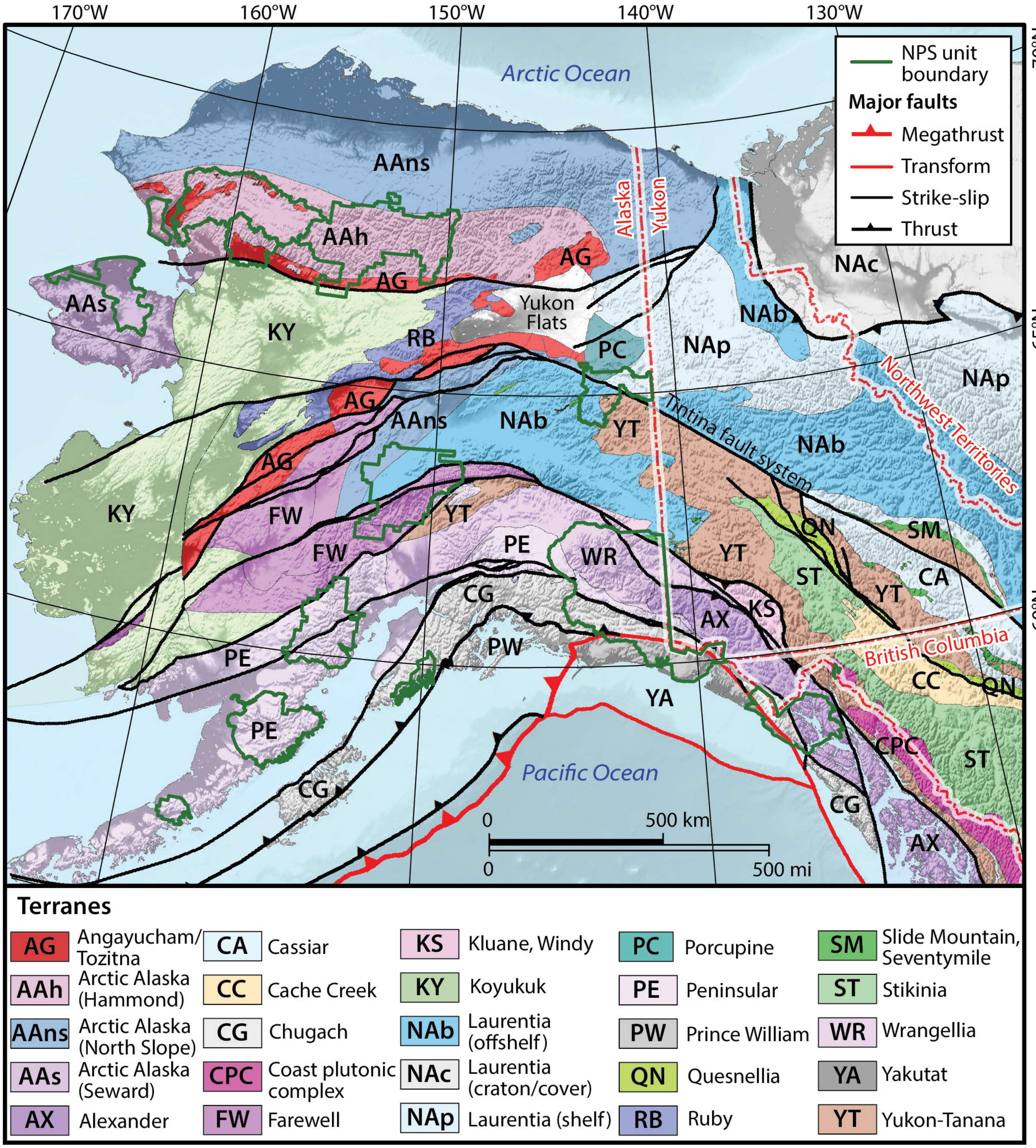


**Figure 6. Terrane map of the preserve.**
**Rocks within the preserve include a portion of Laurentia (NAc), a displaced package of rocks that formed off the Laurentian shelf (NAb), parts of the Yukon-Tanana (YT), Seventymile (SM), Porcupine (PC), and Angayucham/Tozitna (AG) terranes, and their associated overlap assemblages. Overlap assemblages are not included on this terrane map. Overlap assemblages within the preserve include rocks of the Kandik River assemblage, Cretaceous and Tertiary igneous rocks, Cretaceous and Tertiary rocks along the Tintina fault system, and Quaternary surficial deposits. See Table 2 for a correlation of GRI GIS map units to the tectonic grouping. Figure modified from Yukon Geological Survey (2020) to include the Porcupine and Seventymile terranes.**

**Table 2. Tectonic affinity of GRI GIS map units within the preserve.**

Map units within the extent of the GRI GIS map data but not within the preserve boundary have been omitted from this table. See Figure 3 for a map showing the extent of the GRI GIS map data relative to the preserve boundary. *Laurentia shelf/Tatonduk block and Porcupine terrane are grouped together because, in our GRI GIS map data, the geologic units mapped within the Porcupine terrane are also mapped in the portion of Laurentian shelf strata within the preserve (with the exception of the Woodchopper Volcanics and PZPCun).

| Tectonic group | Map units (GRI) |
|---|---|
| Laurentia (shelf)/Tatonduk Block and Porcupine terrane* | Tindir Group (**PCtl**, **PCtlc**, **PCts**, **PCtd**, **PCt**, **PCtu**, **PCtb**, **PCtsl**); undifferentiated sedimentary or slightly metamorphosed rocks (**PZPCun**); Funnel Creek Limestone (**Cf**); Adams Argillite (**Ca**); Hillard Limestone (**OCh**); Jones Ridge Formation (**OCjru**); Road River Formation (**DSOr**); McCann Hill Chert (**Dka**); Ogilvie Formation (**Dof**); Nation River Formation (**Dnr**); Woodchopper Volcanics (**Dwv**); Calico Bluff Formation (**PNMcb**); Ford Lake Shale (**PNMDf**); Tahkandit Limestone (**PZl**); Step Formation (**Pstc**); Lower part of the Glenn Shale (**TRgsl**) |
| Displaced Laurentia (offshelf) | Fairbanks-Chena assemblage of Dusel-Bacon et al. (2006) (**PZPCps**, **PZPCgs**, **PZPCm**); Totatlanika Schist (**MDts**); quartzite, meta-argillite and phyllite (**PZq**); gneiss (**PZg**) |
| Yukon-Tanana terrane | Nasina assemblage of Dusel-Bacon et al. (2006) (**PZqsg**); Fortymile River assemblage of Dusel-Bacon et al. (2006) (**PZPCbg**, **PZPCqs**) |
| Seventymile terrane | Seventymile assemblage of Wilson et al. (2015) (**TRMsm**, **PZgc**, **MZPZPCb**); serpentinized rocks (**MZPZs**) |
| Angayucham/Tozitna terrane | Circle Volcanics (**MZPZc**); Chert and argillite (**MZPZPCca**) |
| Kandik River assemblage | Upper part of the Glenn Shale (**KJTRa**); Kandik Group (**Kb**, **Kke**, **Kka**); unnamed sandstone (**Ku**) |
| Cretaceous and Tertiary igneous rocks | Adamellite (**MZa**); granitic rocks (**TKg**, **TKMZmgr**); mafic igneous rocks (**TMZmi**); felsic igneous rocks (**Tpt**); welded tuff (**Tw**) |
| Sedimentary rocks of the Tintina fault system and Nation River Basin | Sedimentary rocks (**TKs**) |
| Quaternary surficial deposits | Alluvium (**Qa**); Terrace deposits (**Qt**); Old terrace deposits (**QTs**); Alluvial fan deposits (**Qaf**); Alluvium and colluvium (**Qca**); Colluvial deposits (**Qc**); Glacigenic deposits (**Qm**); Loess (**Ql**) |

formed by rifting and characterized by little plate-boundary tectonism). Various researchers have referred to these rocks by several different names. Churkin et al. (1982) and Dover (1994) called these rocks the "Tatonduk Terrane", while other researchers acknowledged this area as the only part of Alaska with undisturbed rocks of Laurentian affinity and did not give it a dedicated terrane name (Silberling et al. 1992; Nokleberg et al. 1994). The Yukon Geological Survey (2020) terrane map used in this report referred to these rocks as "Laurentian shelf," acknowledging that they formed as part of Laurentia, but differentiated them from rocks to the southwest that formed off the Laurentian shelf in deeper water. These rocks are referred to as either the "Laurentian shelf" or the "Tatonduk block" in this report.

The Laurentian shelf succession of the Tatonduk block is made up of predominantly carbonate (composed of carbonate minerals) and clastic (composed of fragments of other rocks) sedimentary rocks that formed in ancient seas at the end of Laurentia. These rocks preserve an unusually continuous record beginning over 900 million years ago, ranging from the Tonian Period (early Neoproterozoic) to the Triassic Period. Rock units assigned to this group include (from oldest to youngest): the Neoproterozoic Tindir Group; Cambrian Funnel Creek Limestone and Adams Argillite; Cambrian–Ordovician Hillard Limestone and Jones Ridge Formation; Ordovician–Devonian Road River Formation; Devonian Ogilvie Formation, McCann Hill Chert, and Nation River Formation; Devonian–Pennsylvanian Ford Lake Shale; Mississippian–Pennsylvanian Calico Bluff Formation; Permian Tahkandit Limestone and Step Conglomerate; and the Triassic lower portion of the Glenn Shale (see Table 2 for the map units and the poster for their spatial distribution; Figure 7). Payne and Allison (1981) divided these strata into six informal sequences separated by unconformities (gaps in the rock record caused by periods of erosion or nondeposition) or formation boundaries that reflect significant regional events or changes. These informal sequences are used here to frame the discussion of the Laurentian shelf succession.

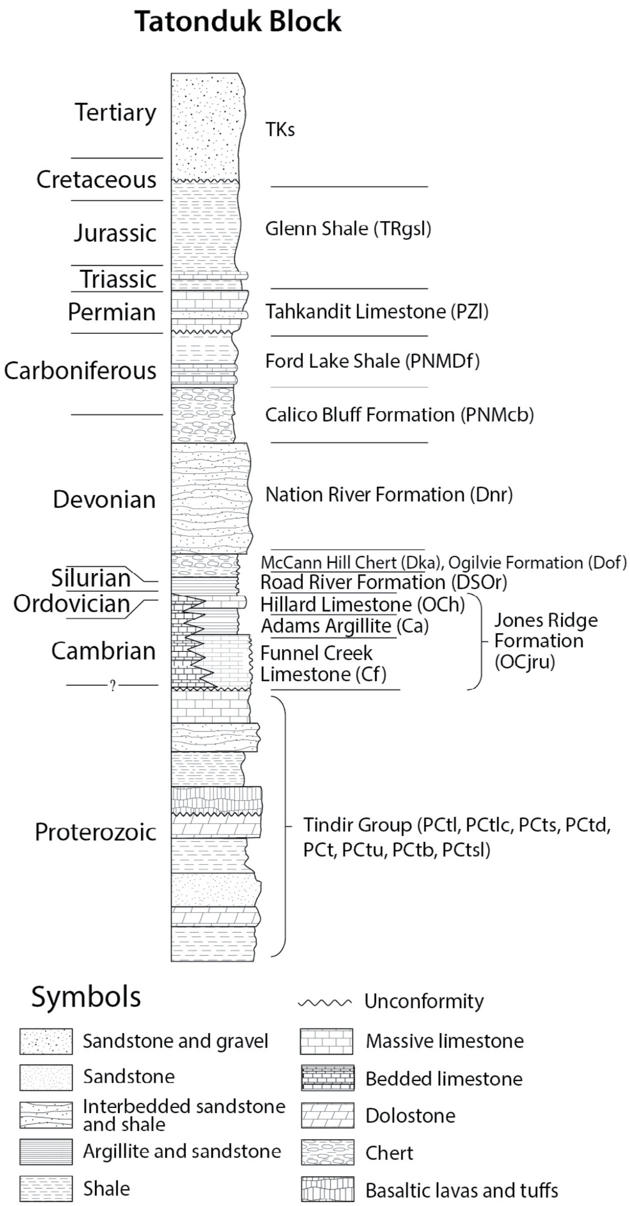


**Figure 7. Stratigraphic column of the Laurentian passive margin strata of the Tatonduk block. Also included is the overlying overlap assemblage composed of the unnamed Cretaceous and Tertiary unit (TKs). Wavy lines between units indicate an unconformity, or gap in the rock record. Figure modified from Johnsson (2000).**

The first sequence of Payne and Allison (1981) encompasses the Tindir Group. The Tindir Group has been informally divided into lower and upper units (Young 1982). Rock types that make up the lower Tindir Group include sedimentary rocks such as shale, mudstone, quartzite, sandstone, and carbonate. Based on regional correlations with other rocks, the lower Tindir Group may have formed between 900 and 700 million years ago (Macdonald et al. 2010b). North-northwest-trending mafic dikes (tabular bodies of iron and magnesium-rich igneous rock) cut through the lower Tindir Group (Young 1982). The upper Tindir Group sequence starts with volcanic pillow basalts and volcaniclastic rocks that were fed by the dikes that cut the lower Tindir Group. Uranium-lead dating (U-Pb dating) of the dikes indicates they formed 713.7+/- 0.9 million years ago (Cox et al. 2018). This volcanism may be associated with the widespread volcanic deposits in Canada called the Franklin large igneous province or, more likely, be the product of rifting along the northwest margin of Laurentia (Cox et al. 2018). This rifting may be associated with the breakup of the supercontinent Rodinia. Deep-marine turbidites (sedimentary rocks formed by underwater landslides) and locally iron-rich diamictites (poorly sorted sedimentary rock) overlie the volcanics (Figure 8). The diamictites are thought to be glacial deposits associated with low-latitude Cryogenian global glaciation, which is known as the Sturtian snowball Earth event (Macdonald et al. 2010b). Snowball Earth is a hypothesis that proposes glaciers covered almost the entire Earth several times during the Neoproterozoic Era. The uppermost part of the Tindir Group is composed of mixed clastic and carbonate sedimentary rocks. Recent work by Macdonald et al. (2011) suggested reassigning the rocks of the Tindir Group to other stratigraphic units found in northwest Canada. According to the new designations, parts of the lower Tindir Group would be reassigned to the Mackenzie Mountains Supergroup, and the upper Tindir Group would be reassigned to the Windermere Supergroup.

The second sequence of Payne and Allison (1981) encompasses Cambrian–Ordovician rocks of the Funnel Creek Limestone, Adams Argillite, Hillard Limestone, and the Jones Ridge Limestone (also referred to as the Jones Ridge Formation by Taylor et al. 2015). The Funnel Creek Limestone is overlain by the Adams Argillite, which is in turn overlain by the Hillard Limestone. The Jones Ridge Limestone formed at the same time as the other three units but further east (Dover 1992). The formation of the shallow-water carbonates that make up the Early Cambrian Funnel Creek Limestone and the coeval Jones Ridge Limestone represents a reestablishment of widespread platform sedimentation following mafic volcanism and glaciation in the upper Tindir Group (Payne and Allison 1981). In particular, the area between Jones Ridge and Hillard Peak was the site of thick shallow-water accumulation until the Early Devonian, whereas areas to the south, west, and northwest record deeper water environments (Payne and Allison 1981; Taylor et al. 2015).

**Figure 8. Photograph of the diamictite and iron formation in the Tindir Group. Diamictites are a type of sedimentary rock characterized by poor sorting or a mixture of large and small rock particles. Note the large clasts amid the fine-grained sediment in the diamictite on the left side of the photograph. The red color of the iron formation on the right side of the photograph is from the high amount of iron oxide within the rocks. Photograph courtesy of Justin Strauss (Dartmouth College).**

The third sequence of Payne and Allison (1981) includes the Ordovician–Devonian Road River Formation, McCann Hill Chert, and Ogilvie Formation. A major marine transgression (deepening) occurred during the Ordovician and Silurian Periods, which is reflected in the deposition of the deep-water shales and cherts of the Road River Formation (Payne and Allison 1981). The McCann Hill Chert overlies the Road River Formation and is composed of limestones, shales, and cherts that formed during the Lower and Middle Devonian Period. Shallow water deposits persisted in the Jones Ridge area at this time, with the deposition of bioclastic (fossil-rich) limestones of the Ogilvie Formation. The depositional environment of the Ogilvie Formation is interpreted to be a shelf and upper-slope environment (Payne and Allison 1981). Overall, the rocks of the third sequence record an overall deepening trend, with shallower water carbonates succeeded by deeper water black cherts and shales (Payne and Allison 1981).

The fourth sequence of Payne and Allison (1981) is the Upper Devonian Nation River Formation. The Nation River Formation is composed of interbedded sedimentary socks such as mudstones, sandstones, and conglomerates with multicolored chert clasts (Figure 9; Dover 1992). Plant fossils are common along bedding planes (Payne and Allison 1981). Exposures of the Nation River Formation form cliffs (e.g., Montauk Bluff) along the Yukon River in the eastern part of the preserve (Figure 9). These clastic sedimentary rocks were deposited in a deep-marine setting with sediment potentially derived from uplift and erosion in the vicinity of the eastern Brooks Range to the north (Payne and Allison 1981), although this is highly speculative because the location of the rocks to the north is uncertain at this time.

The fifth sequence of Payne and Allison (1981) spans the Upper Devonian–Pennsylvanian and includes rocks of the Ford Lake Shale and Calico Bluff Formation. The Ford Lake Shale is composed of deep-water

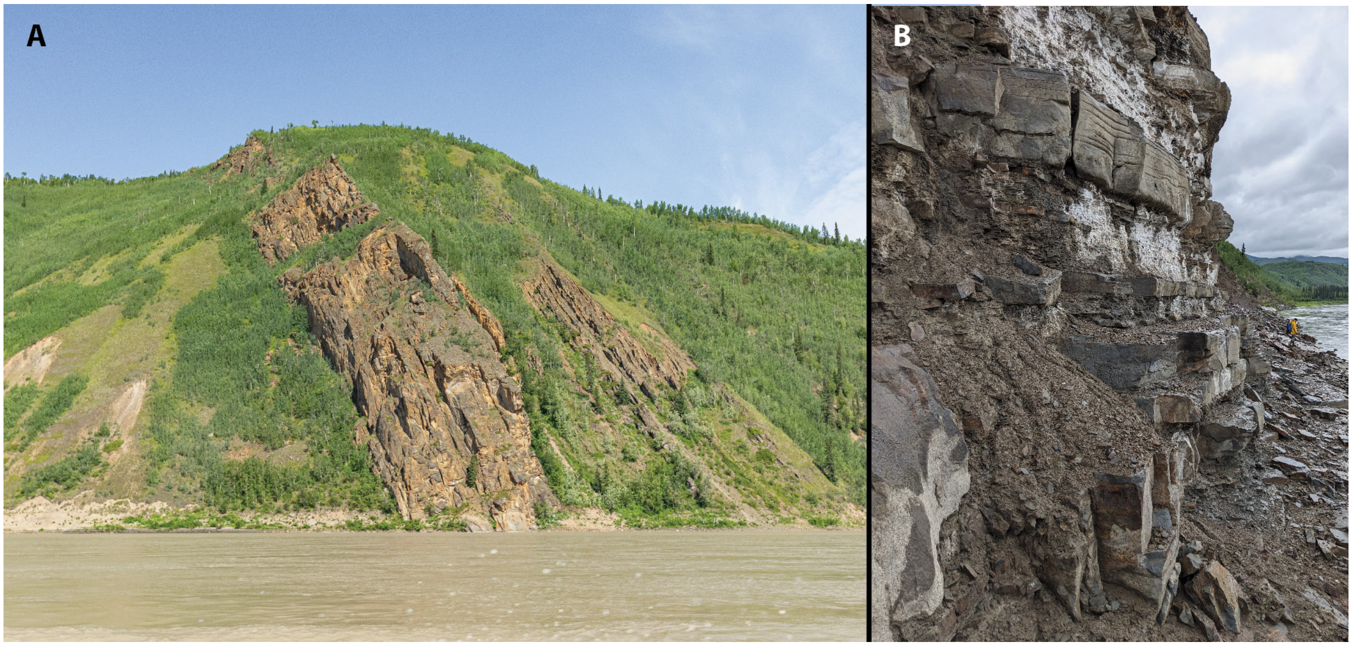


**Figure 9. Photographs of exposures of the Nation River Formation on the Yukon River. (A) Photograph of Montauk Bluff, which is a prominent outcrop of the Nation River Formation that occurs in the eastern part of the preserve. NPS photograph by Matthew Harrington. (B) Photograph of interbedded sandstone (more resistant layers) and mudstone (less resistant layers) of the Nation River Formation. This photograph was taken just east of Montauk Bluff. NPS photograph by Amanda Lanik.**

shales and cherts, which contrast with the coarse submarine channel deposits of the underlying Nation River Formation and the overlying Calico Bluff Formation. Since late September 2012, an oil shale fire has been burning within exposures of the Ford Lake Shale on Windfall Mountain (Figure 10; Stromquist 2013, unpublished draft). The ignition source of the fire is unknown, but it may have been caused by an unreported lightning strike or spontaneous combustion related to oxidation of the pyrite-rich oil shale (Stromquist 2013, unpublished draft). Investigations by NPS staff in 2013 found that potential hazardous gases did not exceed permissible exposure limits (Stromquist 2013, unpublished draft). The Calico Bluff Formation, which overlies the Ford Lake Shale, is a carbonate-rich unit composed of interbedded fossil-rich limestones and black shales (Dover 1992). The depositional environment of the Calico Bluff Formation was likely a submarine slope and rise system (sloping part of the sea floor between the shallower continental shelf and the deeper abyssal plain; Payne and Allison 1981). The exposure of the Calico Bluff Formation at Calico Bluff is characterized by syn-sedimentary folds (deformation that took place during or soon after deposition) sandwiched between undisturbed beds (Figure 11); Payne and Allison (1981) note that this deformation is inconsistent with the rest of the rocks in the area and interpret these features to be the result of marine slope failure shortly after deposition.

The sixth sequence of Payne and Allison (1981) contains the Permian Tahkandit Limestone and Step Conglomerate. Based on sparse biostratigraphic data, it appears that the Tahkandit Limestone and Step Conglomerate were deposited at the same time (Dover 1992). The Tahkandit Limestone is a fossil-rich, coarse-grained limestone, and the Step Conglomerate is primarily a conglomerate composed of well-rounded pebble- to cobble-sized clasts (Dover 1992). A major unconformity, or hiatus in deposition, occurs between the fifth and sixth sequences. This is the only widespread and significant break in Paleozoic sedimentation in the area (Payne and Allison 1981). The unconformity indicates that regional uplift and erosion occurred prior to the Early Permian, with evidence from the Calico Bluff Formation suggesting that uplift began during the Carboniferous and culminated during the Permian (Payne and Allison 1981).

### *Porcupine Terrane*

Map units: see Table 2

In the map area, the Porcupine terrane includes a series of poorly understood rocks ranging in age from the late Proterozoic to upper Paleozoic, situated between the Kandik River assemblage to the east and the Angayucham/Tozitna terrane to the west. Various researchers have assigned these rocks to different terranes. For example, Churkin et al. (1982) grouped

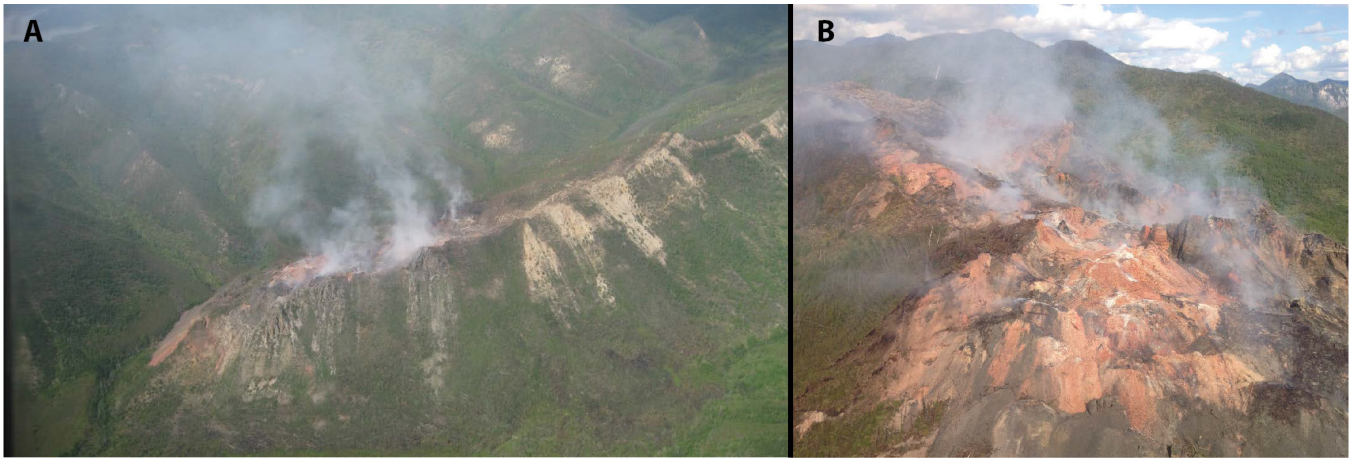


**Figure 10. Photographs of the Windfall Mountain oil shale fire from 2013.**
**(A) Photograph of the Windfall Mountain fire seen from the east. The fire was concentrated along the crest of a ridge on the east side of Windfall Mountain. NPS photograph. (B) Closer photograph of the Windfall Mountain fire. NPS photograph by Linda Stromquist.**

**Figure 11. Photograph of the Calico Bluff Formation at Calico Bluff.**
**The Calico Bluff Formation is composed of deformed, interbedded limestones (light-colored layers) and black shales (dark-colored layers). The folding and faulting of the rocks within the Calico Bluff Formation are probably the result of marine slope failure shortly after deposition and before the sediments were fully lithified (hardened into rock). NPS photograph by Stephen Lias.**

these rocks into the Takoma Bluff terrane, Howell et al. (1992) included these rocks in the Kandik River terrane, and Jones et al. (1987), Silberling et al. (1992) and Nokleberg et al. (1994) included these rocks within the Porcupine terrane. Faehnrich et al. (2021) and Dumoulin et al. (2023) suggested the term "Porcupine terrane" should be eliminated since this region most likely consists of fault-bounded portions of the Angayucham/Tozitna and Arctic Alaska terranes, as well as the rocks of the Laurentian margin (see Figure 6 for the location of the Angayucham/Toztina and Arctic Alaska terranes). Although the Yukon Geological Survey terrane map (2020) used in this report includes these rocks within the North Slope subterrane of the Arctic Alaska terrane, this report follows some of the older terrane maps and uses the term "Porcupine terrane" to differentiate these rocks from the Tatonduk block.

Many of the units of the Porcupine terrane are mapped as the same units found to the east in the Laurentian passive margin strata of the Tatonduk block. These include Proterozoic rocks mapped as the Tindir Group (**PCtu, PCtd, PCtb, PCtsl**), Devonian rocks mapped as the Ogilvie Formation (**Dof**) and tentatively as the Nation River Formation (**Dnr?**), and Permian rocks mapped as the Tahkandit Limestone (**PZl**) and Step Conglomerate (**Pstc**; see poster). Although these units are mapped as the same as those within the Tatonduk block, some researchers have expressed uncertainty about the relationship the Porcupine terrane rocks have with the more studied Tatonduk block (e.g., Payne and Allison 1981; Churkin et al. 1982). Underwood et al. (1996) note that the rocks of the Porcupine terrane (referred to as the Takoma Bluff terrane in their paper) have the same thermal history as rocks of the Kandik River assemblage and some of the other smaller suspect terranes to the west (referred to here as the Angayucham/Tozitna terrane). This indicates that these terranes amalgamated together prior to peak heating and then transported westward together against rocks of the Tatonduk block (Underwood et al. 1996). Payne and Allison (1981) suggested that the Porcupine terrane rocks may be deeper water facies equivalents to those found in the Tatonduk block. Alternatively, the Porcupine terrane rocks could have originated along a different segment of the Laurentia margin and subsequently been tectonically moved to their present position.

The only unit in the Porcupine terrane that is not found in the Tatonduk block is the Devonian Woodchopper Volcanics (**Dwv**; see poster). The Woodchopper Volcanics are composed of volcanic basalts and tuffs with subordinate interbeds of sedimentary rocks including chert, argillite, quartzite, and limestone (Brabb and Churkin 1969; Wilson et al. 2015). These rocks crop out on the north and south sides of the Yukon River between Coal Creek and Thanksgiving Creek. The basalts commonly display amygdaloidal (cavities filled with different minerals) and pillow textures (pillow-shaped basalt formations caused by eruption underwater; Figure 12; Brabb and Churkin 1969). Fossils from the sedimentary rocks of the Woodchopper Volcanics indicate they formed during the Devonian Period (Mertie 1930; Lane and Ormiston 1976; Rohr et al. 2008). Based on the paleogeographic affinity of brachiopods (phylum of marine animals with two shells) collected from the interbedded limestone, Rohr et al. (2008) concluded that the Woodchopper Volcanics represent part of an accreted terrane not related to Laurentia. Rohr et al. (2008) proposed that it may represent the remains of an oceanic island arc that formed adjacent to the Ural Mountains during the Devonian and may be related to the Farewell and Alexander terranes that show similar paleogeographic affinities (see Figure 6 for the locations of the Farewell and Alexander terranes).

**Figure 12. Photograph of pillow basalts of the Woodchopper Volcanics.**
**Pillow basalts form when lava comes into contact with cold water when erupting, causing a solid outer crust to form as the lava cools rapidly. As more lava is fed into the structure it will inflate and produce the pillow-like morphology seen in the photograph. Photograph by David Rohr from Rohr et al. (2008).**

*Yukon-Tanana Terrane and Seventymile Terrane*

Map units: see Table 2

The Yukon-Tanana and Seventymile terranes are "pericratonic" terranes, meaning they have early Paleozoic histories corresponding to the Laurentian margin, but they also record the development of a mid- to late Paleozoic volcanic arc system and marginal basin that does not match the geologic history of Laurentia (Colpron et al. 2006). The Yukon-Tanana terrane represents a volcanic arc built upon rocks rifted away from the edge of Laurentia, while the Seventymile terrane represents remnants of an ocean that opened between the Yukon-Tanana arc and Laurentia (Colpron et al. 2006). Rocks within the preserve that are part of the Yukon-Tanana terrane include metamorphic rocks assigned to the Nasina assemblage (**PZqsg**) and the Fortymile River assemblage (**PZPCbg, PZPCqs**) of Dusel-Bacon et al. (2006; see poster). The Seventymile terrane is composed of rocks of oceanic affinity. Within the preserve, these include basalt, gabbro, greenstone, and chert (**PZgc, MZPZPCb**; see poster).

The Yukon-Tanana terrane is complexly deformed and metamorphosed. This complexity has made studying the internal stratigraphy of the terrane difficult, but the discovery of major mineral deposits in the mid-1990s prompted a joint mapping effort between Canadian and Alaskan geologists to better understand its geologic history (Colpron et al. 2006). As a result of this mapping, the rocks in the southwest part of the preserve and further west (referred to in this report as Laurentian offshelf rocks) that had previously been included in the Yukon-Tanana terrane (Silberling et al. 1992; Nokleberg et al. 1994) were reassigned as portions of the Laurentian margin that had been offset along the Tintina fault system (see Geological Association of Canada Special Paper 45 and papers therein). The rocks that make up the Yukon-Tanana terrane proper (which are found in the south-southeast part of the preserve, see Figure 6 and Table 2) have evidence for the development of mid- to late-Paleozoic arc magmatism and local deformation that do not have known equivalents in the passive margin of Laurentia (Colpron et al. 2006). The divide between the Laurentian rocks to the west and Yukon-Tanana rocks to the east occurs within the preserve as a low-angle fault that is tentatively mapped along the course of the Charley River.

Two units within the preserve are part of the Fortymile River assemblage of the Yukon-Tanana terrane (**PZPCbg, PZPCqs**; Dusel-Bacon et al. 2006). The Fortymile River assemblage consists mainly of rocks that have been metamorphosed to the amphibolite-facies (see Figure 13 for an explanation of metamorphic facies) such as amphibolite, garnet amphibolite, and schist with lesser amounts of orthogneiss and metasedimentary units (Dusel-Bason et al. 2006). U-Pb zircon dating of gneiss has primarily yielded Early Mississippian crystallization ages (Dusel-Bacon et al. 2006). Geochemical data from the amphibolites indicate the magmatic suite (group of intrusive igneous rocks) formed in a volcanic arc environment (Dusel-Bacon et al. 2006). Schists and marble within the Fortymile River assemblage are representative of sedimentary environments developed around the volcanic arc; for example, the marble bodies may reflect small patch reefs that formed around individual arc volcanos (Dusel-Bacon et al. 2006).

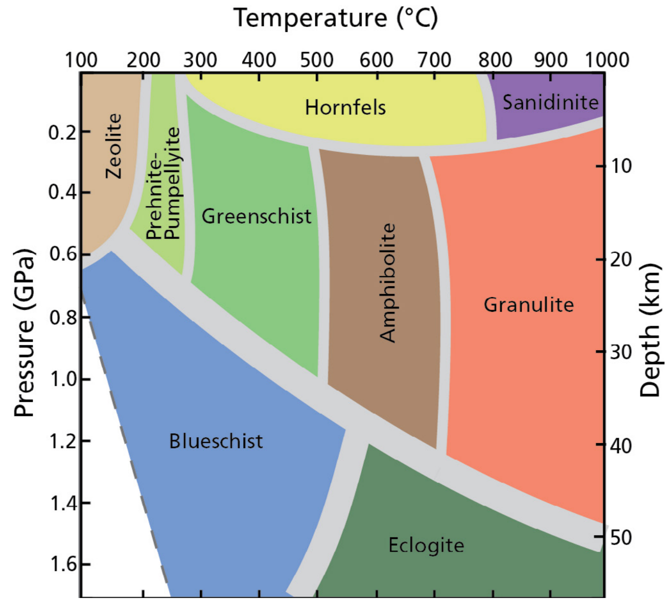


**Figure 13. Pressure-temperature diagram showing metamorphic facies.**
**During metamorphism, various metamorphic minerals will develop depending on original rock chemistry, pressure, and temperature. Metamorphic facies are characterized by mineral assemblages that form under similar pressure-temperature conditions. Rocks in the preserve have undergone amphibolite-facies metamorphism (Fortymile River assemblage of the Yukon-Tanana terrane) and greenschist-facies metamorphism (Nasina assemblage of the Yukon-Tanana terrane and the Kandik River assemablge). Figure modeled after Winter (2001).**

One unit within the preserve is assigned to the Nasina assemblage of the Yukon-Tanana Terrane (**PZqsg**; Dusel-Bacon et al. 2006). The Nasina assemblage is a greenschist-facies sequence of metamorphic rocks including quartzite, phyllite, schist, marble, greenstone, and minor metatuff (see Figure 13; Dusel-Bacon et al. 2006). U-Pb zircon dating of the metatuff unit produced latest Devonian to Early Mississippian, as well as Permian, crystallization ages (Dusel-Bacon et al. 2006). These dates show that some of the felsic (igneous rocks with light-colored minerals) layers are transposed dikes, that the Nasina assemblage was formed from the early Mississippian to the late Permian, or that two very similar sequences are separated by an unrecognized unconformity (Dusel-Bacon et al. 2006).

The Seventymile terrane is composed of scattered oceanic-affinity rocks that structurally overlie the Yukon-Tanana terrane. Within the preserve, Seventymile terrane rocks include mafic igneous rocks such as basalt and gabbro, metamorphosed mafic igneous rocks (greenstone), and deep-water cherts (**PZgc, MZPZPCb**). The Seventymile terrane, along with rocks of the Slide Mountain terrane in Canada, are remnants of an oceanic basin that opened in the back-arc region of the Yukon-Tanana volcanic arc as it rifted away from the western margin of Laurentia (Creaser et al. 1997). Creaser et al. (1997) compared this process to the opening of the Japan Sea during the Miocene. During the Triassic to Middle Jurassic, the Seventymile-Slide Mountain Ocean closed, and the Yukon-Tanana volcanic arc collided with and accreted to the western margin of Laurentia. The return of the Yukon-Tanana terrane caused contraction and imbrication of the Yukon-Tanana terrane strata with rocks of the Laurentian margin (Hansen and Dusel-Bacon 1998; Colpron et al. 2006). Seismic surveys in Yukon and northern British Columbia show that further east, the Yukon-Tanana terrane is composed of a thin fault sliver that is thrust above rocks of the Laurentian passive margin (Cook et al. 2004; Colpron et al. 2006).

### *Laurentian Offshelf*

Map units: see Table 2

Rocks in the southwest portion of the preserve that were previously believed to be part of the Yukon-Tanana terrane have recently been recognized to be a portion of the Laurentian margin offset along the Tintina fault system (Colpron et al. 2006; Yukon Geological Survey 2020). Overall, these rocks represent deeper-water facies that are more metamorphosed and deformed when compared to Laurentian strata found in the eastern part of the preserve (see the "Laurentian Shelf/Tatonduk Block" section of this report). Rocks within the preserve assigned to the Laurentian offshelf tectonic group include rocks of the Fairbanks-Chena assemblage of Dusel-Bacon et al. (2006; **PZPCps, PZPCgs, PZPCm**) and the Totatlanika Schist (**MDts**; see poster).

The Fairbanks-Chena assemblage is widespread, extending from the southwestern portion of the preserve westward beyond Fairbanks (Dusel-Bacon et al. 2006). It consists predominantly of two groups of rocks: (1) a large group of greenschist- and amphibolite facies metamorphic rocks including quartzite, schist, and minor metavolcanic rocks; and (2) a group of amphibolite-facies metamorphic rocks including schist, quartzite, marble, and amphibolite (see Figure 13; Dusel-Bacon et al. 2006). The age of the Fairbanks-Chena assemblage is uncertain, but based on regional correlations with other strata, it is likely Devonian. The Totatlanika Schist is primarily composed of Mississippian metavolcanic rocks.

### *Angayucham/Tozitna Terrane*

Map units: see Table 2

The Angayucham/Tozitna terrane is found in central and northern Alaska and is composed of rocks of oceanic affinity (see Figure 6; Nokleberg et al. 1994; Yukon Geological Survey 2020). The Angayucham/Tozitna terrane in this part of Alaska has been referred to by several other names in the past, including the Slaven Dome and Circle terranes (Churkin et al. 1982). Geologic units in the preserve that are included in the Angayucham/Toztina terrane include the Paleozoic–Mesozoic Circle Volcanics (**MZPZc**) and poorly dated chert and argillite (**MZPZPCca**; see poster).

The Circle Volcanics are composed predominately of mafic igneous rocks, including basalt, diabase, and gabbro, with minor interbeds sedimentary rocks including chert, quartzite, and argillite (Brabb and Churkin 1969). Age estimates for the Circle Volcanics range from the late Paleozoic to early Mesozoic. Churkin et al. (1982) reported Mississippian–Triassic radiolarians from chert beds. Mertie (1930) considered the unit Early Mississippian in age based on correlation with a sparsely fossiliferous volcanic sequence near Rampart. Brabb and Churkin (1969) report a minimum Potassium–argon (K–Ar) radiometric date of about 220 million years ago for an intrusive rock within the Circle Volcanics.

In this report, the Angayucham/Tozitna terrane includes an unnamed and insufficiently dated chert and argillite unit (**MZPZPCca**), which Nokleberg et al. (1994) tentatively assigned to the terrane. This unit is referred to as the Slaven Dome terrane by Churkin et al. (1982). **MZPZPCca** is composed of chert and argillite with minor interbeds of sandstone and chert-pebble conglomerate (Brabb and Churkin 1969; Churkin et al. 1982). For the most part, the paleontology and stratigraphic succession of this unit are poorly understood, but fossils such as goniatites and poorly preserved brachiopods indicate a late Paleozoic age (Churkin et al. 1982).

*Cretaceous and Tertiary Igneous Rocks*

Map units: see Table 2

Cretaceous and Tertiary igneous rocks are found in the preserve on the south side of the Tintina fault system. These rocks include Cretaceous–Tertiary granitic intrusive (**TKMZmgr, TKg, MZa**) and volcanic rocks (**TMZmi, Tpt, Tw**; see poster). The granitic intrusive rocks (igneous rocks that cooled slowly underground with a silicate-rich composition) are much more widespread, composing most of the bedrock in the southwestern part of the preserve. They are primarily quartz monzonite and granodiorites, which are types of felsic intrusive rocks that have moderate to relatively high proportions of plagioclase feldspar (Brabb and Churkin 1969; Foster 1976). The volcanic rocks occur in the headwaters of the Charley River and near Crescent Creek. These units also include mafic rocks such as basalt and gabbro, as well as less widespread felsic rocks such as porphyry, tuff, and volcanic breccia (Foster 1976).

Granitic plutons (bodies of intrusive igneous rocks) intruded the Yukon-Tanana terrane in three phases during the Mesozoic and Cenozoic (Foster et al. 1994). The oldest phase was between 215 and 188 million years ago, during the Late Triassic and Early Jurassic Periods (Foster et al. 1994). Granitic rocks that correspond to this period are mainly found in the eastern part of the Yukon-Tanana terrane, and none of these rocks are within the preserve (Foster et al. 1994). The second phase of granitic magmatism occurred between 95 and 90 million years ago, during the Late Cretaceous Period (Foster et al. 1994). These plutons are found throughout the southwestern part of the preserve. The youngest phase of intrusion was between 70 and 50 million years ago, during the Late Cretaceous and early Tertiary Periods (Foster et al. 1994). Some granitic rocks corresponding to this youngest phase occur in the westernmost part of the preserve, just south of the Tintina fault system (Foster et al. 1994). Isotopic analysis of the Cretaceous and Tertiary granitic rocks that crop out throughout the Yukon-Tanana terrane indicates they were derived from Paleozoic country rock plus various amounts of mafic rocks, either directly from mantle magma or by melting of mafic crust (Aleinikoff et al. 2000). More broadly, Cretaceous and Tertiary granitic plutons occur across much of central and southern Alaska (Moll-Stalcup 1994). This magmatism is related to north-dipping subduction beneath the southern margin of Alaska and involved widespread partial melting of continental material consistent with the tectonic models for arc evolution and terrane accretion.

*Kandik River Assemblage*

Map units: see Table 2

The Kandik River assemblage consists of a sequence of Late Jurassic and Early Cretaceous sedimentary strata in the north-central part of the preserve, located between Laurentian rocks of the Tatonduk block and the Porcupine terrane (see poster; Churkin et al. 1982). Geologic units that make up the Kandik River assemblage include, in ascending order, the upper portion of the Glenn Shale (**KJTRa**) and the three units of the Kandik Group: (1) the Keenan Quartzite (**Kke**), (2) the Biederman Argillite (**Kb**), and (3) the Kathul Graywacke (**Kka**; Figure 14a; Brabb 1969; Dover 1994; Johnsson 2000). These strata have been deformed into a broad synclinorium (U-shape structure), with the youngest rocks in the center and older rocks on the sides (Brabb 1969). The Kandik River assemblage records preorogenic (before a mountain-building event) and synorogenic (during a mountain-building event) sedimentation associated with terrane accretion in the Kandik River area.

The oldest geologic unit assigned to the Kandik River assemblage is the upper part of the Glenn Shale. The Glenn Shale consists of a lower and upper portion that may be separated by an unconformity (Dover 1994; Johnsson 2000). The lower portion of the Glenn Shale contains Triassic fossils (Ladinian to Norian Stage; 242–208.5 million years ago) and is only found in the Tatonduk block, while the upper Glenn Shale contains Lower Cretaceous fossils (Berriasian to Valanginian Stage; 145–132.6 million years ago) and is only found in the Kandik River assemblage (Johnsson 2000). The upper Glenn Shale is likely about 1500 m (4900 ft) thick and consists mostly of grayish-black shale with several 1–5 m (3–16 ft)-thick beds of fine-grained sandstone near the top (Brabb 1969; Johnsson 2000).

The lowermost unit of the Kandik Group, the Keenan Quartzite is a 40–100 m (130–330 ft) thick succession of fine- to medium- grained massive quartz sandstone (Johnsson 2000). The next geologic unit of the Kandik River assemblage is the Biederman Argillite. The Biederman Argillite is composed of rhythmically bedded argillite (weakly metamorphosed mudstone), siltstone, and sandstone (Brabb 1969; Johnsson 2000). The true stratigraphic thickness of the unit is difficult to determine due to folding and faulting, but it is at least 1500 m (4900 ft) thick and possibly up to 4000 m (13,000 ft) thick (Johnsson 2000). The Kathul Greywacke is the uppermost geologic unit of the Kandik River assemblage. The contact between the Kathul Greywacke and the Biederman Argillite is marked by an unconformity in some places, but at most localities there is simply minor scouring between the

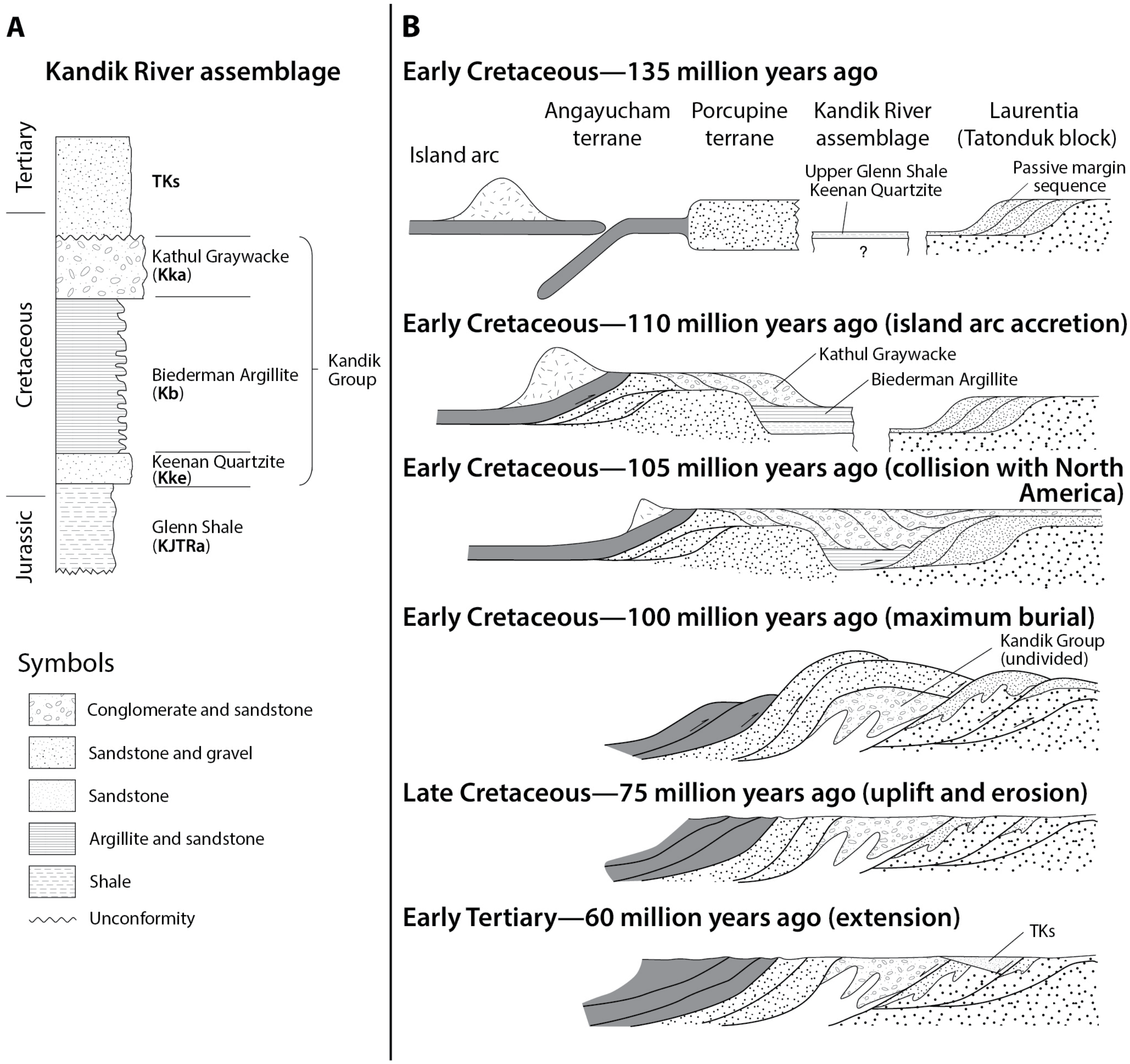


**Figure 14. Stratigraphic column and tectonic diagram for the Kandik River assemblage. (A) Stratigraphic column showing the Jurassic–Cretaceous upper Glenn Shale overlain by the Cretaceous Kandik Group (Keenan Quartzite, Biederman Argillite, and Kathul Graywacke). The Cretaceous–Tertiary unit TKs is also shown, which unconformably overlies both the Tatonduk block and the Kandik River assemblage. (B) Cross sectional diagrams (oriented northwest-southeast) showing a tectonic reconstruction of the rocks in the Kandik area, from the Lower Cretaceous to the early Tertiary. Figure modified from Johnsson (2000).**

two units (Johnsson 2000). The Kathul Greywacke is mainly composed of rock sequences 1–15 m (3–50 ft) in thickness that grade from fine-grained conglomerate and very coarse-grained sandstone upward to siltstone and argillite (Johnsson 2000). The thickness of the Kathul Graywacke ranges from 750–1000 m (2500–3000 ft), but the top of the unit has been eroded, so the original thickness may have been much greater (Johnsson 2000).

The Glenn Shale, Keenan Quartzite, and Biederman Argillite record marine sedimentation that may be continuous with rocks of the Tatonduk block. However, they also indicate regional uplift and the approach of an island arc that are not seen on the passive margin of

Laurentia (Figure 14b; Johnsson 2000). The presence of the Glenn Shale in both the Kandik River assemblage and the Tatonduk block potentially ties the Kandik River assemblage to the Laurentian passive margin (Johnsson 2000). Most of the Glenn Shale represents low-energy, shale-dominated deposition, but the sandstones near the top of the unit and the overlying Keenan Quartzite mark a shift toward continentally derived sand that may record regional uplift (Johnsson 2000).

Continued regional uplift and margin progradation (seaward growth) resulted in the deposition of the Biederman Argillite turbidites (Johnsson 2000). The Kathul Greywacke marks a distinct shift in sedimentation that Johnsson (2000) proposed could be caused by the collision and accretion of an island arc with the Kandik River assemblage. Johnsson (2000) suggested that this island arc accretion also caused westward thrusting, structural thickening, and eventual burial of the older parts of the Kandik River assemblage (Figure 14b). The Kandik River assemblage was buried deep enough to reach temperatures as high as 315°C (600°F), corresponding to a burial depth of roughly 5–8 km (3–5 mi; Underwood et al. 1996). The burial and heating caused the rocks of the Kandik River assemblage to be metamorphosed to the lower greenschist-facies and develop slaty cleavage and abundant quartz-carbonate veins (see Figure 13 for an explanation of metamorphic facies; Underwood et al. 1996). The thermal history of the Kandik River assemblage is similar to the rocks of the Porcupine and Angayucham/Tozitna terranes to the west but differs markedly from the Tatonduk block, which for the most part never reached temperatures above 150°C (300°F). The peak heating occurred approximately 105 million years ago and marked the end of terrane accretion in this part of the preserve (Underwood et al. 1996; Johnsson 2000).

### *Sedimentary Rocks of the Tintina Fault System and Nation River Basin*

Map units: see Table 2

Unnamed Cretaceous and Tertiary nonmarine sedimentary rocks (**TKs**) occur in the preserve along the trace of the Tintina fault system and in a wedge-shaped basin to the northeast referred to by Van Kooten et al. (1996) as the Nation River Basin (see poster). Unit **TKs** is made up of poorly consolidated sandstone, conglomerate, and mudstone containing thin coal seams (Dover and Miyaoka 1988; Wilson et al. 2015). These sedimentary strata unconformably overlie parts of the Angayucham/Tozitna and Porcupine terranes, the Kandik River assemblage, and rocks of the Tatonduk block on the north side of the Tintina fault system and may overlie rocks of the Yukon-Tanana terrane to the south (Foster 1976; Dover 1994; Johnsson 2000; Fiorillo et al. 2014). Gold deposits that spurred over 100 years of mining activity occur within **TKs**, particularly in association with the conglomerate beds (see the "Mineral Resources" section of this report for more information).

Based on fossil evidence and radiometric dating, **TKs** is Late Cretaceous to Eocene in age. Plant fossils have been discovered and described from **TKs** since the early 1900s (Prindle 1913), and subsequent reports of plant macrofossils and pollen primarily indicate ages from the Late Cretaceous to the Eocene (Martin 1926; Hollick 1930; Foster and Igarashi 1990; Dover and Miyaoka 1988; Fiorillo et al. 2014). Radiometric dating of detrital zircons (zircons eroded from other rocks) from **TKs** indicates a Late Cretaceous maximum depositional age (Fiorillo et al. 2014).

The rocks of **TKs** were primarily deposited by streams and rivers in pull-apart (i.e., strike-slip) basins formed by the movement of the Tintina fault system. The thermal history of **TKs**, which reached temperatures no higher than 75°C (150°F), differs from the underlying and more deeply buried Kandik River assemblage (Underwood et al. 1996). The thermal history, combined with a significant unconformity between the units, indicates a relatively long break in deposition between the Kathul Greywacke and **TKs** (Johnsson 2000). **TKs** began forming in the Late Cretaceous and continued into the early Tertiary, which matches the timing of dextral movement along the Tintina fault system (see the "Tintina Fault System" section of this report for more information). Sedimentary analysis of **TKs** shows that these rocks were sourced from a recycled passive margin, which could include a variety of sedimentary and metasedimentary rocks in the region such as the Tatonduk block, Yukon-Tanana terrane, Kandik River assemblage, and Porcupine terrane (see Figure 14; Johnsson 2000).

### *Stratotypes*

The preserve contains 17 stratotypes, which are exposures of rock that form the basis for defining a geologic unit (Figure 15; 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 Calico

**Figure 15. Photograph of the type section of the Biederman Argillite (Kb) at Biederman Bluff. This type section was designated by Brabb (1969). Photograph from Brabb (1969).**

Bluff Formation, named after its type locality exposures at Calico Bluff. Other prominent geographic features within the preserve that have inspired stratotype designations include Adams Peak (Adams Argillite), Hillard Peak (Hillard Limestone), and Biederman Bluff (Biederman Argillite). Table 3 is a summary of the stratotypes designated within the preserve. Stratotypes represent unique geologic reference exposures and are important to protect (see the "Stratotype Monitoring and Protection" section of this report for further discussion). More detailed information about the preserve's stratotypes can be found in the Central Alaska Inventory and Monitoring Network Geologic Type Section Inventory (Henderson et al. 2022).

Several variations of stratotypes exist, including type sections, type areas, type localities, reference sections, and Global Boundary Stratotype Sections and Points (GSSPs). Of the 17 stratotypes within the preserve, ten are type sections, five are type localities, one is a type area, and one is a reference section (Table 3; 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; in cases when a type section has been destroyed, covered, or is otherwise inaccessible; or when multiple exposures are needed to illustrate heterogeneity or some critical feature not found in the type section (North American Commission on Stratigraphic Nomenclature 2021).

**Table 3. Stratotypes in Yukon-Charley Rivers National Preserve.**

Stratotypes are sorted by age with associated reference publications and locations. Table is sourced from Henderson et al. (2022).

| Age | Unit Name | Unit Symbol(s) | Stratotype Description | Reference(s) |
|---|---|---|---|---|
| Proterozoic | Tindir Group | **PCtl, PCtlc, PCts, PCtd, PCt, PCtu, PCtb, PCtsl** | Type locality: along Tindir Creek and between Ettrain and Harrington Creeks along Alaska–Yukon boundary, east-central AK | Cairnes 1914; Mertie 1930 |
| Cambrian | Funnel Creek Limestone | **Cf** | Type area: in valley walls of tributaries of Tatonduk River, from 1.6 km (1 mi) southwest to 4.8 km (3 mi) south of mouth of Funnel Creek, in secs. 17, 20, 21, 27, and 28, T. 2 N., R. 33 E., Hillard Peak area, east-central AK | Brabb 1967 |
| Cambrian | Adams Argillite | **Ca** | Type section: at east end of Limestone Hogback, in W/2 sec. 31, T. 2 N., R. 33 E., east-central AK | Brabb 1967 |

**Table 3, continued. Stratotypes in Yukon-Charley Rivers National Preserve.**

| Age | Unit Name | Unit Symbol(s) | Stratotype Description | Reference(s) |
|---|---|---|---|---|
| Cambrian-Ordovician | Hillard Limestone | **OCh** | Type section (composite): cliffs 2.6 km (1.6 mi) west of Hillard Peak (NE/4 sec. 3, T. 1 N., R. 33 E.); cliff about 2.1 km (1.3 mi) north-northeast of Hillard Peak; and section about 0.8 km (0.5 mi) east-northeast of Hillard Peak, east-central AK | Brabb 1967 |
| Cambrian-Ordovician | Jones Ridge Formation | **OCjru** | Type section: in center sec. 3, T. 3 N., R. 33 E., across Jones Ridge to western part of sec. 10, T. 3 N., R. 33 E., near Canadian border, east-central AK | Brabb 1967 |
| Devonian | Woodchopper Volcanics | **Dwv** | Type locality: outcrops along both banks of Yukon River from mouth of Coal Creek, Woodchopper Creek on downstream extending on south bank just beyond mouth of Thanksgiving Creek, Eagle-Circle district, east-central AK | Mertie 1930; Churkin et al. 1982 |
| Devonian | McCann Hill Chert | **Dka** | Type section: along creek about 0.8 km (0.5 mi) east of Benchmark 4085 except for uppermost 30 m (100 ft) which is on ridge crest extending north, McCann Hill, east-central AK | Churkin and Brabb 1965 |
| Devonian | Nation River Formation | **Dnr** | Type locality: exposures at and below the mouth of the Nation River, on the northeast bank of the Yukon River | Mertie 1930 |
| Devonian-Mississippian | Ford Lake Shale | **PNMDf** | Type section: east and west banks of Yukon River from 3.2 km (2 mi) east of Ford Lake to 4 km (2.5 mi) northeast of Ford Lake in Eagle D-1 Quadrangle, east-central AK | Brabb 1969 |
| Mississippian-Pennsylvanian | Calico Bluff Formation | **PNMcb** | Type locality: Calico Bluff on Yukon River, about 24 km (15 mi) below Eagle, east-central AK | Brooks and Kindle 1908; Brabb 1969; Armstrong 1975 |
| Permian | Tahkandit Limestone | **PZl** | Type section (composite): 1) exposure along a narrow slough of the Yukon River in the northwest corner of sec. 17, T. 4 N., R. 30 E., lat. 65°10.8' N, long. 141°41.9' W. in the Charlie River A-2 Quadrangle; and 2) a prominent limestone cliff located several hundred meters or feet south of the Nation River mouth on the west bank of the Yukon River | Mertie 1930; Brabb and Grant 1971 |
| Triassic-Cretaceous | Glenn Shale | **KJTRa, TRgsl** | Type section: along banks of Washington Creek, a tributary of Yukon River, from NW/4 sec. 24, T. 5 N., R. 26 E. to NW/4 sec.12, T. 5 N., R. 26 E., Charley River B-3 Quadrangle, east-central AK | Brabb 1969 |
| Cretaceous | Keenan Quartzite | **Kke** | Type section: exposures on west bank of Yukon River, 0.8 km (0.5 mi) downstream from mouth of Glenn Creek, in sec. 36, T. 6 N., R. 27 E., Charley River B-3 Quadrangle, east-central AK | Brabb 1969 |
| Cretaceous | Biederman Argillite | **Kb** | Type section: exposures in Biederman Bluff face on northwest side of Yukon River, 6.4 km (4 mi) northwest of mouth of Kandik River, in NW/4 sec. 32, T. 7 N., R. 25 E., Charley River B-4 Quadrangle, east-central AK<br>Reference section: 0.4 km (0.25 mi) downstream from mouth of Glenn Creek to 1.6 km (1 mi) southeast of benchmark 3122 on Kathul Mountain | Brabb 1969 |
| Cretaceous | Kathul Graywacke | **Kka** | Type section: exposures on middle to upper south slope of Kathul Mountain, north of Yukon River, from 0.8–1.5 km (0.5–0.9 mi) southeast of benchmark 3122 (Kat), in sec. 18, T. 6 N., R. 27 E., Charley River B-3 Quadrangle, east-central AK | Brabb 1969 |
| Cretaceous | Kandik Group | **Kke, Kb, Kka** | Type locality: designated as in vicinity of Kandik River and along valley of Yukon River from mouth of Glenn Creek to top of Biederman Bluff, east-central AK | Brabb 1969 |

## Tintina Fault System

The tectonic forces responsible for transporting and accreting the terranes of Alaska to the edge of North America have caused deformation of the rocks, producing faults (planes along which rocks slip past one another) and folds (twists or bends in the rocks). While most of the rocks within the preserve are structurally complex, containing many smaller faults and folds, the Tintina fault system is the main structural feature that subdivides the preserve's bedrock geology.

The Tintina fault system is a major terrane-bounding structure that cuts northwest-southeast through the preserve, running parallel to and south of the Yukon River (see poster). It is expressed topographically as a linear trench filled with Late Cretaceous-Tertiary sedimentary strata (**TKs**; Dover 1994; see Table 1 for the position and dates of the time scale units referenced throughout this report). The Tintina fault system extends far beyond the preserve, stretching from southern British Columbia to western Alaska (Figure 16). It separates weakly to unmetamorphosed rocks of cratonic North America from igneous and metamorphic pericratonic terranes such as the Yukon-Tanana terrane (see Figure 6 for a terrane map). The motion on the Tintina fault system is predominately right-lateral strike-slip, meaning rocks on the outboard (oceanward) side of the fault have slipped northward relative to those inboard (Roddick 1967).

Movement on the Tintina fault system occurred between the Cretaceous Period and Eocene Epoch, and estimates of the amount of displacement range from about 400 km (250 mi) to over 1,000 km (600 mi). This large range is because studies that use paleomagnetic data indicate significantly more movement than studies looking at other geologic evidence, such as the offset of rock units or other faults. Paleomagnetic studies use the ancient magnetism preserved in rocks to figure out at what latitude those rocks formed. Estimates based on the paleomagnetism of rocks found along the Tintina fault system in Yukon and British Columbia indicate between 1,000 and 2,000 km (600 and 1,200 mi) of northward movement since the Cretaceous relative to the North American craton (summarized in Irving et al. 1996). For example, paleomagnetic analysis of the volcanic rocks of the Carmacks Group in Yukon Territory indicates they were 17.2° ± 6.5° (1,900 ± 700 km) south of their present position when they formed in the Late Cretaceous Period (Johnston et al. 1996). This was approximately the latitude of the Yellowstone Hotspot at the time, and Johnston et al. (1996) propose the hotspot was the volcanic source for the Carmacks Group. While geologic evidence indicates the same direction of movement on the Tintina fault system, the amount of offset reported by many of these studies is around 400–500 km (250–300 mi; e.g., Dover 1994; Gabrielse et al. 2006). Additionally, mapping of magnetic anomaly patterns on either side of the Tintina fault system in eastern Alaska and western Canada indicated about 490 km (300 mi) of offset, probably occurring during the Eocene (Saltus 2007). Some researchers argue that both the geologic and paleomagnetic data can support large (>1,000 km) amounts of offset (e.g., Irving et al. 1996).

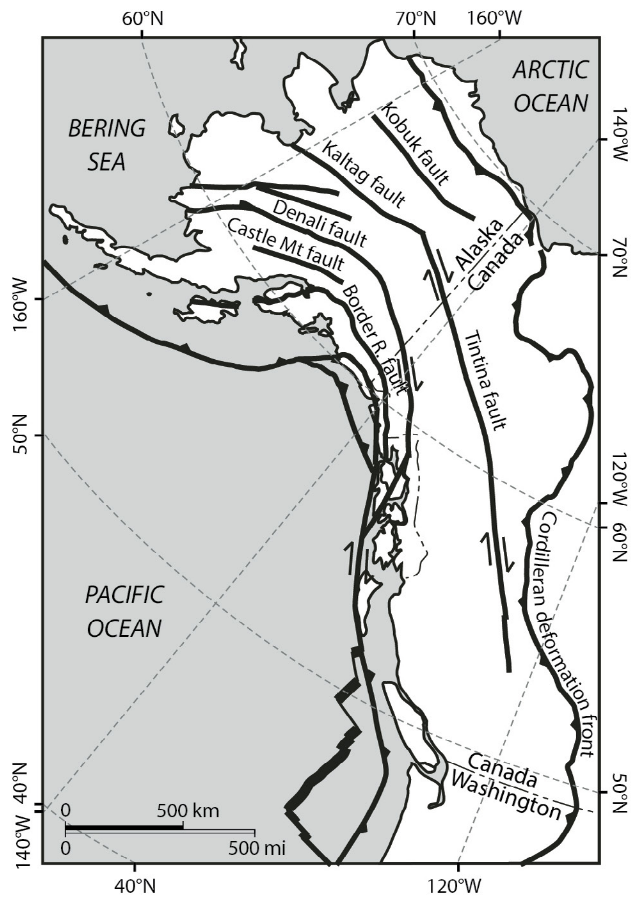


**Figure 16. Map showing major faults in Alaska and western Canada.**
**The Tintina fault system runs from British Columbia to western Alaska, cutting through the central part of the preserve (located near the Alaska-Yukon border). It is a major structural feature in the preserve, juxtaposing relatively unmetamorphosed strata that formed along the edge of North America from more metamorphosed rocks to the south. Figure modified from Till et al. (2007).**

## Paleontological Resources

Map units: see Table 4

The paleontological resources, or fossils, in the preserve record a long and complex history of life that spans over 900 million years. The protection and interpretation of this history are part of the reason the preserve was created (ANILCA 1980). The preserve is one of eighteen NPS areas that have paleontological resources referenced in the enabling legislation. Paleontological resources are any evidence of ancient life that is found in a geologic context. Globally, this encompasses 3.7-billion-year-old microscopic cyanobacteria, 15,000-year-old woolly mammoths, and everything in between. Nearly all the fossils in the preserve are found in sedimentary rocks to the north of the Tintina fault system (see poster). Many paleontological resources were documented by the United States Geological Survey (USGS), academic, and private paleontologists prior to the creation of the preserve in 1980. Table 4 lists the types of fossils found in the preserve's geologic units and acts as a summary of information from the Central Alaska Network Paleontological Resource Inventory (Santucci et al. 2011) and the NPS Alaska Paleontology Database. Both sources provide more detailed information about the paleontology in the preserve and are the primary references for the following discussion.

The preserve contains fossils from nearly every period of the Phanerozoic Eon (539 million years ago–today), as well as older fossils from the Proterozoic Eon (2.5 billion–539 million years ago). Life on Earth is constantly changing, with new species evolving, flourishing for a time, and eventually going extinct. Geologists have used this natural change of life as a framework to divide and organize Earth's history into the geologic time scale (see Table 1). The presence or absence of different species in a rock can reveal if that rock formed before or after other rocks, a process called relative dating. Because the preserve contains relatively unmetamorphosed sedimentary rocks from so many time periods, many of the big shifts in life that define the divisions of the timescale are reflected in the preserve's fossil record.

The oldest fossils in the preserve are found in the Tindir Group, which formed during the Proterozoic Eon. Life throughout most of the Proterozoic was dominated by microbial communities that left behind stromatolites in the rock record. Stromatolites are layered sedimentary structures formed by the buildup of microbial mats over time. The lower Tindir Group contains stromatolites, as well as microfossils representing cyanobacteria (Figure 17a; Churkin 1973; Allison and Moorman 1973).

Early forms of eukaryotic life, which includes protists, algae, animals, and fungi, began to develop in the Proterozoic. Extremely rare and spectacularly preserved mineralized scale microfossils have been described in the Tindir Group at Mount Slipper, located in Yukon about 2.5 mi (4 km) east of the preserve (Allison and Hilgert 1986; Macdonald et al. 2010a; Cohen et al. 2011; Cohen et al. 2017). While the taxonomic affinity of these fossils is still uncertain, they nonetheless provide a glimpse into early eukaryotic diversification (Cohen et al., 2017). The shale directly below the scale microfossil-bearing limestone produced an age of 810.7 +/- 6.3 million years ago, establishing these fossils as the oldest known occurrence of biomineralization (Cohen et al. 2017). Additionally, Allison (1975) reported a new genus and species of microscopic flatworm named *Brabbinthes churkini* from the upper Tindir Group. The preservation of soft bodied, multicellular animals from this time would be extremely rare and scientifically important; however, the interpretation of this specimen has been questioned. For example, Cloud et al. (1976) suggested the specimen is the remains of a sponge. In addition, Cloud et al. (1976) argued that the fossil may not have been collected from the Tindir Group. This is supported by more recent mapping in the region (Strauss, personal communication, 2023), which indicates the sampled unit may instead belong to the Cambrian–Ordovician Jones Ridge Formation.

Fossils in rocks that are younger and overlie the Tindir Group are markedly different than those seen below. This is because there was a major evolution event, called the "Cambrian explosion," that corresponds to the end of the Proterozoic Eon ("early life" in Greek) and the start of the Phanerozoic Eon. The Phanerozoic Eon ("visible life" in Greek) is characterized by a sudden abundance of complex life forms, including abundant animal life. Most of the modern animal phyla evolved during the Cambrian explosion, and many of these new forms of life had hard parts that were more easily preserved as fossils. The Phanerozoic is divided into three eras that are dominated by different types of organisms and separated by major mass extinctions. The eras are the Paleozoic ("old life" in Greek; 541–252 million years ago), Mesozoic ("middle life" in Greek; 252–66 million years ago), and Cenozoic ("new life" in Greek; 66 million years ago–today).

The eastern part of the preserve contains a thick succession of Paleozoic strata with abundant fossils (see Table 4). These rocks formed along the passive margin of North America and contain typical Paleozoic marine fossils such as sponges, corals, bryozoans, brachiopods, trilobites, crinoids, and vertebrates (fish). Additionally, plant fossils are found in some of the Paleozoic units, such as Devonian scale tree fossils in the Nation River

**Table 4. Fossils and fossiliferous strata within Yukon-Charley Rivers National Preserve.**

Information is compiled from the NPS Alaska Region Paleontology Database, Santucci et al. (2011), and Ruga and Lanik (in prep). see Table 1 for the position and dates of the time scale units referenced throughout this report. *Indicates fossils that have been discovered outside preserve boundaries in geologic units that extend into the preserve but have not yet been discovered within the preserve. See the text for more details.

| Age | Unit Name | Unit Symbol(s) | Fossils |
|---|---|---|---|
| Proterozoic | Tindir Group | **PCtl, PCtlc, PCts, PCtd, PCt, Pctu, PCtb, PCtsl** | Stromatolites, blue-green algae microfossils, scale microfossils*, and other protists |
| Cambrian (Paleozoic) | Adams Argillite | **Ca** | Algae, archaeocyathids, sponges, coral-like fossils, trilobites, and invertebrate trace fossils (*Oldhamia*) |
| Cambrian–Ordovician (Paleozoic) | Jones Ridge Limestone | **OCjru** | Archaeocyathids, sponges, corals, brachiopods, trilobites, crinoids, and conodonts |
| Cambrian–Ordovician (Paleozoic) | Hillard Limestone | **OCh** | Algae, archaeocyathids, sponges, corals, brachiopods, trilobites, crinoids, and graptolites |
| Ordovician–Devonian (Paleozoic) | Road River Formation | **DSOr** | Algae, radiolarians, corals, bryozoans, brachiopods, gastropods, bivalves, trilobites, echinoderms, crinoids, graptolites, conodonts, and scolecodonts, |
| Devonian (Paleozoic) | Ogilvie Formation | **Dof** | Stromatoporoids, corals, bryozoans, brachiopods, rostrochonchs, gastropods, trilobites, ostracods, echinoderms, crinoids, graptolites, conodonts, and fish |
| Devonian (Paleozoic) | Woodchopper Volcanics | **Dwv** | Corals, brachiopods, graptolites, and conodonts |
| Devonian (Paleozoic) | McCann Hill Chert | **Dka** | Radiolarians, corals, bryozoans, brachiopods, gastropods, cephalopods, bivalves, trilobites, ostracods, echinoderms, crinoids, graptolites, conodonts, tentaculites, and fish |
| Devonian (Paleozoic) | Nation River Formation | **Dnr** | Palynomorphs and plant macrofossils |
| Devonian–Mississippian (Paleozoic) | Ford Lake Shale | **PNMDf** | Foraminifera, radiolarians, corals, bryozoans, brachiopods, gastropods, ammonoids, bivalves, echinoderms, conodonts, palynomorphs, and plant macrofossils |
| Mississippian (Paleozoic) | Calico Bluff Formation | **PNMcb** | Corals, bryozoans, brachiopods, gastropods, nautiloids, ammonoids, bivalves, echinoderms, crinoids, fish, plant macrofossils, and trace fossils |
| Permian (Paleozoic) | Tahkandit Limestone | **PZl, Pst** | Algae, foraminifera, corals, bryozoans, brachiopods, gastropods, ammonoids, trilobites, ostracods, fish, palynomorphs, and trace fossils |
| Permian (Paleozoic) | Step Conglomerate | **Pstc, Pst** | Brachiopods |
| Triassic–Cretaceous (Mesozoic) | Glenn Shale | **TRgsl, KJTRa** | Corals, hydrozoans, bryozoans brachiopods, gastropods, nautiloids, ammonoids, bivalves, ostracods, crinoids, fish, a reptile bone fragment, and plant macrofossils |
| Cretaceous (Mesozoic) | Kandik Group | **Kb, Kke, Kka** | Foraminifera, ammonites, belemnites, bivalves, plant macrofossils, and trace fossils |
| Cretaceous–Tertiary (Mesozoic and Cenozoic) | Sedimentary rocks | **TKs** | Plant macrofossils and trace fossils (dinosaur tracks) |
| Quaternary (Cenozoic) | Quaternary Surficial Deposits | **Qa, Qt** | Mammals |


**Figure 17. Photographs of fossils from the preserve.**
**(A) Photograph of a stromatolite mound from the Tindir Group. Stromatolites are layered sedimentary structures formed by the buildup of microbial mats over time. They are the most common type of fossil found in Proterozoic rocks such as those of the Tindir Group. Photograph courtesy of Justin Strauss (Dartmouth College). (B) Photograph of scale tree fossil from the Devonian Nation River Formation. The scale bar shows millimeters. NPS photograph by Amanda Lanik. (C) Photograph of the holotype for Spiriferina yukonensis, an Upper Triassic brachiopod described by Smith (1927) from the Glenn Shale. This specimen is curated at the Smithsonian, along with many of the other type specimens collected from within the preserve. The scale bar shows millimeters. NPS photograph by Vince Santucci. (D) Photograph of a partial bison skull that was collected from the preserve and is now housed within the University of Alaska Museum of the North collections.**

Formation (Figure 17b). While fossils are found in many of the rock units, species vary depending on age and depositional environment. For example, trilobites are found in most of the Paleozoic fossiliferous units in the preserve, but the species of trilobites in the Cambrian Adams Argillite are very different than those found in the Permian Tahkandit Limestone because these rocks formed over 200 million years later. In contrast, some types of fossils are only found in certain units. For example, the archaeocyathids that occur in the Cambrian Adams Argillite and Jones Ridge Limestone are a unique group of extinct sponges that formed some of the first reefs. Despite diversifying into hundreds of species, archaeocyathids only existed for a relatively short amount of time and were extinct by the middle Cambrian.

Mesozoic rocks in the preserve that contain fossils include the Glenn Shale, Kandik assemblage, and unnamed sedimentary rocks labeled **TKs** on the geologic map (see Table 4). The transition from the Paleozoic Era to the Mesozoic Era was marked by the largest mass extinction in Earth's history, during which many of the marine organisms that flourished in Paleozoic seas went extinct. This shift in marine ecosystems is reflected in the fossil record, with Mesozoic rocks in the preserve lacking the abundant trilobites, brachiopods, and crinoids of earlier deposits, instead being dominated by ammonites, belemnites, and bivalves. However, in some cases fossils more abundantly found in Paleozoic strata can also be found in Mesozoic strata, such as brachiopods in the Glenn Shale (Figure 17c). **TKs** is a nonmarine unit that provides a view of what life on land was like in this part of Alaska during the end of the Mesozoic Era and beginning of the Cenozoic Era. Dinosaurs were abundant during the Mesozoic, and these emblematic fossils have reportedly been found within the preserve. Fiorillo et al. (2014) described two Late Cretaceous (100–66 million years ago) hadrosaur tracks from the base of **TKs**. This unit has also produced a diverse array of fossil plants, which range in age from the Late Cretaceous Period to as young as the Eocene Epoch (Hollick 1936; Knoll 1976; Tiffney 1976; Fiorillo et al. 2014).

A mass extinction occurred at the end of the Mesozoic Era, which killed off all non-avian dinosaurs as well as marine creatures such as ichthyosaurs and ammonites. The extinction of these groups left space for mammals to radiate and diversify during the Cenozoic Era. Cenozoic mammal fossils, specifically those that lived during the Pleistocene Epoch (2.6 million–12,000 years ago), have been discovered within the preserve (Figure 17d). The end of the Pleistocene was characterized by a widespread glaciation (called the "Ice Age") and many now-extinct mammals—including mammoths, steppe bison, and short-faced bears—thrived in Alaska during that time.

Many of the Pleistocene fossils in the preserve were found during mining activities; however, it is difficult to gauge how many fossils were discovered during the preserve's more than 100 years of mining history because of sparse documentation. A 1909 report on Alaskan mammoth expeditions undertaken by the American Museum of Natural History noted that a portion of a mammoth skeleton was discovered in a mining shaft along a tributary of Woodchopper Creek (Quackenbush 1909; Mead et al. 2020). The recovered mammoth bones included the skull, lower jaw, both tusks, all the molars, pelvis, a scapula, two limb bones, 12 vertebrae, 15 ribs, and some small bones (Quackenbush 1909; Mead et al. 2020). In addition, several historical photographs show people posing with mammoth fossils that were discovered in the preserve. Examples include a photograph from around 1927 of miners on Woodchopper Creek with two mammoth tusks and a photograph of the Biederman family with a mammoth tusk taken near the Yukon River around 1930 (see poster). A Mining Environmental Impact Statement drafted by NPS staff in 1990 noted that miners "often found skeletal remains of animals", some of which had "bits of flesh and hide clinging to them preserved by the permafrost" (National Park Service 1990, p. 37). Additional finds include ancient beaver dams, tree stumps in their original upright positions, and fossil ivory (National Park Service 1990). Finally, Pleistocene fossils from the preserve are recorded within the Yukon-Charley Rivers museum collection and the University of Alaska Museum of the North catalog. These specimens include mammoth, bison, and Dall sheep remains (Figure 17d).

### *Type Specimens*

When a new fossil species is described, a single specimen (called a "holotype") or a series of specimens (called "syntypes") are designated to serve as the name-bearing basis of that new species (International Commission of Zoological Nomenclature 1999). In some cases, name-bearing specimens (called "lectotypes" or "neotypes") can be designated after the initial description of a new species (International Commission of Zoological Nomenclature 1999). Holotypes, syntypes, lectotypes, and neotypes are collectively known as "type specimens" and are the most important point of reference regarding the characteristics that define a species. Type specimens are key to subsequent evaluations of a species, including comparisons with other taxa and determinations regarding its taxonomic and phylogenetic relationships (Tweet et al. 2016). Given the unique scientific value of type specimens, the International Commission of Zoological Nomenclature recommends that type specimens be documented, unmistakably labeled, safely preserved, and made accessible for study (1999).

At least 129 fossil species have been named based on specimens recovered from localities within the preserve. This represents the sixth-most type specimens identified from any NPS area (Tweet et al. 2016). The type specimens include a variety of marine invertebrate fossils such as foraminifera, radiolarians, brachiopods, tentaculites, bivalves, gastropods, cephalopods, trilobites, and ostracods, as well as plant macrofossils, and pollen (Figure 17c; Smith 1927; Hollick 1930; Kobayashi 1935; Cooper 1936; Ulrich and Cooper 1936; Stehli 1962; Ross and Dutro 1966; Skinner and Wilde 1966; Palmer 1968; Tschudy 1969; Churkin and Carter 1970; Berdan and Copeland 1973; Allison 1975; Won et al. 2002). Most of the type specimens have been collected from the sedimentary rocks north of the Tintina fault system. For more information about type specimens from the preserve, contact the Geologic Resources Division (GRD; see the "Guidance for Resource Management" section of this report).

## Mineral Resources

Map units: **TKs, MZPZs**

Mineral resources within the preserve primarily include gold, lead, and zinc deposits, as well as less common occurrences of other minerals. The Alaska Resource Data File (ARDF), which is a compilation of mineral resources in Alaska, includes 39 records within the preserve (https://mrdata.usgs.gov/ardf/, accessed 30 August 2022). Eighteen of these records are mines, fourteen are prospects, and seven are mineral occurrences. In general, mines have had past production, prospects have had some development work completed, and mineral occurrences include unexplored or incompletely explored mineral deposits. Additionally, three occurrences of coal (which are not included in the ARDF), are noted in the NPS Abandoned Mineral Lands database (https://irma.nps.gov/AML/, accessed 2 September 2022). A map of mineral resource locations is not included here due to the sensitive nature of their locations, but park managers can access the "Mine Point Features" layer within the sensitive GRI GIS dataset. Additional detailed information about sites can be found in the USGS Alaska Resource Data File database (https://mrdata.usgs.gov/ardf/) and the NPS Abandoned Mineral Lands database (contact GRD for more information).

In general, the preserve's mineral resources can be subdivided into four categories: (1) placer gold associated with Cretaceous and Tertiary sedimentary rocks (**TKs**; see Table 1 for the position and dates of the time scale units referenced throughout this report); (2) lode gold associated with the Flume trend; (3) zinc and lead prospects in the Tatonduk block strata; and (4) other mineral prospects and occurrences.

Placer gold occurs within the tributaries south of the Yukon River in alluvial sediments that either overlie or are downstream of Cretaceous and Tertiary sedimentary rocks (**TKs**; Brooks 1907; Mertie 1938; Mertie 1942; Barker 1986). Placer gold has been eroded out of its primary, hard-rock (or lode) context and deposited as gold grains and nuggets in clastic sedimentary strata. **TKs** was deposited within an elongated basin referred to by Barker (1986) as the Eagle Trough, which cuts through the central part of the preserve and aligns with the Tintina fault system. Mining of the placer gold deposits began during the late 1800s and has occurred intermittently since then (see National Park Service 1990 and Allan 2015 for a history of mining in the preserve). About 20 placer gold mines and prospects are in the preserve, with the most prominent gold-bearing areas being Woodchopper Creek, Coal Creek, and Fourth of July Creek.

The placer deposits contain two distinct types of gold that likely had different origins (Barker 1986). The first type is characterized by well-rounded, tarnished, variably iron- and manganese-stained gold blebs, while the second type is bright, subangular to subrounded gold scales, flakes, and nuggets with quartz occasionally attached (Barker 1986). Miners and geologists have long noted the correlation of placer gold with the conglomerate beds of **TKs** (Brooks 1907; Mertie 1942; Barker 1986). Mertie (1942) suggested that the conglomerates, and the gold within them, were eroded from Mesozoic granitic rocks found to the south. Barker (1986) agreed that the well-rounded gold was likely sourced from the erosion of older, lode-gold containing rocks; however, they proposed the Circle meta-igneous complex to the west as the most likely source. Furthermore, Barker (1986) pointed out that this model could not account for the subangular to subrounded gold type, which would have been more worn down by the erosive processes. The more angular gold may have instead been formed by local, low-temperature hydrothermal activity along an altered fault lineament of the Tintina fault system, referred to by Barker (1986) as the Bonanza Creek lineament.

Two lode gold prospects associated with the informally named Flume trend occur to the south of the Seventymile River near the preserve's eastern boundary. The prospects are along adjacent creeks called Flume Creek and Bonanza Creek (although it is a different Bonanza Creek that gives the previously discussed Bonanza Creek lineament its name). In addition to the two prospects within the preserve, the Flume trend also encompasses two more prospects (Flanders and Alder Creek) just outside the preserve (https://mrdata.usgs.gov/ardf/, accessed 13 September 2022). In the early 1900s, placer gold was mined near the mouth of Flume Creek, which was likely sourced from the lode prospect upstream.

The Flume trend prospects were formed via hydrothermal alteration of rocks of the Seventymile Terrane (**MZPZs**), which is interpreted to be a segment of oceanic crust (see the "Bedrock Geology" section of this report for more information). The gold at both Flume Creek and Bonanza Creek occurs within quartz veins that cut through zones of hydrothermal alteration (Newberry et al. 1998; https://mrdata.usgs.gov/ardf/, accessed 13 September 2022). In these zones, hydrothermal fluids moved through the serpentinite of the Seventymile Terrane, causing it to alter to a silica-carbonate rock known as listwaenite (Newberry et al. 1998). Dating of mica minerals at Flume Creek indicate the alteration occur about 100 million years ago (Newberry et al. 1998). This mid-Cretaceous age suggests that the hydrothermal fluids that caused the alteration and gold deposition are likely associated with widespread plutonism that was occurring at this time (e.g., **TKMZmgr**; Newberry et al. 1998).

Proterozoic and Paleozoic strata of the Tatonduk block host six prospects and one occurrence of lead and/or zinc, as well as other associated minerals. The sites are located north of the Yukon River in the eastern part of the preserve on private land. Most of these sites were discovered in the mid-1970s, and additional soil and rock samples were collected in 1993 (https://mrdata.usgs.gov/ardf/, accessed 13 September 2022). Four of the prospects are within rocks of the Tindir Group (Nation Gossan, Three Castle Mountain, Hard Luck Creek, and Pleasant Creek); one prospect is within the Funnel Creek Limestone (Casca Zinc) and one prospect (Waterfall Creek) and one occurrence (Nation River) cover areas of 25–50 $km^2$ (10–20 $mi^2$) that are underlain by various Proterozoic–Paleozoic geologic units. In general, the mineralization is associated with faulted and fractured carbonate rocks, and many of the sites are attributed to the carbonate-hosted Zn-Pb depositional model described by Cox and Singer (1986).

Several other mineral resource sites are within the preserve that do not fall into the general categories discussed above. These include two prospects and six mineral occurrences scattered throughout the preserve (see the GRI GIS data or Alaska Resource Data File database for specific locations). The Mount Casca prospect includes phosphorus and uranium within a massive boulder conglomerate of the Road River Formation that may be an upwelling-type phosphate deposit, as described by Cox and Singer (1986). The Copper Creek lode prospect and associated placer occurrences contain copper, gold, uranium, and other associated minerals that formed within Paleozoic marble, amphibolite, and schist. In 1948, the U.S. Geological Survey performed a regional reconnaissance for radioactive deposits and found that these placer concentrates and prospects were slightly radioactive (Wedow 1954). Calico Bluff was also investigated during the 1948 survey, which discovered two units of black shale were slightly radioactive and contained uranium (Wedow 1954). The Mount Sorensen mineral occurrence is an ultramafic body containing as much as one percent chromite and small amounts of platinum and palladium. An unnamed tungsten occurrence is located near Crescent Creek; an unnamed iron occurrence is along Tatonduk River; and an unnamed copper occurrence is located north of Fisher Creek.

## Caves

Map units: **Dof**

Caves exist within the preserve in some of the geologic units composed of carbonate rocks such as limestone (Jeff Rasic, personal communication, 14 May 2023). Caves are naturally occurring underground voids that can occur in rock, soil, or ice. Some of the most common cave types include solution caves, lava tubes, sea caves, and glacier caves. In the preserve, the occurrence of caves in limestone suggests they may be solution caves, which form through the dissolution of carbonate rock. However, investigation of one of these caves found in the Ogilvie Formation (**Dof**) near Funnel Creek indicates it is not a traditional solution cave (Paul Burger, personal communication, 23 January 2023). Instead, this cave appears to have formed through a combination of frost action breaking up rock and the downward movement (piping) of that material to create the cave (Paul Burger, personal communication, 23 January 2023). Other caves within the preserve described by NPS staff are similar to the Funnel Creek cave and may have also been created through frost shatter and piping (Paul Burger, personal communication, 23 January 2023). Many of these caves are shallow and tend to slope downward toward the cliff face (Paul Burger, personal communication, 23 January 2023).

## Glacial History

Map units: **Qm**

The extent of glaciers in Alaska has fluctuated throughout the Quaternary Period (Pleistocene and Holocene Epochs; see Table 1 for the position and dates of the time scale units referenced throughout this report). The glacial advances corresponded to cold glacial periods and glacial retreats correspond to warmer interglacial periods. Over 50 percent of Alaska was covered by glaciers during the glacier periods, however, central and northern Alaska were part of an ancient landmass known as Beringia that remained mostly glacier-free (Figure 18; Péwé 1975). The preserve was traditionally thought to have been unglaciated during the Quaternary, but work by Péwé (1975), Weber (1986), and Weber and Wilson (2012) showed a long history of local alpine glaciation in the Yukon-Tanana uplands (southern part of the preserve). Alpine glaciation was restricted to higher elevations where small icefields or icecaps developed (Weber and Wilson 2012). Deposits from five glacial episodes have been mapped in and around the Eagle quadrangle by Weber and Wilson (2012). The five glacial episodes are the early(?) Pleistocene Charley River advance, the middle(?) Pleistocene Mount Harper advance, the Pleistocene (early? Wisconsin) Eagle advance, the Pleistocene (late? Wisconsin) Salcha advance, and the late Holocene Ramshorn advance (Weber and Wilson 2012).

The oldest of the glacial episodes in the Yukon-Tanana uplands was the Charley River advance, which left an extensive glacial record and shaped the basic pattern of modern drainages during the early Pleistocene (Weber

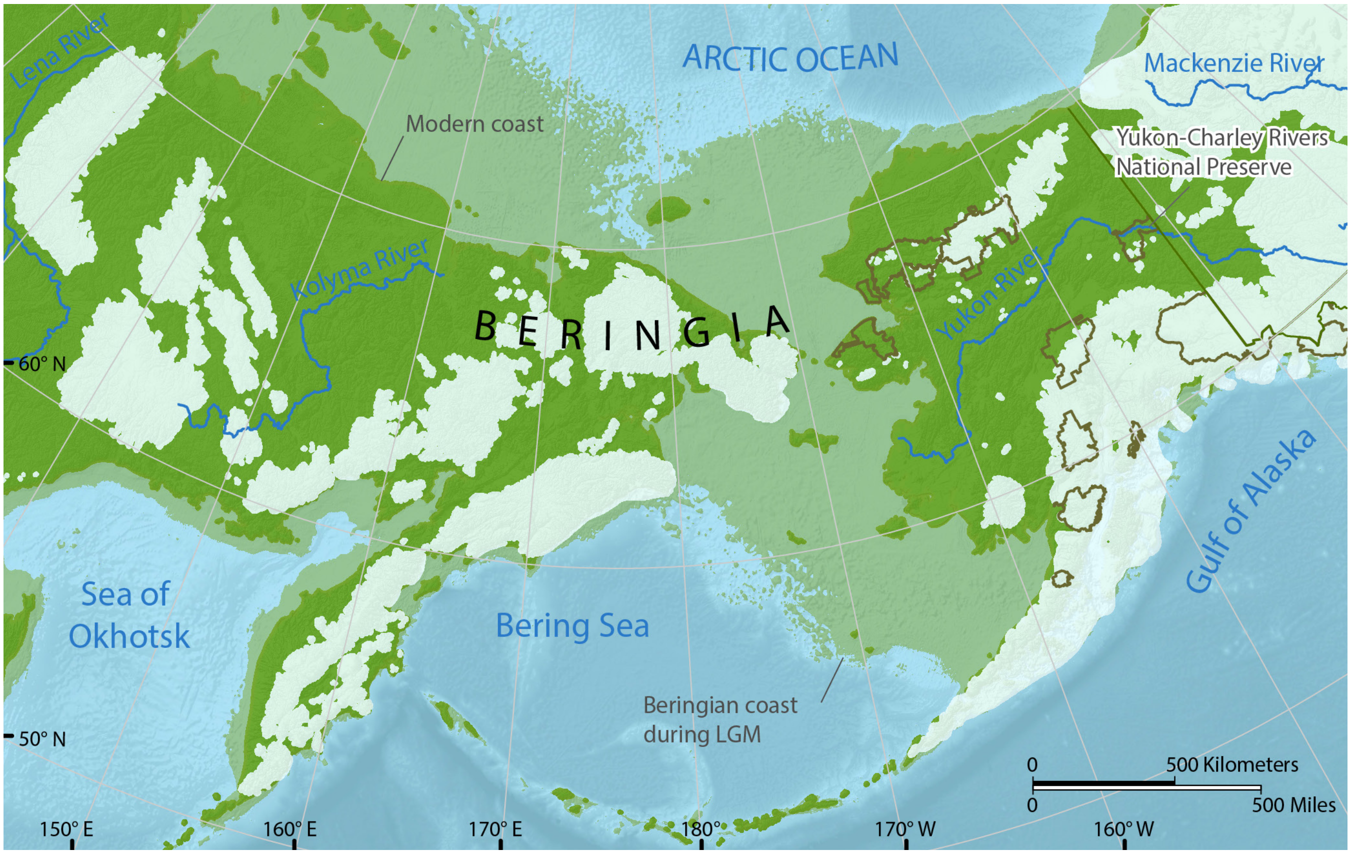


**Figure 18. Map of Beringia.**
**Beringia was a largely unglaciated landmass that stretched from the Mackenzie River in Yukon Territory to the Lena River in Russia. The Bering Land Bridge (light green area on the map) formed the center of Beringia, connecting Asia and North America and providing a conduit for the exchange of terrestrial organism between the two continents (Colinvaux 1964; Hopkins 1967). Although the Bering Land Bridge is shallowly submerged today, it was subaerially exposed during the glacial periods of the Pleistocene because widespread glaciation lowered the global sea level. The modern coastline is shown in dark green and the coastline during the last glacial maximum is shown in light green. Glacier extent during the last glacial maximum is shown in white. Map drafted using information from Becker et al. (2009) and Ehlers et al. (2011).**

1986). The early Pleistocene age was determined because the deposits are highly weathered and correlate with advances elsewhere in Alaska, such as the Anaktuvuk River glaciation in the central Brooks Range (Detterman 1953; Hamilton 1986; Weber and Wilson 2012). Glaciers during this episode formed on all mountains exceeding 900 m (3,000 ft) and flowed out from ice caps for over 50 km (30 mi; Weber and Wilson 2012). Glacial lakes formed in valleys that were impounded by moraines, including the informally named Glacial Lake Harper that developed in the valley of the Middle Fork of the Fortymile River to the south of the preserve (Weber and Wilson 2012). Deposits from this glacial episode include subdued morainal landforms and erratic boulders (Weber and Wilson 2012).

The next glacial episode was the middle Pleistocene Mount Harper advance, which was likely separated from the Charley River advance by a long interglacial period (Weber and Wilson 2012). Glaciers during the Mount Harper episode typically developed on mountains more than 1,200 m (4,000 ft) high; these glaciers extended as low as 600 m (2,000 ft) and attained lengths up to 29 km (18 mi; Weber and Wilson 2012). This advance formed moraine that are commonly deflated and eroded, consisting of low ridges of boulders at the edges of broad plains (Weber 1986). Most of the terminal moraines are found in lower valleys and are partially to fully covered by vegetation (Weber 1986).

The Wisconsin Eagle glacial episode was the next advance seen in the region. Glaciers of this episode formed on mountains of 1,460 m (4,790 ft) or higher, extended to as low as 900 m (3,000 ft) and attained lengths of up to 19 km (12 mi; Weber and Wilson 2012). Eagle advance deposits include prominent end moraines with subdued knob and kettle topography up-valley (landscape characterized by alternating mounds and depressions; Weber and Wilson 2012).

The Salcha glacial episode was the penultimate advance and is inferred to be late Wisconsin in age, corresponding to the last glacial maximum at the end of the Pleistocene Epoch (Weber and Wilson 2012). Most of the glaciers during this advance originated on mountains of 1,580 m (5,200 ft) or higher, extended to as low as 900 m (3,000 ft), and a few of the most extensive glaciers reached lengths up to 9.6 km (6 mi) long (Weber and Wilson 2012). The deposits are found only in high mountain valleys and include end moraines that form ridges across narrow valleys (Weber 1986).

The most recent glacial advance, called the Ramshorn glacial episode, occurred during the late Holocene (Weber and Wilson 2012). Glaciers of this advance were generally small and confined to the highest upland areas, but some glaciers reached lengths of up to 6.5 km (4 mi; Weber and Wilson 2012). Deposits include fresh glacial till found in the highest, mostly north-facing cirques (Weber 1986). The Ramshorn glacial episode included two minor advances, and a few glaciers of the older advance left distinctive terminal moraines (Weber 1986).

Glaciation in the Yukon-Tanana uplands during the early to middle Pleistocene is also recorded by glacial outburst flood deposits exposed along the Yukon River at Chester Bluff (Froese et al. 2003b). The Chester Bluff exposure can be divided into four units, which in ascending order are: (1) 10 m (30ft) of black shale bedrock; (2) 8–10 m (25–30 ft) of stratified gravel deposited by the paleo-Yukon River; (3) 5–12 m (15–30 ft) of stratified sand and silt rhythmites with minor gravel facies; and (4) 20–40 m (65–130 ft) of loess (Froese et al. 2003b). The rhythmites of unit 3 are interpreted to be glacial outburst flood deposits that record multiple abrupt drainage events of glacial lakes in the headwaters of the Charley River (Froese et al. 2003b). The flooding occurred prior to 560,000 +/- 80,000 years ago and probably corresponds to the drainage of glacial lakes that developed during the Charley River advance of Weber (1986) and Weber and Wilson (2012).

## Quaternary Surficial Deposits

Map units: Alluvium (**Qa**); Terrace deposits (**Qt**); Old terrace deposits (**QTs**); Alluvial fan deposits (**Qaf**); Alluvium and colluvium (**Qca**); Colluvial deposits (**Qc**); Glacigenic deposits (**Qm**); Loess (**Ql**)

Geologic processes that operated millions of years ago to form the preserve's bedrock are continuing in modern times to form surficial deposits found throughout the preserve today. Surficial deposits are composed of unconsolidated sediments that were deposited mainly within the Quaternary Period (within the last 2.6 million years; see Table 1 for the position and dates of the time scale units referenced throughout this report). Erosion and deposition are the main processes that produce the preserve's surficial deposits. These forces include rivers and streams, gravity-driven slope movement, glaciers, and wind. Rivers and streams will produce fluvial deposits, such as alluvium, alluvial fans, and terraces (see the "Fluvial Features" section of this report for more information). Gravity will cause the down-slope movement of rock, producing colluvial deposits, debris flows, rockfalls, and landslides (see the "Landslides" section of this report for more information). The movement and melting of glaciers can produce a wide variety of glacier deposits (glaciogenic deposits; see the "Glacial History" section of this report for more information). Finally, wind action can produce fine-grained, wind-blown sediments called loess.

The preserve is within the eastern part of Beringia, which is an area stretching from the Lena River in Russia to the Mackenzie River in Canada, that remained largely ice-free during the glacial periods of the Pleistocene (see Figure 18). Because most of Beringia avoided repeated glacial scouring, sequences of sediments built up that record the evolution of the landscape and environment throughout the Quaternary. Furthermore, the presence of permafrost in many areas has kept these sediments frozen since the last glacial maximum (approximately 24,000–14,000 years ago), resulting in the preservation of organic matter, fossils, and archaeological resources (see the "Permafrost" section of this report for more information about the preserve's permafrost; Buvit and Rasic 2011; Urban et al. 2016). Tephra (volcanic ash) beds produced by volcanism in the Wrangle Volcanic Field and Aleutian Arc can be found interbedded with the sediments, aiding in regional correlations (Figure 19; Jensen et al. 2008; Jensen et al. 2013; Westgate and Pearce 2017). Cross-sectional exposures of Quaternary sediments can be found along some of the bluffs of the Yukon River. One of the best examples in the preserve is Chester Bluff, which contains an extensive middle to late Pleistocene tephra record within thick loess deposited on a terrace (Jensen et al. 2008).

**Figure 19. Photograph of a tephra bed in Quaternary sedimentary deposits exposed along the Yukon River.**
**Volcanism in the region, produced either by the Wrangel Volcanic Field or the Aleutian Arc, has produced multiple tephra (volcanic ash) beds within the preserve's Quaternary surficial deposits. The white layer in the photograph just above the scale bar is an example of a tephra bed. NPS photograph by Amanda Lanik.**

## Fluvial Features

Map units: **Qa, Qca, Qt, QTs**

The preserve encompasses about 200 km (130 mi) of the Yukon River near the Alaska-Yukon border between the towns of Eagle and Circle. Other rivers in the preserve include the Charley, Nation, Kandik, Tatonduk, and Seventymile Rivers (Figure 20). The preserve protects the entire 4,500 $km^2$ (1.1-million-acre) Charley River watershed, and this designated Wild and Scenic River is a fundamental park resource (National Park Service 2012). Rivers and streams act as habitat for plants and animals, transportation corridors, supplies of food and water, and sources of recreation for both residents and tourists alike. Many of the watersheds that flow north into the Yukon River were the sites of placer gold mining during the Alaska-Yukon gold rush of the late 1800s. Mining has continued intermittently since then, resulting in the disturbance of some of the stream's natural functions (see the "Placer-Mined Stream Evaluation" section of this report for more information).

The Yukon River is one of the most prominent geographic features in both the preserve and Alaska as a whole. The Yukon River Basin is the fourth largest drainage basin in North America, covering an area of more than 850,000 $km^2$ (330,000 $mi^2$) in northwest Canada and Alaska (Brabets et al. 2000). Originating about 50 km (30 mi) from the Gulf of Alaska in northwestern British Columbia, the Yukon River flows northwest through Yukon and east-central Alaska (including through the preserve), then turns southeast in central Alaska and eventually empties into the Bering Sea. The path of the Yukon River generally follows a broad arc that mirrors the structural trend of the northern Cordillera and its accreted terranes. Within the preserve, the Yukon River runs parallel to, and north of, the Tintina fault system (see poster). The morphology of the Yukon River in the preserve is characterized by a wandering channel with stable, forested islands (Figure 21; Froese et al. 2003a). A study carried out close to Dawson, Yukon found that the channel has barely moved in the past 3,000 years, demonstrating the stability of the islands (Froese et al. 2005). Downstream of Circle, the Yukon River rapidly shifts to a braided morphology as it flows into the Yukon Flats basin (Froese et al. 2003a).

The present Yukon River Basin was established during the Pliocene Epoch (see Table 1 for the position and dates of the time scale units referenced throughout this report). Prior to that, the Canadian part of the Yukon River Basin drained to the south across the region now occupied by the St. Elias and Coast Mountains (Figure 22; Tempelman-Kluit 1980; Duk-Rodkin et al. 2001). The first major glaciation in the west-central Yukon blocked the existing drainage of the Yukon River to the east and south, impounding an extensive glacial lake (Duk-Rodkin et al. 2001). This lake cut an outlet west of the Fifteenmile River and diverted the Yukon River drainage northwestward into Alaska, establishing the current drainage pattern (Duk-Rodkin et al. 2001; Bender et al. 2018).

The Yukon River freezes each winter, and river ice can reach thicknesses of more than 1.5 m (5 ft; Lindsey 2019). Historical records (1897–2011) compiled by long-time Eagle resident John Borg show that the average freeze-up date occurs around 19–20 November and the average break-up date is around 7 May (Stark et al. 2012). Between 1897 and 2011, freeze-up occurred as early as 21 October (in 1930) and as late as 1 January (in 2003), while breakup occurred as early as 7 April (in 2006) and as late as 19 May (in 1920; Stark et al. 2012). Analysis of the entire historical record found no significant trends with respect to the freeze-up date, however, the break-up date shifted 0.8 days earlier per decade (Stark et al. 2012). Further analysis of the data found that between 1948 and 2011, the break-up date shifted 2.1 days earlier per decade, indicating that the rate of recession for the breakup may be increasing (Stark et al. 2012). The spring breakup of river ice can be accompanied by hazards such as flooding and ice scouring (see the "Geohazards" section of this report for more information).

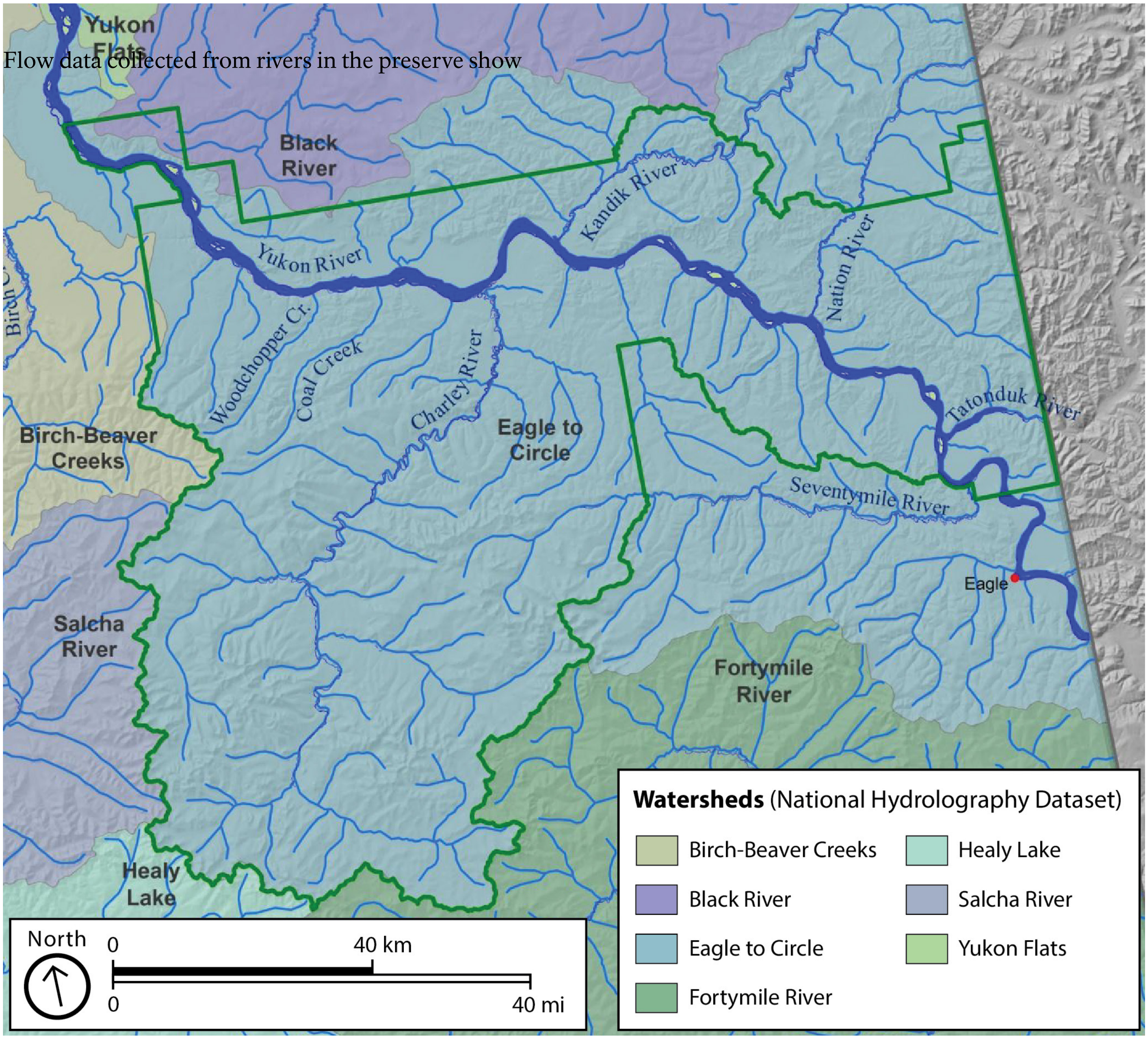


**Figure 20. Watershed map of the preserve.**
**The preserve encompasses many streams and rivers, including the Yukon River, Seventymile River, Tatonduk River, Nation River, Kandik River, Charley River, Coal Creek, and Woodchopper Creek. Map modified from Stark et al. (2012).**

Flow data collected from rivers in the preserve show discharge patterns typical for snowmelt dominated rivers, with peak flow in the spring and gradually decreasing over the summer (Stark et al. 2012). A streamgaging station has measured the discharge for the Yukon River at Eagle since 1950 (Brabets et al. 2000). Peak discharge typically occurs in early June and then decreases until December (Stark et al. 2012). Low flows between December and April constitute the baseflow period and are dominated by groundwater input (Stark et al. 2012). The mean annual discharge at the Eagle gaging station between 1952 and 2009 averaged 85,000 cfs (cubic foot per second; Stark et al. 2012). Studies of the discharge over this period showed no trend in mean annual discharge, however, statistically significant flow increases were found in May and the autumn months (October–December; Brabets and Walvoord 2009; Stark et al. 2012). Streamgaging stations were established in the past within the preserve on the Nation River (1991–2003) and on the Kandik River (1994–2001; Stark et al. 2012). Most of the flow on both the Nation and Kandik Rivers occurred from May through September, reflecting runoff from snowmelt and rain (Brabets 2001).

**Figure 21. Photograph of the Yukon River. In the preserve, the Yukon River has a wandering channel with stable, forested islands like those seen in the photo. NPS photo by Josh Spice.**

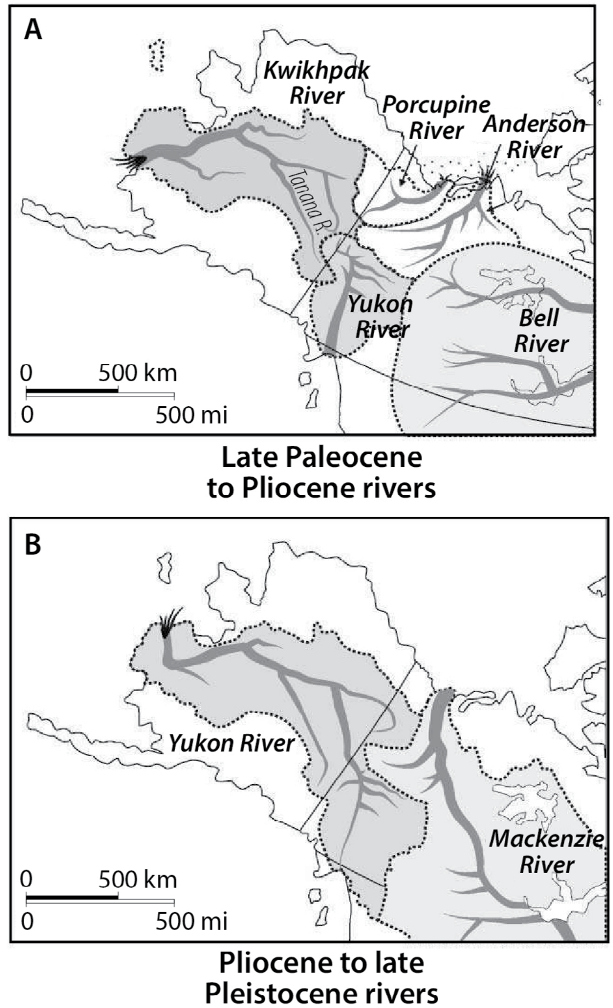


**Figure 22. Map showing the capture of the Yukon River during the Pliocene. (A) Map of Alaska and western Canada showing the configuration of major drainages prior to the Pliocene capture. At that time, the Yukon River drainage was much smaller and emptied to the south. Most of what is now the Yukon River drainage in Alaska was part of the Kwikhpak River drainage. (B) Map of Alaska and western Canada showing the configuration of major drainages after the Pliocene capture. The impoundment of a glacial lake resulted in erosion that connected the Yukon River with the Kwikhpak River and redirected its flow northwestward. Figure modified from Duk-Rodkin et al. (2001).**

## Possible Geothermal Features

Two potential thermal springs have been reported in the preserve; however, their existence has not yet been definitively confirmed (Waring 1917; Nava and Morrison 1974). One of the potential springs was reported on a tributary of the Charley River called Flat Creek (Waring 1917; Nava and Morrison 1974). Waring (1917) reported that a prospector working in the area noted the potential existence of a hot spring on the slopes above Flat Creek because a portion of the creek stayed open and steamed during the winter. However, no definitive vents were observed by the prospector, nor did he note odors of hydrogen sulfide, which commonly accompany hot springs (Waring 1917). A snow-free mound on Flat Creek was also noted as having potential thermal activity by Nava and Morrison (1974), but no water could be seen draining from the mound. Nava and Morrison (1974) reported a second possible thermal spring near the headwaters of the Charley River. A small patch of deciduous trees was in the area where the spring had been reported, but the authors were unable to positively identify thermal activity (Nava and Morrison 1974). Future investigations of these areas could confirm or deny the presence of thermal springs.

## Permafrost

The preserve contains permafrost, which is ground (soil, sediment, or rock plus any ice or organic material) that remains frozen for at least two consecutive years but has often been 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. Some permafrost in the preserve has been frozen for well over the requisite two-year period. For example, the term "yedoma" refers to ice-rich permafrost that formed during the last glacial period, over 10,000 years ago (Kanevskiy et al. 2011). Parts of the preserve that likely contain yedoma include two ecological units from Swanson and Swanson (2001): (1) the High terrace (undulating), and

(2) the Thanksgiving Loess Plain (David Swanson, NPS Arctic Inventory and Monitoring Network, terrestrial ecologist, personal communication, 19 January 2022; see Swanson and Swanson 2001 for the location of these ecological units).

A variety of 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 1981 and 2010, the mean annual air temperatures in the preserve ranged from about -7° C to -2° C (19° F to 28° F; PRISM Climate Group 2018). During this timeframe, the climate was cold enough for permafrost, but in some regions, air temperatures were on the warmer end of those conducive to permafrost. 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).

The factors that influence permafrost have been used to model the distribution of permafrost within the preserve. Figure 23 shows two permafrost models for the preserve, one of which is a portion of a statewide permafrost map by Jorgenson et al. (2008) and the other is the preserve-specific model created by Stark et al. (2012) using draft Natural Resources Conservation Service (NRSS) soils data. Both models show the majority of the preserve being underlain by discontinuous permafrost (landscape underlain by 50 to 90 percent permafrost), with patches of continuous permafrost (landscape underlain by over 90 percent permafrost) along the Yukon River corridor and in the southern part of the preserve.

Permafrost creates distinctive features on the landscape, some of which can be found within the preserve. These include yedoma, ice wedges (features formed by repeated frost cracking and ice growth), pingos (ice-cored hills), thermokarst lakes (lakes formed by melting permafrost), thermokarst-modified features (geographic features altered by melting permafrost), solifluction lobes (ripples of wet, unfrozen material over frozen material), and active-layer detachments (faster sliding of unfrozen material that creates sections of bare soil). Figure 24 shows photographs of these features.

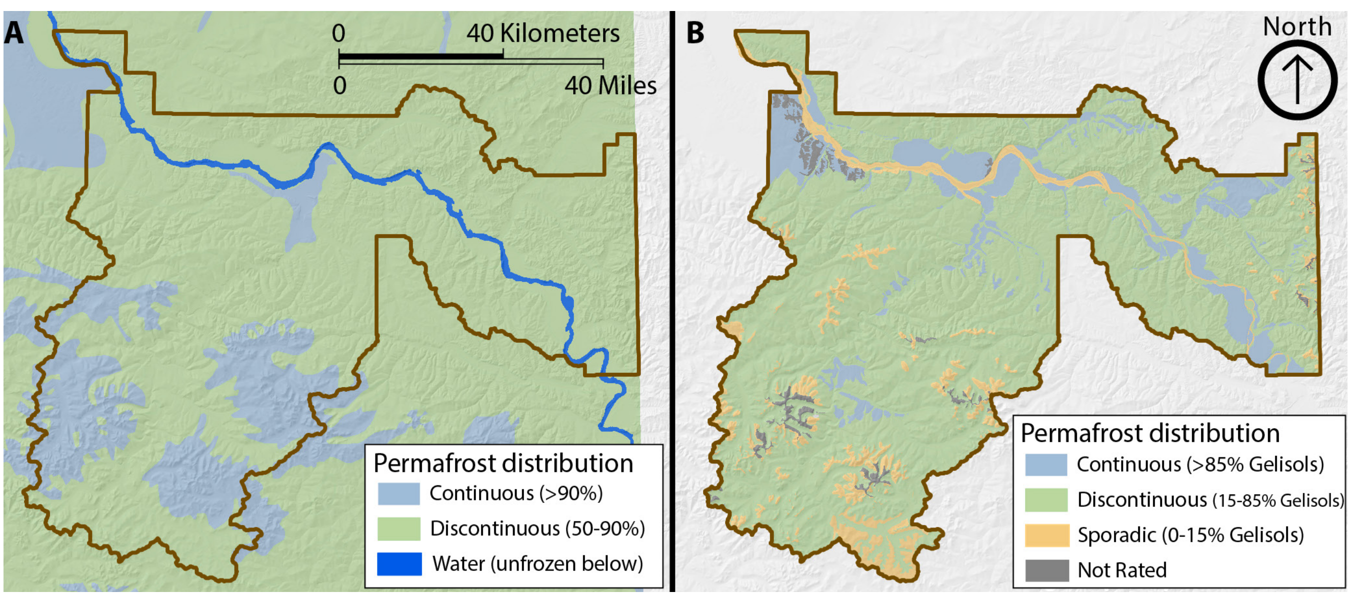


**Figure 23. Maps showing modeled distribution of permafrost within the preserve.**
**Both maps show broadly similar distributions of permafrost, with the majority of the preserve containing discontinuous permafrost and some areas containing continuous permafrost. (A) Alaska state permafrost map by Jorgenson et al. (2008). (B) Permafrost map from Stark et al. (2012), which used draft Natural Resources Conservation Service (NRCS) soils data to model permafrost distribution in the preserve. Gelisols refer to a soil type characterized by permafrost.**

Permafrost will thaw when ground temperature rises above freezing. Increasing air temperatures and ground disturbances, such as fire, are two changes that can cause permafrost to thaw. Climate change is causing temperatures to rise in Alaska, which is projected to continue. Under these warming conditions, permafrost thaw is likely to have significant impacts on the landscape. For more information about monitoring permafrost in the preserve, projected permafrost thaw, and potential impacts, see the "Permafrost Monitoring" section of this report.

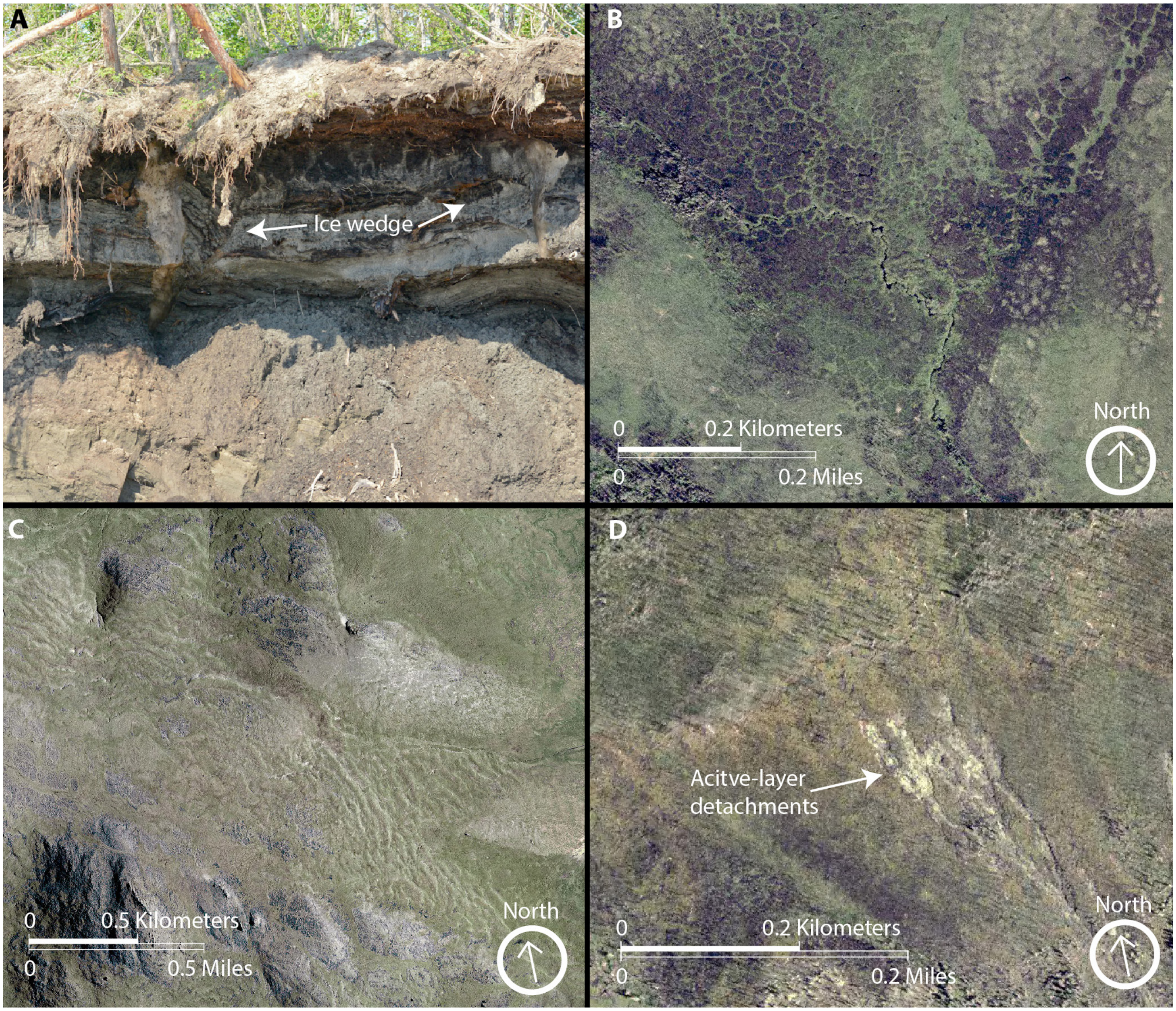


**Figure 24. Images of permafrost-related geomorphic features in the preserve.**
**(A) Photograph of ice wedges along the Yukon River, which form by the repeated frost cracking and growth of ice over many years. NPS photograph by Josh Spice. (B) Aerial image of ice-wedge polygons north of the Yukon River. Ice-wedge polygons are generally wedge-shaped bodies of ice present in permafrost that are produced by ice contraction cracking followed by infilling and freezing of water. NPS photograph. (C) Aerial image of solifluction lobes near Mount Sorenson. The solifluction lobes are marked by horizontal lines of vegetation and are formed by the downslope flow of wet, unfrozen material over frozen material. This process is slower than that which produces active-layer detachments; vegetation and organic soil surface mats on solifluncting material typically remain intact. NPS photograph. (D) Aerial image of active-layer detachments on the south side of the Yukon River. Active-layer detachments are mass movement features that consist of active-layer material that slides along a slip surface of saturated fine-grained material. The slip surface usually develops at the interface between permafrost and the active layer. NPS photograph.**

# Geologic History

*This chapter describes the geologic events that formed the present landscape. Events are discussed more-or-less in order of geologic age (oldest to youngest). See the geologic time scale (Table 1) for an explanation, including the numerical age, of the subdivisions of geologic time referenced here. The geologic features within the preserve record a long and nearly continuous history stretching approximately 900 million years. The geology of the preserve is cut by a major fault called the Tintina fault system. During the Cretaceous–early Tertiary, movement on the Tintina fault system juxtaposed rocks that had, until then, evolved far away from each other. Because of this, the geologic history is separated into north and south of the Tintina fault system until the Cretaceous-early Tertiary.*

## North of the Tintina Fault System

### *Proterozoic*

The oldest rocks within the preserve, the Tindir Group (**PCtl, PCtlc, PCts, PCtd, PCt, PCtu, PCtb, PCtsl**), began forming approximately 900 million years ago during the Proterozoic Eon. These rocks formed during the break-up of the supercontinent known as Rodinia. Rocks from the lower part of the Tindir Group were deposited in a complex basin within Rodinia. The extension that accommodated the lower Tindir Group rocks may have been related to the passing of a volcanic plume under the supercontinent. The upper part of the Tindir Group record subsidence that was linked to the breakup of Rodinia. In addition, the upper Tindir Group contains glacial deposits formed by widespread low-latitude glaciation that occurred across the globe at the end of the Proterozoic. During this period, known as "snowball Earth," massive glaciers developed and eventually covered most of the Earth. The Tindir Group contains microfossils that record life during the Proterozoic, including the dominant form of microbial life at this time, stromatolites, and early forms of eukaryotes.

### *Cambrian to Early Cretaceous*

At the end of the Proterozoic, rifting along the western edge of the North American continent created a passive margin (edge of a continent characterized by little tectonic activity) that persisted throughout the Paleozoic Era and into the Mesozoic Era. The rocks in the easternmost part of the preserve (called the "Tatonduk Block") formed along the passive margin almost continuously for over 400 million years. These rocks include the Cambrian Funnel Creek Limestone (**Cf**) and Adams Argillite (**Ca**); Cambrian-Ordovician Hillard Limestone (**OCh**) and Jones Ridge Formation (**OCjru**); Ordovician–Devonian Road River Formation (**DSOr**); Devonian Ogilvie Formation (**Dof**), McCann Hill Chert (**Dka**), and Nation River Formation (**Dnr**); Devonian–Pennsylvanian Ford Lake Shale (**PNMDf**); Mississippian–Pennsylvanian Calico Bluff Formation (**PNMcb**); Permian Tahkandit Limestone (**PZl**) and Step Conglomerate (**Pst**); and the Triassic–Cretaceous Glenn Shale (**TRgsl**, **KJTRa**). Passive margin deposits could also include the Cretaceous Keenan Quartzite (**Kke**) and Biederman Argillite (**Kb**), although this is speculative.

Variations in these rocks represent evolving sedimentary systems, with changes corresponding to variables such as water depth, sediment supply, and the types of creatures living in the environment. The most significant unconformity (gap in sedimentation) occurs below the Permian rocks. The unconformity indicates that regional uplift and erosion occurred prior to the Early Permian. This is a cryptic tectonic event not found elsewhere in Laurentia and could reflect the early interaction of this part of Laurentia with outboard terranes. The youngest rocks deposited during the Mesozoic Era (Glenn Shale, Keenan Quartzite, and Biederman Argillite) record regional uplift and the approach of an island arc from the west. Overall, these Paleozoic and Mesozoic rocks contain abundant fossils that record marine life during the Paleozoic and Mesozoic, including millions of years of species evolution, adaptation, and extinction.

### *Devonian*

During the Devonian, underwater volcanism formed the Woodchopper Volcanics (**Dwv**), which include volcanic rocks such as basalt and sedimentary rocks such as chert and limestone that record seafloor sedimentation around the volcanoes. Fossils from the sedimentary rocks indicate these rocks did not form close to the Laurentian passive margin. Subsequent tectonic movement translated these rocks to their current position in western North America together with other exotic terranes such as the Farewell and Livengood terranes (see Figure 6 for a terrane map).

### *Cretaceous*

In the Cretaceous, an island arc and intervening oceanic rocks (Angayucham terrane) collided with the western margin of Laurentia. This collision is recorded in the sedimentary rocks of the Kathul Greywacke (**Kka**) of the Kandik River assemblage. The collision caused westward thrusting, structural thickening, and burial of the Kandik River assemblage.

## South of the Tintina Fault System

### *Middle to Late Paleozoic*

During the middle to late Paleozoic, rocks that had been evolving along the Laurentian passive margin rifted away, and an oceanic basin (called the Seventymile-Slide Mountain Ocean) opened between these rifted rocks and Laurentia. A volcanic arc developed on top of the rifted rocks, which are collectively called the Yukon-Tanana terrane (**PZPCbg, PZPCqs, PZqsg**). The Yukon-Tanana terrane includes metamorphic rocks that originally formed in a volcanic arc environment, including rocks that erupted from volcanoes and sedimentary rocks that formed around the volcanoes. Rocks from the ocean that opened between the Yukon-Tanana terrane and Laurentia are also found within the preserve. These rocks are part of the Seventymile terrane and include mafic igneous rocks such as basalt and gabbro, metamorphosed mafic igneous rocks (greenstone), and deep-water cherts (**PZgc, MZPZPCb**, **MZPZs**).

### *Triassic to Middle Jurassic*

During the Triassic to Middle Jurassic, the Seventymile-Slide Mountain Ocean closed, which brought the Yukon-Tanana terrane back to the western margin of Laurentia, albeit not in the current location of the preserve but further to the south. The collision and accretion of the Yukon-Tanana terrane to Laurentia caused metamorphism of the Yukon-Tanana terrane as well as imbrication (stacking) of the Yukon-Tanana strata with that of the Slide Mountain terrane and Laurentia.

## Cretaceous to Early Tertiary

The Tintina fault system is a major structural feature that has moved crustal fragments called terranes northward along the western margin of North America during the Cretaceous–early Tertiary. The Tintina fault system cuts northwest-southeast through the center of the preserve and separates weakly metamorphosed rocks that mostly formed on the Laurentian passive margin from the more highly metamorphosed rocks of the Yukon-Tanana terrane. The motion on the Tintina fault system is predominately right-lateral strike-slip, meaning rocks on the outboard (oceanward) side of the fault slip northward relative to those inboard. While estimates about the amount of offset along the Tintina fault system range from about 400 km (250 mi) to over 1,000 km (600 mi), rocks now found in the southern part of the preserve were undoubtedly translated northward and juxtaposed next to rocks now found in the northern part of the preserve.

The movement of the Tintina fault system formed sedimentary basins along the trace of the fault and to the northwest (Nation River basin) that were filled with unnamed Cretaceous and Tertiary sedimentary rocks (**TKs**). These were mainly deposited in a fluvial environment, with sedimentary characteristics indicating braided river systems overlying meandering river systems that flowed in a westerly direction. Some of the granites that were the source of sediment for **TKs** contained lode gold (*in situ*) deposits. The gold in these rocks was eroded and deposited within the sedimentary deposits of **TKs**, particularly in association with the conglomerate beds. Fossils from **TKs** record terrestrial life that existed in this part of Alaska during the Late Cretaceous and early Tertiary, including plants and possible dinosaurs.

Igneous rocks, including widespread granitic plutons (**MZa, TKg, TKMZmgr**) and less commonly extrusive volcanic rocks (**TMZmi, Tpt, Tw**), formed during the Cretaceous and Tertiary in the southern part of the preserve. This magmatism is broadly related to north-dipping subduction beneath the southern margin of Alaska and involved widespread partial melting of continental material consistent with the tectonic models for arc evolution and terrane accretion.

## Pliocene

During the Pliocene, the first major glaciation in west-central Yukon led to the establishment of the modern Yukon River Basin. Prior to this time, the Canadian part of the basin drained to the south across the region now occupied by the St. Elias and Coast Mountains. Glaciation blocked the existing drainage of the Yukon River to the east and south and impounded an extensive glacial lake. This lake cut an outlet west of the Fifteenmile River and diverted the Yukon River drainage northwestward into Alaska, greatly expanding the Yukon River drainage basin.

## Pleistocene and Holocene

Alpine glaciers advanced and retreated during the Pleistocene and Holocene in the Yukon-Tanana uplands, leaving deposits of five glacial episodes in and around the preserve. The five episodes occurred during the early, middle, and late Pleistocene, as well as a minor advance in the late Holocene. Geologic evidence of these glacial fluctuations includes moraines, glacial lake deposits, and knob and kettle topography. Permafrost also developed in the preserve during the glacial periods of the Pleistocene and persists discontinuously (landscape underlain by 50 to 90 percent permafrost) throughout much of the preserve today. Active geologic processes continue to shape the landscape. These processes include fluvial erosion and deposition associated with the Yukon and Charley River systems, as well as the movement of sediment downslope by gravity (e.g., landslides), wind erosion, and permafrost processes.

# Geologic Resource Management Issues

*Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Alaska Regional Office Natural Resources Team and Geologic Resources Division can provide technical and policy assistance for these issues (see "Guidance for Resource Management" section).*

## Geohazards

The dynamic landscape of the preserve presents a variety of geologic hazards ("geohazards") that 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 preserve include earthquakes, landslides, ice jam flooding, and river erosion (Hults et al. 2019).

### *Earthquakes*

Despite the Tintina fault system cutting through the central part of the preserve, the seismicity hazard is relatively low compared to many other areas of Alaska (Figure 25; Wesson et al. 2007). Although the Tintina fault system is a large, terrane-bounding fault, it does not have much evidence for recent surface ruptures (Plafker et al. 1994; Haeussler 2008). Scattered, low-level seismicity up to magnitude 5 has been recorded along the Tintina fault system (Ruppert et al. 2008; Haeussler 2008), however, the nearest recorded earthquake above magnitude 7 occurred between the Tintina and Denali faults near Fairbanks, Alaska (https://www.usgs.gov/programs/earthquake-hazards/lists-maps-and-statistics, accessed 22 November 2022). Due to the lack of earthquake activity along the Tintina fault system, it was not considered a source for concern in the 2007 seismic hazard map of Alaska (Wesson et al. 2007).

According to the USGS 2007 seismic hazard map of Alaska, in the next 50 years the preserve has a 10% probability of experiencing an earthquake that causes peak ground acceleration between 6% and 9% of the acceleration of gravity (Figure 25; Wesson et al. 2007). This amount of ground acceleration would be perceived as moderate shaking and could cause very light damage (Table 5). Seismicity across Alaska is monitored by the Alaska Earthquake Center (see https://earthquake.alaska.edu/). Seismic monitoring stations within and near the preserve include a station in Eagle, a station to the north of the Kandik River, and a station at the Coal Creek mining camp.

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 those dangers 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*

Map units: **Qc**

Areas of the preserve with steep slopes may be prone to landslides. The term "landslide" 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 already have increased down-slope force. Factors that either increase the effects of down-slope forces or reduce the strength of slope material can cause 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

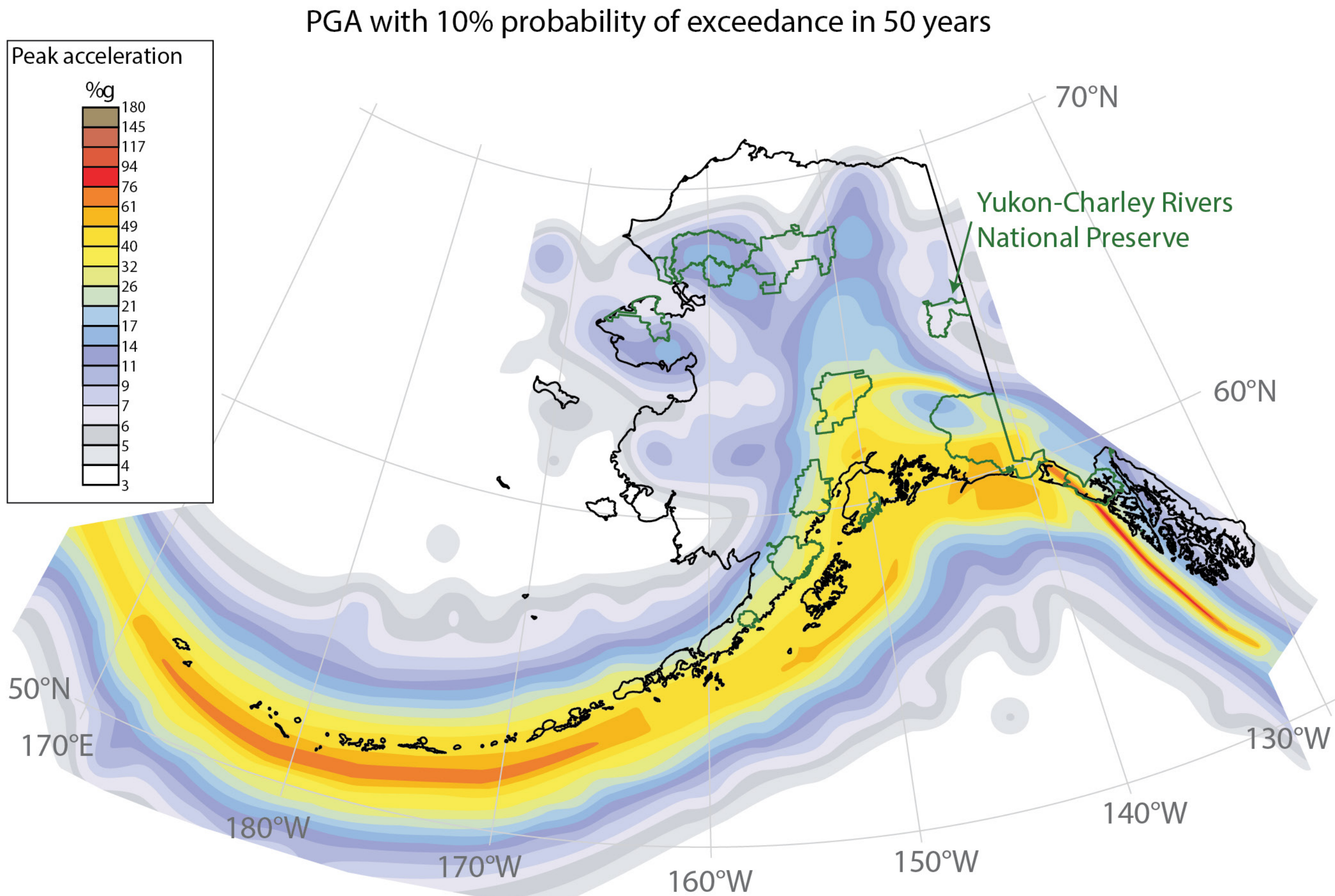


**Figure 25. Earthquake probability map of Alaska.**
**The map shows the greatest amount of acceleration (as a percentage of the acceleration of gravity) produced by an earthquake that has the probability of 10% to occur in the next 50 years. Green outlines are National Park System units. Yukon-Charley Rivers National Preserve is within the 6%–9%g peak acceleration range, corresponding to moderate shaking and very light damage (see Table 5). Map modified from Wesson et al. (2007).**

**Table 5. Degree of earthquake shaking and potential damage based on peak ground acceleration.**

Values in the table are from Wald et al. (1999). These values were developed for southern California but provide a general sense of perceived shaking and damage for earthquakes elsewhere.

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

as heavy rainfall and earthquakes. Heavy rainfall can cause changes to the hydraulics of the sediments on the slope, such as an increase in pore pressure that reduces the overall cohesion of the sediments. Additionally, human activities such as vegetation removal, mining, construction, and other ground disturbing actions can contribute to the likelihood of slope failure.

Parts of the preserve are underlain by permafrost, which if thawed will impact the frequency and magnitude of landslides in the preserve (see the "Permafrost" section of this report for more information). A warming climate causes permafrost to thaw, which in turn increases hillslope susceptibility to landslides (Patton et al. 2019). 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. 2019). Because the strength of bedrock, soil, and sediment is reduced by permafrost thaw, it can affect areas underlain by ice-rich sediments as well as more well-drained and ice-poor areas. Slope movements related to the thaw of ice-rich soil and sediment are usually discussed with other landscape changes, collectively referred to as “thermokarst”. These can include retrogressive thaw slumps, active layer detachments, and solifluction lobes (see the “Permafrost Monitoring” section of this report for more information).

Landslides can pose a threat to park resources, infrastructure, staff, and visitors; however, the lack of major infrastructure and relatively low visitation limit the risks associated with landslides throughout most of the preserve. The consequences of a landslide could be higher in places with frequent visitation, infrastructure, and areas with important, nonrenewable resources. Slopes along the Yukon River where the river is eroding are landslide-prone (David Swanson, NPS Arctic Inventory and Monitoring Network, terrestrial ecologist, written communication, 23 December 2021). For example, an existing landslide along the Yukon River near Adams Peak was reactivated in 2017 and again in 2021 (Figure 26; Chad Hults, NPS Alaska Region, regional geologist, written communication, 29 December 2021). Landslides that reach water, such as the 2017 slide, could pose the additional hazard of creating a wave when slope material enters and displaces large volumes of water. A large tsunami-like wave could be hazardous to watercraft on the river or people camping nearby. Management activities related to landslide risk could include identifying areas prone to slides, determining risks associated with landslides, and monitoring known or potential landslide areas.

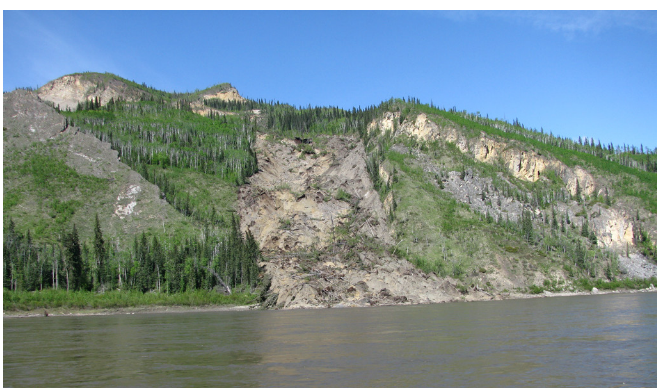

**Figure 26. Photograph of a landslide (potentially a debris flow) along the Yukon River near Adams Peak.**
**This landslide originally occurred sometime before 2017 and was reactivated in 2017 and 2021. NPS photograph.**

### *Ice Jam Flooding*

The Yukon River freezes each winter, and the spring breakup of ice can be accompanied by hazards such as flooding and ice scouring along the river’s banks. As temperatures increase in the spring, water levels in the river rise due to melting snow, and the river ice begins to break apart and flow downstream. Some years, the ice melts and becomes weak before significant amounts of water enter the river. This type of breakup, known as “thermal breakup,” is characterized by soft ice that easily breaks into small pieces and flows downriver (Beltaos 2009). Thermal breakup can result from a slow transition from cold to warm temperatures and is typically not accompanied by flooding (Lindsey 2019). In contrast, “dynamic breakup” is when the ice remains hard and resistant to flowing despite an influx of snowmelt that causes water levels to rise (Beltaos 2009). This scenario occurs when there is normal to above-normal snowpack, thick river ice, and a quick transition from cold to warm temperatures (Lindsey 2019). Large, resistant sheets of ice will float and start to flow as meltwater enters the river, but downstream changes in channel morphology, such as a constriction or a sharp bend, can cause the ice to jam, flow to be restricted, and flooding to occur (Lindsey 2019). Ice jams and flooding on the Yukon River can also cause water to back up on tributaries and flood far upstream of their confluence with the mainstem (Lindsey 2019).

Floodplain sediments along the Yukon River near the Alaska-Yukon border provide a record of ice jam flooding for the last 2000 years (Livingston et al. 2009). Livingston et al. (2009) examined 29 sites containing ice jam flood deposits between Dawson and Circle. Radiocarbon dating at three of the sites, including at Slaven’s Roadhouse within the preserve, indicates that the long-term recurrence interval for ice jam flooding ranges from approximately once every 25 years to once every 38 years (Livingston et al. 2009). This recurrence interval results in a probability of approximately 3–4% for an ice jam flood occurring in a given year, which is broadly similar to the 4–5% probability calculated using historical data at Dawson City between 1898 and 2006 (Livingston et al. 2009). Two of the three study sites recorded a decrease in flood frequency during the Little Ice Age (cold period of glacier growth between 1500 and 1900), which indicates that climate variations influence long-term ice jam flood frequency (Livingston et al. 2009).

Significant historical examples of ice jam-related flooding on the Yukon River occurred in May 2009 and 2013 (Lindsey 2019). In 2009, water levels in the town of Eagle rose by more than 9 m (30 ft) in 48 hours due to an ice jam 16 km (10 mi) downstream (Figure 27a; Lindsey 2019). In addition to this significant flooding, large sheets of ice were shoved onshore. The ice leveled a mature stand of trees on an island in front of Eagle and destroyed many of the homes and buildings near the river just upstream in Eagle Village


**Figure 27. Photographs of ice jam flooding and scouring in Eagle, Alaska.**
**(A) Photograph of Front Street in Eagle during the 2009 ice jam flooding. NPS Photograph. (B) Photograph of the Yukon River at Eagle looking upstream on 7 May 2018. Prior to the 2009 ice jam flooding event, the island in the left foreground was covered with mature trees that were destroyed in 2009 by ice scouring. Photo courtesy of Scott Lindsey, National Weather Service.**

(Figure 27b; Lindsey 2019). As typically occurs with large ice jams, the breakup front continued to stall as it moved downriver, which resulted in flooding in other downstream communities including Circle, Stevens Village, and Tanana (Lindsey 2019). Flooding occurred again in 2013, when late snow accumulation into mid-May and a quick rise in temperatures combined to trigger a dynamic breakup of the river ice. The ice started moving just after midnight on 17 May and, in less than four hours, had stopped and the water level had begun to rise (Lindsey 2019). The resulting flood in Eagle was the second highest on record (behind the 2009 ice jam flood; Lindsey 2019). Like in 2009, the flood event cascaded to communities downstream, affecting Circle, Fort Yukon, and Galena (Lindsey 2019).

The Alaska-Pacific River Forecast Center and the State of Alaska Division of Homeland Security and Emergency Management have collaborated since the 1970s to monitor Yukon River ice breakup and assist communities in the event of flooding (Lindsey 2019). This program, known as Riverwatch, partners hydrologists and emergency management specialists together to monitor river conditions from the air, report information to the National Weather Service, state officials, and residents, and ensure communities are prepared for potential flooding (Lindsey 2019). In the event of severe flooding, the State of Alaska Division of Homeland Security and Emergency Management and, in some cases, the Federal Emergency Management Agency, coordinate the various local, state, federal, and tribal efforts to bring relief to the affected communities (Lindsey 2019).

### *River Erosion*

Erosion of the banks of rivers is a natural process that has the potential to threaten park infrastructure or resources located near waterways. River erosion can be accelerated by other events or factors such as flooding, ice jams, thawing permafrost, and forest fires. Human activity can also accelerate natural erosional rates. Natural bank erosion is generally not an issue unless it threatens important, nonrenewable park resources or infrastructure. Mitigation measures to address erosion issues will vary depending on the specific circumstances. The NPS Alaska Region Natural Resources Team, Water Resources Division, and Geologic Resources Division can provide assistance to park managers.

During the summer of 2022, erosion on a portion of Coal Creek threatened to impact a nearby aircraft landing strip. Coal Creek, along with many other watersheds to the south of the Yukon River, has a long history of placer mining that has destabilized the banks of the creek. In this case, the flow of the creek may be able to be diverted into an older channel further from the landing strip to mitigate impacts (contact the NPS Alaska Region Natural Resource Team for more information).

## Stratotype Inventory, Monitoring, and Protection

Seventeen stratotypes, including ten type sections, one type area, five type localities, and one reference section, are within the preserve (see the “Stratotypes” section of this report for more information; Henderson et al.

2022). The mapping and dividing of an area's rocks into geologic units is an essential process that underpins all other geologic studies. Designating a stratotype is an important step in this process. Stratotypes are unique geologic reference exposures that contain most (if not all) of the diagnostic criteria that ultimately 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 (see 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 management recommendations are discussed in the Central Alaska Inventory and Monitoring Network Geologic Type Section Inventory (Henderson et al. 2022).

### Paleontological Resource Inventory, Monitoring, and Protection

The preserve contains a rich and diverse paleontological record that spans over 900 million years and includes fossils from almost every period of the Phanerozoic Era (539 million years ago–today), as well as older fossils from the Proterozoic Era (2.5 billion–539 million years ago; see the "Paleontological Resources" section of this report for more information). The protection and interpretation of this fossil record are cited in the enabling legislation as one of the purposes of the preserve (ANILCA 1980). 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 preserve was completed by Santucci et al. (2011), and fossil localities have been entered into the NPS Alaska Region Paleontology Database as part of a 2020 Paleontological Resource Focused Condition Assessment project (contact the Alaska Region Natural Resources Team for more information). These resources provide an overview of fossils in the preserve based on available literature and museum collections. Field-based fossil inventories are also important, both for gaining a better 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 between 2004 and 2007 by Anthony Fiorillo (paleontologist, New Mexico Museum of Natural History and Science). This study resulted in the discovery of two dinosaur tracks that had not been recognized in the preserve before (Fiorillo et al. 2014).

Fossils are faced with the potential for damage and destruction from both natural and human sources (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, or destruction of fossils or an increase in erosion rates as a result 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.

### Mineral Development Potential

Although active mining is not currently taking place, future mining can potentially occur within the preserve's original legislative outer boundary on private land or NPS land with unpatented mining claims. The private land on Woodchopper Creek is a patented mining claim with a history of placer mining. Additionally, private land near the Seventymile River and land in the eastern part of the preserve contain mineral resources, many of which have been developed to some degree in the past. The preserve also contains 37 unpatented mining claims, which are located on Woodchopper and Boulder Creeks. Park managers can contact the Alaska Regional Natural Resources Team or the Geologic Resources Division (GRD) Energy and Minerals Team for information and assistance regarding mineral development in the preserve (see the "Guidance for Resource Management" section of this report).

The preserve contains both patented and unpatented mining claims, which are authorized by the General Mining Law (1872). This law allows a U.S. 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 federal land that someone has asserted a right to develop and extract minerals from. A valid claim must contain mineral deposits that would warrant a prudent man to develop a mine. 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. A patented mining claim is a parcel of land that the Federal Government has conveyed title to the claimant, making it private land. Since 1994, the BLM has been prohibited by acts of Congress from accepting any new mineral patent applications.

New mining claims cannot be established on NPS lands; however, existing mining claims are located in the preserve that were established before the preserve was created in 1980. The Alaska National Interest Lands Conservation Act (1980) specifies that NPS units established by this act (which includes the preserve) are withdrawn from the location, entry, and patent of mining claims. However, claims that were located before an area was withdrawn are considered potentially valid existing rights. To conduct a mining operation on any of the preexisting unpatented claims, an operator must submit a proposed plan of operations to the NPS. The NPS will evaluate the proposal, confirm the validity of the mining claim, and add terms and conditions to the permit in order to conserve NPS resources. More information about NPS regulations relating to mining and mining claims can be found in Title 36 of the Code of Federal Regulations, Part 9, Subpart A.

A 1990 Environmental Impact Statement (EIS) assessing the cumulative impacts of mining in the preserve found the preferred alternative is to pursue acquiring all patented and valid unpatented mining claims in the preserve (National Park Service 1990). The EIS stemmed from a 1985 lawsuit that resulted in the restraint of approval of mining plans of operation 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 (National Park Service 1990). The resulting EIS (1990) found that past mining had major impacts on park resources, including wetlands, arctic grayling habitat, and riparian wildlife habitat; furthermore, future mining could result in major cumulative impacts on these resources. The preferred alternative to acquiring mining claims was chosen because it provides the most protection to park resources and causes the least damage to the environment (National Park Service 1990). Until the NPS can acquire all the mining claims, the preserve will conduct a mining plan of operation review and evaluation in accordance with the "Interim Operations" section of the EIS (1990).

Mineral resource exploration and mining can also potentially occur in the future on private land within the preserve's original legislative outer boundary. Mineral resources found on private land include two lode gold prospects and an associated placer mine to the south of the Seventymile River near the preserve's eastern boundary; prospects in the Tatonduk block that primarily contain zinc and lead; an occurrence of zinc and lead north of the Nation River; and an occurrence of uranium at Calico Bluff (https://mrdata.usgs.gov/ardf/, accessed 30 August 2022). Unlike unpatented mining claims, mining on private land does not fall under NPS mining regulation (36 CFR Subpart 9A).

### Abandoned Mineral Land Mitigation

The preserve has a long history of mining that has left its mark in the form of abandoned mineral land (AML) sites and features. AML sites contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. According to the NPS AML database, the preserve contains 41 AML features at 14 sites. Examples of mine-related features found at AML sites include shafts, equipment, surface mines, tailings, airstrips, roads, buildings, and other structures.

The NPS acts under various authorities to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts on resources. Past mitigation efforts have been concentrated at the Coal Creek site. In the 1990s, the NPS undertook a multi-year cleanup effort to mitigate mercury-, lead-, and petroleum-contaminated soils, and remove deteriorating 55-gallon drums and lead-acid batteries (Figure 28; Allan 2015). Allan (2015) provides a detailed account of the past mitigation work at Coal Creek, as well as an overview of the site's mining history. No AML features in the preserve are known to currently pose a physical safety risk to visitors or wildlife that would require mitigation (Burghardt et al. 2014). However, the physical condition of AML features often change over time, and periodic monitoring is recommended. Although contamination and safety hazards have mostly been mitigated, the environmental impacts of mining continue to effect or impede natural systems (see the "Placer-Mined Stream Evaluation" section of this report). Contact the Alaska Region Natural Resources Team or the GRD Energy and Minerals Team for more details and specific information on the AML sites and features within the preserve.


**Figure 28. Photographs of AML cleanup efforts at Coal Creek.**
**(A) Photograph of leaking barrels that were numbered and removed as part of cleanup efforts in the 1990s. NPS photograph. (B) Photograph of members of the cleanup crew shoveling soil into a mechanical separator in 1996. This was part of an effort to mitigate mercury-, lead-, and petroleum-contaminated soils. NPS photograph by Linda Stromquist.**

## Caves and Associated Landscape Management

Caves have been reported within some of the rocks in the preserve, however, a complete survey of caves has not yet been completed. The caves that have been identified occur in geologic units composed of carbonate rocks (see the "Caves" section of this report for more information). Carbonate rocks are widespread within the preserve, particularly in the eastern area, so a survey of these units may uncover additional cave resources. 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. 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 cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request. So far, most of the cave reconnaissance in the preserve has focused on archaeological potential. One cave surveyed by NPS staff contained a very old speleothem and a Pleistocene bone fossil (Jeff Rasic, personal communication, 14 May 2023). 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 more information about inventorying and monitoring cave-related vital signs.

## Placer-Mined Stream Evaluation

Over a hundred years of placer mining have disturbed the natural function of some of the preserve's waterways. Many of the creeks that flow northward into the Yukon River were the site of placer mining in the past (see National Park Service 1990 for an overview of the preserve's mining history). Historic placer mining involved processing unconsolidated sediments found in stream channels, floodplains, and terraces to separate gold from sand and gravel. Miners employed a variety of tools and technologies to accomplish this task, ranging from rudimentary pick-and-shovel methods to large, mechanized dredges (Figure 29a; Allan 2015). These mining activities often disturbed the natural function of streams by digging up stream beds and floodplains and diverting streams out of their original channels. A 1990 EIS found that a total of 4.840 $km^2$ (1,196 acres) of land in four drainages (Woodchopper, Coal, Sam, and Fourth of July Creeks) had been disturbed by past mining activities (National Park Service 1990). Most of this disturbance includes mine waste and tailings along stream channels (Figure 29b; National Park Service 1990). While mining also occurred elsewhere in the preserve, the impacts at those sites were limited to insignificant modifications to the terrain, vegetation, and stream channels (National Park Service 1990).

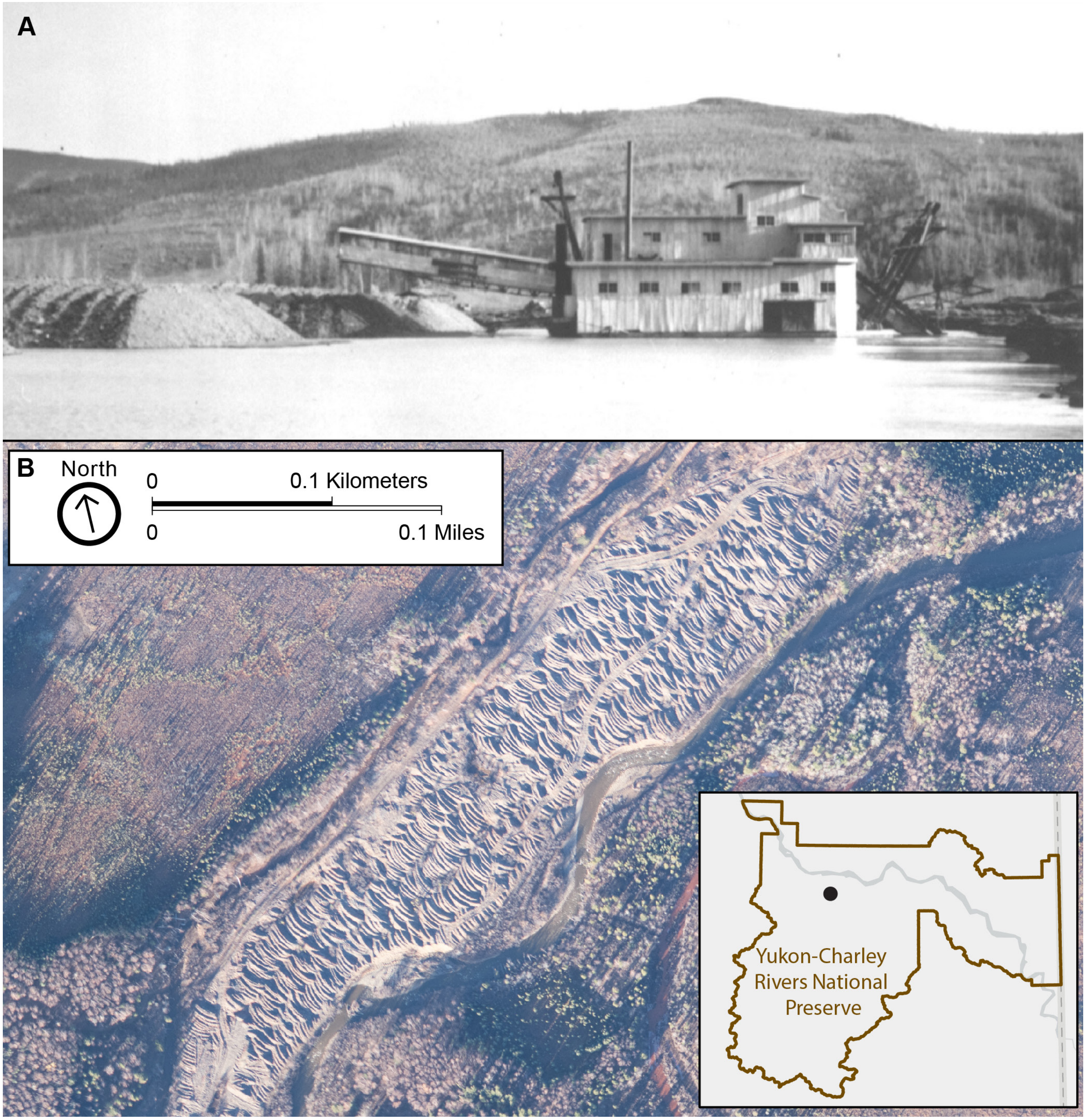


**Figure 29. Photographs of the dredge and mine tailings on Coal Creek.**
**(A) Photograph of the Coal Creek Dredge operating in the early 1940s. The dredge would take in river sediments, sort through the sediments for gold, and deposit the waste material in tailings piles (seen at the rear of the dredge on the left side of the photograph). NPS photograph from the Bill Lemm Collection.**
**(B) Aerial photograph of tailings piles along Coal Creek taken in 2019. NPS photograph.**

The NPS is collaborating with the BLM to quantify, inventory, and assess the reclamation potential of placer-mined streams in the preserve, as well as in Denali National Park and Preserve and Wrangell-St. Elias National Park and Preserve. Stream reclamation could involve returning a previously mined stream corridor to a condition that provides for the recovery of fish habitat and channel stability (Harman 2018). The assessment project will use the BLM's aquatic Assessment, Inventory, and Monitoring strategy to gain baseline data for placer-mined streams and natural reference reaches. Impaired streams in the preserve that will be studied include Coal Creek, Woodchopper Creek, and Fourth of July Creek, as well as unmined reference reaches (Paul Burger, NPS Alaska Region, hydrologist, personal communication, 9 September 2022). This data will allow NPS scientists to quantify differences in natural and mined streams and create clearly defined reclamation goals. Furthermore, the assessments will help prioritize impaired sites and be used to justify potential future funding.

## Permafrost Monitoring

The preserve is underlain by permafrost (see the "Permafrost" section of this report for more general information about permafrost in the preserve). Most of the permafrost in the preserve is geographically discontinuous, thin, and close to the melting point (Loso 2018). Future climate change is likely to cause permafrost in the preserve to thaw. Impacts of permafrost thaw may include the loss of permafrost landscape features, the development of thermokarst, 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.

The warming climate will cause permafrost to become unstable and thaw at many sites in the preserve over the coming decades. Focused modeling to predict permafrost thaw has been completed for the other national parks in central and arctic Alaska (Panda et al. 2014a, Panda et al. 2014b, Panda et al. 2016), but so far, no preserve-specific modeling has been completed. The Geophysical Institute Permafrost Lab (GIPL) permafrost model is an Alaska-wide model that projects ground temperatures to 2100 (https://catalog.snap.uaf.edu/geonetwork/srv/eng/catalog.search#/metadata/c24a957b-8a56-40bf-bc09-43a567182d36, accessed 19 January 2022). According to the GIPL model, by 2050, ground temperatures at 2 m (6.5 ft) depth throughout much of the preserve will be above 0°C (32°F), resulting in widespread permafrost thaw (Figure 30).

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 the shallow and deep ground temperatures keep track of the permafrost's thermal state. At three sites, temperature measurements are made hourly at relatively shallow depths (0.5–2.0 m [1.5–6.5 ft]), and at one site, a single deep (29–63 m [95–206 ft]) case borehole records the ground temperature profile once per year (Loso 2018). The physical state

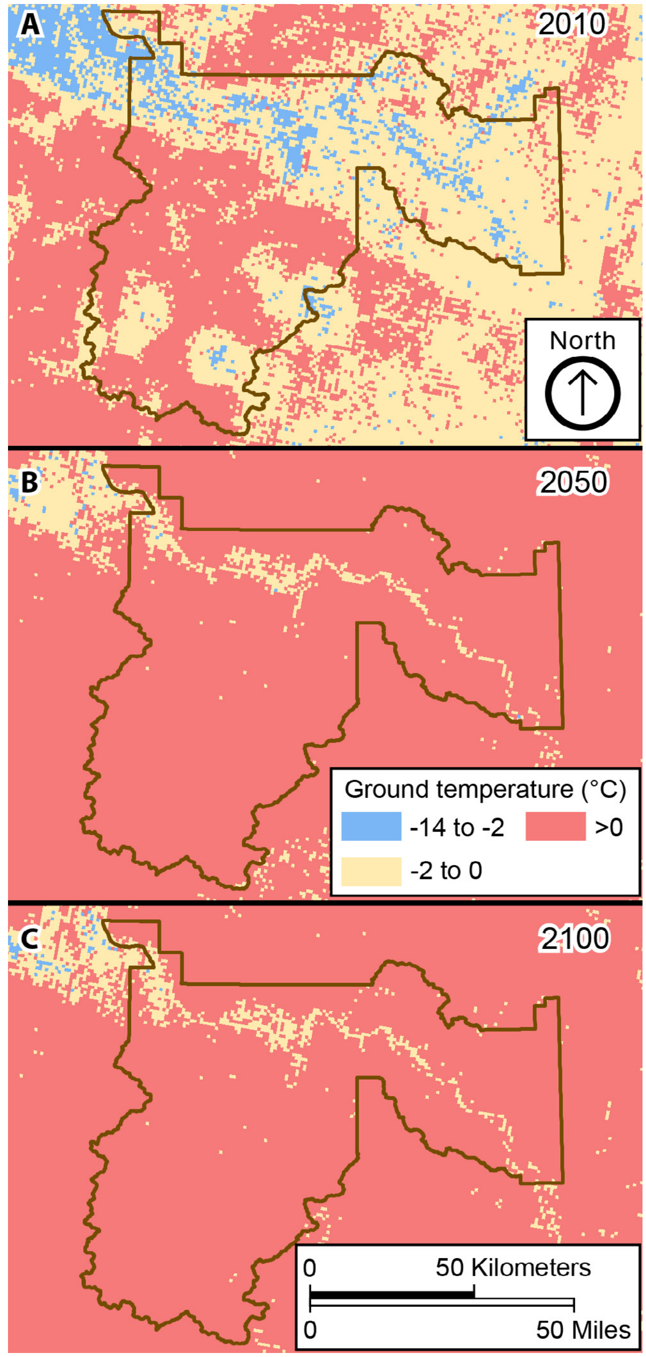


**Figure 30. Permafrost projection maps for the years 2010, 2050, and 2100.**
**These maps are from the GIPL 2.0 model and show projected ground temperatures at 2 m (6.5 ft) depth. (A) Projected ground temperatures for 2010. Some of the southern part of the preserve is projected to have ground temperatures above freezing, but other areas are below freezing. (B) Projected ground temperatures for 2050. Most of the preserve is projected to have ground temperatures above freezing. (C) Projected ground temperatures for 2100. Most of the preserve is projected to have ground temperatures above freezing.**

of permafrost is monitored by measuring active layer thickness and soil surface elevation at four 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).

Thawing permafrost is leading to the development of thermokarst in the preserve. Thermokarst refers to subsidence of the ground due to permafrost thaw, resulting in an irregular landscape. The development of thermokarst is especially likely if the underlying permafrost is ice rich, such as in yedoma deposits. Thermokarst lakes are one of the most visible thermokarst features. These lakes develop in low lying areas, and continued thawing can cause lake areas to expand or even rapidly drain when the edge of the lake is breached. The preserve contains some thermokarst lakes, but they are not as densely abundant as in other areas of northern Alaska where more ice-rich permafrost is thawing (such as the northern coastal plains of Bering Land Bridge National Preserve). Additionally, thermokarst has modified fluvial features in the preserve, such as oxbows.

Permafrost thaw can form erosional and slope movement features such as retrogressive thaw slumps and active-layer detachments. Retrogressive thaw slumps are the most dramatic of these features, consisting of an escarpment that advances up the slope as material thaws; however, none have been identified in the preserve. The preserve does contain active-layer detachments. Active-layer detachments are features that consist of unfrozen material sliding along a slip surface of saturated, fine-grained material that usually develops at the interface between permafrost and the active layer. This results in an exposed area of bare soil with a deformed mat of soil and vegetation at its lower end.

# Guidance for Resource Management

*These references, resources, and websites may be of use to resource managers. The laws, regulations, and policies apply to NPS geologic resources. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), NPS 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).*

To receive geologic resource management assistance, park staff can contact the Alaska Regional Office Natural Resources Team (https://www.nps.gov/orgs/1349/whoweare.htm) or the Geologic Resources Division (GRD; http://go.nps.gov/geology). GRD staff members provide technical and policy support 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; law, policy, and guidance; resource management planning; and data and information management. Park managers can formally request assistance via https://irma.nps.gov/STAR/ (only accessible on DOI network computers).

Park managers can submit a proposal to receive geoscience-focused internships through Scientists in Parks (see https://www.nps.gov/subjects/science/scientists-in-parks.htm). This program places scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. The Geological Society of America and Environmental Stewards are partners of the Scientists in Parks program. The GRD can provide guidance and assistance with submitting a proposal. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring.

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

### Access to GRI Products

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

### Yukon-Charley Rivers National Preserve Documents

The preserve's foundation statement (National Park Service 2012), natural resource condition assessment (Stark et al. 2012), and state of the park report (National Park Service 2017) are primary sources of information for resource management within the preserve.

### NPS Natural Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/upload/MP_2006.pdf
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural Resources Inventory and Monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-century Natural Resource Manager: https://irma.nps.gov/DataStore/Reference/Profile/2283597

### Geologic Resource Laws, Regulations, and Policies

The following table (Table 6), which was developed by the GRD, summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for the protection of a particular resource or when other, more specific laws are not available.

**Table 6. Geologic resource laws, regulations, and policies.**

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

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Paleontological Resources | **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.<br><br>**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.<br><br>**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects.<br><br>**Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa** et seq. provides for the management and protection of paleontological resources on federal lands. | **36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.<br><br>**Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted.<br><br>**43 CFR Part 49** contains the DOI regulations implementing the Paleontological Resources Preservation Act, which apply to the NPS. | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.<br><br>**Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Recreational Collection of Rocks Minerals | **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.<br><br>**Exception: 16 USC. § 445c (c)** – Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone). | **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units.<br><br>**Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown.<br><br>**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. | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. |
| Geothermal | **Geothermal Steam Act of 1970, 30 USC. § 1001** et seq. as amended in 1988, states<br>-No geothermal leasing is allowed in parks.<br>-"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).<br>-NPS is required to monitor those features.<br>-Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects.<br><br>**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. | **43 CFR Part 3200** These regulations require 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. | **Section 4.8.2.3** requires NPS to<br>-Preserve/maintain integrity of all thermal resources in parks.<br>-Work closely with outside agencies.<br>-Monitor significant thermal features. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Mining Claims (Locatable Minerals) | **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.<br><br>**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.<br><br>**Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities. | **36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law.<br><br>**36 CFR Part 6** regulates solid waste disposal sites in park units.<br><br>**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.<br><br>**43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska. | **Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A.<br><br>**Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries. |
| Nonfederal Oil and Gas | **NPS Organic Act, 54 USC § 100751** et seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).<br><br>**Individual Park Enabling Statutes**:<br>16 USC § 230a<br>(Jean Lafitte NHP & Pres.)<br>16 USC §450kk<br>(Fort Union NM),<br>16 USC § 459d-3<br>(Padre Island NS),<br>16 USC § 459h-3<br>(Gulf Islands NS),<br>16 USC § 460ee<br>(Big South Fork NRRA),<br>16 USC § 460cc-2(i)<br>(Gateway NRA),<br>16 USC § 460m<br>(Ozark NSR),<br>16 USC§698c<br>(Big Thicket N Pres.),<br>16 USC §698f<br>(Big Cypress N Pres.) | **36 CFR Part 6** regulates solid waste disposal sites in park units.<br><br>**36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights in parks outside of Alaska to<br>-demonstrate valid right to develop mineral rights;<br>-submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations;<br>-prepare/submit a reclamation plan; and<br>-submit financial assurance to cover reclamation and potential liability.<br><br>**43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska. | **Section 8.7.3** requires operators to comply with 9B regulations. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Federal Mineral Leasing (Oil, Gas, and Solid Minerals) | **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.<br><br>**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 GLCA, which is the only park unit that contains a STSA.<br><br>**Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes 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.<br><br>**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.<br><br>**Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units. | **36 CFR § 5.14** states prospecting, mining, and… leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law.<br><br>**BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing.<br><br>Regulations re: Native American Lands within NPS Units:<br>**25 CFR Part 211** governs leasing of tribal lands for mineral development.<br>**25 CFR Part 212** governs leasing of allotted lands for mineral development.<br>**25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development.<br>**25 CFR Part 224** governs tribal energy resource agreements.<br>**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).<br>**30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases.<br>**30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases.<br>**30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases.<br>**30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases.<br>**43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. | **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. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Transpark Petroleum Product Pipelines | **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:<br>● Natchez Trace Parkway (16 USC §460a);<br>● Blue Ridge Parkway (16 USC §460a-8);<br>● Great Smoky Mountains National Park (P.L. 107-223 – 16 U.S.C. §403 notes);<br>● Klondike Gold Rush (16 USC §410bb(c) (limited authority for the White Pass Trail unit);<br>● 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);<br>● 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)).<br>● 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) | **NPS regulations at 36 CFR Part 14 Rights of Way** | **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. |
| Nonfederal minerals other than oil and gas | NPS Organic Act, 54 USC §§ 100101 and 100751 | **NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. | **Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Coal | **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201** et. seq. prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights. | **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. | None applicable. |
| Uranium | **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. | None applicable. | None applicable. |
| Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.) | **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.<br><br>**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.<br><br>**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. | None applicable. | **Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and:<br>-only for park administrative uses;<br>-after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment;<br>-after finding the use is park's most reasonable alternative based on environment and economics;<br>-parks should use existing pits and create new pits only in accordance with park-wide borrow management plan;<br>-spoil areas must comply with Part 6 standards; and<br>-NPS must evaluate use of external quarries.<br><br>Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Abandoned Mineral Lands and Orphaned Oil and Gas Wells | 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. | None applicable. | None applicable. |
| Coastal Features and Processes | **NPS Organic Act, 54 USC § 100751** et. seq. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).<br><br>**Coastal Zone Management Act, 16 USC § 1451** et. seq. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone.<br><br>**Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit.<br><br>**Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs.<br><br>**Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. | **36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands.<br><br>**36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. | **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress.<br><br>**Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.<br><br>**Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties.<br><br>**Section 4.8.1.1** requires NPS to:<br>-Allow natural processes to continue without interference,<br>-Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions,<br>-Study impacts of cultural resource protection proposals on natural resources,<br>-Use the most effective and natural-looking erosion control methods available, and<br>-Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present. |

**Table 6, continued. Geologic resource laws, regulations, and policies.**

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

**Table 6, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | NPS Management Policies 2006 |
|---|---|---|---|
| Soils | **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.<br><br>**Farmland Protection Policy Act, 7 USC § 4201** et. seq. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS). | **7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements. | **Section 4.8.2.4** requires NPS to<br>-prevent unnatural erosion, removal, and contamination;<br>-conduct soil surveys;<br>-minimize unavoidable excavation; and<br>-develop/follow written prescriptions (instructions). |
| Geologic Hazards | **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 | None applicable. | **Section 4.8.1.3**, Geologic Hazards<br>**Section 9.1.1.5**, Siting Facilities to Avoid Natural Hazards<br>**Section 8.2.5.1**, Visitor Safety<br><br>**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. |

## Additional References, Resources, and Websites

*Geology of Alaska*

- 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 (Minerals) Resource Data File: https://ardf.wr.usgs.gov/index.php
- Alaska Division of Geological & Geophysical Surveys (and Alaska USGS) publications: https://dggs.alaska.gov/pubs/pubs

*NPS Geology*

- NPS Alaska Nature and Science, Active Geology: https://www.nps.gov/subjects/aknatureandscience/activegeology.htm

- NPS Alaska Nature and Science, Geohazards: https://www.nps.gov/subjects/aknatureandscience/geohazards.htm
- Alaska National Parks, Geology (interactive 3D models): https://sketchfab.com/alaska_nps_geology
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Division: https://go.nps.gov/grd
- NPS Geologic Resources Inventory: https://go.nps.gov/gri
- NPS Geology Subject Site: https://go.nps.gov/geology
- NPS Geoscience Concepts: https://www.nps.gov/subjects/geology/geology-concepts.htm
- NPS Glossary of Geologic Terms: https://www.nps.gov/subjects/geology/gri-glossary-of-geologic-terms.htm
- NPS Scientists in Parks: https://www.nps.gov/subjects/science/scientists-in-parks.htm

### *Climate Change Resources*

- Intergovernmental Panel on Climate Change: https://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 15-01 Addressing Climate Change and Natural Hazards for Facilities: https://www.nps.gov/subjects/policy/upload/PM_15-01.pdf
- NPS Sea Level Rise Map Viewer: https://maps.nps.gov/slr/
- US Global Change Research Program: https://www.globalchange.gov/home

### *Geologic Heritage*

- NPS America's Geologic Heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- UNESCO Global Geoparks: https://www.unesco.org/en/iggp/geoparks/about

### *Geologic Maps*

- American Geosciences Institute (provides information about geologic maps and their uses): https://www.americangeosciences.org/environment/publications/mapping
- *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 Geological Society: https://www.alaskageology.org/
- Alaska Volcano Observatory: https://avo.alaska.edu/
- American Geophysical Union: https://www.agu.org/
- American Geosciences Institute: https://www.americangeosciences.org/
- Association of American State Geologists: https://www.stategeologists.org/
- Geological Society of America: https://www.geosociety.org/
- US Geological Survey: https://www.usgs.gov/

### *Landslides and Slope Movements*

- The GRD employs three rockfall management strategies: (1) an Unstable Slope Management Program (USMP) for transportation corridor risk reduction; (2) quantitative risk estimation for specific rockfall hazards; and (3) monitoring of potential rockfall areas. Park managers can contact the GRD to discuss these options and determine if submitting a technical assistance request is appropriate.
- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): https://go.nps.gov/geomonitoring
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): https://pubs.usgs.gov/circ/1325/

### *NPS Reference Tools*

- NPS Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loans): https://pubs.nps.gov/
- 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 the 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.

*Relevancy, Diversity, and Inclusion*

- NPS Office of Relevancy, Diversity and Inclusion: https://www.nps.gov/orgs/1244/index.htm
- Changing the narrative in science & conservation: an interview with Sergio Avila (Sierra Club, Outdoor Program coordinator). Science Moab radio show/podcast: https://sciencemoab.org/changing-the-narrative/

*Soil*

- 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

*USGS Reference Tools*

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): https://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/us-board-on-geographic-names/domestic-names
- GeoPDFs (download PDFs of any topographic map in the United States): https://store.usgs.gov/ (click on "Map Locator")
- National Geologic Map Database (NGMDB): https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Tapestry of Time and Terrain (descriptions of physiographic provinces): https://pubs.usgs.gov/imap/i2720/
- USGS Publications Warehouse (many publications available online): https://pubs.usgs.gov/

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