National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Lake Clark National Park and Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2021/2331

ON THE COVER
Photograph of Iliamna Volcano with Lateral Glacier flowing down its flank towards a broad outwash plain along the Johnson River.
NPS photograph by Buck Mangipane.

THIS PAGE
Photograph of Lower Twin Lake nestled behind volcanic rocks of the Meshik Arc.
NPS photograph by T. Vaughn

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National Park Service
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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 received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

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 information, geologic expertise, or means to complete such an undertaking. 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.

Lake Clark National Park and Preserve, hereafter also referred to as "the park," is situated on the geologically active southern margin of Alaska where the oceanic Pacific plate is subducting beneath the continental North American plate. This subduction zone and the tectonic deformation associated with it is responsible for many of the geologic features and processes in the park. The descent of the Pacific plate into the mantle creates volcanoes of the Aleutian volcanic arc, including the park's active Redoubt and Iliamna Volcanoes. Movement along the boundary between the upper and lower plates generates frequent earthquakes in the region, including large megathrust earthquakes such as the 1964 Great Alaska Earthquake. Tectonic stress associated with subduction is responsible for the formation of the Cook Inlet fore-arc basin, which includes the modern marine system of Cook Inlet. The park's mountains are a result of subduction-related compression and volcanism. These mountains provide a barrier to moisture-laden air from the Gulf of Alaska and consequently are centers of glacier formation, both now and during past glacial periods when glaciers were more extensive.

The bedrock that underlies the park is also intimately tied to subduction and volcanism. Most of the park's bedrock is associated with the ancient Talkeetna volcanic arc, formed through the subduction of one oceanic plate beneath another. Between 213 million and 164 million years ago, rocks of the Talkeetna arc formed far off the coast of Alaska in the proto-Pacific Ocean. Subsequent tectonic movement transported these rocks to their present location in southcentral Alaska. Paleontological resources record the creatures that lived on and around the Talkeetna arc. Some of the bedrock in and around the park contains minerals and hydrocarbons that were developed in the past and continue to be explored today.

This GRI report consists of the following chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI, highlights the GRI process and products, and recognizes collaborators. Two geologic maps, one surficial and one bedrock map, in GIS format are the principal deliverable of the GRI. This chapter highlights the source maps used by the GRI team in compiling the GRI GIS data for the park and provides specific information about the use of these data. It also calls attention to the posters that illustrate these data.

Geologic Setting and Significance—This chapter describes the regional geologic setting of Lake Clark National Park and Preserve and summarizes connections among geologic resources, other park resources, and park stories.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance for Lake Clark National Park and Preserve. The features and processes discussed are volcanoes, bedrock geology, faults and folds, mineral resources, paleontological resources, glacial features and modern changes, past glaciations, Lake Clark water level history, permafrost, and coastal features and change.

Geologic History—This chapter describes the geologic events that formed the present landscape. The geologic events are discussed in chronological order, starting in the Triassic Period (251.9 million–201.3 million years ago) and ending with modern active geologic processes.

Geologic Resource Management Issues—This chapter discusses management issues related to Lake Clark National Park and Preserve's geologic resources, features, and processes. Issues discussed are geohazards; mineral development potential; abandoned mineral lands mitigation; paleontological resources inventory, monitoring, and protection; glacier monitoring; and coastal issues. Geologic resource management guidance is also provided to resource managers with a variety of ways to find and receive management assistance with geologic resources.

Literature Cited—This chapter is a bibliography of references cited in this GRI report. Many of the cited references are available online, as indicated by an Internet address included as part of the reference citation. Park staff may contact the GRI team for more information about literature cited in this report.

Additional References—This chapter lists additional references, resources, and websites that may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Appendices—This report includes two appendices: Appendix A and Appendix B. Appendix A is a summary of the early history of geologic exploration in the Lake Clark area, prior to 1961. Appendix B contains a table of 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 protection of a particular resource or when more specific laws are not available.

Introduction to the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) 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, which is administered by the Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate, is one of 12 inventories funded by the NPS Inventory and Monitoring Program. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team, which is a collaboration between staff at the National Park Service (NPS) and Colorado State University's Department of Geosciences, completed three tasks as part of the GRI for Lake Clark National Park and Preserve: (1) conducted a scoping meeting and provided a scoping summary, (2) provided digital geologic map data in a geographic information system (GIS) and poster formats, and (3) 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 from the unit list. Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

GRI Scoping Meeting

On 14-18 February 2005, the National Park Service held a scoping meeting in Anchorage, Alaska. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (Graham 2005) summarizes the findings of that meeting.

GRI GIS Data and Posters

Following the scoping meeting, the GRI team compiled the bedrock and surficial GRI GIS data for Lake Clark National Park and Preserve from source maps. Two geologic map posters illustrate these data. Because these data are the principal deliverable of the GRI, a more detailed description of the product is provided in the "Geologic Map Data" section of this chapter.

GRI Report

On 26 September 2018, the GRI team hosted a follow-up conference call for park staff. The call provided an opportunity to get back in touch with park staff, introduce "new" (since the 2005 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.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2005, the follow-up conference call in 2018, and additional geologic research. The selection of geologic features was guided by the previously completed GRI map data, and writing reflects the data and interpretation of the source map author.

Use Constraints

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

Geologic Map Data

A geologic map is the fundamental tool for depicting the geology of an area. A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter.

Introduction to Geologic Maps

Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Geologic maps are generally one of two types: bedrock or surficial. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, or igneous rocks. Bedrock map units are generally differentiated based on age and rock type. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period). Geomorphic surfaces, geologic process, or depositional environment differentiate surficial geologic map units. The GRI GIS data for the park includes both a bedrock and surficial geologic map.

The colors on a geologic map indicate the rocks or deposits and their ages. In addition to color, map unit symbols delineate rocks on geologic maps. Usually, a map unit symbol consists of an uppercase letter indicating age (e.g., **K** for Cretaceous and **Q** for Quaternary) and lowercase letters indicating the rock formation's name or the type of deposit. Other symbols on geologic maps depict the contacts between map units or structures such as faults or folds. Some map units, such as mudflow deposits, delineate locations of past geologic hazards, which may be susceptible to future activity. Geologic maps may also show human-made features, such as sample locations, wells, or mines.

GRI Geologic Map Posters

Two posters of the GRI GIS data of Lake Clark National Park and Preserve and surrounding area are the primary figures referenced in this GRI report. Throughout the report, the bedrock map poster will be referred to as "bedrock poster" and the surficial map poster will be referred to as "surficial poster." Map unit symbols listed at the beginning of sections in this report indicate which map units will be discussed in that section. Map unit symbols are also cited within the text.

The posters are not a substitute for the GRI GIS data but are 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 posters (Table 1; Table 2). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

The map unit colors on the bedrock map poster are different from the unit colors in the bedrock GRI GIS data. The colors were simplified to make the map more legible in a poster format. Additionally, some of the map units in the bedrock GRI GIS data have been grouped together on the bedrock poster and given new map unit symbols. This was done to decrease the number of units in the legend on the poster and tell a simpler visual story. Map units grouped together on the bedrock poster include surficial units that are displayed in detail on the surficial map poster. See Table 3 for a correlation of the GRI GIS data map units to the simplified map units on the poster.

The posters are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS IRMA portal https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.

Use Constraints

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

Table 1. Bedrock GRI GIS data layers for Lake Clark National Park and Preserve.

Data Layer	On Poster?	Google Earth Layer?
Geologic Sample Localities	No	No
Glacial Feature Lines	No	Yes
Geologic Line Features	No	Yes
Volcanic Feature Lines	No	Yes
Alteration and Metamorphic Area Boundaries	No	No
Alteration and Metamorphic Areas	No	No
Faults	Yes	Yes
Linear Dikes	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Table 2. Surficial GRI GIS data layers for Lake Clark National Park and Preserve.

Data Layer	On Poster?	Google Earth Layer?
Glacial Feature Lines	Yes	Yes
Volcanic Line Features	No	Yes
Alteration and Metamorphic Area Boundaries	No	No
Alteration and Metamorphic Areas	No	No
Faults	Yes	Yes
Surficial Contacts	No	No
Surficial Units	Yes	Yes

Table 3. Correlation of simplified map units on the bedrock poster to detailed map units in the bedrock GRI GIS data.

Map unit on bedrock poster	Map units in bedrock GRI GIS data
Qld – Lacustrine deposits (Quaternary)	**Ql** – Lacustrine deposits (Quaternary), **Qsw** – Swamp deposits (Quaternary), **Qgl** – Glaciolacustrine deposits (Quaternary)
Qlc – Landslides and colluvium (Quaternary)	**Qc** – Colluvium (Quaternary), **Qls** – Landslide deposits (Quaternary)
Qaud – Alluvium and undifferentiated deposits (Quaternary)	**Qa** – Alluvium (Quaternary), **Qaf** – Alluvial Fan and talus deposits (Quaternary), **Qd** – Dune deposits (Quaternary), **Qs** – Surficial deposits, undifferentiated (Quaternary), **Qt** – Terrace deposits (Quaternary), **Qsu** – Silt deposits, undifferentiated (Quaternary), **Qac** – Abandoned channel deposits (Quaternary)
Qvd – Volcanic deposits (Quaternary)	**Qhv** – Holocene volcanic rocks (Quaternary), **Qafd** – Ash and tephra deposits (Quaternary), **Qmf** – Mudflow deposits (Quaternary), **Qav** – Volcanic avalanche deposits (Quaternary), **Qdf** – Debris-flow deposits (Quaternary), **Qlv** – Natural levee deposits (Quaternary), **Qv** – Volcanic rocks, undivided (Quaternary), **Qpd** – Pyroclastic (ash and debris flow) deposits (Quaternary), **Qanp** – Andesite plug domes (Quaternary), **QTi** – Intrusive rocks (Quaternary and Tertiary), **QTv** – Quaternary and/or Tertiary volcanic rocks, undifferentiated (Pleistocene or Pliocene)
Qmd – Marine deposits (Quaternary)	**Qtf** – Tidal flat and estuarine deposits (Quaternary), **Qb** – Beach deposits (Quaternary), **Qes** – Estuarine deposits (Quaternary), **Qmt** – Marine terrace deposits (Quaternary), **Qge** – Glacio-estuarine deposits (Quaternary), **Qdl** – Deltaic deposits (Quaternary)
Qgd – Glacial deposits (Quaternary)	**Qrg** – Rock glacier deposits (Quaternary), **Qsf** – Solifluction deposits (Quaternary), **Qhg** – Drift, neoglaciation (Quaternary), **Qho** – Outwash deposits, neoglaciation (Quaternary), **Qbld** – Drumlin deposits in ground moraine fields of Brooks Lake glacial deposits (late Quaternary), **Qm** – Glacial deposits, undivided (Quaternary), **Qwu** – Drift, undivided, Late Wisconsin-age glaciations (Quaternary), **Qsg** – Superglacial drift (Quaternary), **Qek** – Esker deposits (Quaternary), **Qoc** – Channeled glacial deposits, kame and kettle (Quaternary), **Qgme** – Ground moraine modified by estuarine water (Quaternary), **Qewd** – Drumlins associated with early glaciations (Quaternary), **Qmi** – Illinoian glaciations (Quaternary), **Qmio** – Outwash older than Wisconsin-age (Quaternary), **Qsb** – Scoured bedrock (Quaternary), **Qglf** – Glacial outwash derived fans deposited in ephemeral glacial lakes (Quaternary), **Qwr** Glacial deposits, latest Wisconsin, Iliuk, Riley Creek, and other glaciations (Quaternary), **Qw2** – Late Wisconsin, Newhalen and other till (Quaternary), **Qw1** – Late Wisconsin, Iliamna and other till (Quaternary), **Qw0** – Till, Brooks Lake, Kvichak (Quaternary), **Qwo** – Outwash deposits, late Wisconsin-age glaciations (Quaternary), **Qew** – Glaciations older than Late Wisconsin (Quaternary), **Qmhg** – Early Wisconsin (Mak Hill and Iowithla) ground moraine (Quaternary), **Qow** – Older Wisconsin age outwash (Quaternary), **QTod** – Deposits related to but peripheral to older glaciations (Quaternary or late Tertiary, Pliocene)

Source Maps

The GRI team does not conduct original geologic mapping. Scoping participants and the GRI team identify the best available geologic maps for a park unit. Determinations are made based on coverage (extent or area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area. The GRI team then compiles and converts digital data to conform to the GRI GIS data model and digitizes paper maps. The GRI team may compile multiple source maps to cover a park boundary or provide a greater extent as needed for resource management. The source map publications also provided information for this report.

The following maps were compiled into the bedrock GRI GIS data for Lake Clark National Park and Preserve:

- Geologic Map of Alaska (Wilson et al. 2015)
- Alaska Resource Data File: Dillingham Quadrangle, Alaska (Hudson 2001)
- Alaska Resource Data File: Kenai Quadrangle, Alaska (Huber 1999)
- Alaska Resource Data File: Lime Hills Quadrangle, Alaska (Hudson and Millholland 2002)
- Alaska Resource Data File: Tyonek Quadrangle, Alaska (Millholland and Riehle 1998)
- Alaska Resource Data File: Lake Clark Quadrangle, Alaska (Bickerstaff 1998)
- Alaska Resource Data File: Taylor Mountains Quadrangle, Alaska (Hudson 2001)
- Alaska Resource Data File: Iliamna Quadrangle, Alaska (Hawley 2004)
- Alaska Resource Data File, New and Revised Records Version 1.6 (U. S. Geological Survey 2008)

The following map is the source of the surficial GRI GIS data for Lake Clark National Park and Preserve:

- Quaternary Geologic Map of Lake Clark National Park and Preserve; Western Alaska Range, Alaska (Wilson et al. 2009)

The source data above consists of digital geologic datasets of the following quadrangles:

  - Tyonek 1 x 3 Quadrangle
  - Lime Hills 1 x 3 Quadrangle
  - Kenai 1 x 3 Quadrangle
  - Lake Clark 1 x 3 Quadrangle
  - Taylor Mountains 1 x 3 Quadrangle
  - Seldovia 1 x 3 Quadrangle
  - Iliamna 1 x 3 Quadrangle
  - Dillingham 1 x 3 Quadrangle

GRI Geodatabase Model and Data Set

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Lake Clark National Park and Preserve was compiled using data model version 2.3, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software.

The GRI GIS Data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS IRMA portal https://irma.nps.gov. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the bedrock GRI GIS data set for the Lake Clark National Park and Preserve:

- A GIS readme file (lacl_geology_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- A Frequently Asked Questions (FAQ) metadata file (lacl_geology_metadata_faq.pdf);
- Data in ESRI geodatabase GIS format (lacl_geology.gbd);
- Layer files with feature symbology (Table 1);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (lacl_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- An ESRI map document (lacl_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (lacl_geology.kmz) and associated metadata (lacl_geology_metadata.txt).

The following components are part of the surficial GRI GIS data set for the Lake Clark National Park and Preserve:

- A GIS readme file (lacl_geology_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- A Frequently Asked Questions (FAQ) metadata file (lacl_surficial_geology_metadata_faq.pdf);

- Data in ESRI geodatabase GIS format (lacl_surficial_geology.gdb);
- Layer files with feature symbology (Table 2);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (lacl_surficial_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- An ESRI map document (lacl_surficial_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (lacl_surficial_geology.kmz) and associated metadata (lacl_surficial_geology_metadata.txt).

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This compilation could not have been accomplished without the research produced by countless scientists working in the Lake Clark area for over a century. We are extremely appreciative to those who took the time to share their expertise with us and provide feedback that greatly increased the quality of this report. The GRI team would like to thank our reviewers Jamey Jones (US Geological Survey Alaska Science Center, research geologist) Tim Orr (US Geological Survey Alaska Volcano Observatory, geologist), and Marwan Wartes (Alaska Division of Geological & Geophysical Surveys, geologist). Thank you to Chad Hults (NPS Alaska Regional Office, regional geologist) for providing consistent guidance, encouragement, and feedback throughout the writing process. Additional thanks goes to Sarah Venator (NPS Alaska Regional Office, geologist) and Kyle Hinds (NPS Geologic Resources Division, AML mining engineer) for reviewing the minerals and Abandoned Mineral Lands sections; Tahzay Jones (NPS Alaska Regional Office, coastal oceans coordinator) for reviewing the coastal sections; Justin Tweet (NPS Geologic Resources Division, paleontologist) for reviewing the paleontology sections; Eric Bilderback (NPS Geologic Resources Division, geomorphologist) for reviewing the geohazards section; and Jack Wood (NPS Geologic Resources Division, physical scientist) for reviewing the coastal and geohazard sections.

We would also like to thank the participants of the 2005 scoping meeting and 2019 follow-up conference call for their assistance in this inventory. The lists of participants (below) reflect the names and affiliations of these participants at the time of the meeting and call. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the US Geological Survey (USGS) for its maps of the area. This report and accompanying GIS data could not have been completed without them. Thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing some of the figures in this report and to Katie KellerLynn (Colorado State University) for developing standard report content and organization.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Lake Clark National Park and Preserve and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment

Lake Clark National Park and Preserve (Figure 1), also referred to as “the park” throughout this report, was established by the passage of the Alaska National Interest Lands Conservation Act (ANILCA) on 2 December 1980. The park was established to protect a region of dynamic geologic and ecological processes that create scenic mountain landscapes, unaltered watersheds supporting the largest sockeye salmon run in the world, and habitats for wilderness-dependent populations of fish and wildlife. The park contains two active volcanoes and protects a complex mosaic of landforms and ecosystems that continue to evolve due to dynamic tectonic, volcanic, glacial, and climatic processes. Finally, the park protects a tapestry of cultural places woven from 10,000 years of human habitation that is vital to the cultural and spiritual continuation of the Dena’ina people.

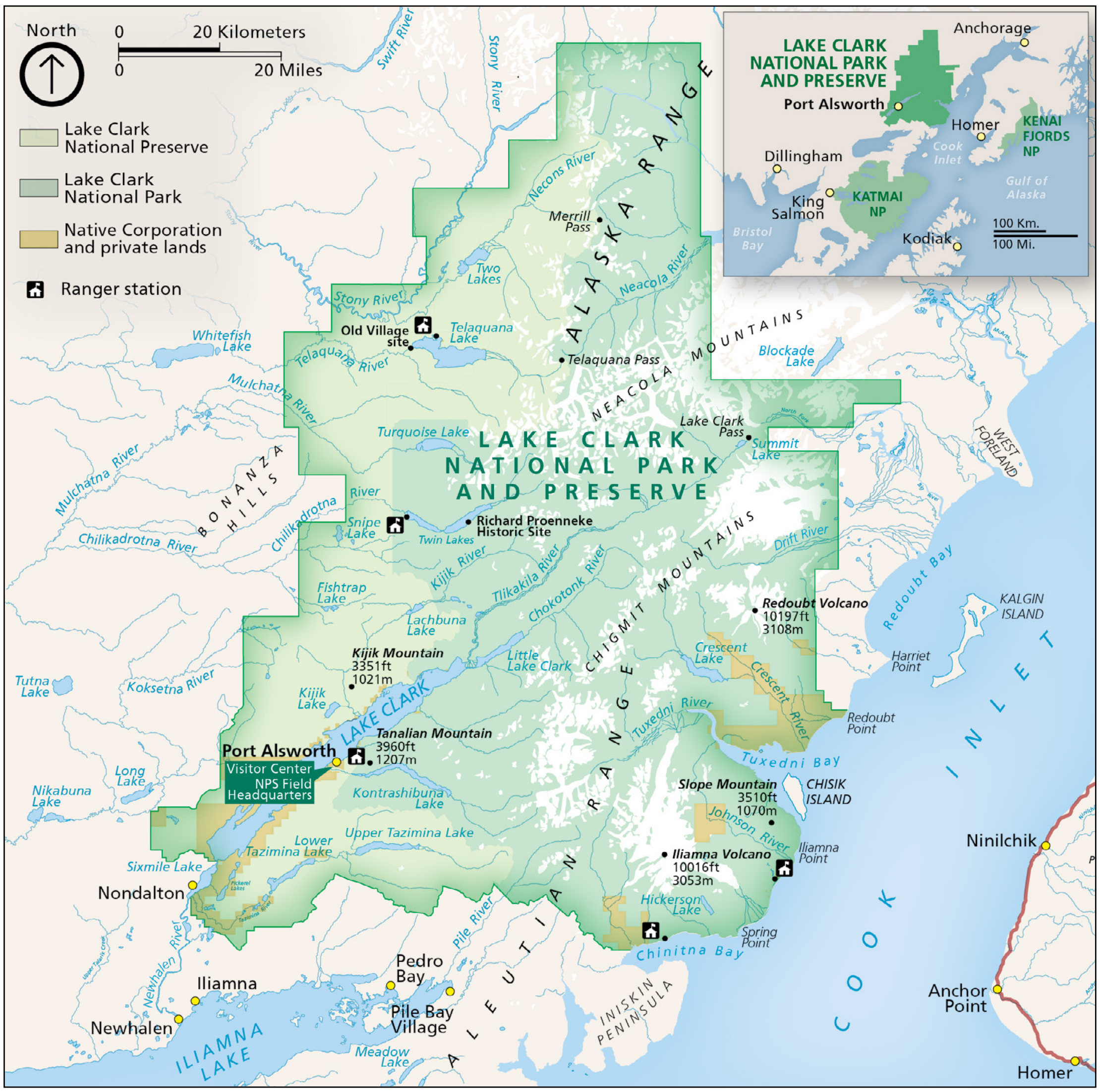


Figure 1. Geographic map of Lake Clark National Park and Preserve and the surrounding area. The park is on the west side of Cook Inlet, about 160 km (100 mi) southwest of Anchorage (see inset map). The park encompasses a landscape characterized by jagged mountains, active volcanoes, and glacially fed rivers and lakes that support the largest sockeye salmon fishery in the world. The park's headquarters and visitor center are in the town of Port Alsworth, on the southern shore of Lake Clark. Other communities close to the park include Nondalton, Iliamna, Newhalen, Pedro Bay, and Pile Bay Village on the west side of Cook Inlet, and Ninilchik, Anchor Point, and Homer on the east side of Cook Inlet.

Lake Clark National Park and Preserve is in southwestern Alaska, approximately 160 km (100 mi) southwest of Anchorage (Figure 1). The 16-thousand-square kilometer (4-million-acre) park stretches from the Bristol Bay lowlands to the western coast of Cook Inlet and encompasses parts of the Alaska and Aleutian mountain ranges, including the Chigmit and Neacola subranges. The park contains two active volcanoes, Redoubt and Iliamna Volcanoes. The volcanoes form the two tallest peaks in the park. As of 2008, approximately 14% of the park was covered by glaciers; glacier coverage is undoubtably smaller today, but glaciers still represent a significant part of the park's landscape. Glaciers radiate down from the mountainous areas to feed a series of rivers and lakes, some of which support the spawning area for the Bristol Bay sockeye salmon fishery. The park contains three wild and scenic rivers: the Chilikadrotna River, Mulchatna River, and Tlikakila River. Most of the park's lakes occur in the western lowlands. The largest of these lakes is Lake Clark, for which the park is named. For the most part, the park's lakes were formed by glacial erosion, but Lake Clark also occurs along the trace of the Lake Clark Fault (see the bedrock poster).

The park's visitor center and field headquarters are in the town of Port Alsworth, located on private land on the southern shore of Lake Clark (Figure 1). According to the 2010 census, Port Alsworth has a population of 159. The park's administrative headquarters are in Anchorage. Some of the most visited areas in the park include Port Alsworth and the surrounding area, the historic Proenneke cabin on Upper Twin Lake, and the Cook Inlet coast. Popular activities include hiking, camping and backpacking, boating, wildlife viewing, fishing, and hunting. Park visitation estimates have exceeded 10,000 visitors annually since 2012. In 2019, the park received an estimated 17,157 visitors (https://irma.nps.gov/STATS/).

Geologic Setting

Lake Clark National Park and Preserve is on the upper tectonic plate of the Aleutian-Alaska subduction zone. The Aleutian-Alaska subduction zone is where the oceanic Pacific plate is subducting beneath the continental North American plate (Figure 2). The boundary between the plates is a fault called the Aleutian megathrust and is the focus of frequent earthquakes. Some of these earthquakes can be very large and cause tsunamis. Earthquake epicenters get progressively deeper with increasing distance from the subduction zone trench, which traces the descent of the Pacific plate beneath Alaska (Figure 3).

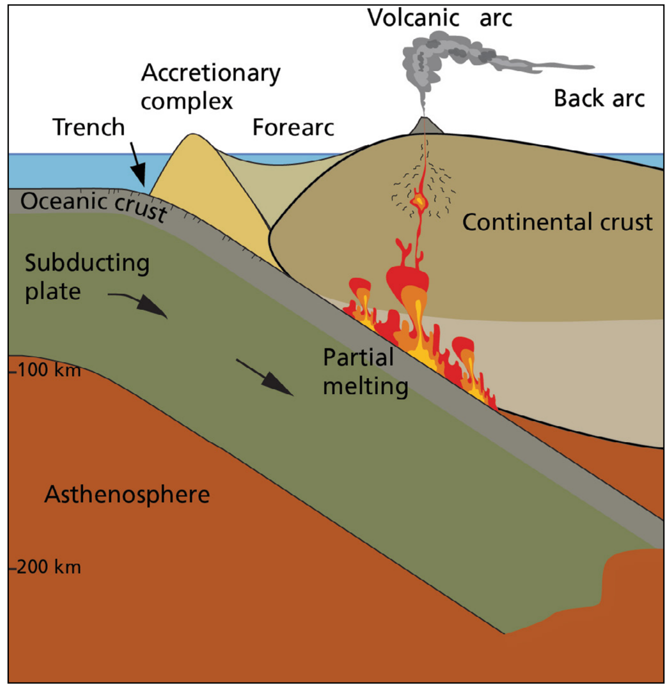


Figure 2. Cross-sectional diagram of a subduction zone.
The volcanoes within the park are part of the Aleutian volcanic arc, which is generated by subduction of the oceanic Pacific plate beneath the continental North American plate. Water from the subducting plate reacts with the dry mantle beneath the continental crust, which causes melt to form and rise into the overlying crust. Volcanoes form where this melt, or magma, reaches the surface of the Earth and erupts as lava or ash. A forearc basin, such as the Cook Inlet Basin, is a low-lying region of deposition that forms between the subduction trench and volcanic arc. Kilometers marked on the left indicate depth. Modified from original graphic provided by Trista L. Thornberry-Ehrlich (Colorado State University).

The volcanoes in the Lake Clark area are part of the Aleutian volcanic arc, which spans 2,500 km (1,600 mi) from the Cook Inlet to the far western Aleutian Islands (Figure 3). As the Pacific plate descends into the mantle, water contained within the subducting plate is released and causes the overlying mantle wedge to partially melt. The resulting melt coalesces into magma. This magma buoyantly rises into the crust where it forms magma chambers that crystallize into plutons or batholiths. Some magma continues to rise through the crust to feed volcanoes or form other volcanic features. The arrays of volcanoes above active subduction zones commonly form an arc parallel to the plate boundary, and these features are collectively called a volcanic arc.

The sedimentary rocks in the southeastern part of the park and the modern marine system of Cook Inlet are both part of a larger, long-lived fore-arc basin called Cook Inlet Basin (Figure 2). Cook Inlet Basin has persisted through a complex history of tectonic events that included the generation and erosion of two volcanic arcs: the ancient Talkeetna volcanic arc and the modern Aleutian volcanic arc (Figure 4). The Talkeetna volcanic arc was active during the late Triassic and Jurassic (between 213 million and 164 million years ago). Many of the rocks in the park are either igneous rocks that formed as part of the arc itself (e.g. Talkeetna Formation and Alaska-Aleutian Range batholith) or sedimentary rocks that were eroded from the arc and deposited in the adjacent Cook Inlet Basin (e.g. Tuxedni Group, Chinitna Formation, and Nakanek Formation). Today, Cook Inlet Basin is situated in front of the modern Aleutian volcanic arc and is receiving sediments from the surrounding mountains. Cook Inlet Basin stretches from Shelikof Strait in the southwest to the Matanuska Valley in the northeast. The park is within the Cook Inlet segment of the basin, which contains significant hydrocarbon resources. Oil and gas have been extracted in Cook Inlet since the 1950s and continues to be developed today (LePain et al. 2013).

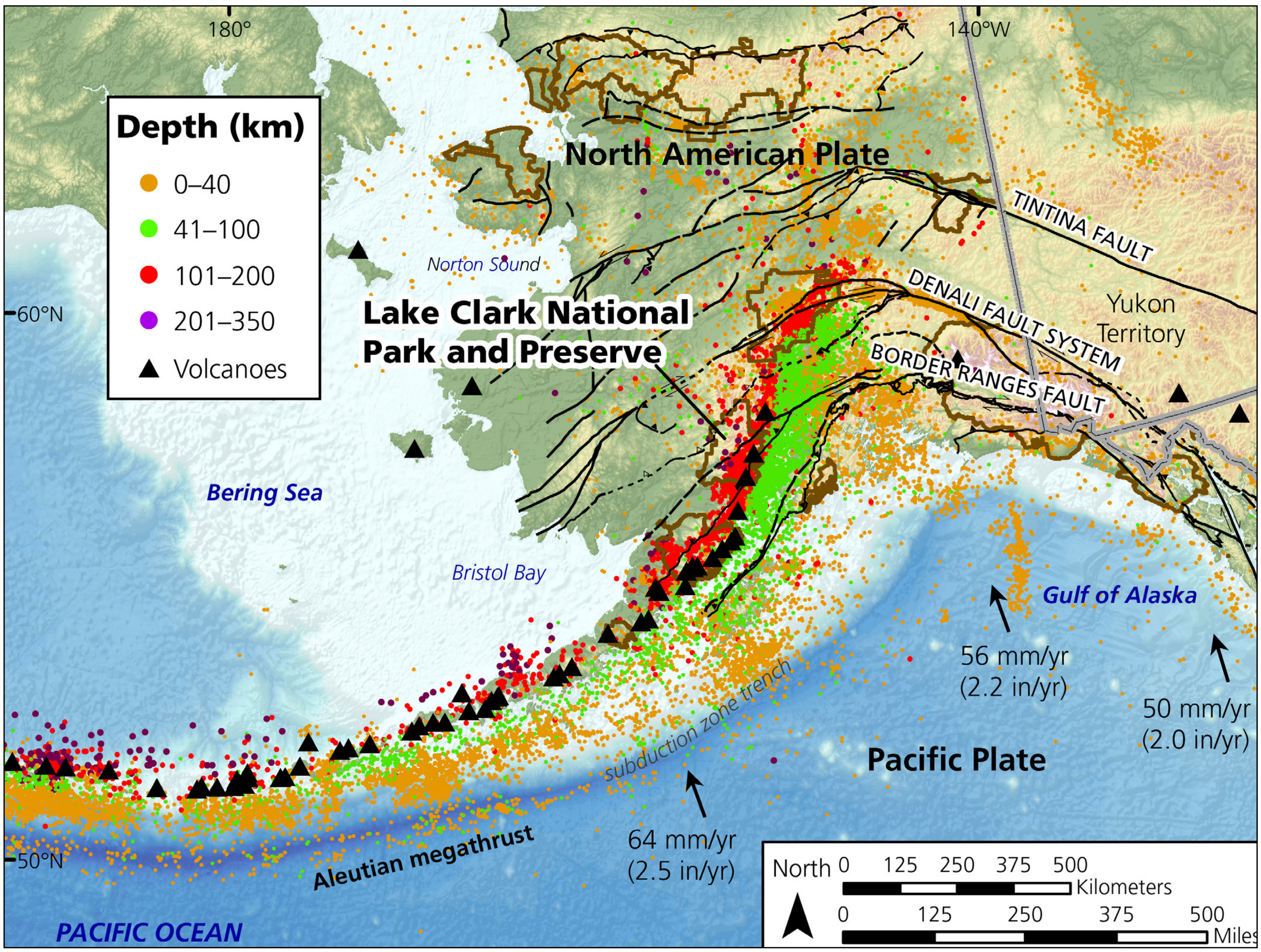


Figure 3. Map of earthquake epicenters in Alaska.
The map shows earthquakes greater than magnitude 3.0, colored by depth (1889 to 2015). Earthquakes get progressively deeper with increasing distance from the subduction zone trench, which traces the descent of the Pacific plate beneath Alaska. The Aleutian volcanic arc (black triangles) is on top of the subduction zone where the Pacific plate reaches a depth of 100 km (60 mi; where the earthquake epicenters transition from red to purple). The Pacific plate motion is shown with arrows. NPS areas outlined in brown. Earthquake data downloaded from http://www.aeic.alaska.edu (accessed 1 January 2015).

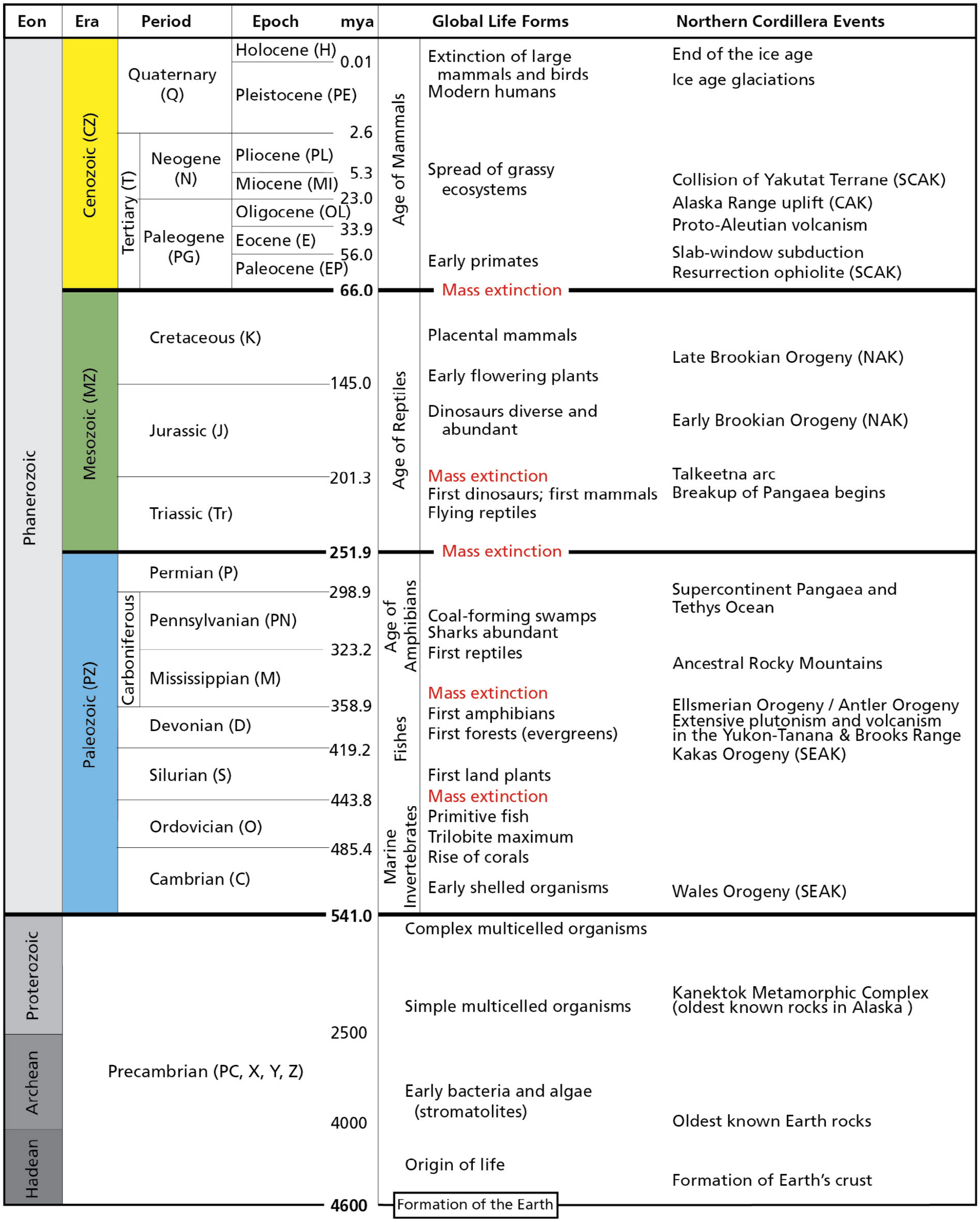


Figure 4. Geologic time scale.
The time scale shows the onset of major global evolutionary and tectonic events of the North American continent and the Northern Cordillera (SCAK, south-central Alaska; SEAK, southeast Alaska; NAK, northern Alaska; CAK central Alaska). The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Ages are millions of years ago (mya) and the scale of ages changes from the bottom to the top of the diagram (the Proterozoic, which spans about 2,000 million years is about the same size as the Quaternary, which spans about 2 million years)e. Ages are from the International Commission on Stratigraphy (https://stratigraphy.org/chart; accessed 11 February 2021).

Geologic Significance and Connections

The landscape of the park is a product of many different geologic processes: tectonic forces causing the mountains to uplift and Cook Inlet to flex downward; active volcanism forming the park's tallest peaks; past glaciations carving out the park's valleys and lakes, leaving behind thick glacial deposits; and active glaciers still capping many of the park's mountains, providing cold, sediment-rich water to the surrounding rivers, lakes, and ocean. Lake Clark, from which the park gets its name, exists because of glacial erosion along the mapped trace of the Lake Clark Fault.

Natural resources, rooted in geology, originally brought people to the Lake Clark area and continue to attract people today. The region is known for its abundant salmon, which spawn in cold, glacially fed streams and lakes. Mineral resources emplaced during past phases of igneous activity brought miners to the area in the 1900s and continue to be of interest. The extensive hydrocarbon industry that exists offshore in Cook Inlet is tapping into oil and gas sourced from some of the same rocks as those found within the park. Many visitors come to the park to experience the beauty of rugged glacier-capped mountains, pristine lakes, and coastal environments.

Although dynamic geologic processes are responsible for creating the region's stunning landscape, these same processes can also present threats to park resources, staff, and visitors. The steep slopes that characterize the park's mountains are prone to landslides, the two active volcanoes in the park may erupt, earthquakes are common, and large earthquakes or landslides that enter the water can generate tsunamis. Past notable geohazards that affected the park and surrounding area include the 1964 Great Alaska Earthquake and the 2009 eruption of Redoubt Volcano.

Geologic Features and Processes

These geologic features and processes are significant to the park's landscape and history. At the beginning of each section, map units corresponding to those on the surficial or bedrock poster will be listed; these indicate which map units will be discussed in the following section. Some map units are referenced directly in text as well. Some sections may not directly relate to a map unit on the posters, in which case no units will be listed. The map units can also be viewed in the GRI GIS data. See Table 3 for a correlation of the simplified bedrock poster map units to the detailed map units found in the GRI GIS data.

Volcanoes

Surficial poster units: **Qdr, Qhv, Qvr, Qdf1, Qdf2, Qav, Qpd, Qca, Qdf, Qad, QTv**

Bedrock poster units: **Qvd** (see Table 3)

From the ancient Talkeetna arc to the modern volcanic activity of Redoubt and Iliamna volcanoes, Lake Clark National Park and Preserve has been shaped by volcanism over hundreds of millions of years. Both the past and present volcanism is the product of subduction, a process in which convergence forces one tectonic plate beneath another (see Figure 3). As the down-going plate descends into the mantle, water is released and the overlying mantle wedge begins to partially melt. The rising magma produces a linear belt of volcanoes called an arc. The Jurassic-aged (201.3 million–145.0 million years ago) volcanic and plutonic rocks in the park are associated with the ancient Talkeetna arc (discussed in more detail in the "Bedrock Geology" section), which was the result of oceanic crust subducting beneath oceanic crust. A modern example of an oceanic volcanic arc is the Mariana Islands in the western Pacific Ocean. In contrast, the modern Aleutian arc in the Lake Clark region, which includes Redoubt and Iliamna volcanoes (Figure 5A), is the result of oceanic crust (Pacific plate) subducting beneath continental crust (North America Plate; Figure 5B). The Aleutian arc (Figure 5C) forms part of the "Ring of Fire," a 40,000 km (25,000 mi) subduction-related region of volcanic and seismic activity that rings the Pacific Ocean.

The park contains three volcanoes: Redoubt Volcano, Iliamna Volcano, and Double Glacier Volcano (Figure 5). Redoubt and Iliamna are both considered "active volcanoes," while Double Glacier has not been active within the last 10,000 years (https://www.avo.alaska.edu/volcanoes/; accessed 23 June 2019). The park's volcanoes produced a variety of deposits that built the edifice of each volcano. See Figure 6 for examples of typical volcanic deposits and hazards. Iliamna Volcano is located furthest south between Chinitna and Tuxedni Bays, Redoubt Volcano is north of Tuxedni Bay and contains widespread volcanic deposits formed during eruptions as recent as 2009, and Double Glacier Volcano is the small area of volcanic rock immediately north of Redoubt. At more than 10,000 ft (3,000 m), the active volcanoes Redoubt and Iliamna form the two tallest peaks in the park. For information on hazards associated with volcanism in the park, see the "Geohazards" section.

Redoubt Volcano

Redoubt Volcano is a stratovolcano, which is a type of volcano composed of alternating layers of lava and pyroclastic deposits (Figure 5; Figure 6; Figure 7). The summit of Redoubt stands 3,108 m (10,197 ft) above sea level, making it the tallest peak in the park. The base of Redoubt is about 10 km (6 mi) in diameter and the volume of the cone is between 30 and 35 km^3 (7.2 and 8.4 mi^3; Miller et al. 1998). An ice-filled crater sits just northwest of the true summit. The crater is dissected by a glacier, informally known as Drift glacier, that flows northwest into the Drift River valley (Miller et al. 1998). A lava dome (see Figure 6) formed during the last major eruption in 2009 and is often visible steaming within the crater (Figure 7C).

Redoubt Volcano first began to erupt during the Pleistocene (2.6 million–0.01 million years ago). Continued activity since the Pleistocene constructed the current edifice and left volcanic deposits in the surrounding drainage systems. Till et al. (1994) divided the evolution of the volcano into four stages: (1) an early explosive stage, (2) an early cone-building stage, (3) a late cone-building stage, and (4) a post-glacial stage. The following constraints and descriptions are from Till et al. (1994), unless otherwise stated. The early explosive stage involved one or more explosive eruptions that produced a small dome or shallow intrusive complex, as well as pyroclastic and lahar deposits (see Figure 6 for a depiction of these types of deposits). These deposits, dated to 0.89 million years ago, form the base of Redoubt Volcano and sit directly on granitic rocks of the Alaska-Aleutian Range batholith (for more information see the "Bedrock Geology" section). The early cone-building stage, which spanned at least 0.34

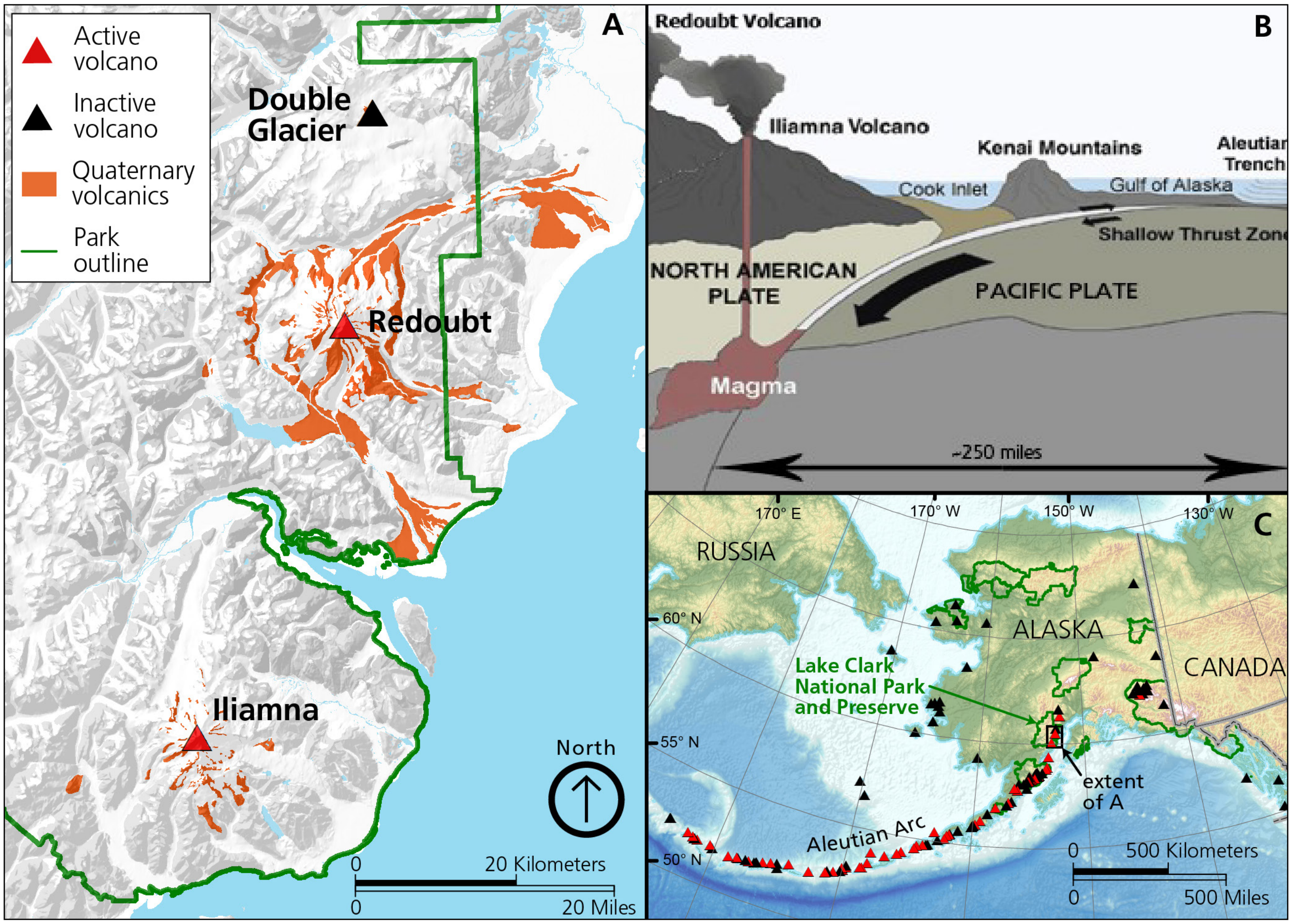


Figure 5. Maps and diagram showing the volcanoes in the park and throughout Alaska. (A) Map of the volcanoes in the park, including the active Iliamna and Redoubt volcanoes and the inactive Double Glacier volcano. Quaternary volcanic deposits are shown in orange. (B) Cross section showing the tectonic setting of Redoubt and Iliamna volcanoes (note: vertical is not to scale). US Geological Survey (USGS) graphic. (C) Map of the active and inactive volcanoes in Alaska.

million to 0.18 million years ago, produced a cone that stood 1,000–1,200 m (3,000–4,000 ft) above its base. The cone was composed of lava flows and flow breccias more mafic (rich in iron and magnesium) than earlier deposits. While volcanic rocks accumulated on all sides of the volcano during this stage, they became thickest on the north side. The late cone-building stage, which has not been dated, produced thick accumulations of columnar-jointed lava flows and volcaniclastic deposits (composed of broken fragments of volcanic rock). These lava flows and volcaniclastic deposits make up most of Redoubt's present edifice. So much volcanic material accumulated during this stage that Redoubt Volcano was, in fact, taller than it is today. The final, post-glacial stage is currently underway and encompasses volcanism since the Last Glacial Maximum (LGM; approximately 20,000–18,000 years ago).

Voluminous debris-flow and lahar deposits from the post-glacial stage are preserved in the valleys surrounding Redoubt (Beget and Nye 1994), including the Crescent River drainage to the south and the Drift River drainage to the north (Figure 8). About 3,600 years ago hydrothermally altered rocks on the southern flank of Redoubt Volcano collapsed, causing at least two clay-rich mudflows to travel 30 km (19 mi) down the Crescent River valley (labeled "Crescent River lahars" on Figure 8; Beget and Nye 1994). The Crescent River drainage continued to be affected by lahars for another 1,500 years (labeled "North Fork lahars" on Figure 8; Beget and Nye 1994). These deposits, combined with preexisting glacial moraines, created the dam that impounds Crescent Lake (**Qdf1** and **Qdf2**). The youngest volcanic activity, however, affected the Drift River drainage to the north of Redoubt Volcano (**Qdr**). This includes the Rust Slough lahar emplaced 500–200 years ago and several flood deposits produced by recent eruptions (Figure 8; Beget and Nye 1994).

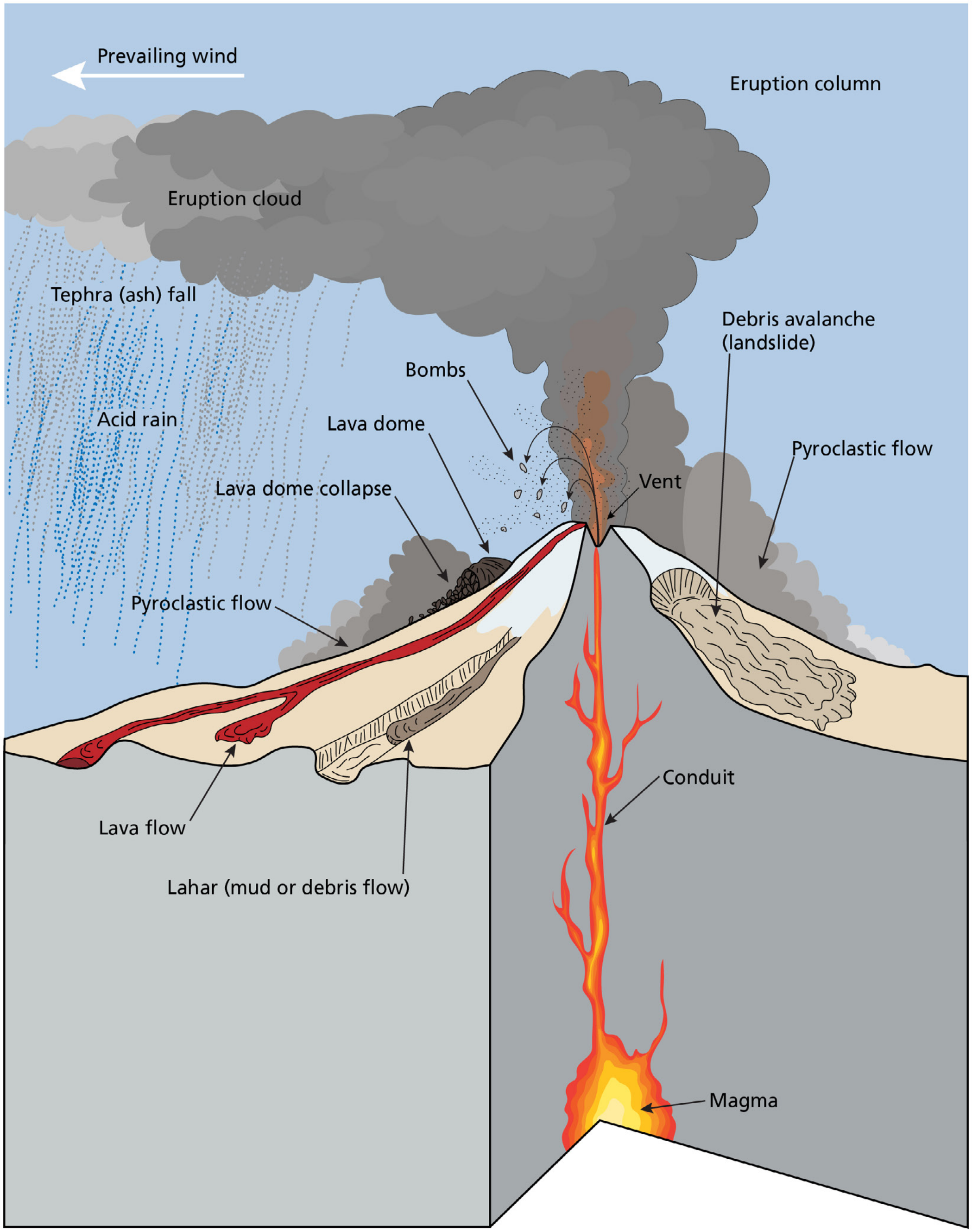


Figure 6. Diagram of volcanic hazards and the general types of volcanic deposits and hazards. Many of these volcanic deposits and hazards have been generated by past eruptions of Redoubt and Iliamna Volcanoes. Parts of the volcano are depicted in the diagram, such as the magma chamber that stores magma at depth, the conduit that feeds this magma to the surface, and the vent through which lava is erupted. When a volcano erupts it can create a variety of deposits and hazards. Eruption clouds formed via explosive eruptions are composed of small volcanic particles, called ash or tephra. Ash can be carried by wind, producing tephra (ash) fall and associated acid rain in areas both proximal and distal to the volcano. Volcanic bombs are pebble- to boulder-sized pieces of rock that are ejected within a few kilometers of the vent during an eruption. Lava flows are relatively slow-moving outflows of lava and a lava dome is a plug-like mass of lava that accumulates at the top of a volcanic conduit. A pyroclastic flow is a hot mixture of gas and rock debris that can be generated by the collapse of a lava dome or eruption column. A lahar is a flowing mass of water, rock debris, and mud. Debris avalanches or landslides can occur because volcanoes are typically composed of poorly consolidated, possibly altered volcanic rock. These events can range in scale from small rockfalls to large flank failures. Modified by Trista Thornberry Ehrlich from Myers and Brantley (1995).

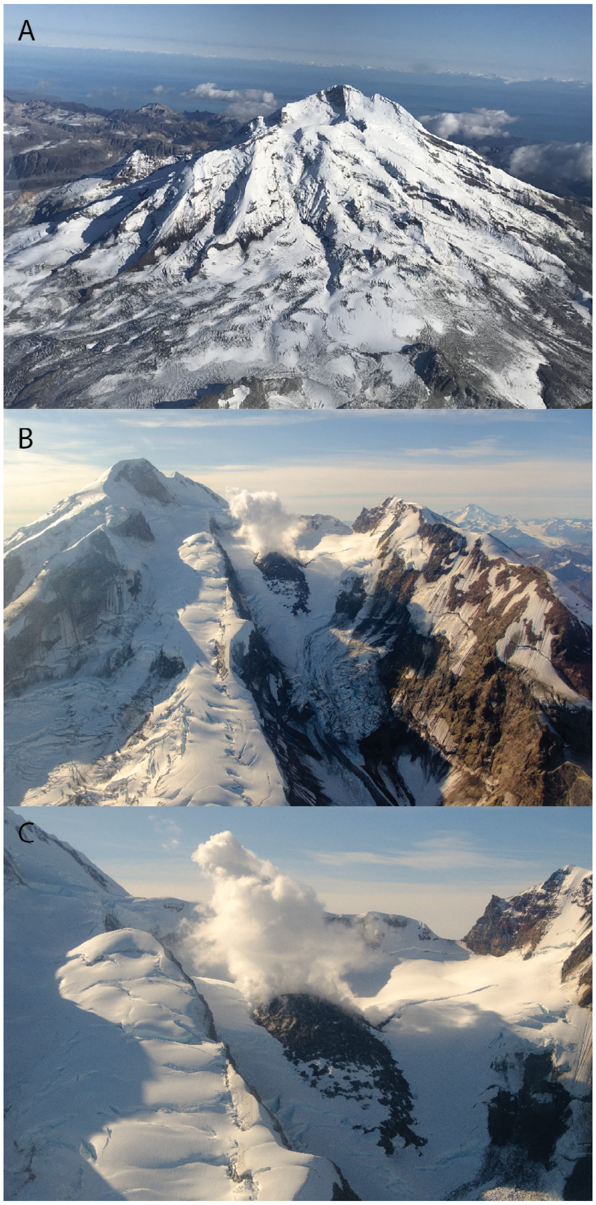


Figure 7. Photographs of Redoubt Volcano. (A) View of the west flank of Redoubt Volcano. NPS photograph by Claire Schmidt. (B) View of the summit of Redoubt Volcano, looking south. A crater that may have been formed during the emplacement of the Rust Slough lahar between 500 and 200 years ago (Beget and Nye 1994) sits just to the north of the true summit (high point at the top left part of the photograph). The informally named Drift glacier bisects the crater in the center of the photo, flowing northwest into the Drift River valley. During past eruptions, melting of the Drift glacier has contributed to the formation of lahars that inundated the Drift River valley. A lava dome formed during the 2009 eruption can be seen in steaming in the middle of the crater. USGS photograph by Matt Loewen. (C) Close-up view of the 2009 lava dome. USGS photograph by Matt Loewen.

Redoubt Volcano has erupted at least four times. Eruptions occurred in 1902, 1966–1968, 1989–1990, and 2009 (https://avo.alaska.edu/volcanoes/volcact.php?volcname=Redoubt; accessed 23 July 2019). The 1902 eruption happened in late January and deposited tephra over a wide area, including in the towns of Hope, Kenai, and Kasilof (Till et al. 1993). Redoubt erupted intermittently from 1966 to 1968. Six explosions occurred in January and February 1966, and five explosions occurred from December 1967 to April 1968 (Wilson and Forbes, 1969). A seismic crew working in the Drift River area during one of the explosions in January 1966 reported that the ice-covered river broke up and water levels rose 1–1.2 m (3.3–3.9 ft) in 15 minutes, carrying large chunks of ice and boulders (Till et al. 1993). The 1989–1990 eruption consisted of 23 major explosive events between December 1989 and April 1990 (Miller et al. 1998). A lava dome grew and was destroyed multiple times, ash clouds were produced, pyroclastic flows traveled across the Drift glacier, and debris flows flooded the Drift River valley (Miller et al. 1998). The ash clouds deposited tephra on surrounding communities and caused hazardous conditions for air traffic in the region. Most significantly, a Boeing 747 flew into an ash cloud and experienced complete engine failure (Waythomas et al. 1998). Thankfully, the crew was able to restart the engines and land safely in Anchorage. Debris flows and flooding of Drift River threatened the Drift River Oil Terminal, an oil storage facility located north of the park near the mouth of Drift River. Debris flows and flood water surrounded and partially flooded the facility, but the flooding did not affect the one million barrels of oil stored there at the time (Waythomas et al. 1998). The 1989–1990 Redoubt Volcano eruption was one of the costliest eruptions in US history, with total estimated economic losses at over $160,000,000 (Miller and Chouet 1994).

The most recent eruption of Redoubt Volcano occurred March–July 2009. Precursory unrest started as early as July 2008 and included elevated levels of volcanic gasses, increased melting of Drift glacier, and increased seismicity (Bull and Buurman 2013). The early phase of the eruption was explosive, producing ash plumes, pyroclastic flows, and lahars (Bull and Buurman 2013). The ash plumes reached heights up to 18.9 km (12.3 mi) above sea level and deposited ash on the nearby communities of Homer, Anchor Point, Seldovia, and Anchorage (Schaefer 2011). Most of the pyroclastic flows stayed within 2 km (1 mi) of the vent (Bull and Buurman 2013). Lahars with flows up to 10 m (30 ft) in depth inundated the Drift River valley, partially flooding the Drift River Oil Terminal on two separate occasions (Schaefer 2011). During the explosive phase, two or three lava domes were formed by lava

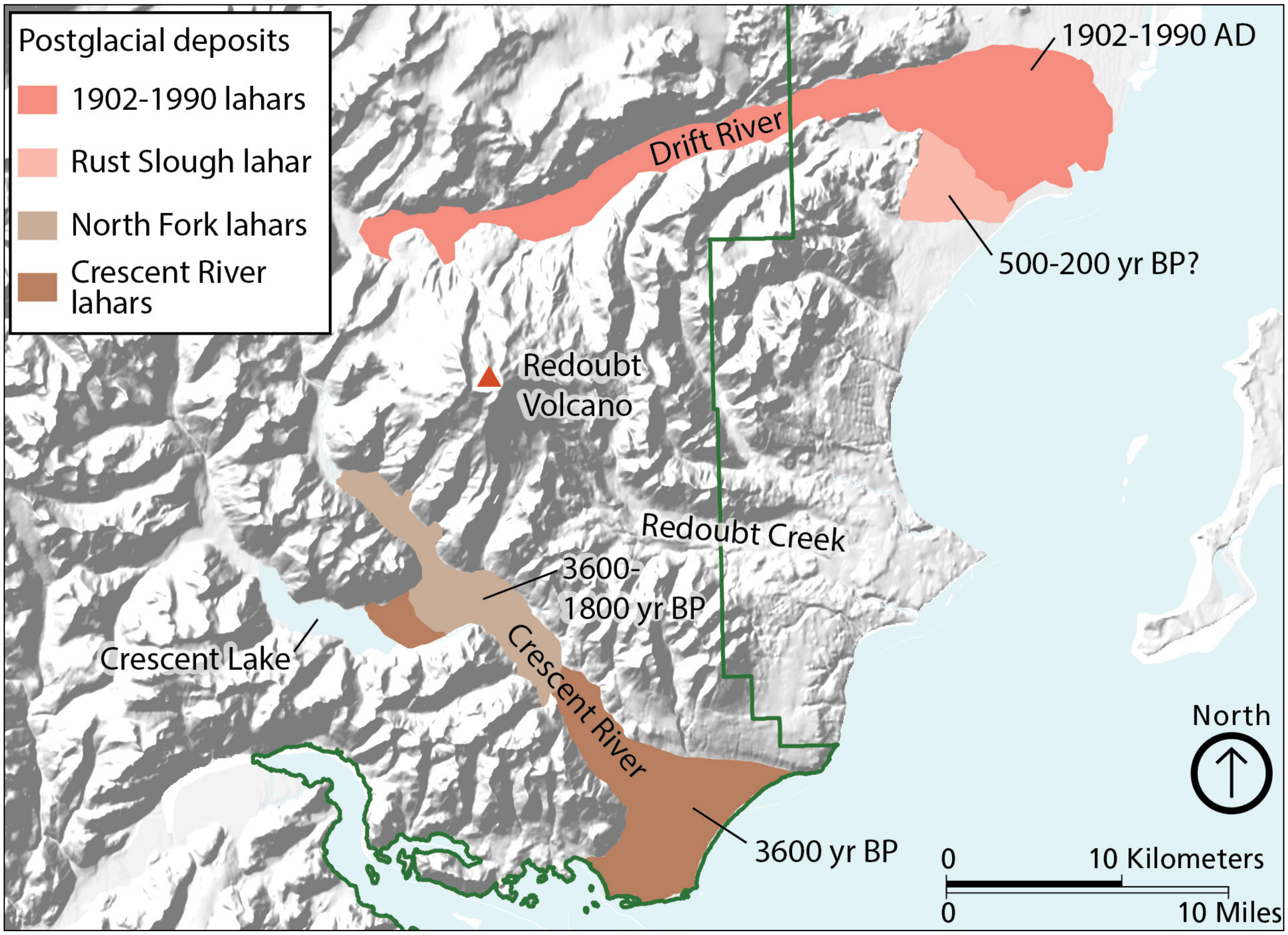


Figure 8. Map of deposits produced by Redoubt Volcano.
Lahars dating to 3600–1800 yr BP (years before 1950) are found within the Crescent River valley to the south of Redoubt Volcano. Lahars generated by more recent eruptions of Redoubt Volcano have inundated the Drift River valley to the north of Redoubt Volcano. These include the Rust Slough lahar that formed between 500 and 200 yr BP and the lahars generated in eruptions since 1900. The mapping shown here by Beget and Nye (1994) does not correlate directly with the map units on the GRI surficial and bedrock maps, but the Crescent River lahars are primarily encompassed by unit Qdf (Debris-flow deposits) in the map data and the Drive River lahars are primarily mapped as Qmf (Mudflow deposits). Not included in this figure are the lahars formed during the 2009 eruption, but they also covered much of the Drift River valley. Modified from Beget and Nye (1994).

effusion and subsequently destroyed by explosions (Bull and Buurman 2013). In early April the eruptive style transitioned from explosive to purely effusive. Lava effusion continued through early July, building the final lava dome that still exists today (Figure 7; Bull and Buurman 2013).

Iliamna Volcano

Iliamna Volcano is a broad stratovolcano that rises 3,053 m (10,016 ft) above sea level (Figure 5; Figure 9). Most of the volcano is covered year-round by snow and glacier ice. Several large glaciers radiate down from the summit of Iliamna, including Tuxedni Glacier, Lateral Glacier, Red Glacier, and Umbrella Glacier (see the "Glacier Features and Modern Changes" section for more information). The steep southern and eastern flanks of Iliamna expose the volcanic stratigraphy, which is composed primarily of interbedded andesite lava flows, lahars, pyroclastic flows, and debris-avalanche deposits (see Figure 6 for a description of these types of deposits; Miller et al. 1998; Waythomas and Miller 1999). A zone of fumaroles (opening in or near a volcano where sulfurous gases are emitted) is located near the summit on the south side of the volcano (Figure 9; Waythomas and Miller 1999). These fumaroles often steam and can sometimes be seen on clear days from nearby communities.

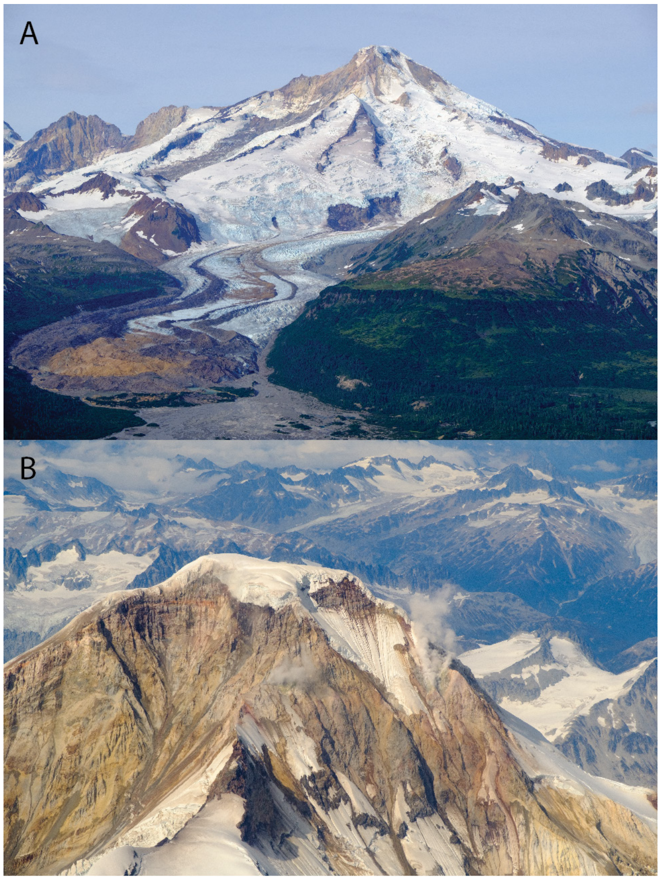


Figure 9. Photographs of Iliamna Volcano. (A) Photograph showing the east flank of Iliamna Volcano with Lateral Glacier in the foreground. (B) Close-up view of the south flank of Iliamna Volcano. Two distinct regions of fumarolic activity are visible in the center and right side of the peak. USGS photographs by Matt Loewen.

Waythomas and Miller (1999) reported that the oldest lava flows preserved and exposed on Iliamna Volcano erupted about one million years ago, but for the most part, snow and ice obscure the eruption record prior to about 7,000 years ago. A series of dikes and sills (intrusive igneous rocks) intrude the Red Glacier Formation on the flank of Iliamna (Stanley et al. 2013). These rocks have been radiometrically dated using $^{40}Ar/^{39}Ar$ isotopes to 7.3 million and 2.3 million years ago, indicating that Iliamna Volcano is the site of long-lived late Cenozoic arc volcanism (Marwan Wartes, Alaska Division of Geological & Geophysical Surveys, geologist, written communication, 14 September 2020). About 4,000 yr BP (years before 1950) Iliamna Volcano produced a large plinian-style eruption (explosive eruption that produces a large column of volcanic particles called ash or tephra), which led to the deposition of pumiceous lapilli tephra on the flanks of the volcano and fine-grained volcanic ash on the Kenai Peninsula (Waythomas and Miller 1999). Another fine-grained ash layer found on the Kenai Peninsula attributed to Iliamna Volcano dates to about 7,000 yr BP. This ash layer indicates that Iliamna produced an even older plinian eruption, but the proximal deposits associated with this eruption have not been discovered (Waythomas and Miller 1999). Waythomas et al. (2000) studied several non-cohesive lahar deposits in the river valleys around Iliamna Volcano, which they interpreted as having been induced by eruptions. These include a lahar in the West Glacier Creek valley dated to >2,430 yr BP, two lahars in the Red Creek/Johnson River area dated to >1542 yr BP and <305 yr BP, and the remains of a lahar in the Red River alluvial fan dated to about 300 yr BP (Waythomas et al. 2000). Iliamna Volcano has no verified historical eruptions (since about 1760; Waythomas and Miller 1999). Several reports from the 1860s and 1870s report "smoke" or "steam" rising from Iliamna, but this does not clearly indicate an eruption and could be attributed to fumarole activity (Miller et al. 1998; Waythomas and Miller 1999). Seismic swarms and elevated carbon dioxide and sulfur dioxide gas emissions were detected at Iliamna in 1996, indicating that the volcano remains restless and may erupt in the future (Miller et al. 1998; Waythomas and Miller 1999).

In addition to deposits generated by eruptions, slope failure of the volcanic edifice generated cohesive lahars and debris-avalanche deposits that are found on the flanks of Iliamna and in the surrounding valleys (Waythomas et al. 2000). Some of the avalanche deposits are mapped as unit **Qav** (volcanic avalanche deposits) in the surficial map data. Two clay-rich lahar deposits are present in the valleys around Iliamna, one at the head of Red Glacier dating to around 90 yr BP and one in the West Glacier Creek valley that dates to around 1,300 yr BP (Waythomas et al. 2000). No known eruption occurred during the timeframe of the Red Glacier lahar, and it may be that these cohesive lahars are related to large flank failures of the volcanic edifice without volcanic activity (Waythomas et al. 2000). Small-volume debris-avalanche deposits have been found in the drainages surrounding Iliamna and cover most of the major glaciers on the volcano (Waythomas et al. 2000). These deposits are produced by slope failures of volcanic rock that has been hydrothermally altered and weakened by fumarole activity near the summit (Waythomas et al. 2000). The debris-avalanche deposits were probably generated within the last 500 years and occurred relatively frequently (Waythomas et al. 2000). In 1994, 1996, and 1997, several debris-avalanches originated from near the summit of Iliamna and flowed down Red and Umbrella glaciers for about 3–8 km (2–5 mi; Waythomas and Miller 1999). Rock-ice avalanches are also common at Iliamna Volcano. Between 1960 and 2004, 13 rock-ice avalanches occurred at Iliamna

Volcano: nine rock-ice avalanches originated on Red Glacier, three originated on Umbrella Glacier, and one originated on Lateral Glacier (Huggel et al. 2007). Rock-ice avalanches continue to frequently occur at the volcano; one recent avalanche occurred on 21 June 2019 at Red Glacier. The frequency and magnitude of Red Glacier avalanches is extraordinary and possibly unique worldwide (Huggel et al. 2007).

Double Glacier Volcano

Double Glacier Volcano (**Qad**) is a small, inactive dome complex composed of andesite and dacite that sits between Redoubt and Spurr Volcanoes (Figure 5; Figure 10; Reed et al. 1992). Today, it is exposed as a 2.3-km- (1.4-mi-) long oval-shaped nunatak (peak or ridge surrounded by ice) that stands 430 m (1,400 ft) above the ice of Double Glacier (Reed et al. 1992). A rough estimate of the original size indicates a volume of 2–4.8 km^3 (0.5–1.2 mi^3), making it one of the smaller volcanoes in the Cook Inlet region (Reed et al. 1992). This estimate was made by assuming a cylindrical shape with a diameter of 2.3–3.5 km (1.4–2.2 mi) and height of 500 m (1600 ft) above the present ice surface (Reed et al. 1992). K-Ar radiometric ages suggest that Double Glacier Volcano was active between 900,000 and 600,000 years ago (Reed et al. 1992).

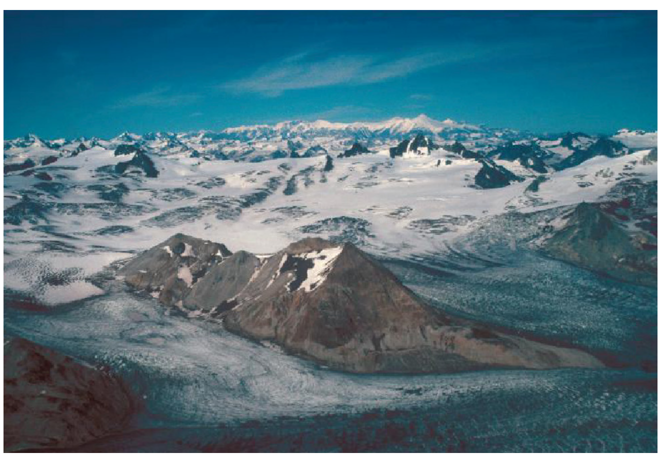


Figure 10. Photograph showing Double Glacier Volcano.
Double Glacier Volcano is a small inactive dome complex surrounded by ice and found in the park north of Redoubt Volcano. Radiometric dating suggest that this volcano was active between 900,000 and 600,000 yeas ago. USGS photograph by Tom Miller.

Bedrock Geology

Terrane Translation and Accretion

Alaska, along with the rest of the Cordilleran region of western North America, is composed of a network of displaced rocks grouped into "terranes" (Figure 11; Coney et al. 1980; Silberling et al. 1992). A terrane is a fault-bounded package of rocks with a geologic history that differs from adjacent rocks (Jones et al. 1983). The crust of the earth is broken up into tectonic plates that have undergone large-scale motion throughout geologic history. Alaska terranes have been transported by plate tectonics (i.e., displaced) from where they originally formed and accreted together to the edge of the North American continent. Only a small portion of Alaska along the north end of Yukon-Charley National Preserve is an in-place, undisturbed part of the North American continent (Figure 11). The rest of Alaska consists of pieces of crust that arrived from elsewhere or moved from their original locations.

Many of the rocks within the park belong to the Peninsular terrane (labeled PE on Figure 11). The Peninsular terrane is a package of rocks that records the formation and subsequent erosion of an ancient chain of volcanoes called the Talkeetna arc (Plafker and Berg 1994). The Talkeetna arc formed to the south in the proto-Pacific Ocean between 213 million and 164 million years ago (Packer and Stone 1974; Rioux et al. 2010). Rocks assigned to the Peninsular terrane include older oceanic rocks that the Talkeetna arc was built upon (e.g., Cottonwood Bay Greenstone, and Kamishak Formation), the igneous rocks that form the arc itself (e.g., Alaska-Aleutian Range batholith, and Talkeetna Formation), and flanking packages of sedimentary rocks that were shed off the arc as it eroded (e.g., Tuxedni Group, Chinitna Formation, and Naknek Formation).

The Peninsular terrane is part of the larger Wrangellia composite terrane, which also includes the Wrangellia and Alexander terranes (labeled WR and AX on Figure 11; Jones et al. 1981; Gardner et al 1988; Plafker et al. 1989; Plafker et al. 1994; Nokleberg et al. 1994). Paleomagnetic evidence from rocks of the Wrangellia composite terrane in other places in Alaska, including Wrangell-St. Elias National Park and Preserve, suggests that the terrane was offshore in the equatorial region of the proto-Pacific ocean during the Triassic Period (252 million–201 million years ago; Hillhouse 1977; Hillhouse and Gromme 1984). Subsequent tectonic movements transported the Wrangellia composite terrane, causing it to collide with and accrete to the western margin of North America. The timing and placement of this accretion has generated considerable debate among geologists (see Cowan et al. 1997 for

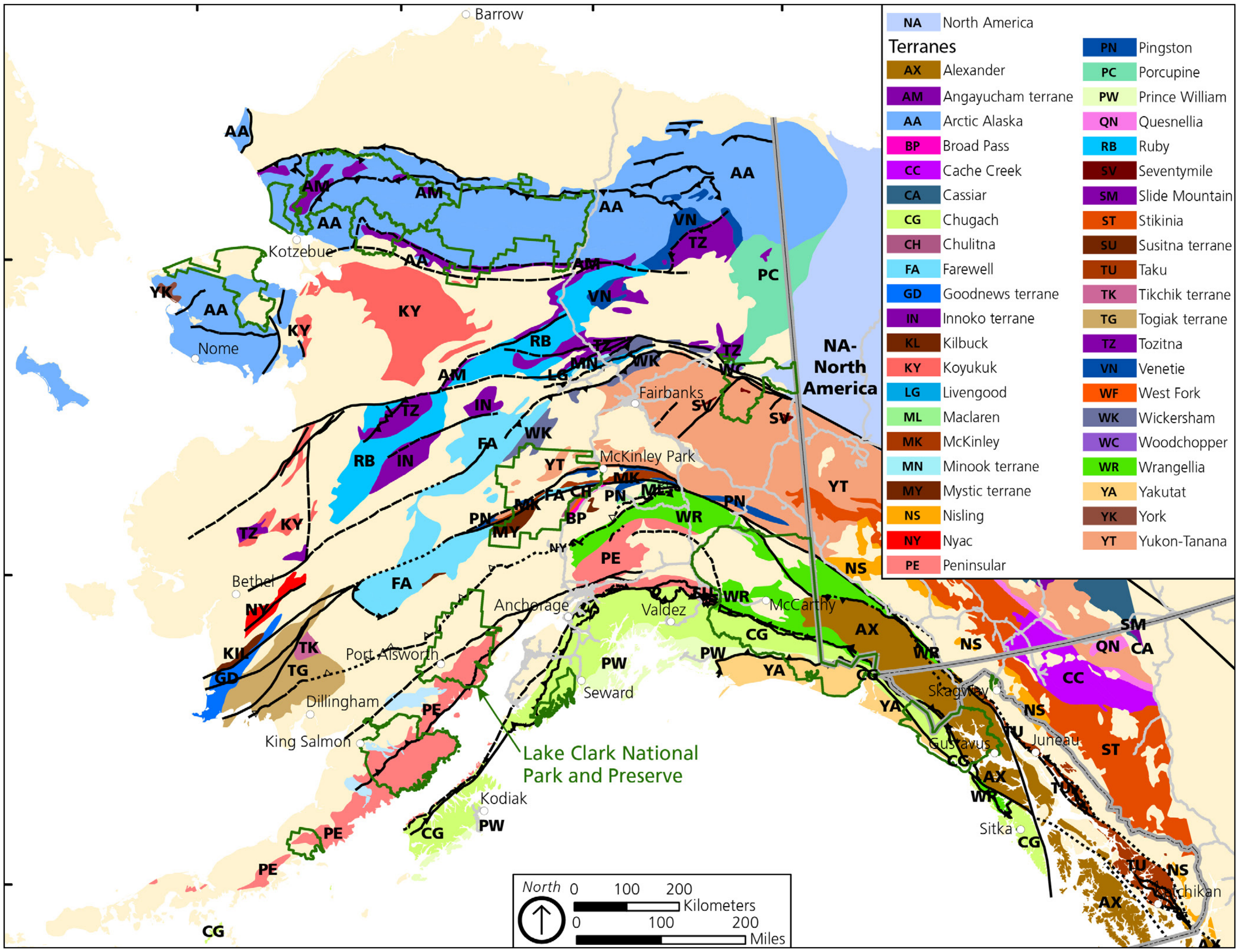


Figure 11. Map of the geologic terranes of Alaska.
National Park Service boundaries are outlined in dark green, roads in light grey, and major faults in black. The light tan areas are underlain by terranes but are covered by younger sedimentary deposits. The bedrock units on the bedrock poster primarily correspond to the Peninsular terrane (PE; salmon colored). The Peninsular terrane is grouped together with the Wrangellia terrane (WR; bright green) and the Alexander terrane (AX; brown), and these terranes are collectively referred to as the Wrangellia composite terrane. Modified from Silberling et al. (1992).

a summary). This longstanding debate, commonly referred to as the “Baja-BC hypothesis,” is centered on the question of how much northward translation the Wrangellia composite terrane has undergone since its collision with North America in the Cretaceous. Paleomagnetic studies indicate that the Wrangellia composite terrane was situated around the latitude of Baja California during the Cretaceous and moved to its current position by largescale northward translation (Figure 12; Beck 1976; Stone and Packer 1977; Irving 1985; Hillhouse and Coe 1994).

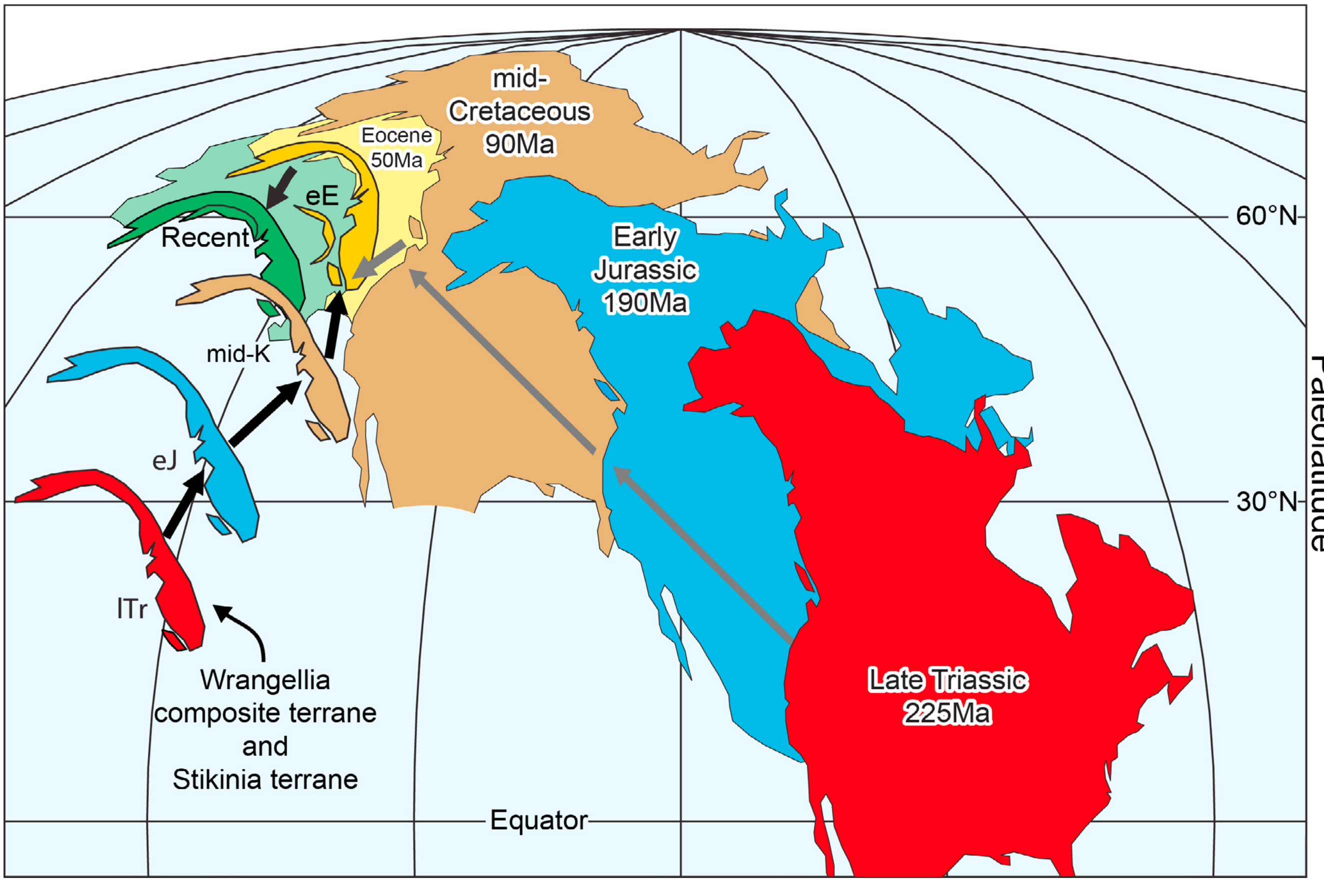


Figure 12. Paleogeographic map showing the Wrangellia composite terrane translation history from the Late Triassic (237 million years ago) to the present.
Rocks of the Lake Clark area are located on the Peninsular terrane, which is the far western end of the Wrangellia composite terrane (Plafker et al. 1989; Nokleberg et al. 1994; Rioux et al. 2010). Evidence from fossils suggests that the terrane was far offshore of North America during the Late Triassic and Jurassic Periods (237 million–145 million years ago), but how far offshore is not known. lTr stands for Late Triassic, eJ stands for Early Jurassic, mid-K stands for mid-Cretaceous, and eE stands for Eocene. Modified from Kent and Irving (2010) to include the Peninsular terrane.

Cottonwood Bay Greenstone

Bedrock poster units: **MZPZcb**

The Cottonwood Bay Greenstone is composed of dark green to grey mafic volcanic rocks that have undergone low grade metamorphism (Detterman and Reed 1980). The rocks have been altered to the hornfels metamorphic facies (hornfels is a high-temperature, low pressure metamorphism caused by “baking” from intruded magma; Figure 13). Most of the rocks of the Cottonwood Bay Greenstone occur to the south and west of the park boundary, but there is one small mapped area of this unit within the park on the north side of the Neacola River valley (see the bedrock poster). Detterman and Reed (1980) determined that it likely formed in the Late Triassic (237 million–201.3 million years ago) because it is interbedded with the base of the Kamishak Formation. The Cottonwood Bay Greenstone is the same age and compositionally similar to the Nikolai Greenstone, which is a signature rock type of the Wrangellia terrane found in the McCarthy area of Wrangell-St. Elias National Park and Preserve (Jones et al. 1977; Nokleberg et al. 1994).

Kamishak Formation

Bedrock poster units: **JTRku, TRrk, TRkm, TRkb**

The Kamishak Formation (**TRrk**) is a sequence of marine rocks deposited in the Late Triassic (237 million–201.3 million years ago) composed primarily of limestone, but also contains chert, as well as volcanic and volcaniclastic rocks (Detterman and Reed 1980; Wang et al. 1988; Detterman et al. 1996). Most of the Kamishak Formation occurs in the Kamishak Bay area south of the park, but a small portion extends into the park near Lower Tazimina Lake (see the bedrock poster). The Kamishak Formation has been divided into three members, which are, in ascending order, the Bruin Limestone Member (**TRkb**), the middle member (**TRkm**), and the Ursus Member (**JTRku**; Detterman and Reed 1980).

The members of the Kamishak Formation record first a deepening and then a shallowing of the depositional environment. The Bruin Limestone Member contains the remnants of an echinoderm and coral bioherm (reef-like structure) that was probably deposited in a shallow-water high-energy environment (Detterman and Reed 1980). The middle member is composed of dark, fossil-poor bedded limestone and chert interpreted to have been deposited in a deep basin environment (Detterman and Reed 1980). The Ursus Member, which is the only member found in the park, contains thin-bedded light grey limestone with minor amounts of chert that records a transition from a deep water to a shallow water depositional environment (Detterman and Reed 1980). Volcanic ash in the middle and Ursus members in the Kamishak Bay area (Detterman and Reed 1980), and volcanic breccia and basalt in the Puale Bay section (Wang et al. 1988; Dettermen et al. 1996; Whalen and Beatty 2008) indicate that volcanism was occurring during deposition of the Kamishak Formation. Wang et al. (1988) proposed that the Kamishak Formation records a shift from sedimentation derived primarily from the shells, teeth, and other parts of creatures living in the ocean to sedimentation derived from a nearby eroding volcanic arc.

Kakhonak and Tlikakila Complexes

Bedrock poster units: **MZPZk, MZPZb**

The Kakhonak Complex and Tlikakila Complex are mapped together (**MZPZk, MZPZb**). Both complexes are composed of Triassic marine rocks that have been metamorphosed at the greenschist metamorphic facies (Figure 13). The Kakhonak Complex is found in the southeastern part of the park and to the south of the park, within and associated with plutonic rocks of the Talkeetna arc (see the bedrock poster). The Tlikakila Complex is inboard of the Talkeetna arc rocks, forming a narrow belt through the center of the park (see the bedrock poster).

The Kakhonak complex (called "Metamorphic rocks undifferentiated" in Detterman and Hartsock [1966]) is a heterogenous mix of metamorphic rocks that occur primarily as roof pendants within the Alaska-Aleutian Range batholith. Prior to metamorphism, these rocks were sedimentary, volcanic, and intrusive igneous rocks formed in a marine environment (Detterman and

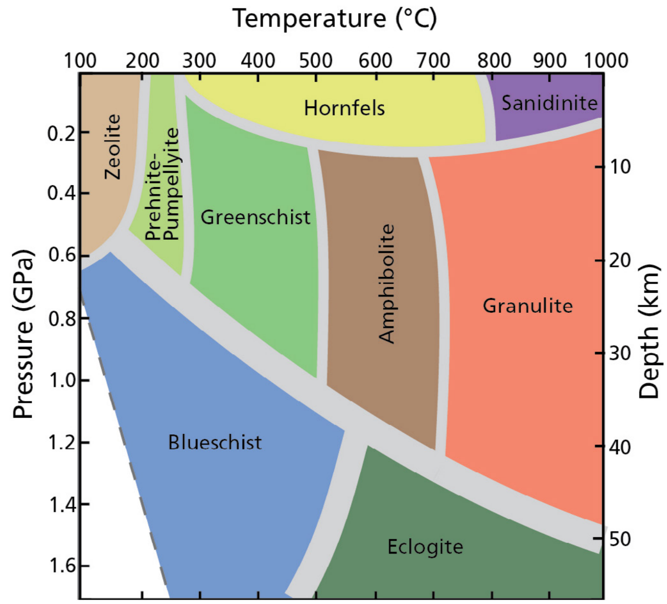


Figure 13. Pressure-temperature diagram showing metamorphic facies.
During metamorphism, various metamorphic minerals will develop depending on original rock chemistry, pressure, and temperature. Metamorphic facies are characterized by mineral assemblages that form under similar pressure-temperature conditions. The processes that led to metamorphism can sometimes be inferred by metamorphic facies. For example, hornfels- and sanidinite-facies minerals form under high temperature and low-pressure conditions, which is typically the result of contact metamorphism (metamorphism of rocks that come into contact with magma). Rocks of the Kakhonak and Tlikakila complexes were mainly metamorphosed to the greenschist facies, but, locally, metamorphism produced hornfels, and amphibolite facies. Figure modeled after Winter (2001).

Hartsock 1966; Detterman and Reed 1980). Parts of the Kakhonak complex were dated to the Late Triassic based on sparse fossil occurrences and its location on strike with the Kamishak Formation (Detterman and Hartsock 1966). Detterman and Reed (1980) proposed that the Cottonwood Bay Greenstone, Kamishak Formation, and Talkeetna Formation are the unmetamorphosed equivalents of the Kakhonak complex. Contact metamorphism occurred during the Jurassic and Cretaceous with the emplacement of plutonic rocks of the Alaska-Aleutian Range batholith (Detterman and Hartsock 1966; Detterman and Reed 1980). The heat of the magma metamorphosed the rocks mainly to greenschist metamorphic facies, but also locally to the hornfels and amphibolite facies (Detterman and Reed 1980).

The Tlikakila complex is a northeast striking, 5-km-(3-mi-) wide and 75-km- (47-mi-) long belt of greenschist-facies metamorphic rocks found both to the north and south of Lake Clark. Before metamorphism, the rocks of the Tlikakila complex included basalt, gabbro, ultra-mafic rocks, limestone, chert, mudstone, chert-pebble conglomerate, and minor quartz sandstone (Wallace et al. 1989; Amato et al. 2007). Radiometric dating of the metasedimentary rocks indicate that they were deposited between approximately 293 million and 192 million years ago, and fossils from nearby correlative limestone indicate part of the complex is Late Triassic (237 million–201.3 million years ago; Amato et al. 2007). Metamorphism occurred at 177 +/- 1 million years ago (Early Jurassic) and reached peak temperatures of 350–450°C (Amato et al. 2007). Amato et al. (2007) interpreted the Tlikakila complex as a dismembered ophiolite (section of oceanic crust) that originated near a subduction zone in the Late Triassic (237 million–201.3 million years ago). Furthermore, they suggest this subduction zone is the same that later created the Talkeetna arc, and metamorphism of the Tlikakila complex coincided with either collision of the Talkeetna arc with the continental margin or a shallowing of the subduction angle at around 177 million years ago (Amato et al. 2007).

Talkeetna Arc

Bedrock poster units: **Jtk, Jtkh, Jtkp, Jtkm, Jgaa, Jla, Jqt, Jdg, Jqd, Jgd, Jtr**

The Talkeetna arc is an ancient oceanic volcanic arc, or chain of magmatic activity, that was active during the Late Triassic and Jurassic (radiometric ages date the arc to between 212 million and 164 million years ago [Rioux et al. 2010]). Rocks of the Talkeetna arc extend over 1,000 km (600 mi) from the Alaska Peninsula and Kodiak Island in the southwest to the Chugach and Talkeetna Mountains in the northeast. It also may have been continuous further down the margin and correlative to the Bonanza Arc on Vancouver Island. The Talkeetna arc is one of the best preserved, most complete oceanic arc sequences known on Earth; it includes preserved ultramafic rocks formed in the upper mantle, lower and mid-crustal plutons, and extrusive volcanic rocks (Greene et al. 2006). In the park, rocks of the Talkeetna arc include volcanic and volcaniclastic rocks of the Talkeetna Formation (**Jtk, Jtkh, Jtkp, Jtkm**) and Jurassic plutonic rocks of the Alaska-Aleutian Range batholith (**Jgaa, Jla, Jqt, Jdg, Jqd, Jgd, Jtr**).

The Talkeetna Formation (**Jtk**) is composed of the uppermost, extrusive part of the Talkeetna arc. The Talkeetna Formation is exposed in a northeast-southwest trending belt in the southeastern part of the park and in the area between Lake Clark and Iliamna Lake (see the bedrock poster). In the area between Lake Clark and Iliamna Lake, the Talkeetna Formation is not subdivided (**Jtk**), but in the southeastern part of the park the Talkeetna Formation has been split into three members, as described by Detterman and Hartsock (1966): the Marsh Creek Breccia Member (**Jtkm**), the Portage Creek Agglomerate Member (**Jtkp**), and the Horn Mountain Tuff Member (**Jtkh**). The Marsh Creek Breccia Member is dominated by dark-green volcanic breccia. The Portage Creek Agglomerate Member mainly consists of red or pink agglomerate and lapilli tuff (rock composed of volcanic ejecta between 2 and 64 mm [0.08 and 2.5 in] in a fine-grained matrix). The Horn Mountain Tuff Member is dominated by bedded tuff and tuffaceous feldspathic sandstone. More recent studies in the area (Bull 2014; Bull 2015) have not been able to distinguish between the three members along strike and suggested subdividing the Talkeetna Formation based on facies instead (Bull 2015).

Most of the Talkeetna Formation formed in a submarine volcanic environment (e.g. Draught and Clift 2006), but there are some notable exceptions where deposition was subaerial. One such subaerial portion occurs in the park, in the Horn Mountain Tuff Member on Horn Mountain. The rocks on Horn Mountain contain terrestrial plant fossils such as leaves and tree stumps (Detterman and Hartsock 1966; Bull 2015; LePain et al. 2016). LePain et al. (2016) examined the stratigraphy and determined the rocks were formed on an alluvial plain in a volcanic setting, similar to the mouth of the modern Drift River. Brown and maroon siltstones dominate the section and represent oxidized, well-drained overbank deposits. These siltstones are cut by small fluvial channels of trough-cross stratified sandstone. Several tabular bodies of poorly sorted conglomerates, some containing large, silicified logs, were formed by flood and debris flows. The presence of small trees in growth position, combined with the logs in the debris flow deposits, indicate that the alluvial plain was vegetated, with larger trees growing beyond the margins of the channels (LePain et al. 2016). Aerial reconnaissance conducted by LePain et al. (2016) indicated that similar stratigraphy continues for a considerable distance above and below the measured section, and the discovery of a fern fossil in the Johnson River basin (see the "Paleontological Resources" section for more details) indicates that this subaerial facies of the Talkeetna Formation may be more widespread than just Horn Mountain.

The extrusive volcanic rocks of the Talkeetna arc were fed by plutons of the Alaska-Aleutian Range batholith, which extends from near Becharof Lake on the Alaska Peninsula to about 650 km (400 mi) northeast in the Talkeetna Mountains (Reed and Lanphere 1973).

The Alaska-Aleutian Range batholith is a geographic grouping of plutons that were emplaced during three distinct magmatic phases: (1) a Late Triassic–Jurassic phase, dated to between 212 million and 164 million years ago (Rioux et al. 2010); (2) a Cretaceous–early Paleogene phase, dated to between about 110 million and 55 million years ago (Reed and Lanphere 1973; Todd and Jones 2020); and (3) a middle–late Paleogene phase, dated to between 48 million and 22 million years ago (Wilson 1985; Figure 14). The Talkeetna arc is associated with the earliest phase of magmatism during the Late Triassic and Jurassic. In the park, these plutonic rocks form a southwest-northeast belt parallel to the Talkeetna Formation (see the bedrock poster). The plutons crystallized deep in the crust but have been brought up by bedrock exhumation and erosion that, in some areas, was accommodated by large faults such as the Bruin Bay Faults (see the "Faults and Folds" section for more information).

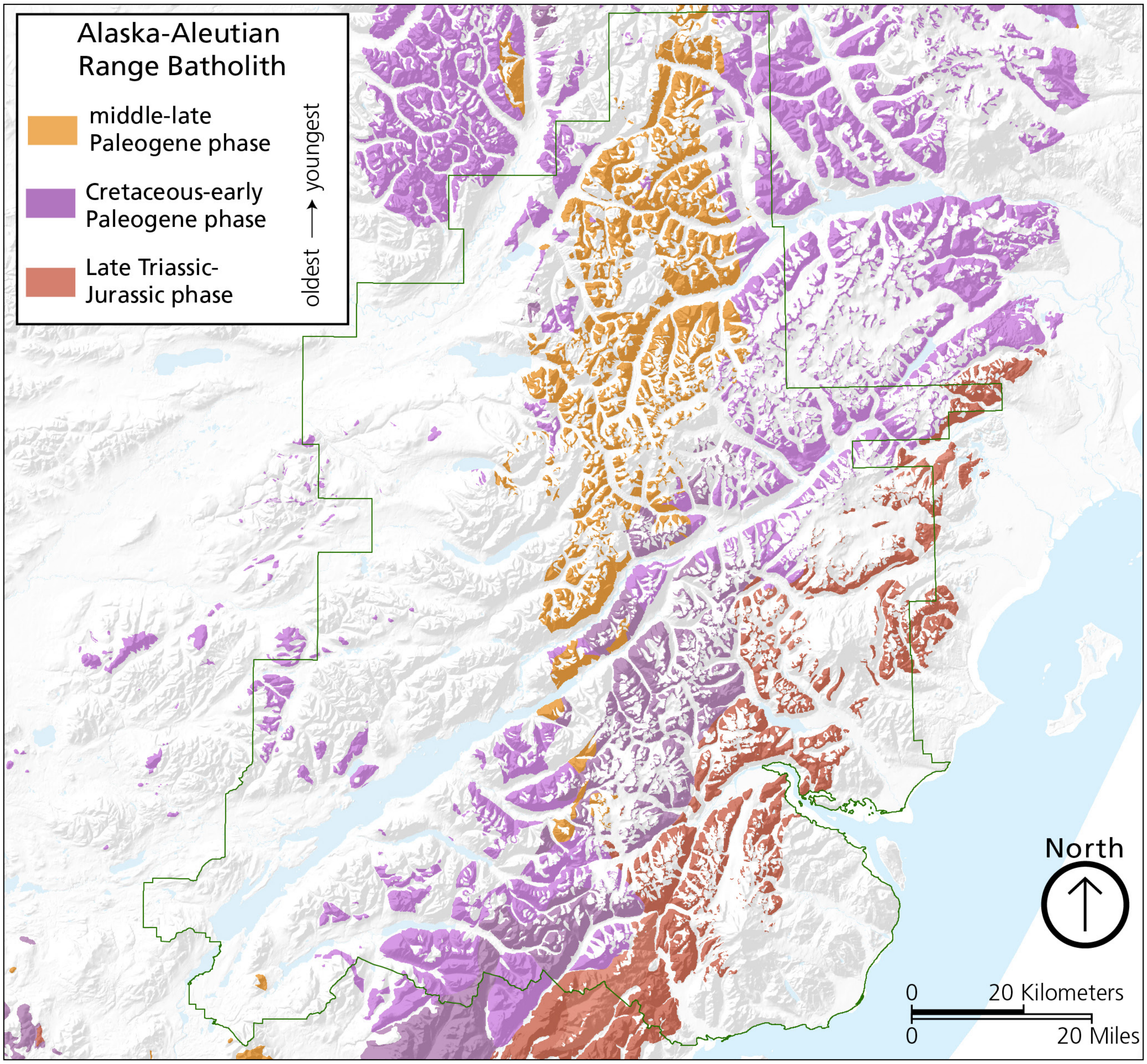


Figure 14. Map showing the distribution of rocks of the Alaska-Aleutian Range batholith. The Alaska-Aleutian Range batholith is a geographic grouping of igneous plutonic rocks that dominate much of the central region of the park. The Alaska-Aleutian Range batholith formed during three phases of active magmatism separated by magmatic lulls: Late Triassic–Jurassic phase (212–164 million years ago), Cretaceous–early Paleogene phase (110–55 million years ago), middle–late Paleogene phase (48–22 million years ago). Graphic modified from Wilson et al. (2015).

The composition of the Jurassic plutons of the Alaska-Aleutian batholith in the park is variable, including gabbroic rocks (**Jgaa**), lamprophyre and mafic dikes (**Jla**), diorite and gabbro (**Jdg**), quartz diorite (**Jqd**), quartz diorite and tonalite (**Jqt**), granodiorite (**Jgd**), and trondhjemite (**Jtr**; bedrock poster). Figure 15 shows the classification of many of these rocks based on the abundance of the minerals plagioclase feldspar, alkali feldspar, and quartz. Trondhjemite is a type of light-colored tonalite, and lamprophyre is a type of porphyritic (crystals are two distinct sizes) igneous rock found in dikes. The generally mafic composition of the Jurassic plutons supports the interpretation that they represent an oceanic arc, which lack the felsic rocks found in continental arcs (volcanic arcs formed through the subduction of an oceanic plate beneath a continental plate).

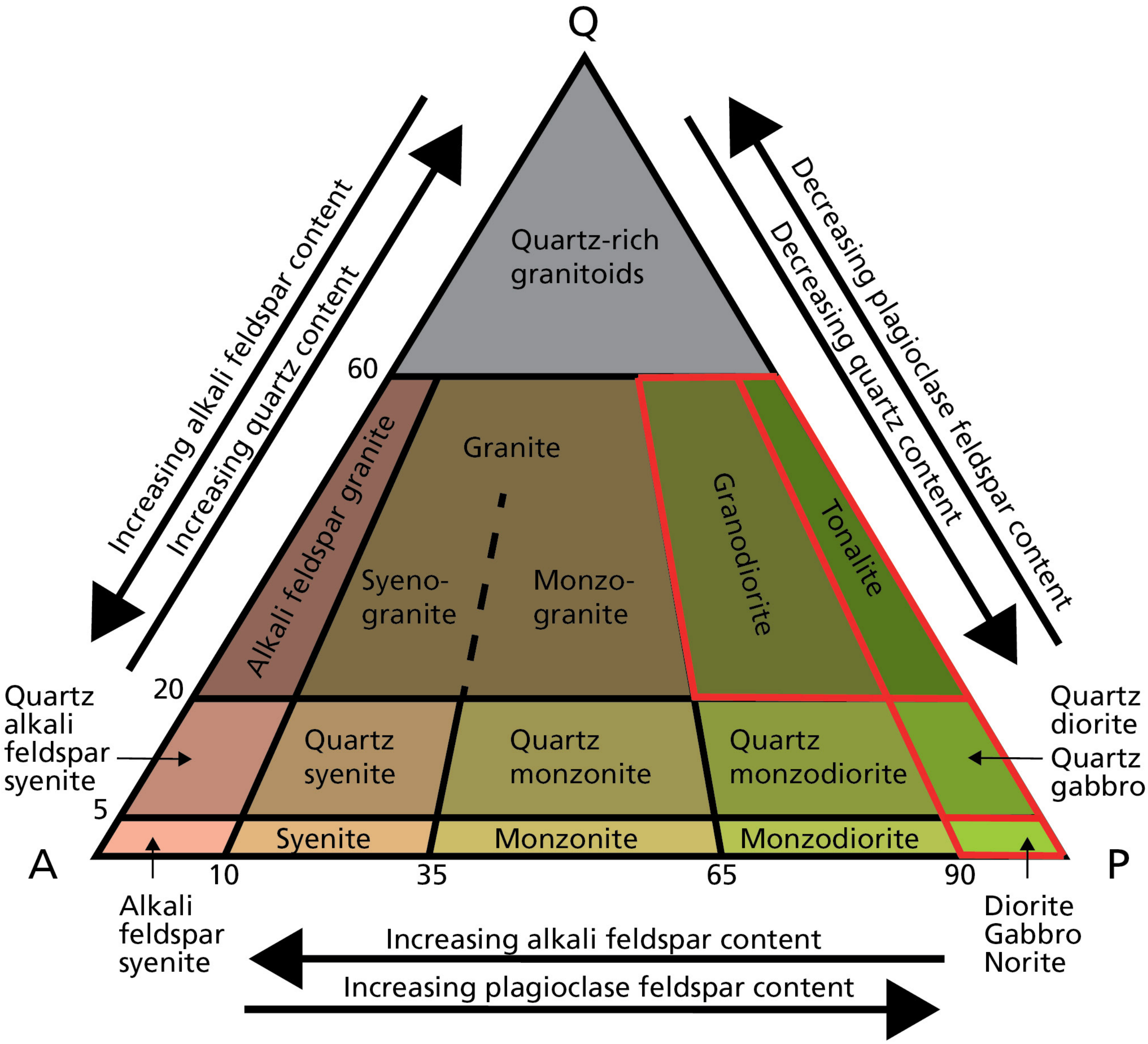


Figure 15. Diagram showing the classification of intrusive igneous rocks.
Classification is based on the relative percentages of the minerals quartz (Q), plagioclase feldspar (P), and alkali feldspar (A). Jurassic plutons in the park fall into the categories that are higher in plagioclase feldspar and quartz, including gabbro, diorite, quartz diorite, tonalite, and granodiorite (highlighted in red). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Tuxedni Group

Bedrock poster units: **Jtb, Jtt, Jtc, Jtf, Jtg, Jtrg**

The Tuxedni Group is a Middle Jurassic (174.1 million–163.5 million years ago) package of sedimentary rocks that forms a northeast-southwest trending belt overlying and adjacent to the Talkeetna Formation. During the Middle Jurassic, deeper parts of the arc were uplifted and eroded, potentially by movement along the Bruin Bay fault (see the "Faults and Folds" section for more details; LePain et al. 2011; Wartes et al. 2013). Sediments eroding off the exposed Talkeetna arc were deposited in the adjacent Cook Inlet fore-arc basin, forming the rocks of the Tuxedni Group. As such, the rocks of the Tuxedni Group are compositionally dominated by volcanic and plutonic rock fragments (Detterman and Hartsock 1966; Helmold et al. 2016). The Tuxedni Group is subdivided into six formations, which in ascending order are the Red Glacier Formation (**Jtrg**), Gaikema Sandstone (**Jtg**), Fitz Creek Siltstone (**Jtf**), Cynthia Falls Sandstone (**Jtc**), Twist Creek Siltstone (**Jtt**), and Bowser Formation (**Jtb**; Detterman and Hartsock 1966). All the formations contain fossils, which primarily include marine invertebrates such as ammonites, bivalves, and belemnites (see the "Paleontological Resources" section for more information). The basal unit of the Tuxedni Group (Red Glacier Formation) is known to be sourcing some of the oil in Cook Inlet basin (Magoon and Anders 1992); to better understand this economically important unit, the Alaska Division of Geological and Geophysical Surveys recently undertook a series of studies in and around the park to characterize the stratigraphy, sedimentology, structure, and petroleum potential of the Tuxedni Group (Herriott 2016).

Generally, the formations of the Tuxedni Group alternate between dominantly mudstone or sandstone lithologies, which reflect fluctuations of relative sea level (Detterman and Hartsock 1966; LePain et al. 2011). The basal formation within the Tuxedni Group, the Red Glacier Formation, is composed of shale, siltstone, and sandstone (Detterman and Hartsock 1966). The depositional environment for this unit is interpreted to be a deep marine setting grading into a shallower prodeltaic setting (LePain and Stanley 2015). Some variations in the rocks occur along strike within the Red Glacier Formation, which may reflect variations in water depth at the time of deposition. For example, the coarser grained rocks at Hungryman Creek record proximity to a coarse-grained deltaic depocenter (LePain et al. 2016). The overlying Gaikema Sandstone is predominately composed of sandstone, with subordinate amounts of siltstone, shale, and conglomerate (Detterman and Hartsock 1966). The Gaikema Sandstone has been interpreted to be the remains of a shallow marine delta built by swift, sediment-laden rivers that drained a mountainous volcanic area to the west of the Bruin Bay fault (Stanley et al. 2015). The shift from primarily deep-water deposition of the Red Glacier Formation, to more shallow marine deposition of the Gaikema Sandstone was caused by a drop in relative sea level in the Cook Inlet fore-arc basin (LePain et al. 2011). This trend of deeper-water, pro-deltaic marine deposition transitioning into shallower, deltaic environments is repeated throughout the Tuxedni Group. The Red Glacier Formation, Fitz Creek Siltstone, and Twist Creek Siltstone are all mainly fine-grained units that were deposited in relatively deep water (Stanley et al. 2015). Separating these episodes of marine flooding, the coarse-grained Gaikema Sandstone, Cynthia Falls Sandstone, and Bowser Formation were deposited as marine deltas that prograded (built outward) into the fore-arc basin (Stanley et al. 2015).

Chinitna Formation

Bedrock poster units: **Js, Jc**

The Middle Jurassic (174.1 million–163.5 million years ago) Chinitna Formation occurs stratigraphically above the Tuxedni Group, cropping out in a belt running southwest-northeast between Chinitna and Tuxedni Bays (Figure 16 and see the bedrock poster). Like the Tuxedni Group, the Chinitna Formation is composed of sedimentary rocks that were sourced from the eroding Talkeetna arc and deposited in the Cook Inlet fore-arc basin. It is subdivided into two members: the lower Tonnie Siltstone Member (**Js**) and the upper Paveloff Siltstone Member (**Jc**; Detterman and Hartsock 1966). The color of the siltstones is the main difference between the members. The Tonnie Siltstone weathers to a reddish brown, while the Paveloff Siltstone weathers to dark grey (Detterman and Hartsock 1966). The base of each member is characterized by coarse sedimentation with probable delta associations that transitions into finer-grained rocks towards the top (Herriott et al. 2017). These finer-grained rocks may reflect a rise in relative sea level, causing a change in depositional setting from a near-shore delta to prodelta and shelf environments, perhaps below storm wave base (Herriott et al. 2017). Both the Tonnie Siltstone and the Paveloff Siltstone contain marine invertebrate fossils, including ammonites that correspond to the late Middle Jurassic (Callovian; 166 million–164 million years ago; Imlay 1975). However, recent dating of detrital zircons indicate that the Tonnie Siltstone is not older than 160 million years, which is several million years younger than the biostratigraphic age. This disagreement between the biostratigraphy and radiometric dating may be due to discrepancies with faunal correlations or time-scale calibration (Herriott et al. 2019a; Herriott et al. 2019b).

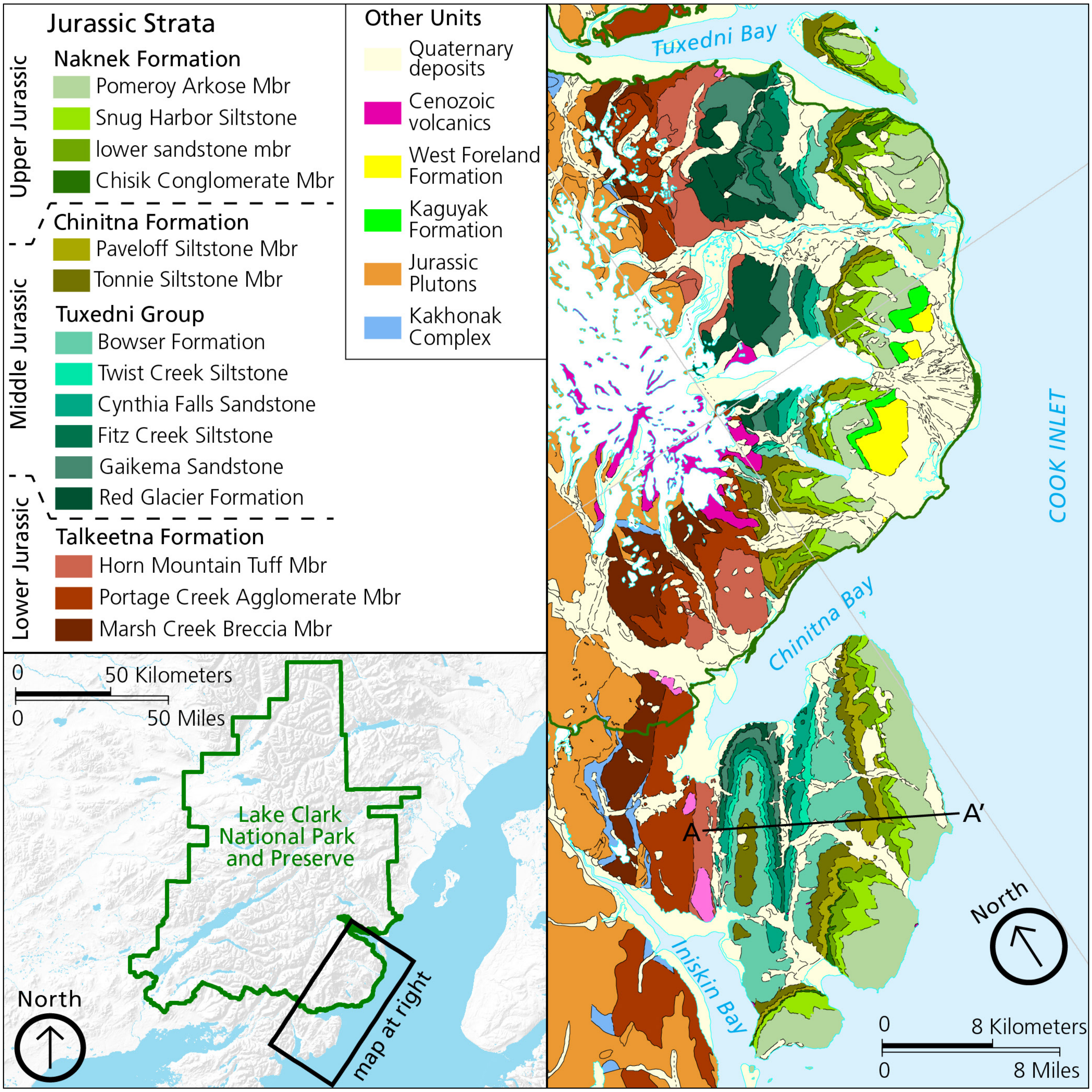


Figure 16. Map of the Jurassic (201.3–145 million years ago) fore-arc basin strata. The fore-arc basin strata in the southeastern part of the park was deposited in the Jurassic part of the Cook Inlet fore-arc basin. This basin formed next to the Talkeetna arc (Talkeetna Formation and Jurassic plutons) during the Jurassic and persists today. The Jurassic fore-arc basin strata are the focus of this figure, and include the Talkeetna Formation, Tuxedni Group, Chinitna Formation, and Naknek Formation. See Figure 23 for a cross-sectional diagram along the A-A′ transect. Modified from Wilson et al. (2015).

Naknek Formation

Bedrock poster units: **Jn, Jnc, Jns, Jnn, Jnp**

The Upper Jurassic (163.5 million–145 million years ago) Naknek Formation (**Jn**) occurs in the southeastern part of the park, overlying the Chinitna Formation (Figure 16 and see the bedrock poster). It crops out discontinuously for over 1,000 km (600 mi), from the Alaska Peninsula to the Talkeetna Mountains. Like the underlying Chinitna Formation, the biostratigaphic and radiometric ages conflict. The apparent inconsistency between the biostratigraphy and radiometric dating also may be due to discrepancies with faunal correlations or time-scale calibration (Herriott et al. 2019a; Herriott et al. 2019b).

The Naknek Formation has been subdivided into four members: the lowermost Chisik Conglomerate Member (**Jnc**), the Northeast Creek Sandstone Member (**Jnn**; referred to as the "lower sandstone member" by Detterman and Hartsock [1966]), the Snug Harbor Siltstone (**Jns**), and the Pomeroy Arkose Member (**Jnp**; Detterman and Hartsock 1966). The Chisik Conglomerate unconformably overlies the Chinitna Formation, and is restricted to Chisik Island, Slope Mountain, and the southern part of the Iniskin Peninsula. It is primarily a very thick-bedded conglomerate with minor amounts of sandstone (Detterman and Hartsock 1966; Wartes et al. 2013; Herriott and Wartes 2014; Herriott et al. 2017). The Northeast Creek Sandstone Member is a lateral equivalent of the Chisik Conglomerate and forms the base of the Naknek Formation where the conglomerate is absent (Detterman and Hartsock 1966). In areas where the Chisik Conglomerate and Northeast Creek Sandstone Member are both found, the Northeast Creek Sandstone Member overlies the Chisik Conglomerate (Herriott et al. 2017). The Northeast Creek Sandstone Member is composed primarily of very fine- to fine-grained sandstone and is often bioturbated (reworked by plants or animals; Detterman and Hartsock 1966; Wartes et al. 2015; Herriott et al. 2017). The Snug Harbor Siltstone Member is composed mainly of dark grey siltstone and very fine-grained sandstone (Detterman and Hartsock 1966; Herriott et al. 2017). The Pomeroy Arkose Member is composed of arkosic (at least 25% feldspar) sandstone with subordinate amounts of siltstone and sandstone (Detterman and Hartsock 1966; Herriott et al. 2017). The Pomeroy Arkose Member is resistant to weathering and erosion and forms the top of many of the park's dipping coastal mountains (Figure 17).

Figure 17. Photograph of Slope Mountain as seen from Silver Salmon Creek.
Slope Mountain is composed of rock belonging to the Naknek Formation. The Pomeroy Arkose Member of the Naknek Formation is quite resistant and forms the top of Slope Mountains. The cliff face visible in the top middle of the photograph display the alternating light-dark beds of the Pomeroy Arkose Member. The smaller hill in front of Slope Mountain on the left side of the photograph is August Hill, which is also composed of rocks of the Naknek Formation. NPS photograph by Kara Lewandowski.

The four members of the Naknek Formation were deposited in Cook Inlet basin, in environments ranging from shallow to deep marine (Herriott et al. 2017). The basal Chisik Conglomerate Member is interpreted to be the remains of a shallow-water fan delta, the overlying Northeast Creek Sandstone Member was formed in an inner shelf setting with shoreface and deltaic influences, the Snug Harbor Siltstone was formed through outer shelf to slope sedimentation, and the Pomeroy Arkose Member records sediment gravity flows at the base of the slope and on the basin floor (Figure 18; Wartes et al. 2013; Herriot et al. 2017). Herriott et al. (2017) identified three deep-water paleocanyons located in the Chisik Island, Hickerson Lake, and Mount Pomeroy areas. These canyons incised the slope strata of the Snug Harbor Member and are filled primarily with channelized sandstones of the Pomeroy Arkose Member (Herriott et al. 2017). The rocks of the Naknek Formation are more feldspar-rich than the underlying Tuxedni Group and Chinitna Formation (Helmold et al. 2013), indicating they were sourced from the deeper, plutonic roots of the Talkeetna arc (Figure 18; Detterman and Hartsock 1966; Trop et al. 2005; Herriott et al. 2017). The exposure of deeper plutonic rocks may have been accommodated by movement along the Bruin Bay fault (Figure 18) and could possible due to tectonic convergence of the Peninsular terrane with the North American margin (Trop et al. 2005).

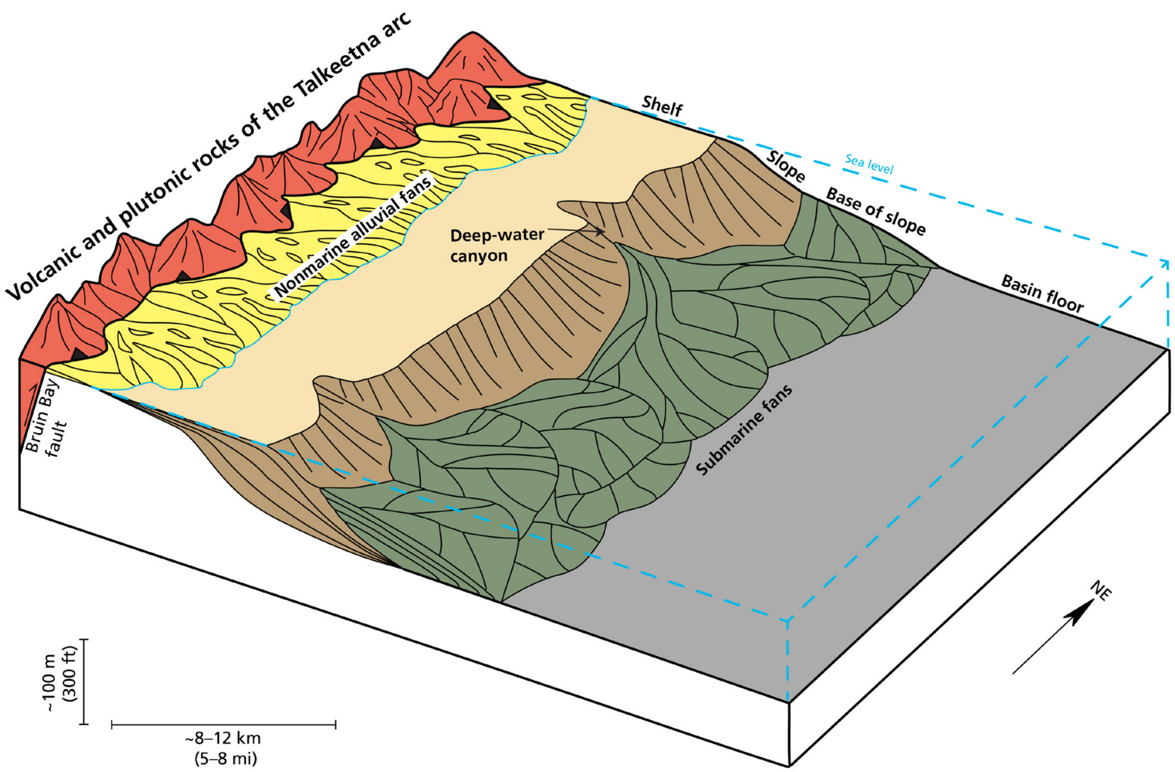


Figure 18. Diagram of the depositional environments of the Naknek Formation.
The Chisik Conglomerate Memberand Creek Sandstone Member both formed on the shelf, the Snug Harbor Siltstone formed on the outer shelf to slope, and the Pomeroy Arkose Member formed at the base of the slope and on the basin floor. Three deep-water paleocanyons have been found in the Naknek Formation in the Lake Clark region. These canyons incised the slope strata of the Snug Harbor Member and are filled primarily with channelized sandstones of the Pomeroy Arkose Member. The Bruin Bay fault (left side of the graphic) is a major reverse fault that may have accommodated the exhumation of volcanic and plutonic rocks of the Talkeetna arc (see the "Faults and Folds" section). Redrafted from Herriott et al. (2015) after Reading and Richards (1994).

Koksetna River Sequence and Kuskokwim Group

Bedrock poster units: **KJkr, Kesv, KJk, KJs**

The northern part of the park contains highly deformed clastic sedimentary rocks that were deposited during the Jurassic (201.3 million–145 million years ago) and Cretaceous (145 million–66 million years ago). These rocks include the Koksetna River sequence (**KJkr**), the Kuskokwim Group (**KJk**), turbiditic sedimentary and volcanic rocks (**Kesv**), and a flysch sequence (**KJs**) (see the bedrock poster). Many of these rocks are part of a larger belt of Jurassic–Cretaceous deep-water, clastic sedimentary rocks known as the Kahiltna assemblage. The Kahiltna assemblage formed between the Wrangellia composite terrane and older, inboard pericratonic terranes (Figure 19). The Kahiltna assemblage transitions to the Kuskokwim Group to the west. The Kuskokwim group is mainly Late Cretaceous in age (100.5 million–66 million years ago), while the rocks of the Kahiltna assemablage span the Jurassic and Cretaceous. Both the Kahiltna assemblage and the Kuskowim Group are primarily composed of deep water turbidite and debris-flow deposits, with minor amounts of shallow-marine deposits (Box et al. 2019). Despite the similar appearance and depositional environments of the rocks assigned to the Kahiltna assemblage and Kuskokwim Group, detailed study has determined they can be divided into a northern belt and southern belt derived from different sources and formed in different areas. These belts of sedimentary rock were later juxtaposed along the Chilchitna fault zone (Figure 19; Wallace et al. 1989; Hults et al. 2013; Box et al. 2019).

The Koksetna River sequence and other rocks of the southern flysch belt were derived from and deposited adjacent to rocks of the Wrangellia composite terrane, while the Kuskokwim Group and other rocks of the northern flysch belt were sourced from more inboard pericratonic terranes, such as the Farewell and Yukon-Tanana terranes (see the “Terrane Translation and Accretion” section for more information on terranes; Wallace et al. 1989; Hults et al 2013; Box et al. 2019). The Koksetna River sequence contains detrital zircons that match the Wrangellia composite terrane and is dominated by volcanic and plutonic clasts derived from igneous rocks such as the the Talkeetna arc (Wallace et al. 1989; Hults et al 2013; Box et al. 2019). In contrast, the northern flysch belt rocks have detrital zircons with ages similar to those found in the inboard pericratonic terranes and is compositionally more dominated by quartz grains (Wallace et al. 1989; Hults et al 2013; Box et al. 2019). Box et al. (2019) interpreted the northern flysch belt to be fore-arc deposits shed off a south-facing continental magmatic arc located in southern Alaska during the Jurassic–Cretaceous (201.3–66 million year ago). The Koksetna River sequence represents backarc deposits shed from the Wrangellia composite terrane prior to its accretion to southern Alaska. The two successions begin to overlap one another and are deformed together around 80 million years ago, indicating that by this time the Wrangellia composite terrane had reached the southern Alaska margin (Box et al. 2019).

Cretaceous–early Paleogene Igneous rocks

Bedrock poster units: **Tvbs, Tfv, Tgh, Tpg, Thgd, Tpd, Tgl, TKd, Tkgs, Tkgb, Tkgg, TKv, TKgbu, TKgp, TKg, TKqd, TKgdt, TKqdt, TKvb, TKeogr, TKvr, TKvd, TKmv, TKdg, TKgr, TKgm, TKJg, Kvi, Kgd, Kqd, Kgl, Kgk, Kmg, Kmqm, Kmgd, Kivs**

Cretaceous–early Paleogene (110 million–55 million years ago) plutonic and minor amounts of volcanic rocks occur extensively in the park, exposed along a wide northeast–southwest-trending belt inboard of the plutons associated with the Talkeetna arc (Figure 14 and see the bedrock poster). These Cretaceous–early Paleogene plutons are part of the Alaska-Aleutian Range batholith (Reed and Lanphere 1973). The Alaska-Aleutian Range batholith is a geographic grouping of plutons that were emplaced during three distinct magmatic phases: (1) a Late Triassic–Jurassic phase, dated to between 212 million and 164 million years ago (Rioux et al. 2010); (2) a Cretaceous–early Paleogene phase, dated to between about 110 million and 55 million years ago (Reed and Lanphere 1973; Todd and Jones 2020); and (3) a middle–late Paleogene phase, dated to between 48 million and 22 million years ago (Wilson 1985). Plutons formed during the Cretaceous–early Paleogene phase are mainly found in the northern extent of the batholith (Reed and Lanphere 1973). The emplacement of these plutons between about 110 million and 55 million years ago is interpreted to represent subduction that led to and continued after final accretion of the Peninsular terrane to the southern Alaska margin about 80 million years ago (Box et al. 2019; Todd and Jones 2020). After collision and accretion of the Peninsular terrane, subduction-related magmatism integrated across the entire southern Alaska margin, extending north across the southern Farewell terrane. Cretaceous and early Paleogene magmatism was broadly related to continued north-dipping subduction beneath the Peninsular terrane. However, unlike the earlier Talkeetna arc magmatism, Cretaceous and early Paleogene plutons involved more widespread partial melting of continental material consistent with the tectonic models for arc evolution and terrane accretion (Todd and Jones 2020).

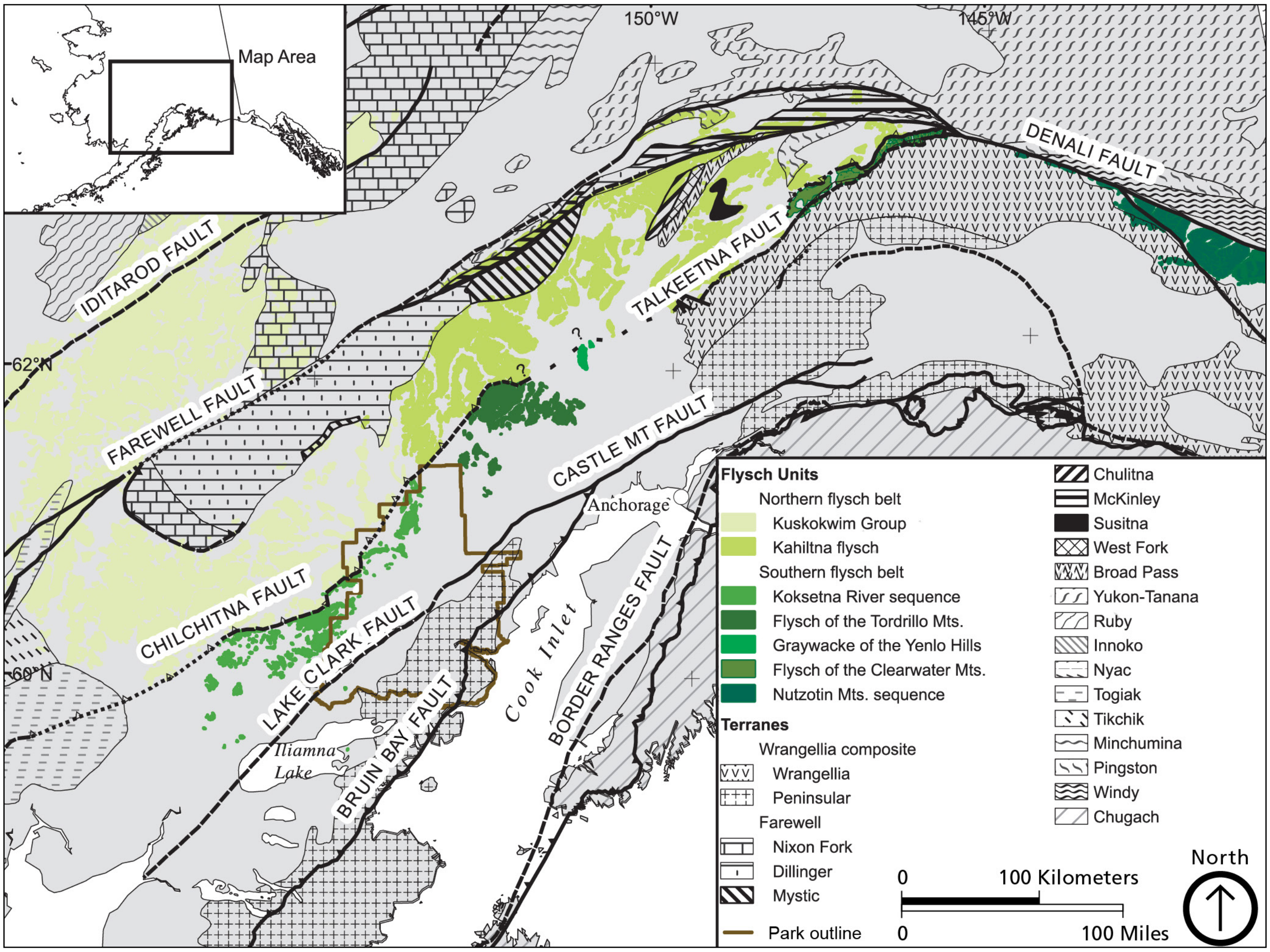


Figure 19. Map showing the distribution of Jurassic–Cretaceous (201.3–66 million year ago) flysch units in southcentral Alaska.
The northern flysch belt units, such as the Kuskokwim Group, were derived from inboard pericratonic terranes, while the southern flysch belt units, such as the Koksetna River sequence, were shed off the Wrangellia composite terrane. Rocks assigned to both the northern flysch belt and southern flysch belt are found in the northwestern part of the park (modified from Hults et al. 2013).

Kaguyak Formation

Bedrock poster units: **Kks**

Rocks mapped as the Kaguyak Formation (**Kks**) unconformably overlie the Naknek Formation on Saddle Mountain and between Hickerson Lake and the Red River (Figure 16 and see the bedrock poster). These rocks are mainly known from an 83 m- (270 ft-) thick section located about 3 km (2 mi) east of Saddle Mountain, as well as two additional exposures on either side of Shelter Creek (southwest of Saddle Mountain; Gillis 2016); the map distribution was extrapolated from these sections (Magoon et al. 1980; Bradley et al. 1999). LePain et al. (2012) argued that these rocks should not be referred to as the Kaguyak Formation because they record a non-marine depositional environment as compared to a marine environment for the rest of the Kaguyak Formation, which is defined and described to the south of the map area (including in Katmai National Park and Preserve, see Hults and Fierstein 2016). The rocks that define the Kaguyak Formation to the south are very different from those exposed at Saddle Mountain, and so far there is no evidence from subsurface exploration to support this lateral variation in stratigraphy for the Kaguyak Formation (Marwan Wartes, Alaska Division of Geological & Geophysical Surveys, geologist, written communication, 21 September 2020).

The Kaguyak Formation in the map area includes sandstone, mudstone, conglomerate, and associated coal deposited in a nonmarine environment (Magoon et al. 1980; LePain et al. 2012). Fossil pollen dates the rocks to Upper Cretaceous (Maastrichtian; 72.1 million–66 million years ago; Magoon et al. 1980). This is the only exposure of nonmarine Upper Cretaceous rocks in the Cook Inlet area (Magoon et al. 1980). The nonmarine depositional environment is supported by the absence of marine macrofossils, the presence of coaly laminae, lateral discontinuity of the bedding, and the disorganized appearance of the conglomerates (LePain et al. 2012). LePain et al. (2012) interpreted the Saddle Mountain section as a broad, nonmarine paleovalley incised into the underlying Naknek Formation.

West Foreland Formation

Bedrock poster units: **Twf**

The West Foreland Formation (**Twf**) is an Eocene (56.0 million–33.9 million years ago) unit that unconformably overlies the Kaguyak Formation in the southeastern part of the park (Figure 16 and see the bedrock poster). It is composed of nonmarine sedimentary rocks, including conglomerate, sandstone, laminated siltstone, silty shale, and minor coal beds (Detterman and Hartsock 1966). These sediments were derived from the Peninsular terrane to the west (Bradley et al. 1999) and contain plant fossils, such as fossilized logs (see the "Paleontological Resources" section for more details; Detterman and Hartsock 1966; Ruga et al. 2020).

Meshik Volcanics

Bedrock poster units: **Tib, Tvu, Ta, Thf, Tgr, Tgd, Toqd, Tpgr, Tap, Trd, Togr, Tpag, Toem, Tegr, Tvr, Tvba, Tbn, Tbc, Tvs**

Rocks of the Meshik volcanic arc occur in the northwestern portion of the park (see the bedrock poster). The plutons associated with the Meshik volcanic arc form the youngest, middle–late Paleogene portion of the Alaska-Aleutian Range Batholith (Figure 14; Reed and Lanphere 1973). The Meshik volcanic arc includes volcanic and plutonic rocks ranging in composition from basalt to dacite, as well as associated volcaniclastic units of the Meshik and Stepovak formations (Figure 20; Wilson 1985). Radiometric dates of the volcanic rocks yielded ages ranging from 48 million to 22 million years ago (Wilson 1985). The Meshik volcanic arc is subparallel to the modern Aleutian arc, but further inboard. In contrast with the Cretaceous and Early Paleogene igneous rocks, the Meshik Volcanics occupied a narrower geographic zone. This may indicate subduction zone parameters, such as subduction angle, stabilized. The Meshik volcanics are generally thought to be the precursor to the modern Aleutian arc, as the configuration of the tectonic plates have remained unchanged since their eruption.

Figure 20. Photograph of volcanic rocks of the Meshik volcanics.
Photograph was taken to the south of Lower Twin Lake. NPS photograph by Kara Lewandowski.

Faults and Folds

Tectonic forces can cause rocks to deform, producing faults (planes along which rocks slip past one another) and folds (twists or bends in rocks). While most of the rocks in the park are structurally complex, containing many small faults and folds, three major faults are mapped or inferred to project through the park: the Chilchitna fault, the Lake Clark fault, and the Bruin Bay fault (Figure 21). All three faults trend northeast–southwest. The Chilchitna fault zone is in the northwest part of the park, separating sedimentary rocks derived from the Peninsular terrane (locally Koksetna River Sequence) from those derived from North America (locally Kuskokwim Group; see the "Bedrock Geology" section for more information; Wallace et al. 1989; Hults et al. 2013). The Lake Clark fault projects through the center of the park, and Lake Clark itself is parallel to the inferred fault trace. The Bruin Bay fault lies in the southeastern part of the park, generally separating fore-arc sedimentary rocks from the volcanic and plutonic rocks of the Talkeetna arc (see the "Bedrock Geology" section for more information; Detterman and Hartsock 1966). Movement along faults can cause earthquakes; for information on earthquakes in and around the park, see the "Geohazards" section.

Lake Clark Fault

The Lake Clark fault projects along a prominent topographic lineament running northeast to southwest through the center of the park. Lake Clark itself occupies an elongate valley along this lineament in the southwestern part of the park, and the Tlikakila and Chokatonk rivers run along the fault in the northeast. Near the Beluga River to the northeast, the Lake Clark fault is interpreted to merge into the active Castle

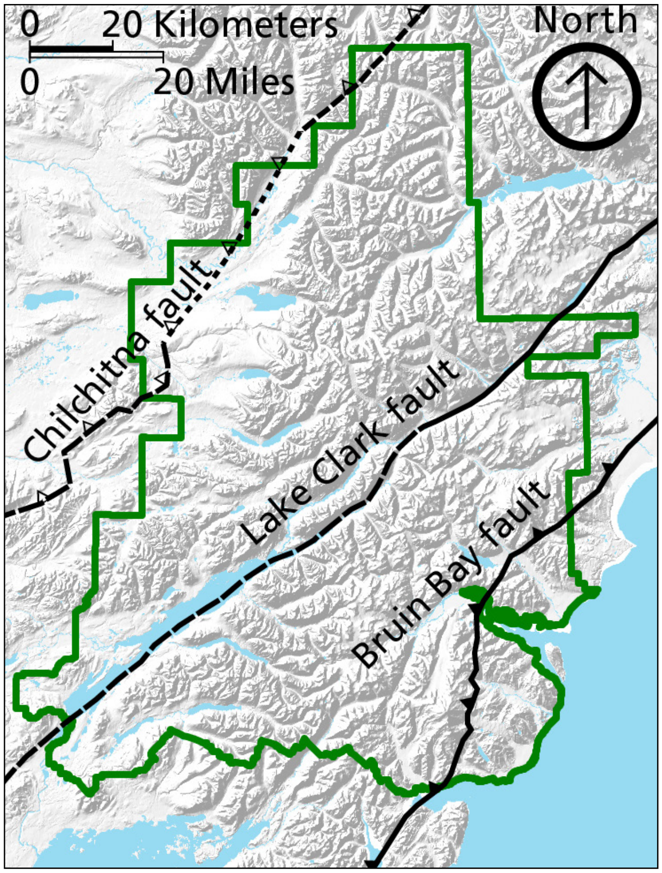


Figure 21. Map of the three major faults in the park. Faults are planes along which rock rocks slip past one another and are produced by compression, extension, or shear forces. The major fault systems in the park include the Chilchitna fault in the north, the Lake Clark fault in the central part of the park, and the Bruin Bay fault in the south. All three major fault systems in the park trend northeast–southwest.

Mountain fault. These two faults are thought to be part of the same fault system because they have the same orientation and sense of motion (Detterman et al. 1976).

Estimates of offset for the Lake Clark fault range from 5 km (3 mi) to 26 km (16 mi). The Lake Clark fault is a right-oblique reverse fault, which means movement on the fault is a combination of upward motion of the hanging wall and right-lateral strike-slip (Figure 22). Detterman et al. (1976) reported 500–1,000 m (1500–3000 ft) of northwest-side-up offset on the Lake Clark fault based on the displacement of Paleogene (66 million–23 million years ago) rocks on the Chuitna River and an estimated 5 km (3 mi) of right-lateral offset based on contacts between the Talkeetna Formation, a Paleogene pluton, and older metamorphic rocks near Lake Clark. A more recent study used the offset of magnetic anomalies associated with granitic plutons (**Tegr**) and found the Lake Clark fault may have accommodated 26 km (16 mi) of right-lateral offset in the past 34 million–39 million years (Haeussler and Saltus 2005). Movement on the Lake Clark fault is driven by the collision of the Pacific plate and the Yakutat block with the southern margin of Alaska.

Little evidence for recent activity along the Lake Clark fault has been observed despite its hypothesized connection with the more active Castle Mountain fault to the east. The Castle Mountain fault has ruptured four times in the past ~2700 years (Haeussler et al. 2002). Similar Holocene (11,000 years ago–present) activity on the Lake Clark fault could be expected, however, a recent study by Koehler and Reger (2011) found little evidence for such activity. Koehler and Reger (2011) mapped the surficial geology around the Tyonek-Capps Glacier area and found that glacier deposits dating to 60 thousand–75 thousand years ago were not offset along the Lake Clark fault in this area. Additionally, no streams in the area were laterally displaced, but some streams that cut through the fault had convex-up profiles that may be a result of north-side-up motion (Koehler and Reger 2011).

The apparent discrepancy between recent activity on the Castle Mountain fault and the lack of motion on the Lake Clark fault has several possible explanations. It may be due to a transition from right-lateral motion on the Castle Mountain fault to right transpressional deformation in the Cook Inlet Basin. Haeussler et al. (2000) supported this idea by interpreting Quaternary slip along the Castle Mountain fault as transferring to the folds in the Cook Inlet area. Other explanations include the insufficient examination or masking by vegetation of structures on the Lake Clark fault that record slip. Furthermore, uncertainty in the amount of lateral slip along the two faults may hinder activity-rate comparisons (Koehler and Reger 2011). Additional studies examining the bedrock geology and surficial deposits along different sections of the Lake Clark fault would provide more information to illuminate this uncertainty.

Bruin Bay Fault

The Bruin Bay fault runs along the west side of Cook Inlet, extending from where it merges with the Castle Mountain Fault near Mount Susitna northeast of the park, down the Alaska Peninsula to Becharof Lake, located southwest of Katmai National Park and Preserve (Detterman and Reed 1980). This fault is one of the major structural features in the Cook Inlet region, separating the Lower Jurassic (201.3 million–174.1 million years ago) volcanic and plutonic roots of the

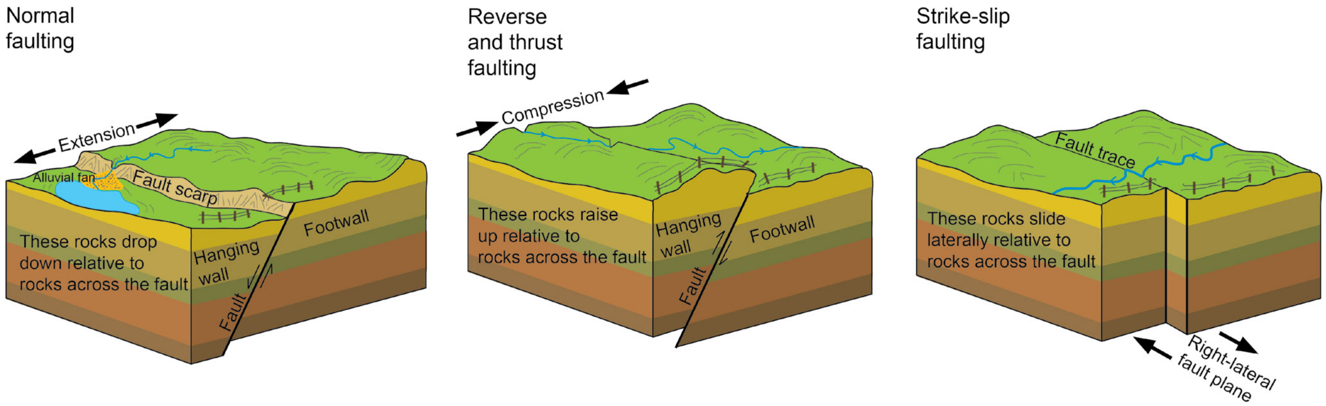


Figure 22. Diagram showing the different types of faults and the relative motion that produces them. The Lake Clark fault is a right-oblique reverse fault, which is a combination of a reverse fault and right lateral strike-slip fault. Oblique slip faults have a combination of movement in the direction of the dip of the fault as well as horizontal movement and are formed through oblique compression. The Bruin Bay fault is primarily a reverse fault, formed through region-wide compression. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Talkeetna arc from the younger fore-arc basin strata. The Bruin Bay fault runs through the southeast part of the park, cutting just south of Redoubt and Iliamna Volcanoes. The fault does not consist of a single plane but is instead a zone, up to a few kilometers wide, of steeply dipping subparallel reverse faults (Detterman and Reed 1980; Gillis et al. 2013). Reverse faults offset rocks in such a way that the rocks above the fault plane move up relative to the rocks below the fault plane (Figure 22). The Bruin Bay fault dips to the northwest, so the rocks moving upward are on the northwest side of the fault. Between Redoubt and Iliamna, the Bruin Bay fault juxtaposes the plutons of the Alaska-Aleutian range batholith against the Talkeetna Formation and south of Iliamna the fault juxtaposes the Talkeetna Formation against the younger sedimentary rocks of the Tuxedni Group (see the bedrock poster).

The Bruin Bay fault has a long history spanning the Jurassic–Oligocene (201.3 million–23 million years ago) that includes possible reverse motion during the Jurassic (201.3 million–145 million years ago) and a significant leftward transpressional event during the Paleogene (66 million–23 million years ago; Detterman and Hartsock 1966; Betka et al. 2017; Rosenthal et al. 2017).

Stratigraphic evidence from sedimentary rocks in the Cook Inlet fore-arc basin show that parts of the Talkeetna arc were probably being exhumed during deposition of these rocks (LePain et al. 2011; Gillis et al. 2013; Wartes et al. 2013). This exhumation may have been accommodated by reverse motion along the Bruin Bay fault system. A recent study of the Bruin Bay fault focused on fault slip analysis within the park and to the south (between Tuxedni Bay and Ursus Head) found evidence for activity primarily in the Paleocene (66 million–56 million years ago) but continuing to the early Oligocene (33.9 million–27.8 million years ago; Betka et al. 2017). Betka et al. (2017) suggested that the Paleogene sinistral transpression may have been caused by the subduction of a spreading ridge beneath the southern margin of Alaska or the accretion of the Chugach-Prince William terrane.

Folds

Just to the south of the park on the Iniskin Peninsula, Jurassic (201.3 million–145 million years ago) sedimentary rocks are folded into a "U" shaped syncline and an "A" shaped anticline called the Tonnie syncline and Fitz Creek anticline, respectively (Figure 23; Detterman and Hartsock 1966). Both folds formed as a result of movement along the Bruin Bay fault, which lies immediately west of the Tonnie syncline (Detterman and Hartsock 1966). The Tonnie syncline and Fitz Creek anticline are both northeast-trending asymmetrical folds with steeper western limbs (Detterman and Hartsock 1966). Faults that cross the Fitz Creek anticline are a conduit for underlying hydrocarbons, producing natural oil and gas seeps (Detterman and Hartsock 1966). The oil and gas seeps were identified in the late 1800s, which spurred intermittent petroleum exploration in the area starting as early as 1900 (see the "Coastal Issues" section for more details; Detterman and Hartsock 1966; Blasko 1976).

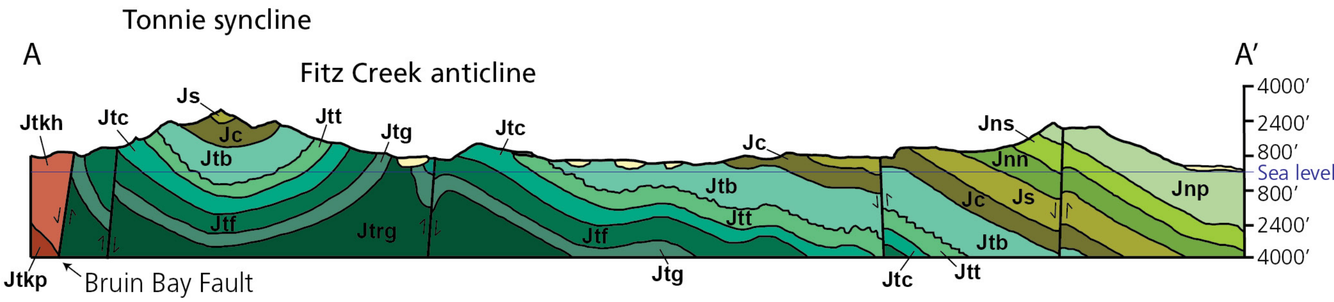


Figure 23. Cross section of the Tonnie syncline and Fitz Creek anticline on the Iniskin Peninsula. A syncline is a "U" shaped bend in rocks and an anticline is an "A" shaped bend. The bend of the rocks can be seen in the cross section by tracing the contacts between the different geologic units, which would have been horizontal before the bending. This syncline-anticline pair is located just south of the park on the Iniskin Peninsula and formed because of compression related to motion on the Bruin Bay fault. See Figure 16 for the location of A-A′ and an explanation of the geologic unit colors. Modified after Detterman and Hartsock (1966).

Mineral Resources

The US Geological Survey (USGS) Alaska Resource Data File (https://ardf.wr.usgs.gov/) lists 52 metalliferous mineral occurrences in the park. The main mineral commodities found include gold, copper, silver, zinc, molybdenum, and lead. Less commonly found minerals include a few occurrences of tin in the northern part of the park, iron-bearing deposits in the hills south of Lake Clark and along Tuxedni Bay, and an asbestos deposit on the north shore of Lake Clark. Many of the mineral occurrences and prospects are Paleogene (66 million–23 million years ago) in age and are found within the Meshik igneous rocks and surrounding metasedimentary rocks (see the "Bedrock Geology" section for more information). In the southeast part of the park, mineralization occurred during the Jurassic (201.3 million–145 million years ago) and is associated with the Talkeetna arc volcanic and plutonic rocks. These deposits are described in the next section. For information on the potential for mineral development and mitigation of abandoned mineral lands in the park, see the "Mineral Development Potential" and "Abandoned Mineral Lands Mitigation" sections of this report, respectively.

Johnson River Prospect

The Johnson River prospect is a mineral deposit located in the upper Johnson River basin near the toe of Johnson Glacier (Steefel 1987). The deposit occurs within the Lower Jurassic (145 million–100.5 million years ago) Talkeetna Formation (**Jtkp**), which is a thick succession of volcanic and volcaniclastic rocks that crop out in the southeastern part of the park (for more information about the Talkeetna Formation, see the "Bedrock Geology" section). Gold is the primary commodity, but silver, copper, lead, and zinc also occur in the deposit (USGS Alaska Resource Data File (https://ardf.wr.usgs.gov/). The Alaska Native regional corporation Cook Inlet Region Incorporated (CIRI) owns the tract of land including subsurface rights on which the prospect is located. North of the fully owned tract is an area with split estate ownership where CIRI owns the subsurface rights and NPS manages the surface.

The Johnson River prospect is thought to have formed synchronously with the Talkeetna Formation, during two distinct stages of mineralization. Steefel (1987) proposed a genetic model that involves base metal-rich hydrothermal fluids interacting with seawater-saturated volcanic rocks just below the sea floor (Figure 24). The first stage was characterized by the formation of nodular anhydrite ($CaSO_4$) without significant amounts of base metals and gold (Steefel 1987). Anhydrite mineralization occurred over an area of roughly 1,150 m by 375 m (3,800 ft by 1,200 ft). At the core of the mineralized area, anhydrite replaced up to 80 percent of the host rock, grading to 10 to 60 percent towards the edges (Steefel 1987). The second stage of mineralization was characterized by the formation of quartz-sulfide; this stage includes all the high-grade mineralization at the Johnson River prospect (Steefel 1987). A complex system of veins and massive sulfide lenses compose a body of mineralization that is irregular, pipe-like, and cuts to various depths through the anhydrite zone (Steefel 1987). Minerals formed during this stage include quartz (SiO_2), sphalerite (ZnS), pyrite (FeS_2), chalcopyrite ($CuFeS_2$), galena (PbS), anhydrite ($CaSO_4$), barite ($BaSO_4$), Fe chlorite, and native gold (Steefel 1987). The highest gold values are associated with areas of significant copper mineralization (e.g. chalcopyrite) at intermediate stratigraphic depths (Steefel 1987).

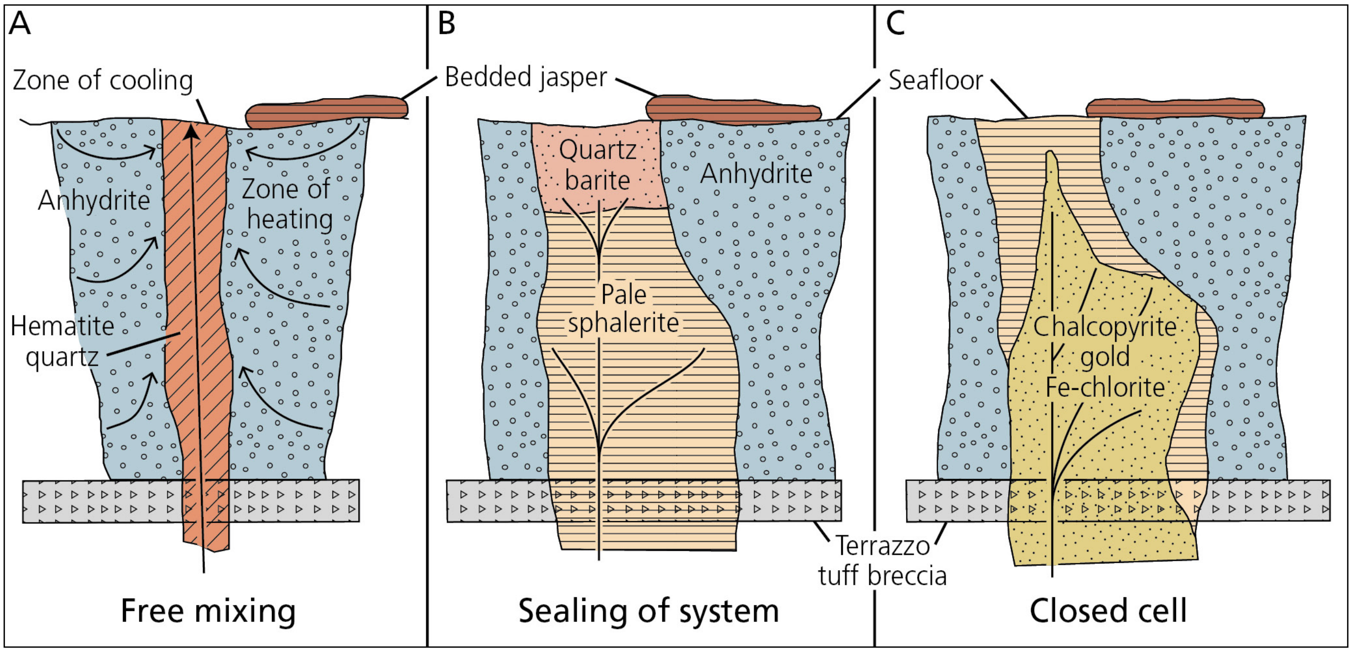


Figure 24. Diagram of the genetic model for the Johnson River prospect by Steefel (1987). (A) Hydrothermal fluids carrying base metals and gold move up through a section of ocean floor saturated with cold seawater, causing the hydrothermal fluids to react with the seawater and anhydrite to precipitate (correlating to the first stage of mineralization described above). (B) Precipitation of anhydrite partially seals the system by reducing permeability and the influx of seawater. This partial sealing allows large amounts of quartz to form with barite and sphalerite. Precipitation of these mineral further seals the system. (C) Eventually, precipitation of quartz and anhydrite cut off the seawater in the system entirely and the ascending metal-rich hydrothermal fluids dominate. Base metal- and gold-rich mineralization occurs, including the precipitation of chalcopyrite, pyrite, Fe-chlorite, galena, and native gold. Figure modified from Steefel (1987).

Paleontological Resources

Bedrock poster units: **TRrk, TRkb, TRkm, JTRku, Jtkh, Jtrg, Jtg, Jtf, Jtcf, Jtt, Jtb, Js, Jc, Jn, Jnc, Jns, Jnn, Jnp, KJkr, Kesv, KJk, KJs, Kks, MZPZcb, MZPZk, MZPZb, Twf, Ttyh**

Paleontological resources, or fossils, are any evidence of life preserved in a geologic context. Fossils in the park are concentrated in the southeast, within the sedimentary rocks that crop out between Chinitna and Tuxedni bays (area known as the Iniskin–Tuxedni region). From oldest to youngest, these rock units include the unnamed Triassic rocks in the middle glacier area, Talkeetna Formation (**Jtkh**), Tuxedni Group (**Jtrg, Jtg, Jtf, Jtcf, Jtt, Jtb**), Chinitna Formation (**Js, Jc**), Naknek Formation (**Jn, Jnc, Jns, Jnn, Jnp**), Kaguyak Formation (**Kks**) West Foreland Formation (**Twf**), and Kenai Group (**Ttyh**; see the “Bedrock Geology” section for more information on these units. Note, the Kenai Group is not mapped within the park or discussed in the “Bedrock Geology” section, but older mapping reported fossils from this unit within the park, so it is included here). These rocks contain a rich assortment of Mesozoic (251.9 million–66 million years ago) marine invertebrate fossils, as well as Cretaceous (145 million–66 million years ago) pollen and Cenozoic (66 million years ago to present) plant fossils. Fossiliferous units elsewhere in the park include the Kamishak Formation (**TRrk, TRkb, TRkm, JTRku**), the Cottonwood Bay Greenstone (**MZPZcb**), the Kakhonak/Tlikakila Complex (**MZPZk, MZPZb**), the Koksetna River sequence (**KJkr, Kesv**), and the Kuskokwim Group (**KJk, KJs**). While all these units are known to contain fossils, only the Tlikakila complex has produced fossils within park boundaries (Wallace et al. 1989). An overview of the types of fossils found in the park and their context follows (Figure 25); more information can be found in the Southwest Alaska Network Paleontological Resource Inventory and Monitoring report (Kenworthy and Santucci 2003) and the Lake Clark Paleontological Resource Focused Condition Assessment (Ruga et al. 2020). For information on management of paleontological resources see the “Paleontological Resources Inventory, Monitoring, and Protection” section.

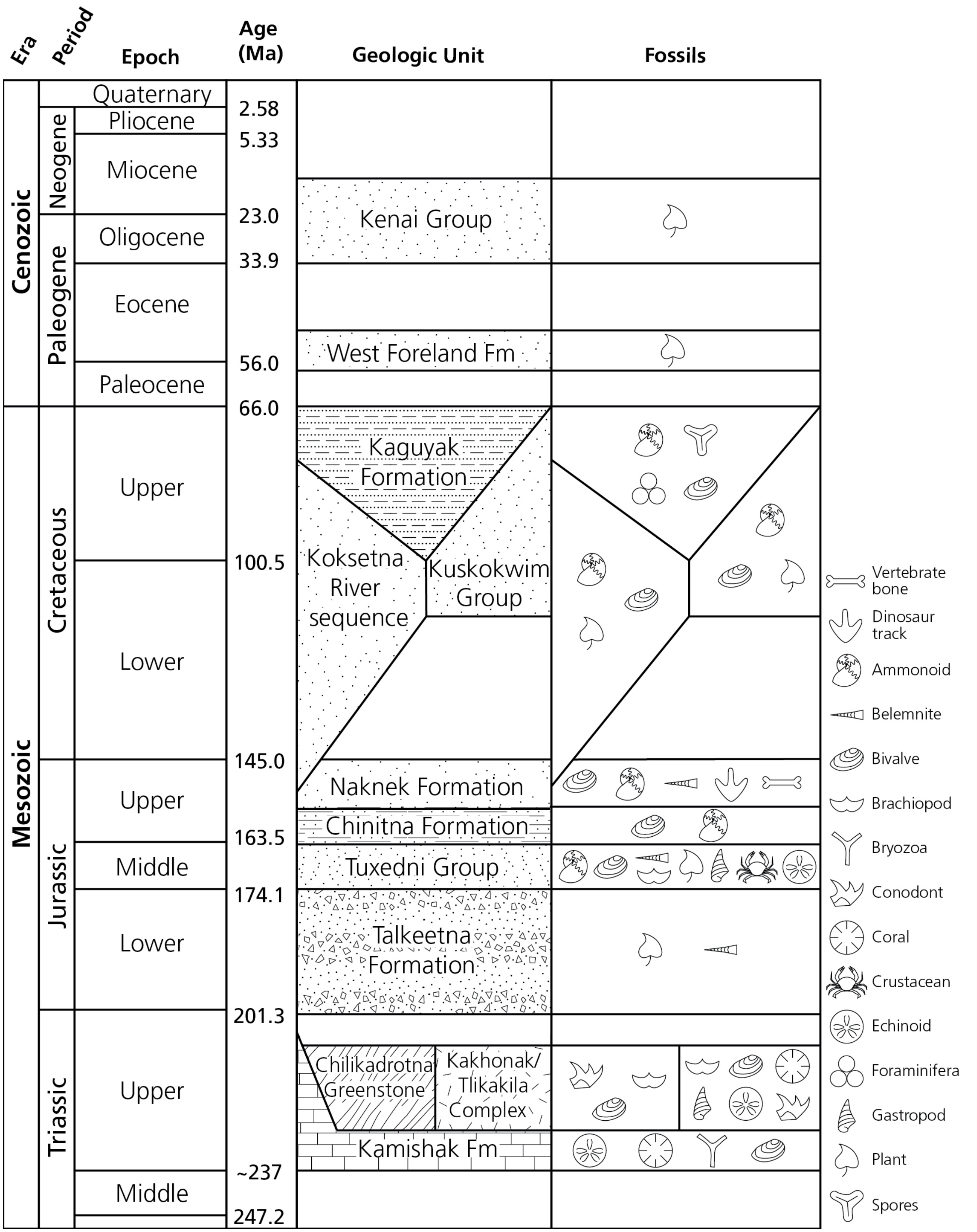


Figure 25. Stratigraphic column of fossil-bearing rock units in Lake Clark National Park and Preserve. Fossil icons represent the general types of fossils found in each rock unit, not necessarily the types of fossils that have been found in the park. The white areas of the column either indicate time periods when no rocks were forming in the park or no rocks containing fossils were forming in the park. Fossil and rock symbols are standard geologic map symbols from U. S. Geological Survey (2006).

The Lower Jurassic Talkeetna Formation formed the edifice of the Talkeetna arc (see "Bedrock Geology" section for more information), so the fossils it contains are the remains of the creatures that lived on and around this series of ancient oceanic volcanoes. Fossils reported from the Talkeetna Formation within the park include belemnites (extinct, squid-like cephalopod with an internal shell), plant fragments (Detterman and Reed 1980), and tree stumps (Detterman and Hartsock 1966). In 1996, NPS hydrologist Nancy Deschu discovered a fossil fern on a tributary of the Johnson River that may be from the Talkeetna Formation (Figure 26; Kathryn Myers, Lake Clark National Park and Preserve, museum curator, written communication, 17 March 2019). The presence of terrestrial fossils is unusual within the Talkeetna Formation and indicates that part of this formation in the Lake Clark area formed in a nonmarine setting. In the Talkeetna Mountains, the Talkeetna Formation contains marine invertebrates; to the south of the park, at Puale Bay, the formation contains ammonites (extinct cephalopod similar to the modern nautilus), gastropods, and bivalves (Detterman et al. 1996).

Figure 26. Photograph of the fern fossil found near Johnson River.
This photograph was taken in 1996 by NPS hydrologist Nancy Deschu. Based on the location and the fact that other plant macrofossils have been found in the Talkeetna Formation elsewhere in the park, this fern was likely from the Talkeetna Formation. NPS photograph by Nancy Deschu.

The Middle Jurassic Tuxedni Group are marine sedimentary rocks that overlie the Talkeetna Formation and contain sediments that were shed from the Talkeetna arc as it eroded. In the area in and around the park, the Tuxedni Group is particularly fossiliferous, containing abundant invertebrate marine fossils including bivalves, belemnites, and ammonites (Figure 27; Eichwald 1871; Martin and Katz 1912; Imlay 1964; Detterman and Hartsock 1966; Blodgett et al. 2015; Dzyuba et al. 2018; Schraer et al. 2021). An ichthyosaur was collected from the Tuxedni Group in the southeastern Talkeetna Mountains (Druckenmiller and Maxwell 2014). This was the first Jurassic ichthyosaur described from Alaska and the only Middle Jurassic ichthyosaur known from North America (Druckenmiller and Maxwell 2014). Although no vertebrate remains have been reported from the Tuxedni Group within the park, it is possible ichthyosaur fossils exist that have not yet been discovered.

Three of the Tuxedni Group formations are exposed along the coast of Tuxedni Bay at Fossil Point: the Red Glacier Formation, the Fitz Creek Siltstone, and the Cynthia Falls Sandstone. Both the Red Glacier Formation and the Fitz Creek Siltstone produce diverse marine invertebrate fossils at Fossil Point, while the Cynthia Falls Sandstone contains lesser ammonite assemblage (Blodgett et al. 2015). Both the Red Glacier Formation and the Fitz Creek Siltstone contain ammonites, belemnites, and bivalves; the ammonite fauna of each formation are distinct for the most part. The Fitz Creek Siltstone has an great abundance of bivalves belonging to the genus *Retroceramus*, while the Red Glacier Formation contains fewer bivalves (Blodgett et al. 2015). See Blodgett et al. (2015) for more information about Fossil Point and a detailed inventory of the fossils. The fossils collected and described in Blodgett et al. (2015) are housed at the NPS Alaska Region Curatorial Center in Anchorage, where they are available to the public and park staff for research and education.

The Middle Jurassic Chinitna Formation overlies the Tuxedni Group and, like the Tuxedni Group, contains fossils of marine creatures that lived along the eroding Talkeetna arc. Fossils reported from the Chinitna Formation in the park include ammonites, bivalves, belemnites, echinoids (sea urchins), and gastropods (Martin and Katz 1912; Detterman and Hartsock 1966). Fossiliferous limestone concretions containing ammonites, crustaceans, and plant fragments occur throughout the formation; in the lower portion, concretions often enclose a single ammonite (Detterman and Hartsock 1966).

Figure 27. Photographs of the most common types of fossils in the Tuxedni Group.
The rocks of the Tuxedni Group formed underwater, along the edges of an ancient chain of volcanoes called the Talkeetna volcanic arc. A variety of creatures thrived in this warm, oceanic environment. The remains of some of these creatures have persisted as fossils for millions of years and can now be found eroding out of the cliffs along the coast of the park. (A) Inoceramid bivalve, which is the remains of an ancient clam-like organism. (B) Ammonite, which is the remains of an ancient cephalopod similar to a modern nautilus. (C) Belemnite, which is the internal shell that belonged to an ancient squid-like organism. NPS photographs.

The Upper Jurassic Naknek Formation contains marine invertebrate fossils, but it is not as fossiliferous as the underlying Chinitna Formation and Tuxedni Group. Fossils reported in the Naknek Formation in the park include ammonites, bivalves, and belemnites (Detterman and Hartsock 1966). The most fossiliferous part of the Naknek Formation is the Snug Harbor Siltstone, which predominately contains bivalves belonging to the genus *Buchia* (Detterman and Hartsock 1966). Surprisingly, despite the Snug Harbor Siltstone being exposed extensively between Chinitna and Tuxedni bays, no fossils have been reported from this unit within park boundaries (Ruga et al. 2020). This could be due to a lack of fossils surveys in this area rather than a true lack of fossils. Vertebrate fossils have been found in the Naknek Formation at several locations outside of the park. Dinosaur tracks attributed to a small- to medium-sized bipedal theropod have been recorded near Black Lake on the Alaska Peninsula (Druckenmiller et al. 2011). The tracks are the first dinosaur fossils from Alaska of Jurassic age, predating the next oldest dinosaur tracks in Alaska by about 50 million years (Druckenmiller et al. 2011). A bone fragment interpreted to be dinosaurian has also been found in the Naknek Formation in Katmai National Park and Preserve (Fiorillo et al. 2004). Finally, a fragmented humerus (arm bone) belonging to a pliosaur genus called *Megalneusaurus* was found near the mouth of the Kejulik River, just to the southwest of Katmai National Park and Preserve (Weems and Blodgett 1996). Given the discovery of vertebrate bones and tracks in the Naknek Formation elsewhere, there is the potential that similar fossils could occur within the park that have not yet been discovered.

Upper Cretaceous (100.5 million–66.0 million years ago) rocks within the park, here mapped as the Kaguyak Formation, have yielded a few pollen taxa but no marine fossils, indicating a nonmarine depositional setting (Magoon et al. 1980).

The Upper Paleocene to Lower Eocene West Foreland Formation and the Upper Oligocene Kenai Group both contain plant fossils. Plant fossils from the West Foreland Formation and Kenai Group have been described from the area around Redoubt Point (Wolfe et al. 1966; Magoon et al. 1976). The Kenai Group outcrop in this area includes fossils of trees such as ginkgo, redwood, poplar, cottonwood, alder, and beech. Wolfe and Tanai (1980) interpret this assemblage to resemble a mixed hardwood forest. Along the shore of Chinitna Bay, a series of fossilized tree stumps was found by an NPS research group in the summer of 2018 (Ruga et al. 2020). This locality is within the West Foreland Formation and may be the same area described by Detterman and Hartsock (1966) and Wolfe et al. (1966).

Outside of the Iniskin-Tuxedni region, fossils have been discovered in the Kakhonak/Tlikakila Complex in the park. Fossils from the Kakhonak/Tlikakila Complex are rare and poorly preserved, and include sponge-like fossils, bivalves, conodonts, corals, and indeterminate brachiopod, echinoderm, and gastropod fragments (Martin and Katz 1912; Detterman and Hartsock 1966; Wallace et al. 1989). Outside of the park, bivalves, ammonites, and plant fragments have been discovered in the Koksetna River sequence (Wallace et al. 1989).

Glacial Features and Modern Changes

Surficial poster units: **Qsg, Qrg, Qnd, Qno**

Bedrock poster units: **Qgd** (see Table 3)

Lake Clark National Park and Preserve has been carved by glaciers for thousands of years. Both past glacial advances and modern glacial processes have sculpted the landscape into the rugged peaks and valleys that exist today. Although the extent of glaciers has been greater in the past (see the "Past Glaciations" section for more details), approximately 14% of the park is covered by ice as of 2008 (Loso et al. 2014). Glaciers are perennial masses of ice that flow from high elevations, where more snow falls than melts (accumulation zone), to lower elevations, where more melting than snowfall occurs (ablation zone). Glaciers are found in the central and eastern portions of the park, concentrated around Redoubt and Iliamna Volcanoes and along the crests of the Chigmit and Neacola Mountains (Figure 28). These glaciers range in size from small cirque glaciers that cover less than 1 km^2 (0.4 mi^2) to Double Glacier, a mountain glacier that covers 137 km^2 (52.9 mi^2; Loso et al. 2014). As of 2008, the park contained over 1,500 glaciers, 17 of which are formally named (Figure 28).

Glacial features and deposits in the park include landforms formed by modern glacial processes and relict deposits from when glaciers were more extensive than today. See Figure 29 for an illustration of the types of features and deposits created by glaciers, as well as specific examples in and around the park. During past glaciations, glaciers extended far into areas that are now ice-free, including the park's western foothills and lowlands. Past glaciers carved out sharp peaks and ridges, broad U-shaped valleys, and many of park's lakes, while also leaving behind deposits. These deposits reflect the landscape that existed when glaciers were more extensive: moraines mark the ends of glaciers at different times; outwash deposits show areas where water flowed out of glaciers; eskers are the remains of rivers that ran beneath glaciers; and glaciolacustrine deposits show ancient glacial lakes (see the surficial poster).

Today, glaciers are still eroding peaks, ridges, and valleys in the eastern part of the park. Sediments eroded from the mountain sides and valley bottoms are transported on top, within, and beneath the glaciers. Sediments melting out of the ice can accumulate on the sides or end of a glacier, forming moraines. Rivers transport the poorly sorted sediment released by melting glaciers down valleys and eventually into lakes or Cook Inlet. These glacially fed rivers are often braided because of a high influx of non-cohesive sand- and gravel-sized sediment. Additionally, the waterbodies fed by glacier melt often have a milky appearance due to high amounts of fine-grained sediment called "glacial flour."

Changes in a variety of factors, such as precipitation and temperature, cause glaciers to either grow (advance) or shrink (retreat) over time. Glaciers are dynamic and can change significantly in size over mere decades. Overall, glaciers have been retreating since the end of the Pleistocene (about 11,000 years ago), but minor re-advances such as the Little Ice Age (1540s–1710s and 1810s–1880s) have occurred in southern Alaska (Barclay et al. 2009). Today, most glaciers worldwide are retreating as a response to increasing global temperatures (RGI Consortium 2017). Between 1957 and 2008, the area in the park covered by glaciers decreased by 12%, from 2,956 km^2 to 2598 km^2 (1,141 mi^2 to 1,003 mi^2; Figure 28; Loso et al. 2014). Terminus retreat was most significant at Tanaina Glacier, Shamrock Glacier, and Double Glacier (numbered 5, 6, and 8, respectively, on Figure 28; Loso et al. 2014). Diminishing glacier extent will continue to impact the surrounding hydrologic, geologic, and ecological systems, so understanding current and potential future change is important for managing the park's natural resources (see "Glacier Monitoring" section).

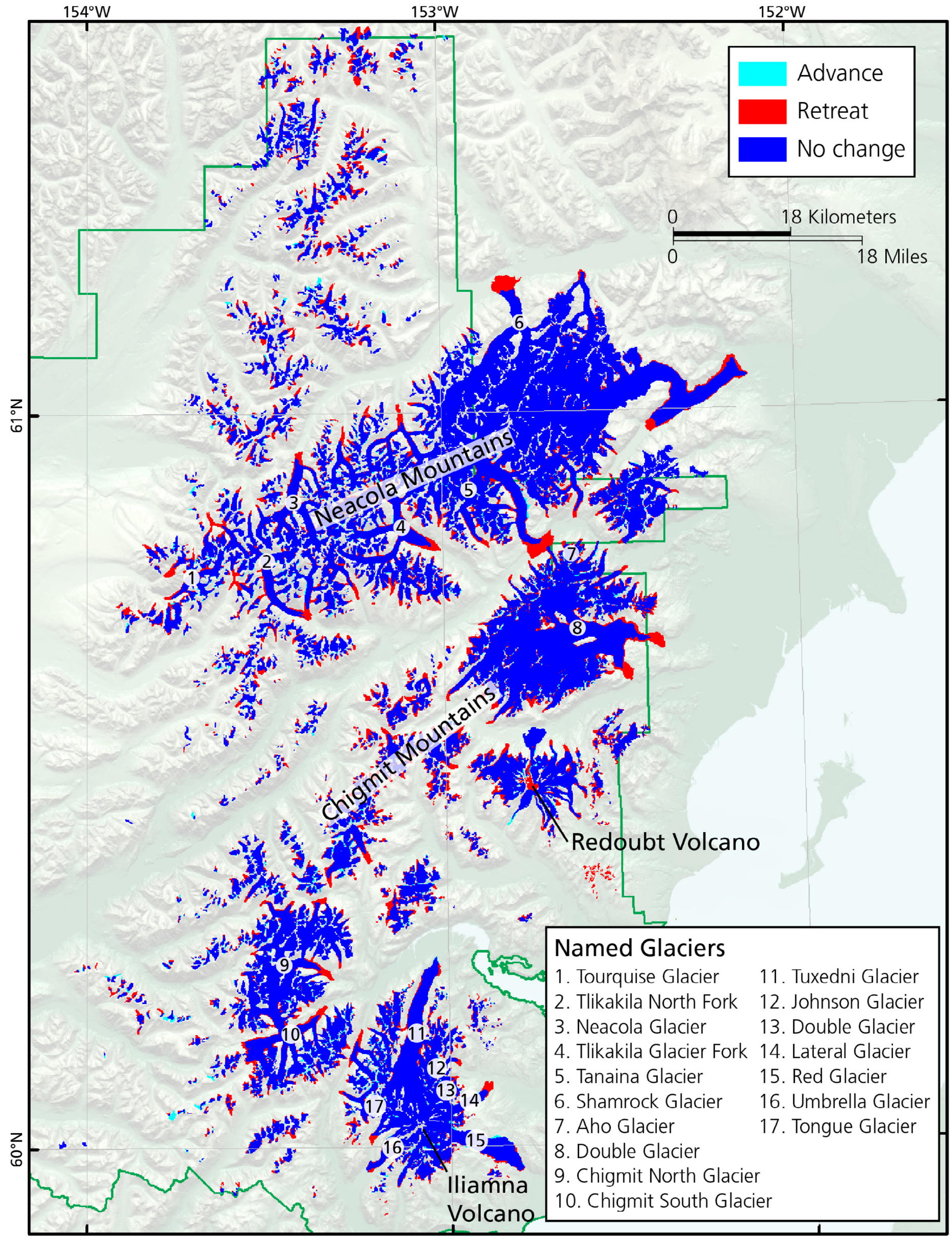


Figure 28. Map of the glaciers and glacier change in the park between 1957 and 2008.
Not all the glaciers within the park are named, but those that are formally named are labeled. Many glaciers retreated between 1957 and 2008, amounting to a decrease in glacier area by 12%. The dark blue part of the glaciers saw no advance or retreat between 1957 and 2008, the red shows areas of the glaciers that retreated during this time, and the light blue shows areas that advanced. Note, the two glaciers named "Double Glacier" in the park is not an error. They are both officially named "Double Glacier" on the topographic map. Map modified after Loso et al. 2014.

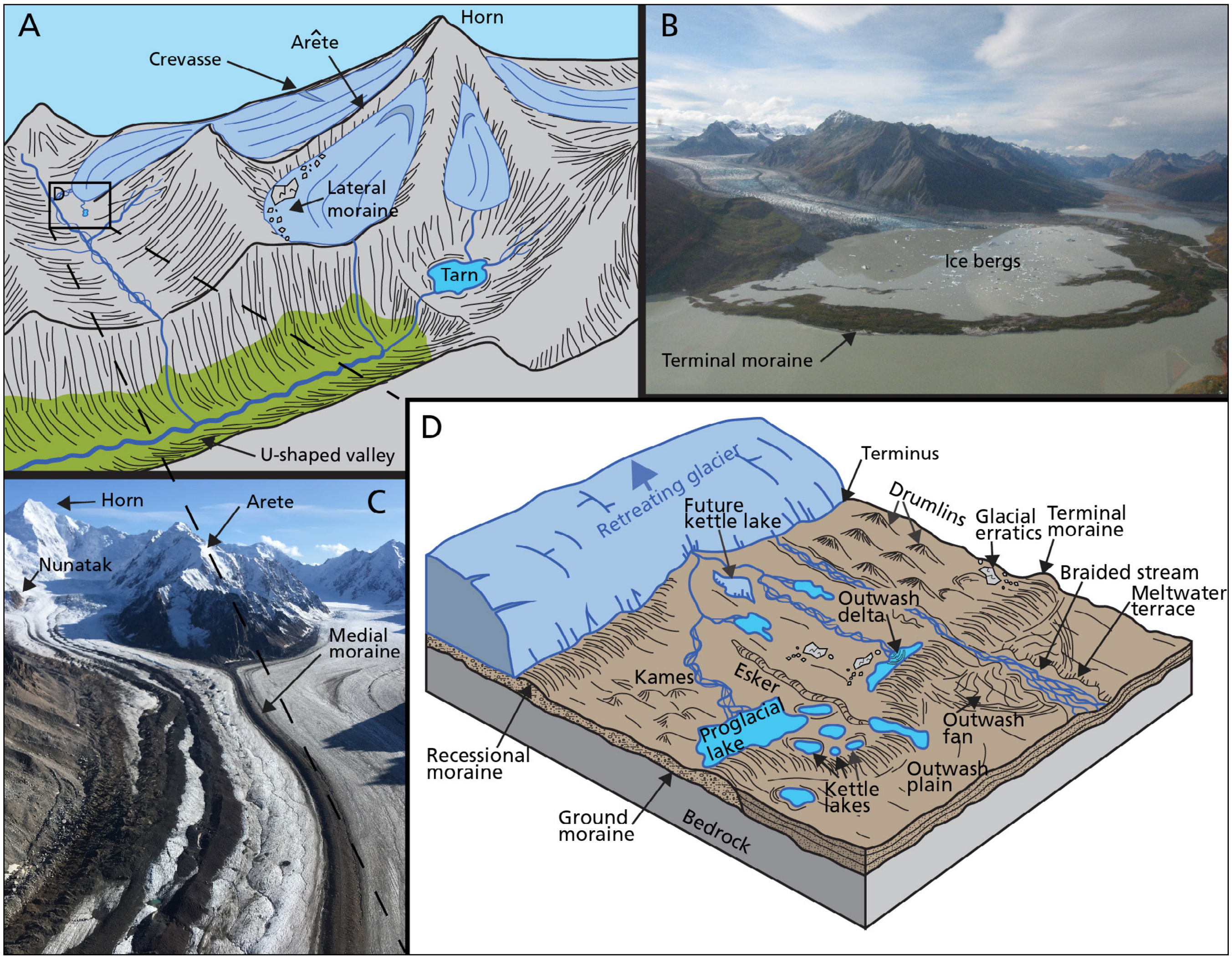


Figure 29. Diagrams and photographs of common glacial features and deposits.
(A) Diagram of common mountain glacier features. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). (B) Annotated photograph of the terminus of Shamrock Glacier. NPS photograph by Chad Hults. (C) Annotated photograph of two glaciers merging in the Alaska Range. NPS photograph by Chad Hults. (D) Diagram of common types of glacial deposits. See Figure 28 for the location of Shamrock Glacier. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Past Glaciations

Surficial poster units: **QTgu, Qwg, Qwg1, Qwgo, Qek, Qwg2, Qwg3, Qwg4, Qgme, Qew, Qmg, Qewo, Qiu, Qio**

Bedrock poster units: **Qgd** (see Table 3**)**

The Lake Clark area has been extensively shaped by repeated, episodic glaciation throughout the Pleistocene (2.58 million–10,000 years ago). The park lies at the intersection of the southern Alaska Range and the northern Aleutian Range. These mountains, rising to about 1600 m (5,000 ft) above sea level and higher, provided a barrier to moisture-laden air from the Gulf of Alaska, and consequently were centers of ice cap formation during glacial periods. At the height of the last glacial period (Last Glacial Maximum, approximately 20,000 – 18,000 years ago) most of the park was encompassed by the western extension of the Cordilleran Ice Sheet (Figure 30; Kaufman and Manley 2004). Prior to and during the Last Glacial Maximum, glaciers on the eastern side of the park flowed downward into the Cook Inlet basin, coalescing with those from the Kenai Peninsula (Reger et al. 2007). On the interior side of the park, ice flowed west towards the Kuskokwim piedmont and Bristol Bay lowlands via the Lake Clark trough and other major river valleys (Harvey 2009). Glaciers originated on the major volcanoes (Iliamna Volcano, Redoubt Volcano, Mt. Spurr Volcano) and in large ice fields along the crest of the Chigmit Mountains.

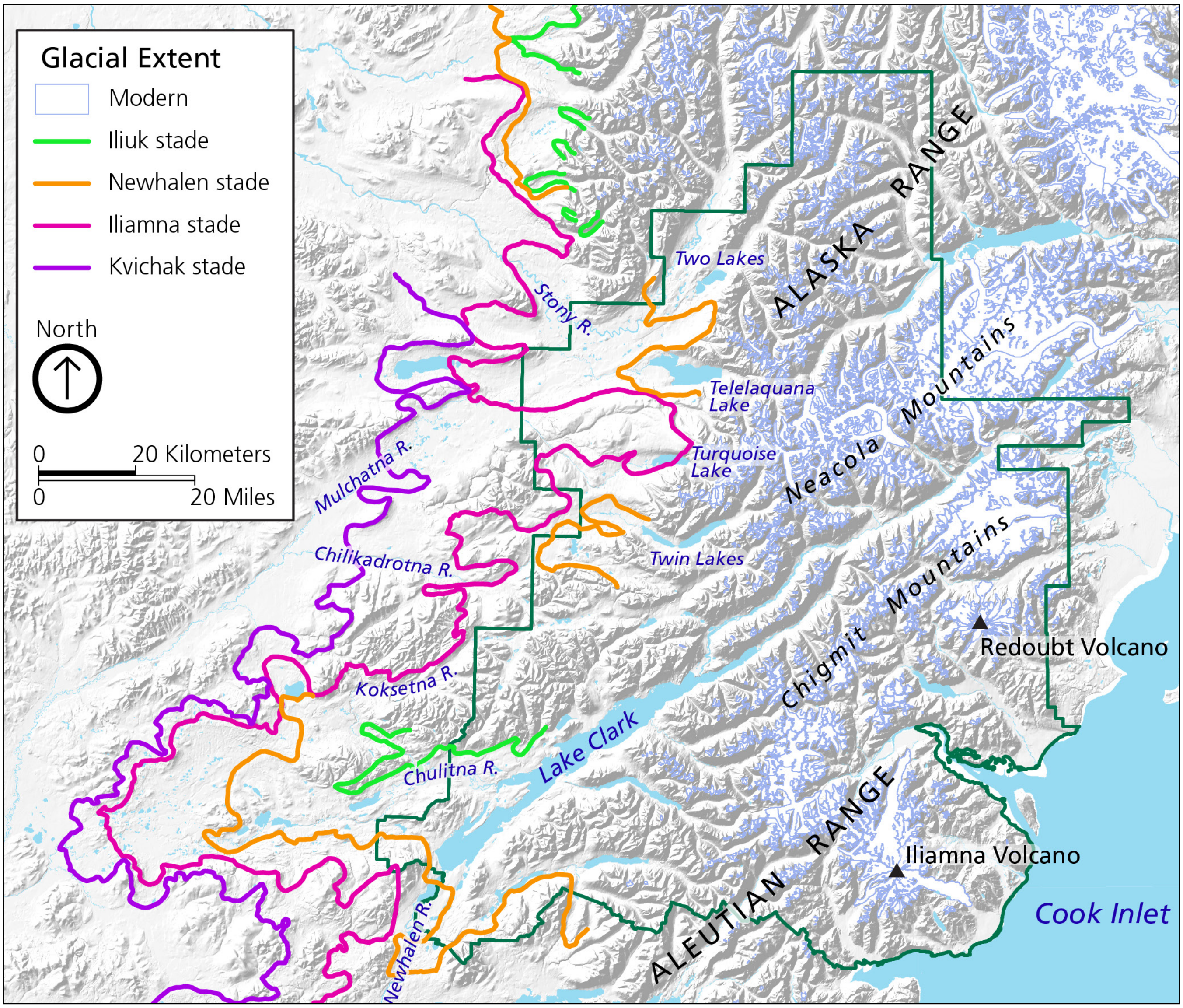


Figure 30. Map showing the western extent of Brooks Lake glacial stades.
The Brooks Lake glaciation was defined to the south of the Lake Clark area and is age equivalent to the broader late Wisconsin glaciation. The same terminology as that developed in the Brooks Lake region to describe the late Wisconsin moraines is used in the Lake Clark area. Glacial deposits corresponding to four stades of the Brooks Lake glaciation are mapped to the west and within the park. The oldest glaciations extend furthest out (west), with younger stadial extents occurring further east. The extents are approximate and drawn based on the western limits of glacial deposits corresponding to each stade (Qwg4, Qwg3, Qwg2, Qwg1) on the surficial poster.

Nearly all landforms and surficial deposits within the park were created or modified during the most recent glacial period, the late Wisconsin (approximately 75,000–11,000 years ago). Lake Clark itself occupies a trough carved by glaciers along the projected trace of the Lake Clark fault (see the “Folds and Faults” section for more details; Hamilton and Klieforth 2010; Koehler and Reger 2011). Major moraines marking the maximum extent of glacial advance are located west of the park’s boundary, however, because the park’s Cook Inlet coast rises abruptly and steeply from the sea, glacial deposits of Pleistocene age are sparsely preserved in this area (Figure 30 and see the surficial poster).

No comprehensive investigation of glacial deposits in the Lake Clark region has been conducted, but a relative timeline for glacial advances can be constructed using corresponding data from the Iliamna and Naknek Lake region (Abrahamson 1949; Muller 1952; Detterman and Reed 1973; Detterman 1986), from adjoining areas of the Alaska Range (Briner and Kaufman 2008; Tulenko et al. 2018), and from Cook Inlet and the Kenai Peninsula (Karlstrom 1964; Reger et al. 2007; Reger et al. 2015). See Figure 31 for a depiction of how the glacial stades (relatively short periods of very cold climatic conditions) in different areas correspond to each other.

Three Pleistocene glaciations are identified in the Alaska Peninsula and Aleutian and Alaska mountain ranges. From oldest to youngest they are the (1) Johnston Hill, (2) Mak Hill, and (3) Brooks Lake. The Brooks Lake glaciation is the local equivalent to the broader late Wisconsin glaciation. Glacial remains throughout the park are almost entirely composed of Brooks Lake or younger materials; evidence for earlier glaciations (**Qio, Qiu, Qewo, Qmg, Qew, Qge**) is restricted to glacial erratics and glacio-estuarine sediments along the Kvichak River and other areas outside the park, and little is known about their age (Detterman 1986; Mann and Peteet 1994; Harvey 2009). Evidence for earlier glaciations may be sparse because younger glaciations overran older deposits. Deltaic sediments at the outlet of Lake Clark (**Qglf**) have been dated to approximately 20,000 years ago, indicating that the area of the delta was ice-free at that time (Harvey 2009). Analysis of bog cores taken at locations around the lake suggests that the entire Lake Clark basin was deglaciated by about 15,000 years ago (Heiser and Cohn 2004).

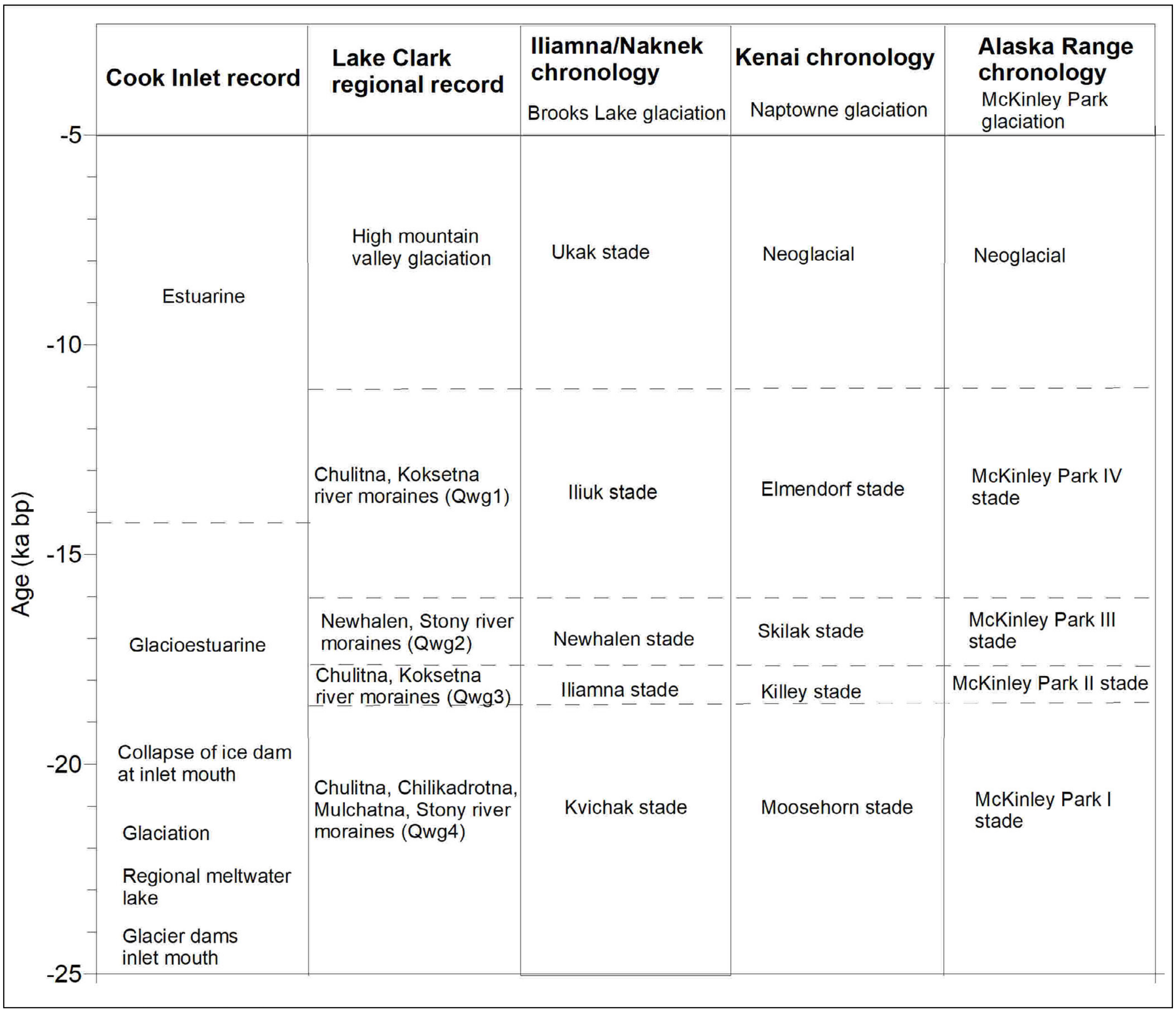


Figure 31. Diagram showing the correlation of glacial stades across southcentral Alaska.
The glacial stades used to describe the deposits in the Lake Clark area have been adopted from south of the park in the Brooks Lake area. These include, from oldest to youngest, the Kvichak stade, Iliamna stade, Newhalen stade, Iliuk stade, and Ukak stade. See Figure 30 for the location of deposits in and around the park correlating to the different stades.

Brooks Lake Glaciation

The Brooks Lake glaciation was defined by Muller (1952) and refined by Detterman and Reed (1973) based on the well-preserved terminal moraines in Brooks Lake and Lake Naknek, south of Lake Clark. Brooks Lake drift deposits cover most of the lowland areas of the Alaska Peninsula and form an almost continuous belt along the western extent of the Lake Clark region (see the surficial poster). During the Brooks Lake glaciation, alpine valley glaciers coalesced with ice caps that formed off the Cook Inlet coast, creating a formidable ice front across the northern portion of the Alaska Peninsula. Four stades have been identified within the Brooks Lake glaciation, named after prominent moraines in the Lake Iliamna area (Detterman 1986). Although geochronological data are lacking, many moraine limits appear to be contiguous, and the same terminology has been adopted for late Wisconsinan stades in the Lake Clark region. From oldest to youngest, the stades are the Kvichak, Iliamna, Newhalen, and Iliuk (Figure 30). The Brooks Lake glaciation correlates to the Naptowne glaciation of Cook Inlet and the Kenai Peninsula, and corresponding stadials are noted in the following descriptions.

The Kvichak stade (**Qwg4**) is named for a large and prominent terminal moraine approximately 40 km (25 mi) down the Kvichak River from Lake Iliamna (Stilwell and Kaufman 1996). During the Kvichak stade, large icefields at the crest of the Chigmit Mountains produced glaciers that pushed through the Lake Clark trough and bifurcated at the southwestern end to flow south into Iliamna via the lowlands now occupied the Newhalen River, and west into the Bristol Bay lowlands through the Chulitna trough (Hamilton and Klieforth 2010). This stade is represented in the Lake Clark region by extensive and prominent moraines on the Chulitna, Chilikadrotna, Mulchatna, and Stony River drainages. The Kvichak stade correlates to the Moosehorn stade of Cook Inlet and the Kenai Peninsula, dated by Reger et al. (2007) to approximately 30,000 to 18,500 years ago. Terminal moraines of the corresponding McKinley Park I stade are dated to approximately 21,000 years ago (Porter et al. 1983), and the Farewell 2-I to 21,300 years ago (Tulenko et al. 2018).

The Iliamna stade (**Qwg3**) is named after the prominent terminal moraine that impounds Iliamna Lake. As with the preceding Kvichak stade, ice filled the Lake Clark trough and coalesced with the huge lobe that filled the Iliamna basin. Large ice lobes pushed westward through the Chulitna and Koksetna drainages. Smaller Iliamna stade moraines are also found to the north on the Stony River, just outside the park's boundary. The Iliamna stade corresponds to the Killey stade of Cook Inlet, dated by Reger et al. (2007) to approximately 18,500 to 17,500 years ago.

The Newhalen stade (**Qwg2**) occurred after the retreat of the Cordilleran ice sheet around 18,000 years ago, when a confluent system of mountain glaciers readvanced through the Lake Clark trough. The flow again bifurcated west into the Chulitna drainage and south into the Newhalen but did not reach the Iliamna basin. The type locality end moraine crosses the Newhalen River some 10 km (6 mi) north of the village of Iliamna (Stilwell and Kaufman 1996). Newhalen moraines are also present on the Stony River, northwest of Telelaquana Lake. The Newhalen stade corresponds to the Skilak stade of Cook Inlet, dated to approximately 17,500 to 16,000 years ago (Reger et al. 2007).

The Iliuk stade (**Qwg1**), named after a moraine in the Naknek valley, was a late readvance of mountain glaciers, although with much lesser extent than previous stades. The Iliuk stade is represented in the Lake Clark region by moraines on the Chulitna and Koksetna drainages. In Cook Inlet, the corresponding Elmendorf stade is dated to approximately 16,000 to 11,000 years ago (Reger et al. 2007). It is possible that Iliuk stade moraines form the complexes that impound modern lakes on the west side of the park (e.g. Twin Lakes, Turquoise Lake, and Two Lakes).

Lake Clark Water Level History

As identified by Heiser and Cohn (2004), Lake Clark has experienced significant changes in lake level since deglaciation (approximately 15,000 years ago). However, detailed research into spatial and temporal changes of lake level has not yet been conducted. Preliminary investigations suggest that mechanisms for lake level changes likely include a combination of isostatic adjustments following the glacial period, downcutting of the outlet or dam, and tectonic activity. In the immediate post-glacial period, the water level of Lake Clark was at least 20 m (65 ft) and possibly as much as 40 m (130 ft) higher than modern levels (Heiser and Cohn 2004). As the immense glacier retreated up the Lake Clark trench, the outlet was downcut and the lake level dropped rapidly. Dating of deposits approximately 16 m (52 ft) above the modern lake at Port Alsworth indicate that the lake was at this height about 16,000 years ago (Harvey 2009). By around 12,000 years ago, the lake's outlet had incised considerably from post-glacial levels, and the lake had dropped to around 10 m (30 ft) higher than current levels. By the beginning of the Holocene (11,000 years ago), the lake was around 5 m (16 ft) higher and soon stabilized at current levels (Heiser and Cohn 2004; Heiser 2007). As valley glaciers retreated and water levels dropped, tributary rivers and streams developed alluvial fan deltas where they emptied into the lake.

Post-glacial History of Tanalian Point (Port Alsworth)

At Tanalian Point, a major Gilbert-type alluvial fan delta formed where the Tanalian River (representing the outlet of Kontrashibuna Lake and the retreating Kontrashibuna glacier) empties into Lake Clark (**Qal, Qbd**; Figure 32). Gilbert-type alluvial fan deltas form where steep high-velocity streams and rivers carrying large amounts of coarse material empty into a relatively deep marine or lacustrine basin. They contain a tripartite stratigraphy consisting of bottomset, foreset, and topset beds (Gilbert 1885). Bottomset beds are created from the suspended sediment that settles out of the water as the river flows into the lake and loses energy. These sediments are generally finer-grained and settle in horizontal layers. Foreset beds consist of larger sediment sizes (gravels, cobbles, and even boulders) carried by the current, that are carried or rolled along the main channel. When they reach the end of the delta, the bedload rolls over the edge and builds steeply inclined subaqueous layers over the bottomset beds. As bedload deposition continues, the delta progrades (builds outward into the lake). The foreset beds are in turn overlain by a horizontal topset of fluvial delta-plain deposits (smaller sediment sizes that are deposited as the main channel shifts; Postma 1990; Prior and Bornhold 1990; Gobo et al. 2014).

Figure 32. Map showing the Tanalian River outwash fan, upon which the town of Port Alsworth is built. The Tanalian River outwash fan is a Gilbert-type alluvial fan delta that occurs where the Tanalian River empties into Lake Clark. Gravel pit label is indicating the approximate location of the photograph in Figure 33.

The area of the Tanalian Point delta is approximately 3.85 km^2 (950 acres). Foreset and topset beds are visible in major excavations, for example in the gravel pit just to the south of the NPS landing strip (Figure 33). The terrace where the gravel pit is located may represent a 16,000-year-old shoreline. The terrace stabilized during this period, and a lower terrace formed as lake level dropped (Harvey 2009). Late Pleistocene and Holocene sediments consisting of peats and "pondy" lacustrine sediments overlie extensive bedded tephras (often with corresponding charcoal layers), representing dynamic mid- to late- Holocene volcanism. At its northern margin, the Tanalian delta reached large outcrops of bedrock, resulting in a complex truncation that created modern Hardenburg Bay. In later stages of development, the main channel of the Tanalian river shifted to the southwest, where the main channel and anabranches (side channels) are currently located.

Archaeological sites around the Tanalian delta are dated to approximately 4,000 years before present and younger. Several archaeological components date to approximately 1,000–2,000 years ago and late prehistoric/early historic occupation of the area is well-documented (Branson 2014). The modern settlement of Port Alsworth is almost entirely on the Tanalian delta formation. Other notable Gilbert-type deltas in the park are located at the outlets of Kijik River and Current Creek into Lake Clark, Kasna Creek into Kontrashibuna Lake, and Hope Creek into Upper Twin Lake.

Figure 33. Photograph of the tripartite stratigraphy of the Tanalian Point Delta.
The Tanalian Point delta is a Gilbert-type alluvial fan delta. The characteristic tripartite stratigraphy develops where a high-velocity stream carrying coarse material deposit sediments into a relatively deep basin. NPS photograph by Jason Rogers.

Permafrost

Surficial poster units: **Qsu, Qsf**

Lake Clark National Park and Preserve does not contain continuous permafrost (permafrost that underlies the entire landscape), but it does contain zones of discontinuous (50–90 percent of the landscape), sporadic (10–50 percent), and isolated permafrost (less than 10 percent; Jorgenson et al. 2008). Permafrost is ground (soil, sediment, or rock, plus any ice or organic material) that remains frozen for two or more consecutive years. 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. Warming climate and ground disturbances can cause permafrost to thaw, which in turn results in a variety of physical and biological changes to the landscape. By understanding the current distribution and condition of permafrost in the park, park managers may be able to anticipate how areas of the park with permafrost will evolve as climate changes.

A variety of physical and ecological factors determine if permafrost will form or persist in a given area (Shur and Jorgenson 2007). Climate is probably the most important and obvious factor that affects ground temperature and therefore permafrost. While air temperatures can be colder at higher elevations, cold-air inversions cause the low-lying areas of the park's interior to be upwards of 10–15°C colder than adjacent higher elevations (Wells et al. 2013). These cold air sinks are associated with lowland areas likely to support ice-rich permafrost (Figure 34). Vegetation can also play an important role in either forming permafrost or protecting permafrost that formed when climate was colder (Shur and Jorgenson 2007). For example, patches of permafrost exist in black spruce bogs near Anchorage where mean annual air temperature is above freezing (2.2°C; 36°F; Kanevskiy et al. 2013). In the park, environments that support permafrost have the thickest accumulations of surficial organic material and ice-rich permafrost is commonly associated with mats of peat moss in excess of 20 cm (8 in) that insulate the frozen ground (Wells et al. 2013).

Wells et al. (2013) modeled the likelihood of permafrost existing in the upper 2 m (7 ft) of ground throughout the park and directly observed permafrost at several soil-sampling plots (Figure 34). Additionally, several scattered patches of frozen silt (**Qsu**) are mapped northwest of the park on the surficial geology map (see the surficial poster). Ice-rich permafrost (over 50% ice by volume) is predicted to be likely or highly likely in the northwestern lowlands of the park, as well as in isolated areas around Lake Clark (Figure 34; Wells et al. 2013). Ice-poor permafrost (less than 50% ice by volume) is predicted to be highly likely in alpine areas of the northern interior region of the park where soils have a mean annual soil temperatures at or below 0°C (32°F; Figure 34; Wells et al. 2013). The soil-sampling plots that contained permafrost were all located near the western boundary of the park (Figure 34).

Permafrost will thaw when ground temperatures warm to above freezing. Increasing air temperature and ground disturbance are two changes that can initiate permafrost thaw. When permafrost thaws, especially ice-rich permafrost, the ground may subside and produce an irregular land surface known as thermokarst. Wells et al. (2013) observed thermokarst features, including scar bogs and drunken forests, in the "Interior Lowland Frozen Loamy-Organic Black Spruce Forest" ecotype in the park (see Wells et al. [2013] for the distribution of this ecotype). This ecotype contains sporadic ice-rich permafrost in the early to middle stages of degradation (Wells et al. 2013). Observations of thermokarst in permafrosted areas suggest that thaw is currently occurring, and future warming and disturbances (such as wildfire) will greatly impact permafrost in the park over time (Wells et al. 2013).

Coastal Features and Change

Surficial poster units: **Qtf, Qmt, Qbd, Qes, Qdl**

Bedrock poster units: **Qmd** (see Table 3)

Lake Clark National Park and Preserve includes 350 km (220 mi) of coastline along the western side of lower Cook Inlet, from Redoubt Point in the north to Chinitna Bay in the south (Curdts 2011). See Figure 35 for photographs of some of the park's coastal geomorphology. Major areas of the coast include the Crescent River/Polly Creek delta, Tuxedni Bay, Fossil Point, Johnson River delta, Red River delta, and Chinitna Bay. Chisik Island lies just off the coast at the southern end of Tuxedni Bay and, except for a few small areas of private ownership, is part of the Alaska Maritime National Wildlife Refuge. Understanding the coast and how it is changing is important for managing the many biological, archaeological, and paleontological resources located along the coast (see the "Coastal Issues" section for more details).

The bathymetry offshore of the park slopes shallowly in Tuxedni and Chinitna Bays, which are mostly less than 10 m (30 ft) deep (Figure 36; Zimmerman and Prescott 2014). While the coast of Lake Clark National Park and Preserve generally consists of gradually sloping bathymetry there is one notable exception. A steep sloped, deep channel exists between the park and

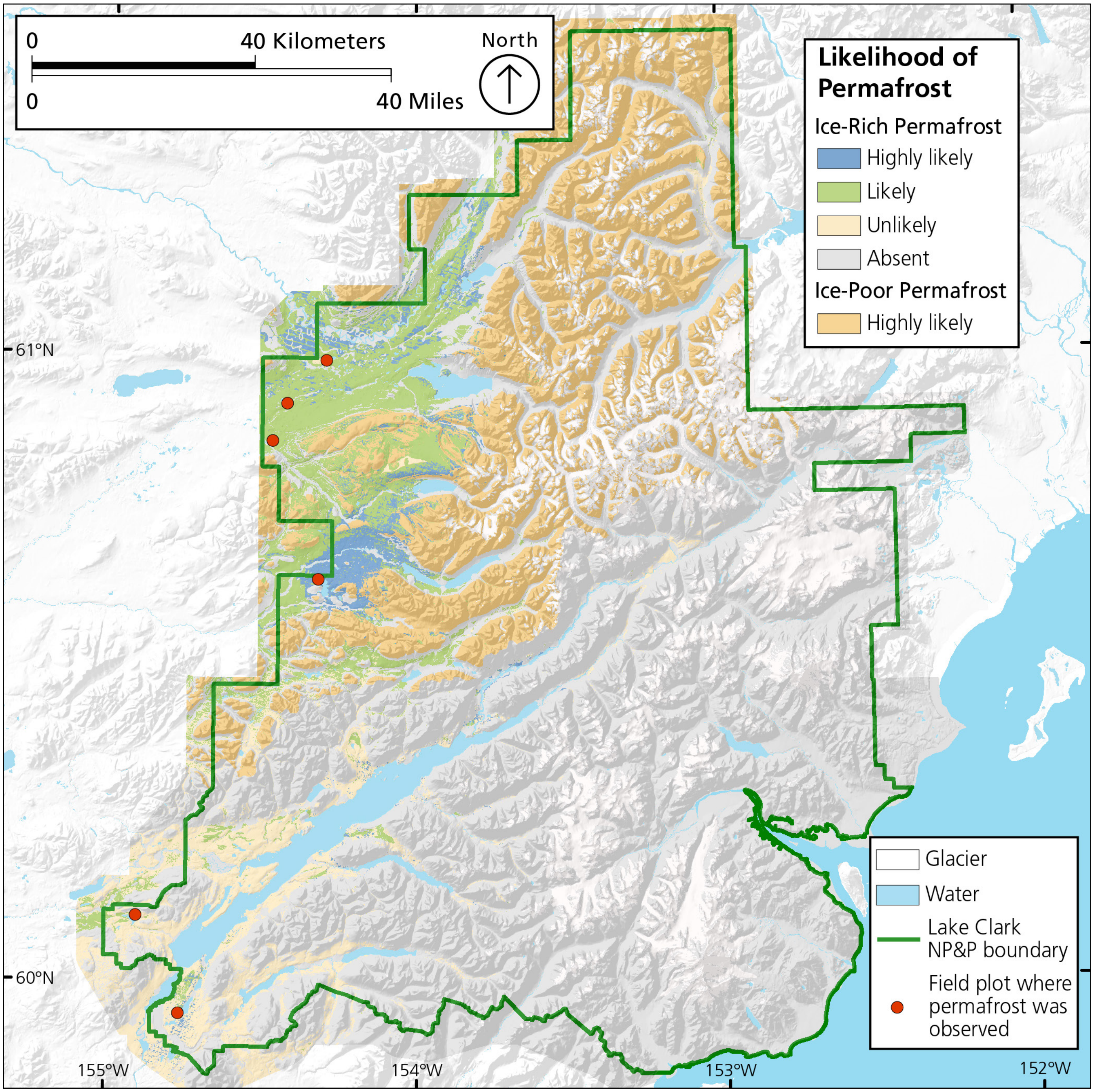


Figure 34. Map showing the distribution of modeled permafrost.
The likelihood of ice-rich and ice-poor permafrost was modeled throughout the park soil temperatures and field observations. The colors show the likelihood of ice-rich or ice-poor permafrost, and the red dots indicate a field plot where permafrost was observed. Modified from Wells et al. (2013).

Chisik Island, extending from the western edge of the island approximately 27 km (17 mi) in a southeasterly direction and ending approximately six kilometers (four miles) offshore of Johnson River. The channel reaches depths of over 50 m (150 ft) with three notable basins.

Cook Inlet is a semi-enclosed marine body of water between the Kenai Peninsula and the southcentral Alaskan mainland (Figure 37). It stretches about 290 km (180 mi) from the Gulf of Alaska northeast to Anchorage, where the inlet splits into the Knik Arm to the north and the Turnagain Arm to the southeast. The majority of Cook Inlet is less than 70 m (230 ft) deep, however several deeper channels run down the center of the inlet and water depth at the mouth increases to over 200 m (650 ft; Zimmerman and Prescott 2014).

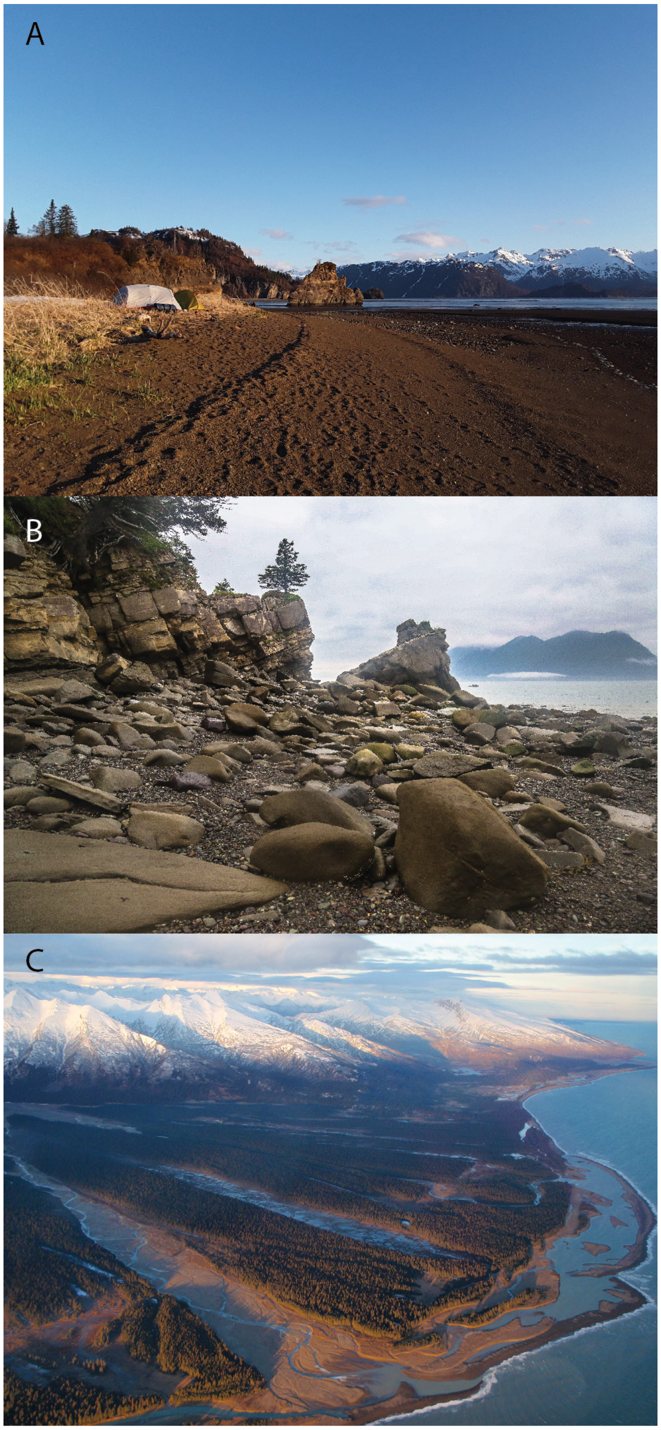


Figure 35. Photographs of coastal geomorphology in the park.
(A) Sandy beach grading to tidal flats along the south shore of Tuxedni Bay. NPS photograph by Amanda Lanik. (B) Pebble-cobble beach near Silver Salmon Creek. NPS photograph by A. Langan. (C) Red River delta and spits. NPS photograph by M. Richotte.

Tidal variation in Cook Inlet are some of the largest in the world, reaching tidal ranges of up to 10 m (30 ft; Archer and Hubbard 2003). Rivers and glacial melt from the surrounding area flow into Cook Inlet and discharge fresh water and sediment. A lot of the sediment in the waters of Cook Inlet are primarily composed of very fine clay-sized particles known as “glacial flour.” This sediment is transported south by Cook Inlet’s currents and is deposited either in low energy areas around the edges of the inlet or carried south to Shelikof Strait. Surface circulation along the west side of Cook Inlet has a net north to south flow, with generally counterclockwise transport in Chinitna Bay (Figure 37).

Cook Inlet is part of the low-lying area called Cook Inlet Basin, which is a northeast-trending fore-arc basin extending from Shelikof Strait in the southwest to Matanuska Valley in the northeast (LePain et al. 2013). The sediments being deposited in Cook Inlet today are just the latest in a long history of fore-arc sedimentation that has occurred in Cook Inlet Basin for at least 200 million years. Fore-arc basins form in subduction zone settings, between the volcanic arc and the subduction trench. Cook Inlet Basin first formed adjacent to the ancient Talkeetna arc, which was active between approximately 200 to 150 million years ago; now Cook Inlet Basin sits adjacent to the modern Aleutian arc (for more information on the Aleutian arc see the “Volcanoes” section). An emergent accretionary prism composes the Kenai and Chugach Mountains on the east side of Cook Inlet Basin, and even further outboard lies the Aleutian trench. Cook Inlet Basin accommodates over 10,000 m (35,000 ft) of Jurassic–Cretaceous (201.3 million–66 million years ago) strata and 8,000 m (25,000 ft) of Cenozoic (66 million years ago to present) strata, although this total thickness does not occur anywhere in one place (Shellenbaum et al. 2010). These strata are an important archive of the geologic history of southern Alaska and contain significant hydrocarbon resources that are being developed in parts of Cook Inlet (see the “Coastal Issues” section for more details).

The coast of Lake Clark National Park and Preserve is dynamic and constantly evolving in response to a variety of factors, one of which is relative sea level. Relative sea level is sea level in a specific area and is the combination of global sea level fluctuations and vertical movement of the land. Global sea level is influenced by the total mass of water in the oceans (e.g. water being tied up on land in the form of glaciers), changes in the size of ocean basins (e.g. changes in seafloor spreading rates), and density changes of ocean water (e.g. thermal expansion). Between 1901 and 2010, global sea level rose by 1.7 mm/yr (0.67 in/yr), primarily as a result of glacier mass loss and ocean thermal expansion (IPCC

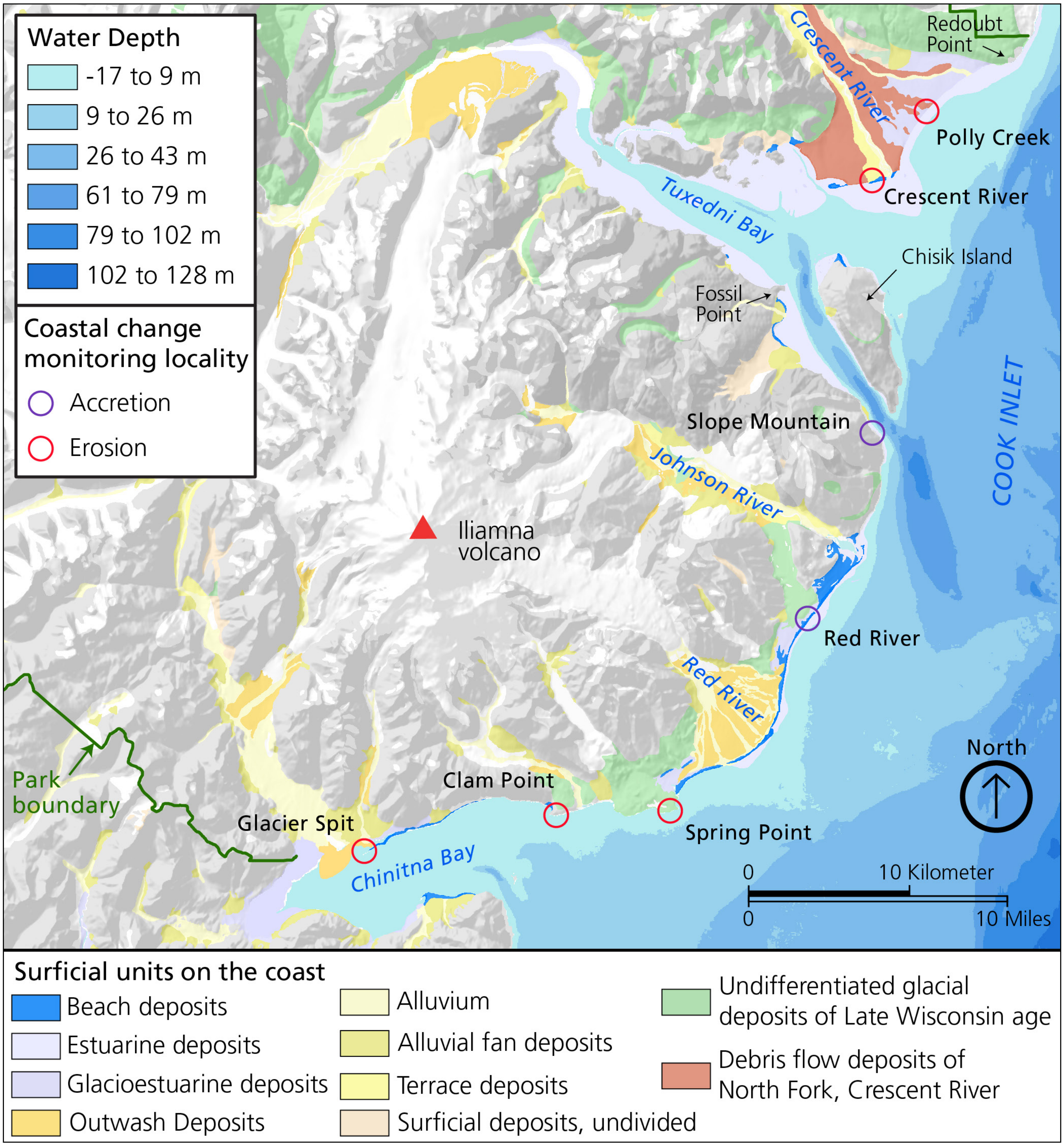


Figure 36. Map of the park showing coastal features.
Features include surficial units along the coast, offshore bathymetry, and the location of coastal change monitoring plots. The park boundary is shown in green but was removed from the coastal edge of the park so beach deposits are more visible. Bathymetry from Zimmermann and Prescott (2014) and coastal change monitoring plot locations from Cusick and Bennett (2005).

Figure 37. Map of the net surface circulation in lower Cook Inlet.
The arrows indicate general current flow direction, while the solid (dashed, where approximate) lines indicate general locations of rip currents. The circulation along the coast of the park, which is located between Tuxedni and Chinitna Bays, is generally southward, with a counterclockwise circulation near the mouth of Chinitna Bay. Figure modified from Jones et al. (2019) after a circulation schematic in Burbank (1977).

2014). Vertical land movements are driven by local forces, such as plate tectonic stress either pushing land up or down and isostatic rebound that occurs after glaciers melt and retreat. Freymueller et al. (2008) measured the modern deformation across Alaska using precise GPS measurements over the period 1992–2007. Stations in and around Lake Clark National Park and Preserve showed uplift of around 10 mm/yr (0.4 in/yr). Stations along the coast at Slope Mountain and Redoubt Point measured a vertical change of 15 mm/yr (0.6 in/yr) and 10.8 mm/yr (0.425 in/yr), while a more inland station near Crescent Lake showed an uplift rate of 6.7 mm/yr (0.26 in/yr; Freymueller et al. 2008). While there is no tide gauge along the coast of the park, or even on the western side of Cook Inlet, the nearest tide gauge in Seldovia records a decreasing sea level of -10 mm/yr (-0.4 in/yr; https://tidesandcurrents.noaa.gov/sltrends/, accessed 29 September 2020). Considering nearby tide gauges and the fact that the uplift measured by Freymueller et al. (2008) is outpacing global sea level rise, it is inferred that sea level along the park's coast is going down.

In addition to crustal deformation that happens slowly over a long period of time, relatively large magnitude crustal deformation can seemingly occur instantaneously during earthquakes. During the magnitude 9.2 1964 Great Alaska Earthquake for example, significant uplift and subsidence occurred in Prince William Sound area and on the Kenai Peninsula, while the west coast of Cook Inlet underwent only slight uplift (Plafker 1969). Residents along Chinitna and Tuxedni Bays reported a decrease in the height of tides that, combined with observed changes on the northwest side of Cook Inlet, suggest the park's coast uplifted 0.3–0.7 m (1–2.5 ft) during the 1964 earthquake (Plafker 1969).

The coast is also affected by processes such as waves, storms, tides, nearshore currents, and landslides. These processes can act to either add sediment to the coast (accretion) or remove sediment from the coast (erosion). The addition or removal of sediment can be a discreet event, such as the removal of sediment after a large storm, or represent a longer-term trend, such as gradual building of a delta or spit. Shoreline change is one of the "vital signs" monitored by the NPS Southwest Alaska Inventory and Monitoring Network.

In 1992 and 2005, seven localities along the park's coast were surveyed to assess the change in cross-shore beach profiles during this timeframe (Figure 35; Cusick and Bennett 2005). Erosion, or the landward migration of mean high water, was observed at five of the sites (Polly Creek, Crescent River, Spring Point, Clam Point, and Glacier Spit), while accretion, or seaward migration of mean high water, was observed at two profiles (Slope Mountain and Red River). Overall, data suggests that beaches are accreting and growing between the Red River and the west entrance to Tuxedni Channel and erosion of the shoreline is occurring between Chisik Island and Polly Creek in the north, and between West Glacier Creek and Spring Point in the south (Figure 36; Cusick and Bennett 2005).

Bluff erosion and landward migration of mean high water were observed at the two sites near the Crescent River/Polly Creek delta. The position of mean high water shifted landwards by 0.28 m/yr (0.92 ft/yr) at Polly Creek and by 0.18 m/yr (0.59 ft/yr) at Crescent River, while the bluff edge at these sites eroded by 0.50 m/y (1.5 ft/yr) and 0.96 m/yr (3.1 ft/yr), respectively (Cusick and Bennett 2005). The area between these two sites exhibit fallen tree litter in the backshore that suggests bluff erosion is widespread in the area.

Slope Mountain and Red River were the two sites that exhibited accretion, with mean high water shifting seaward by 0.55 m/yr (1.8 ft/yr) and 3.1 m/yr (10 ft/yr), respectively (Cusick and Bennett 2005). Both sites show features characteristic of accretion, including beach ridges at Slope Mountain, and wide beaches and well-developed berms at Red River (Cusick and Bennett 2005).

Farther south, Spring Point and Clam Point both underwent erosion. Mean high water at Spring Point shifted landwards by 0.28 m/yr (0.92 ft/yr) and at Clam Point mean high water shifted landwards by 0.34 m/yr (1.1 ft/yr). Glacier spit is a narrow strip of sand that protects a salt marsh further inland. Erosion occurred at this site, with mean high water eroding by 0.48 m/yr (1.6 ft/yr; Cusick and Bennett 2005). Examination of historical aerial photographs revealed that the spit is growing southwestward (Cusick and Bennett 2005).

Geologic History

The following is a brief chronology of the geologic events leading to the present landscape of the park. The "Geologic Features and Processes" chapter provides additional details for the geologic map units and features mentioned here. See Figure 4 for more information about the geologic time periods discussed in this section.

Triassic (251.9 million–201.3 million years ago)

The Cottonwood Bay Greenstone and Kamishak Formation are the oldest rocks in the park. They formed during the Triassic Period in the ocean, far away from their present-day location. The slightly metamorphosed mafic igneous rocks that compose the Cottonwood Bay Greenstone are probably the remains of oceanic crust upon which the marine sediments of the Kamishak Formation accumulated. The Kamishak Formation is primarily limestone, but also contains chert and volcanic rocks. The chert formed in deep water, while the limestone formed in a shallower-water reef environment.

Late Triassic–Middle Jurassic (237 million–163.5 million years ago)

In the Late Triassic, the marine environment changed as a series of oceanic volcanoes called the Talkeetna arc began to erupt. This volcanism was caused by the subduction of one tectonic plate beneath another and persisted from the Late Triassic into the Middle Jurassic. The volcanic and volcaniclastic rocks erupted from these ancient volcanoes are grouped together as the Talkeetna Formation. Most of the Talkeetna Formation was erupted underwater, however some portions of this formation in the park record the terrestrial environment of the volcanic arc. The Talkeetna arc was fed by magma chambers. The magma chambers eventually cooled and crystalized into plutons known as the Alaska-Aleutian Range batholith. Heat generated from the intruding magma caused some of the existing older rocks in the Kakhonak complex to be metamorphosed. The rocks of the Kakhonak complex occur as "roof pendants" of metamorphic rock overlying the Alaska-Aleutian Range plutons. Further inboard, more of the Triassic oceanic rocks located behind the Talkeetna arc were also metamorphosed in the Early Jurassic (around 177 million years ago), forming the Tlikakila Complex.

Middle Jurassic–Late Jurassic (174.1 million–145 million years ago)

In the Middle and Late Jurassic, the volcanic and plutonic rocks of the Talkeetna arc were pushed upward during deformation related to Peninsular-Wrangellia terrane interactions with the southern Alaska margin. Erosion of the uplifted and exhumed arc supplied sediment to the adjacent Cook Inlet fore-arc basin. The rocks formed as a result of this sedimentation include the Tuxedni Group, Chinitna Formation, and Naknek Formation.

Cretaceous–Early Paleogene (145 million–56 million years ago)

During the Cretaceous, subduction-related magmatism renewed, cross-cutting the exhumed and eroded Talkeetna arc and contributing to growth of the Alaska-Aleutian Range batholith. Clastic sedimentary rocks were deposited northwest of the plutons. These include rocks of the Kahiltna assemblage, such as the Koksetna River sequence, and the Kuskokwim Group. The Koksetna River sequence was sourced from rocks related to volcanic arcs that formed offshore, in the proto-Pacific Ocean (including the Talkeetna arc). In contrast, the Kuskokwim Group was formed by the accumulation of sediments shed from North America. About 80 million years ago the Koksetna River sequence and Kuskokwim Group were affected by a shared deformation event. This event indicates the rocks associated with the Talkeetna arc had reached their current position in southcentral Alaska.

The Cretaceous was generally a time of uplift and erosion along the margins of the Cook Inlet basin, as indicated by a lack of fore-arc sedimentary deposits. The exception to this trend is a spatially limited outcrop of terrestrial sedimentary rocks in the southeast part of the park attributed to the Kaguyak Formation. Pollen in these rocks indicate they formed during the latest Cretaceous in a broad, nonmarine paleovalley.

After final collision and accretion of the rocks related to the Talkeetna arc, igneous activity continued in the region through the Late Cretaceous and into the early Paleogene. Plutons of the Alaska-Aleutian range batholith were emplaced to the northwest of the older Jurassic plutons. The more inboard shift of plutonism could be a result of shallowing of the subduction angle as younger, more buoyant oceanic crust was subducted. There is a gap in igneous activity in the early late Paleocene and early Eocene, which could have been caused by the subduction of a spreading ridge and formation of a slab window. Rocks associated with this early Paleogene subduction of a spreading ridge, including the Resurrection Ophiolite and near-trench plutons, can be found in and around Kenai Fjords National Park to the southeast (see Lanik et al. 2018 for more information).

Middle–Late Paleogene (56 million–23 million years ago)

Igneous activity resumed in the middle Paleogene with the eruption of the Meshik volcanics and emplacement of associated plutons. The Meshik volcanics are situated subparallel to the modern Aleutian volcanic arc and represent the tectonic precursor of the modern arc system. Meshik arc volcanism was driven by the subduction of the oceanic Pacific plate beneath the southern Alaska margin.

Quaternary (2.58 million years ago to present)

The Pleistocene was characterized by repeated glacial advances, which carved out many of the park's lakes and valleys and left behind distinctive glacial deposits. Glaciers have been retreating since the end of the last glacial period about 10,000 years ago, but glaciers still exist in the mountainous regions of the park. Permafrost also formed during cold glacial periods; ice-poor permafrost exists at high elevations in the northern part of the park and remnants of ice-rich permafrost are found in the western part of the park. The park's active volcanoes, Redoubt Volcano and Iliamna, began to erupt as early as one million years ago and are still active today. The most recent eruption was the 2009 Redoubt Volcano eruption. Modern erosion and deposition in fluvial, lacustrine, and coastal environments continue to shape the park's landscape.

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 Geologic Resources Division provides technical and policy assistance for these issues. At the beginning of each section, map units corresponding to those on the surficial or bedrock poster will be listed; these indicate which map units will be discussed in the following section.

During the 2005 scoping meeting (see Graham 2005) and 2018 conference call, participants (see Appendix A) identified the following resource management issues.

- Geohazards
- Mineral Development
- Abandoned Mineral Lands
- Paleontological Resource Inventory, Monitoring, and Protection
- Glacier Monitoring
- Coastal Issues

Geologic Resource Management Guidance

In addition to this report, general information concerning geologic resource management are provided in the park's foundation statement (NPS 2009), natural resource condition assessment (NPS 2016a), and state of the park report (NPS 2016b).

Resource managers may find the book *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. Chapter 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.

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) and the Geologic Resources Division (http://go.nps.gov/geology). The 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/.

Park managers can submit a proposal to receive geoscience-focused internships through the Scientists in Parks (SIP; 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 SIP program. The Geologic Resources Division can provide guidance and assistance with submitting a proposal. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring.

Geohazards

This section describes the potential geologic hazards ("geohazards") in the Lake Clark National Park and Preserve area along with a brief description of each hazard and areas susceptible to them. Geohazards are active geologic processes that have the potential to cause widespread damage or risk. They can be hazardous to people or infrastructure, or they may occur in remote areas with no hazardous impact. Geohazards in the park include volcanic hazards, earthquakes, landslides, and tsunamis.

Volcanic hazards

Surficial poster units: **Qdr, Qhv, Qvr, Qdf1, Qdf2, Qav, Qpd, Qca, Qdf, Qad, QTv**

Bedrock poster units: **Qvd** (see Table 3)

The potential for volcanic eruptions in Lake Clark National Park and Preserve is high because the park contains two active volcanoes, Redoubt Volcano and Iliamna Volcano. According to the USGS volcanic threat assessment (Ewert et al. 2018), Redoubt Volcano is considered a very high threat and Iliamna Volcano is a high threat. Augustine and Spurr volcanoes are rated as very high threat volcanoes, both of which are within 80 km (50 mi) of the park (Ewert et al. 2018). A large part of the high threat these volcanoes pose is their proximity to large population centers in southcentral Alaska. Redoubt Volcano erupted at least four times historically, and two of these eruptions (1989–1990 and 2009) occurred after the creation of the park. Iliamna Volcano has not erupted in historic times, but seismic swarms and elevated gas emissions detected in 1996 indicate the volcano remains restless and may erupt (Miller et al. 1998; Waythomas and Miller 1999).

A preliminary volcano-hazard assessment has been completed for Redoubt Volcano (Waythomas et al. 1998). This report was published prior to 2009 so does not contain insights from the most recent eruption. Volcanic hazards that occurred during past eruptions of Redoubt volcano which should be expected in future eruptions include volcanic ash clouds and fallout, lahars, and pyroclastic flows and surges (see Figure 6 for depiction of these hazards; Waythomas et al. 1998).

Past eruptions of Redoubt have been characterized by powerful tephra explosions. Tephra is composed of rock fragments expelled during explosive eruptions, and the smallest of these fragments (volcanic ash) can be carried by wind a significant distance from the source vent. Air traffic in the Cook Inlet region is high and volcanic ash clouds create hazardous conditions for aircraft. A Boeing 747 encountered an ash cloud during the 1989–1990 eruption and experienced complete engine failure (Waythomas et al. 1998). The crew was able to restart the engines and land safely in Anchorage, but repairs to the aircraft were estimated to cost $80 million. Ash produced during explosions is transported downwind, resulting in ashfall on the surrounding areas (Figure 38). During the 2009 eruption, minor ash accumulation (>0.8 mm [0.03 in] thick) covered over 80,000 km^2 (30,000 mi^2), which included Anchorage and communities on the Kenai Peninsula, and trace ash (<0.8 mm [0.03 in]) was reported as far away as Fairbanks (Wallace et al. 2013). Depending on the accumulation of ash, impacts can range from eye and respiratory irritation to heavy infrastructure damage and loss of plants and animals (Table 4; https://www.avo.alaska.edu/volcanoes/hazards.php, accessed 4 February 2019). Tephra can destroy anything with moving parts, including any electronics that require cooling such as cell towers or other communication stations.

Sudden or abrupt increase in stream discharges on the slopes of volcanoes can become fast-moving slurries of mud, rocks and pyroclastic debris or mudflows, and are called lahars. During the 1966-68, 1989-90 and 2009 eruptions, lahars inundated the Drift River Valley (**Qdr**). A future eruption would probably produce similar lahars in the Drift River Valley. During an extreme volcanic eruption, larger and more destructive flows may occur along any of the drainages emanating from Redoubt Volcano (Waythomas et al. 1998). During the 1989–1990 and 2009 eruptions, the lahars threatened an oil storage facility located near the mouth of Drift River known as the Drift River Oil Terminal (Figure 39). An oil spill was narrowly avoided during the 2009 eruption. In 2019, Hilcorp began decommission of the Drift River Oil Terminal in favor of transporting oil via pipelines below Cook Inlet (https://www.radiokenai.net/hilcorp-works-to-fully-decommission-drift-river-terminal/ accessed 4 August 2020).

Figure 38. Photographs of a volcanic ash produced during the 2009 Redoubt eruption. (A) Photograph of Redoubt's eruption plume taken from Kasilof Beach at about 3:30 pm on March 28, 2009. USGS photograph by Jacob Buller. (B) Photograph of ash fallout from the same March 28 eruptive event, taken in Nikiski. Ash fall began at approximately 4:16 pm and lasted maybe 5 minutes. USGS photograph by Kristi Wallace.

Table 4. Impacts of ash fallout.

Table modified from the Alaska Volcano Observatory (https://www.avo.alaska.edu/volcanoes/hazards.php).

Term	Accumulation	Key Impact Thresholds (cumulative)
Trace or dusting	<0. 8 mm (<0.031 in)	Eye and respiratory irritant, very low-level impacts for most people.
Minor	0.8–6.4 mm (0.031–0.25 in)	Possible crop, animal, equipment, and infrastructure; widespread clean-up likely.
Moderate	6.4–25.4 mm (0.25–1.0 in)	Ash removal efforts significant.
Heavy	25.4–100 mm (1.0–4.0 in)	Weaker roofs can fail at about 10–12 centimeters (4–5 inches) of compacted, we ash accumulation ~200 kg/m^2 (~40lb/ft^2).
Very Heavy	100–300 mm (4.0–12.0 in)	Danger of roof collapse increases, damage to trees, essential services interrupted.
Severe	>300 mm (>12 in)	Roads impassable, severe infrastructure damage, heavy plant and animal loss.

Figure 39. Photograph of a lahar at the Drift River Oil Terminal during the 2009 Redoubt eruption. Photograph shows the west of the runway, helipad, and service buildings at Drift River Oil Terminal. The lahar deposit is at least half a meter thick at the buildings. USGS photograph by Cyrus Read.

An eruption of Redoubt Volcano would likely produce pyroclastic flows and surges, which are hot, fast moving volcanic debris flows. They were generated in both the 1989–1990 and 2009 eruptions. Pyroclastic flows and surges destroy most things in their path are a serious hazard within about 15 kilometers of the volcano (Waythomas et al. 1998).

Several other hazards may occur at Redoubt Volcano but are less likely than those described above. These hazards are debris avalanches (**Qdf1, Qdf2**), volcanic tsunamis, directed blasts, and volcanic gases (Waythomas et al 1998). A debris avalanche is a rapidly moving mass of rock generated through volcano flank failure. If a large debris avalanche were to enter the sea, it could cause a volcanic tsunami (see the "Tsunamis" section for more information). The probability of a debris avalanche occurring at Redoubt Volcano that travels far enough to reach Cook Inlet and generate a tsunami is low (Waythomas et al. 1998). A directed blast is a lateral explosion of a volcano that can accompany slope failure. No evidence for directed blasts has been found at Redoubt Volcano, but similar volcanos have been known to produce them (Waythomas et al. 1998). Volcanoes emit gases that can be harmful to humans, however frequent windy conditions at Redoubt Volcano generally prevent the buildup of these gases and the hazard is minimal (Waythomas et al. 1998).

A preliminary volcano-hazard assessment has been completed for Iliamna Volcano (Waythomas and Miller 1999), and many of the hazards identified for Iliamna are the same as those identified for Redoubt. The greatest hazards identified for Iliamna Volcano are volcanic ash clouds, volcanic ash fallout, lahars and floods, pyroclastic flows and surges (**Qpd**), and debris avalanches (Waythomas and Miller 1999). Volcanic ash clouds could impact aircraft, volcanic ash fallout could impact surrounding communities (Table 4), lahars and floods could affect surrounding drainages and could be hazardous to people or facilities in those areas, and pyroclastic flows and surges could be hazardous in the valleys directly around the volcano. Multiple prehistoric and several small historical debris avalanches have occurred at Iliamna Volcano, but these did not extend very far beyond the base of the volcano (Waythomas and Miller 1999). Fumarole activity near the summit hydrothermally alters and weakens the surrounding rocks, causing rock-ice avalanches (see the "Landslides" section for more information). Other, uncommon hazards that could be possible at Iliamna Volcano include directed blasts, volcanic gases, and lava flows (Waythomas and Miller 1999).

Redoubt and Iliamna volcanoes are monitored by the Alaska Volcano Observatory (AVO). Generally, volcanic eruptions are preceded by earthquakes that can be detected by the AVO seismic network. AVO maintains a network of seismometers on both Redoubt and Iliamna Volcanoes and seismic activity is monitored in real time. AVO also maintains two webcams monitoring Redoubt Volcano and one webcam monitoring Iliamna Volcano. Data are examined daily by AVO analysts; some of the data are shared with the public via the AVO website: https://avo.alaska.edu/webicorders. In addition to the seismic network and webcam monitoring, the following methods are used to detect volcanic unrest at Alaska volcanoes:

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

For more information on the hazards associated with Redoubt and Iliamna Volcanoes and monitoring, see the preliminary volcano-hazard assessments (Waythomas et al. 1998; Waythomas and Miller 1999), and the Alaska Volcano Observatory website (http://avo.alaska.edu). *Volcanism in National Parks: Summary of the Workshop Convened by the US Geological Survey and National Park Service, 26–29 September 2000, Redding, California* (Guffanti et al. 2001) provides more information for resource management issues related to volcanoes in national parks and is available at http://pubs.usgs.gov/of/2001/0435/.

Landslides and Rockfall

Surficial poster units: **Qav, Qca, Qcf, Qcd, Qtc, Qsf, Qls**

Bedrock poster units: **Qlc** (see Table 3)

Many of the mountainous areas of the park are characterized by steep slopes that may be prone to landslides (**Qls**) and rockfall (**Qcd,** in part). Landslides and rockfall occur particularly on slopes greater than 40°, and can be triggered by high rainfall, seismicity, volcanic events, or a combination of factors. Retreating glaciers can increase the risk for landslides because of a process known as glacial debuttressing. As a glacier retreats, slopes over-steepened by glacial erosion that were formerly propped up by ice, no longer have that lateral support and may fail. Widespread glacier retreat, as well as thawing permafrost could increase landslide and rockfall occurrence in the park.

One area of the park that frequently experiences mass-movement events is Iliamna Volcano. Iliamna Volcano exhibits frequent, large rock-ice avalanches down its eastern and southern flanks. The lack of infrastructure and low visitation in the area limits the risks associated with these avalanches. Between 1960 and 2004, 13 rock-ice avalanches occurred at Iliamna Volcano: nine rock-ice avalanches originated on Red Glacier, three originated on Umbrella Glacier, and one originated on Lateral Glacier (see Figure 28 for glacier locations; Huggel et al. 2007). Rock-ice avalanches continue to frequently occur at the volcano; one recent avalanche occurred on 21 June 2019 at Red Glacier (Figure 40). The frequency and magnitude of Red Glacier avalanches is extraordinary and possibly unique worldwide (Huggel et al. 2007). Many of the avalanches are preceded by up to two hours of seismic activity that can be detected on the AVO maintained seismometers (Caplan-Auerbach and Huggel 2007).

Landslide potential and associated hazards and risk have not yet been studied in the park. Landslides are hazardous and can pose a significant risk if they occur in areas with infrastructure or high visitation. Additionally, if a landslide travels into the ocean it could generate a tsunami that would impact a larger and potentially distant geographic area. Wieczorek and Snyder (2009) described five vital signs that may be useful for managers to understand and monitor slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. The unstable slope management program (USMP) tool may be helpful to managers to assess unstable slopes and rockfall along transportation corridors. For more information visit https://usmp.info/client/credits.php.

Earthquakes

Earthquakes are common in the Lake Clark area because the park overlies an active fault zone—the Aleutian megathrust—and contains two active volcanoes—Redoubt and Iliamna. Tectonic earthquakes are associated with movements of tectonic plates

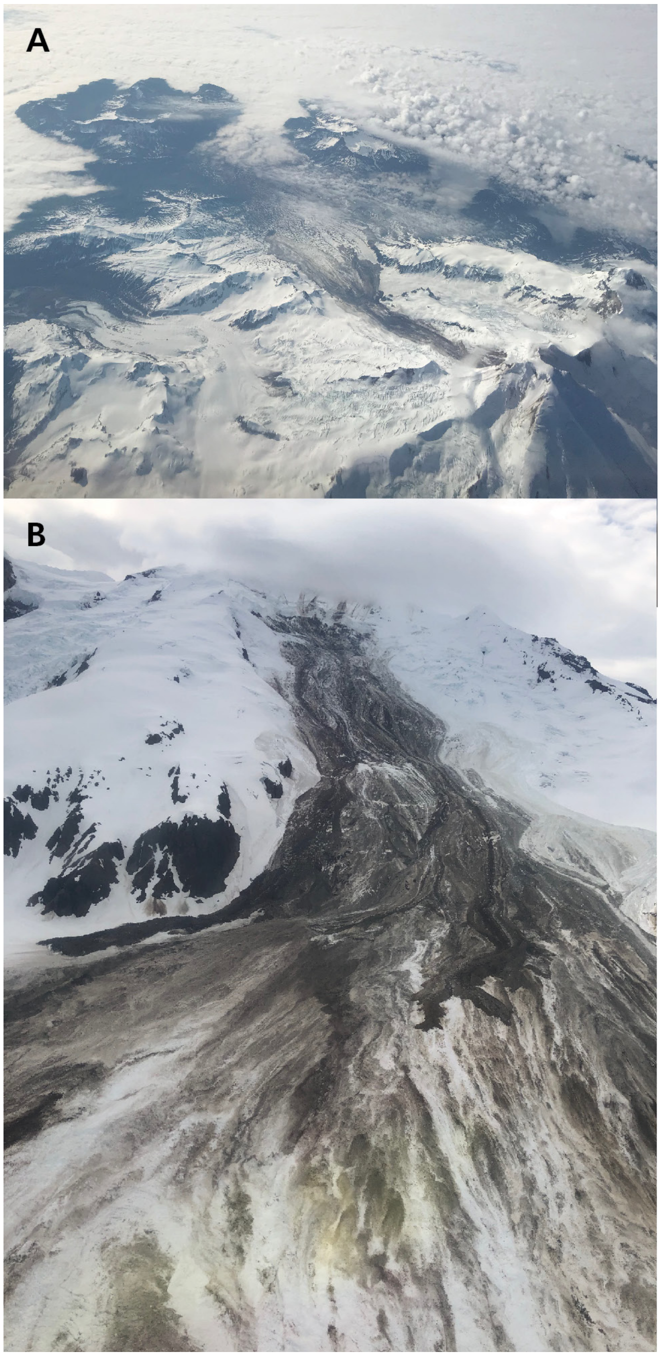


Figure 40. Photographs of a rock-ice avalanche that occurred on Iliamna Volcano in 2019. (A) Photograph showing the summit of Iliamna Volcano (bottom right), the rock-ice avalanche, and the surrounding area. USGS photograph by Greg Johnson. (B) Close-up photograph of the rock-ice avalanche. USGS photograph by Loren Prosser.

and commonly occur at plate boundaries. Volcanic earthquakes are associated with movement of magma beneath a volcano or the eruption of lava onto the surface. Volcanic earthquakes are generally mild to moderate in strength, but tectonic earthquakes, particularly those produced along subduction megathrusts, have the potential to be much stronger. For example, the 1964 Great Alaska Earthquake was a subduction megathrust earthquake that registered a magnitude 9.2, making it the most powerful earthquake in North American history. The strongest shaking during the 1964 earthquake occurred close to the epicenter in Prince William Sound; the most damage and loss of life occurred in coastal communities in southcentral Alaska. Despite being approximately 200 miles from the epicenter, shaking along the coast of the park was strong (Modified Mercalli Intensity scale [MMI] 6.5) and the interior of the park experienced moderate to strong shaking (MMI 5–6; https://earthquake.usgs.gov/earthquakes/eventpage/iscgem869809/map accessed 2 August 2020). The 1964 earthquake also produced uplift along the park's coast of 0.3–0.7 m (1–2.5 ft; Plafker 1969).

Since 1950, five earthquakes with a magnitude of 6.0 or greater occurred within or near the park (Figure 41; USGS Earthquake Catalog, https://earthquake.usgs.gov/earthquakes/search/ accessed 2 August 2020). The strongest of these earthquakes was a magnitude 7.1 that occurred in 2016 just outside the park with an epicenter near the Iniskin Peninsula. This earthquake was the result of strike-slip faulting at intermediate depths within the subducting Pacific plate. Shaking from the 2016 earthquake was felt widely in southcentral Alaska, causing minor damage. 30 homes were evacuated and four were destroyed in the nearby community of Kenai due to a gas leak. Additional effects of the earthquake include power outages in Anchorage and road damage near Kasilof.

The Alaska Earthquake Center maintains seismic monitoring stations near the park and actively monitors earthquake hazards in conjunction with the USGS (see http://earthquake.alaska.edu/). The Alaska Volcano Observatory maintains seismometers on Redoubt and Iliamna Volcanoes. According to Wesson et al. (2007), the park has a 10% probability for an earthquake to cause peak ground acceleration of between 17% and 40% of the acceleration of gravity (9.8 m/s^2 [32 ft/s^2]) in the next 50 years (Figure 42). This amount of peak horizontal acceleration would be perceived as strong to severe shaking and could cause light to moderate/heavy damage.

Ground shaking from an earthquake can damage infrastructure, which in turn can directly threaten human safety. Indirect effects of an earthquake, such as rockfall, landslide and tsunamis, can also be hazardous to park resources and visitors. The lack of major infrastructure and low visitation throughout most of the park limits the risks associated with earthquakes in the park. However, a strong earthquake could pose a threat to park staff, visitors, and infrastructure, including the park headquarters and visitor's center in Port Alsworth or the remote ranger cabins. Visitors and staff along the coast of the park may be at an increased risk in the event of a large earthquake due to the potential for earthquake-induced tsunamis.

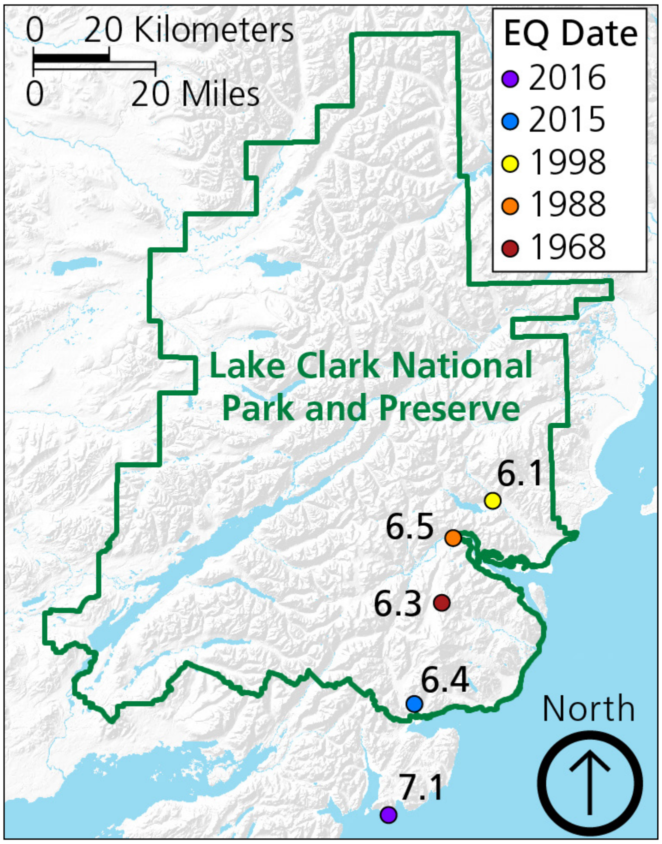


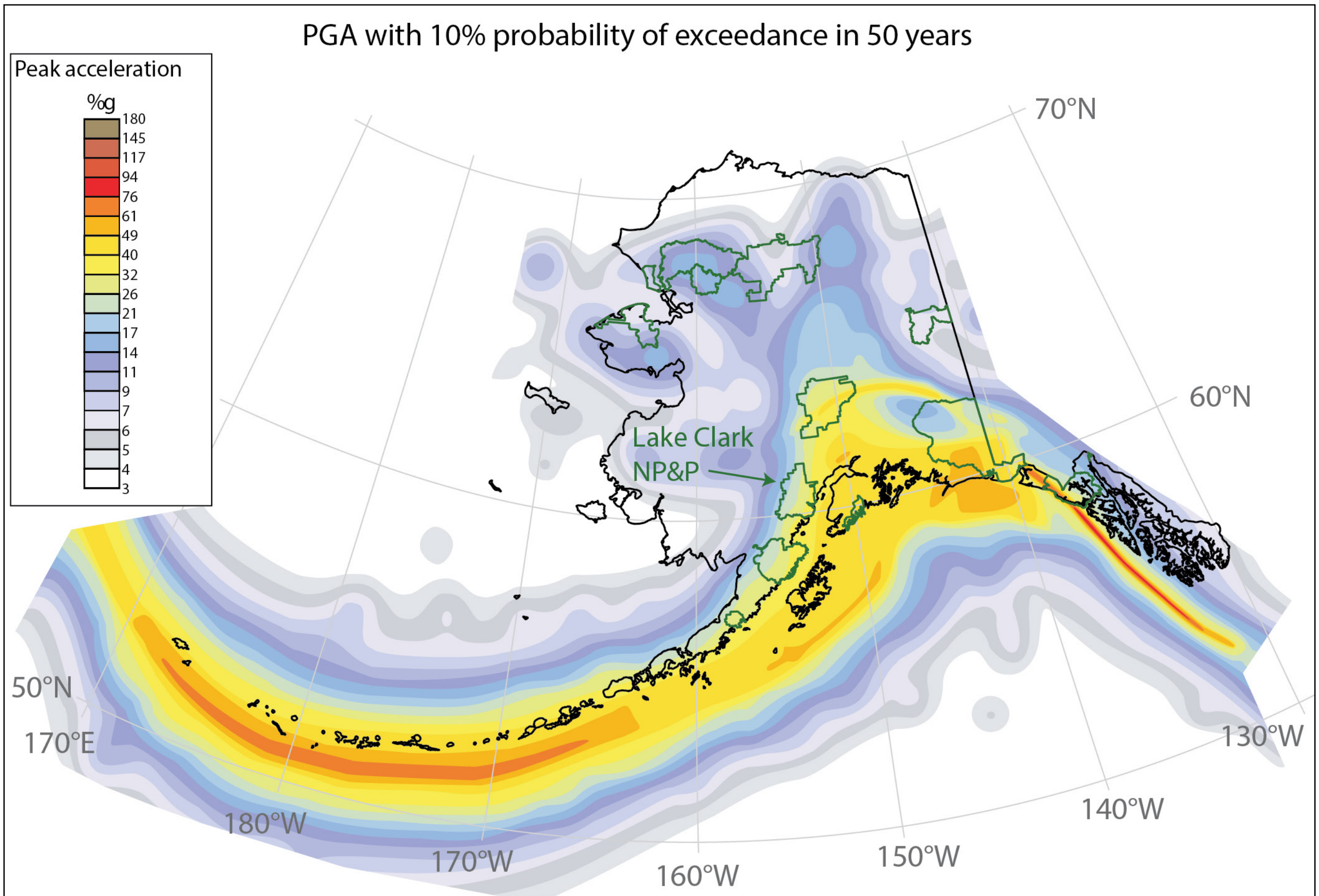
Figure 41. Map of large earthquakes in the Lake Clark region.
The map illustrates epicenters of magnitude 6.0 or greater earthquakes since 1950. In 1968, a magnitude 6.3 earthquake occurred 110 km (68 mi) deep beneath the flank of Tuxedni Glacier; in 1988, a magnitude 6.5 earthquake occurred 138 km (86 mi) deep beneath the head of Tuxedni Bay; in 1998, a magnitude 6.1 earthquake occurred 131 km (81 mi) deep near Crescent Lake; in 2015, a magnitude 6.4 earthquake occurred 119 km (74 mi) deep beneath the shore of Chinitna Bay; and in 2016, a magnitude 7.1 earthquake occurred 126 km (78 mi) deep beneath the south shore of the Iniskin Peninsula. Earthquake dates, magnitudes, depths, and locations are from the USGS Earthquake Catalog (https://earthquake.usgs.gov/earthquakes/search/ accessed 2 August 2020).

Tsunamis

Tsunamis can be generated by earthquakes, underwater landslides, landslides originating on land that run into the water, or volcanic deposits flowing into the water. Coastal areas throughout southcentral Alaska are vulnerable to tsunamis, including the coast of the park. During the magnitude 9.2 1964 Great Alaska Earthquake, tsunamis generated both by the earthquake itself and associated landslides devastated many communities on the Kenai Peninsula and in Prince William Sound. The Kenai Peninsula and relatively shallow waters of Cook Inlet largely protected the coast of the park during the 1964 earthquake, but a large earthquake closer to the park could produce significant tsunamis.

An 1883 eruption of Augustine Volcano, located about 56 kilometers (35 miles) south of the park, produced a tsunami when a debris flow avalanche entered Cook Inlet (Beget et al. 2008). Based on historical accounts and paleotsunami deposits, the 1883 wave affected coastal sites throughout southern Cook Inlet, including the coast of the park (Beget and Kowalik 2006). Beget et al. (2008) present evidence for four prehistoric volcanically-induced tsunamis in the lower Cook Inlet area including the 1883 Augustine Volcano event, as well as paleotsunami deposit near Homer they correlate to the 3600 yr. BP Crescent River debris avalanches produced by Redoubt Volcano (see the "Volcanoes" section for more information).

Coastal areas in southcentral Alaska are vulnerable to tsunamis and tsunami hazard modeling has been produced for many coastal communities in southcentral Alaska (see https://earthquake.alaska.edu/tsunamis). While tsunami modeling has not been conducted for the Lake Clark National Park and Preserve coast, visitors and staff along the coast should be aware of the potential for volcanic-, landslide-, or earthquake-induced tsunamis, especially in the event of a large earthquake. Another factor that will affect tsunamis in Cook Inlet are tides. Cook Inlet experiences dramatic tidal shifts, and the interaction between tides and tsunamis can either intensify or dampen the effect of tsunamis (Kowalik and Proshutinsky 2010). The National Oceanic Atmospheric Administration Pacific Tsunami Warning Center (based in Palmer, Alaska) monitors global earthquakes and tsunami potential for the coast of North America and publishes real-time watches, warnings, and advisories on its website (http://ptwc.weather.gov/).



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

Figure 42. 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 Service System units. Lake Clark National Park and Preserve (shortened to Lake Clark NP&P) is labelled with a green arrow. Map modified from Wesson et al. (2007). Values for the table located at the bottom of the figure 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.

Mineral Development Potential

The USGS Alaska Resource Data File (https://ardf.wr.usgs.gov/) lists 52 metalliferous mineral occurrences in the park. Three of these mineral occurrences are located on land that is either non-federally owned or the subsurface is non-federally owned, two of which are associated with the Johnson River Prospect and one is a mine site known as Portage Creek. The Portage Creek mine site is a placer gold mine, which involves mining unconsolidated deposits that have been eroded out of a mineralized area. Mining began at Portage Creek around 1903 and was mined by various people throughout the 1900s using primitive 'pick and shovel' methods as well as hydraulic methods (Bundtzen and Kline 1979). Bundtzen and Kline (1979) stated that Howard Bowman conducted prospecting, mining, and development work on the nine claims associated with the Portage Creek mine since the late 1950s. Portage Creek is a patented mining claim, which is a claim for which the Federal Government has passed its title to the claimant making it private land. Mining claims are authorized by the General Mining Law of 1872, however all park units are now closed to the establishment of new mining claims. Mining claims, such as the Portage Creek mine, that existed before the park was created are subject to the Mining in the Parks Act of 1976, which requires mine operators to submit a mining plan of operations to the NPS. For more information, see the NPS Energy and Minerals Management website, https://www.nps.gov/subjects/energyminerals/index.htm.

Johnson River Prospect

The Johnson River prospect is a gold-copper-lead-zinc deposit located about 12 km (7.5 mi) northeast of Illiamna Volcano, near the toe of the Johnson Glacier. Resource Associates of Alaska under contract to the Cook Inlet Regional Incorporated (CIRI) discovered the prospect in 1975; in 1976, CIRI selected the tract of land containing the prospect, including the subsurface rights, under the Alaska Native Claims Settlement Act (ANCSA 1971). In addition, CIRI has subsurface ownership of an adjacent tract of land immediately north of the Johnson Tract. At least nine prospect areas of alteration and mineralization have been discovered within 12 km (7.5 mi) of the Johnson River Prospect (Athey and Werdon 2019). Under ANCSA (1971), the park is required to permit a right of way to access the subsurface right.

Mineral exploration of the Johnson Tract occurred in the past and is currently underway. In 1981, CIRI entered into a joint-venture agreement with Anaconda Minerals Company to evaluate the mineral potential of the Johnson Tract. Anaconda Minerals Company conducted exploration, including surface sampling, mapping, geophysical surveys, and drilling, until 1985 when the company ceased operations (Sutherland 2019). In addition to studying the Johnson River prospect, Anaconda Minerals Company identified several other prospects in the area (Sutherland 2019). Between 1985 and 1992, Hunt, Ware and Proffett continued exploration of the mineral potential of the Johnson Tract, which included drilling of the Johnson River Prospect and a deposit to the northeast inferred to be an offset portion of the main deposit (Sutherland 2019). In 1993, Westmin Resources Ltd took over mineral exploration, which continued until 1997 (Sutherland 2019). Between 1997 and 2018, no significant mineral exploration occurred on the Johnson Tract. Mineral exploration resumed in 2018, when CIRI entered into a lease agreement with Constantine Metal Resources Ltd (Athey and Werdon 2019). As of December 2019, exploration of the Johnson Tract is currently ongoing under the Canadian gold exploration company HighGold Mining (https://www.highgoldmining.com/projects/johnson-tract-project/; accessed 11 December 2019).

Between 1993 and 1997, Westmin Resources Ltd was exploring the possibility of developing a mine at the Johnson River Prospect. As of 1997, the Johnson River Prospect was estimated to contain drilled out reserves at $50/tonne cutoff of 997,542 tonnes (1,099,580 tons) grading 10.35 g/tonne (0.32 oz/ton) gold, 7.84 g/tonne (0.24 oz/ton) silver, 0.76% copper, 1.17 % lead, and 8.37% zinc (Swainbank et al. 1997). Westmin Resources Ltd and CIRI ended their partnership in 1997 before a mine was developed. Resampling of historic drill cores in late 2018 produced similar results to the historic grade and extent of mineralization (Sutherland 2019). The price of the main commodity targeted by a potential mine, gold, has more than doubled between 1997 and 2018; the average gold price in 1997 was $530.69 dollars (accounting for inflation) and the average gold price in 2018 was $1,268.49 (https://www.statista.com/statistics/268027/change-in-gold-price-since-1990/, accessed 11 December 2019). The current lease agreement between HighGold and CIRI includes an initial 10-year term, followed by a 5-year development term to reach a mine construction decision (Sutherland 2019).

Abandoned Mineral Lands Mitigation

Lake Clark National Park and Preserve contains over 50 mineral occurrences and has a history of mining activity that persists today (see the “Mineral Resources” and “Mineral Development Potential” sections for more information). Past mining activities have left their marks on the park in the form of abandoned mineral land (AML) sites and features. Abandoned mineral lands are lands, waters, and surrounding watershed that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. According to Burghardt et al. (2014), Lake Clark National Park and Preserve contains eight AML sites, but one of these sites is the Johnson River Prospect that is currently being explored and would not be considered abandoned (see the “Mineral Development Potential” section for more information) . Four of the AML sites are on federal land, while others are on private or Cook Inlet Regional Inc. land within the boundaries of the park. Mitigation is currently underway to remove abandoned petroleum products and drilling equipment at the Crystal Creek Pass exploratory drilling site, with an anticipated completion date in 2021. The physical conditions of AML features often change through time and periodic monitoring is recommended. No identified AML features in the park are currently known to pose a physical safety risk to visitors or wildlife. Underground features at two remote AML sites are noted as needed assessment or monitoring. The NPS acts under various authorities to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources. Contact the Alaska Region Natural Resources Team or the Geologic Resource Division Energy and Minerals team for more details and specific information on the AML sites and features within the park.

Paleontological Resources Inventory, Monitoring, and Protection

Bedrock poster units: **TRrk, TRkb, TRkm, JTRku, Jtkh, Jtrg, Jtg, Jtf, Jtcf, Jtt, Jtb, Js, Jc, Jn, Jnc, Jns, Jnn, Jnp, KJkr, Kesv, KJk, KJs, MZPZcb, MZPZk, MZPZb, Twf, Ttyh**

Paleontological resources, or fossils, are any evidence of life that has been preserved in the geologic record. This definition encompasses 3.7 billion-year-old cyanobacteria, 15,000-year-old woolly mammoths, and everything in between. Most of the fossils in the park are marine invertebrate and plant fossils found in the sedimentary rocks between Tuxedni Bay and Chinitna Bay. Fossils have been also been collected from the Tlikakila complex elsewhere in the park, but that unit is not as fossil rich. The Tuxedni–Chinitna bay region contains Triassic (251.9 million–201.3 million years ago) invertebrate fossils, Jurassic (201.3 million–145 million years ago) plant fossils from the Talkeetna Formation, Middle–Late Jurassic (174.1 million–145 million years ago) marine invertebrate fossils (e.g. ammonites, bivalves, and belemnites) from the Tuxedni Group, Chinitna Formation, and Naknek Formation, and Late Cretaceous–Oligocene (100.5 million–23.0 million years ago) plant fossils from the Kaguyak Formation, West Foreland Formation, and Kenai Group. The Jurassic strata in the region is remarkably complete and the fossils contained in these rocks have global significance. For more information on the characteristics of the paleontological resource found in the park see the "Paleontological Resources" section, and for a more in-depth discussion of paleontological resources and management issues see Ruga et al. (2020).

Paleontological resources 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), geographic location where the rock formed (paleobiogeography), and the environment in which the rock was deposited. Paleontological resources are nonrenewable, meaning once a fossil is destroyed it can never be replaced and that piece of Earth's history is lost forever. As such, the National Park Service is mandated by Federal law (Paleontological Resources Preservation Act 2009), regulation (36 CFR 2.1), 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 from both NPS land and Alaska state land (below mean-high-tide) without a permit.

Due to their intrinsic value and nonrenewable status, baseline documentation of paleontological resources is an important first step towards management of fossils. An inventory of fossils in the park was completed by Kenworthy and Santucci (2003) and a focused condition assessment was completed by Ruga et al. (2020). Both documents provided a literature-based overview of fossils in the park, and the information in those reports have been incorporated into the Alaska-wide NPS paleontology database (contact the Alaska Region Natural Resources Team for more information). A field-based inventory of Fossil Point was completed by Blodgett et al. (2015), which included the collection of representative fossils samples that are now housed at the NPS Alaska Region Curatorial Center in Anchorage.

Fossils are faced with the potential for damage and destruction from both natural and human sources. Natural processes, primarily weathering and erosion, are responsible for exposing fossils at the surface of the Earth, enabling their discovery and study. However, the progression of these same processes leads to the eventual destruction of exposed 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 or removal of fossils, or an increase in rates of erosion as a result of visitor traffic. Fossil sites especially prone to human disturbance are those easiest to access or proximal to areas frequented by visitors. These include fossils exposed along riverbanks, coastal bluffs, or near roads and trails.

Most of the fossils in the park are concentrated in rocks exposed along the coast, making those fossils particularly vulnerable to both natural and human threats. Many areas along the coast are experiencing erosion that can lead to fossil destruction. Likewise, the coast is one of the most visited areas of the park and there is a higher chance of illegal fossil collection. The most prominent fossil locality in the region, Fossil Point, was monitored during the summers of 2018 and 2019 to determine visitation, paleontological resource loss, and erosional rates. Findings from this monitoring indicate that unauthorized fossil collection is occurring, and preliminary results show high rates of natural erosion (Figure 43; for more details see Lanik et al. [2019]). While paleontological resource issues, especially unauthorized collection, are likely most severe at Fossil Point, the findings from this monitoring could be an indication of the vulnerability of other fossil localities along the park's coast (Ruga et al. 2020).

Figure 43. Photographs of an ammonite at Fossil Point.
(A) Photograph of a large ammonite embedded in the bedrock at Fossil Point in October 2018. (B) Photograph of that same ammonite six month later in May 2019. The difference between these two photographs demonstrates the high erosional rates at Fossil Point, especially during the winter months. (C) Photograph taken two months later in July 2019 and shows the area where the ammonite was in the first two photographs. Sometime between May and July 2019 this fossil was removed from Fossil Point, most likely by someone chiseling it out of the rock. NPS photographs by Amanda Lanik.

Glacier Monitoring

Maintaining glaciers in their natural state is one of the management purposes stated in the park's enabling legislation, and mountain vistas, including the park's hundreds of glaciers, is noted as a fundamental resource in the Foundation Statement (ANILCA 1980; NPS 2009). Glaciers are dynamic and change in response to a variety of factors. Temperature is one of the main parameters that glaciers are sensitive to and therefore glaciers provide some of the most visible evidence of climate change. For the most part, glaciers in the park have undergone widespread shrinking and retreat since the end of the Little Ice Age (1540s–1710s and 1810s–1880s). The consequences of this retreat include local changes to surrounding hydrologic, geologic, and ecological systems, a transformation of the scenic and recreational values for park visitors, and global rise in sea level. Monitoring glacial changes is vital to understanding glacier retreat, the effects of this retreat today, and predicting the future impacts of continued retreat. As such, glacial extent is one of the "vital signs" monitored by the Southwest Alaska Inventory and Monitoring Network. For more information on glacier monitoring in the park, visit the Southwest Alaska Inventory and Monitoring network website (https://www.nps.gov/im/swan/glaciers.htm#4699D740EEF15912D55754C6FE699AC3) and for more information on the glaciers and glacial features found in the park, see the "Glacier Features and Modern Changes" section.

Loso et al. (2014) determined the amount of glacial change in the park between 1957 and 2008, finding that glacier area has decreased by 12%, from 2,956 km^2 to 2598 km^2 (1,141 mi^2 to 1,003 mi^2; Figure 28). Park glaciers shrank primarily by terminus retreat, most significantly at Tanaina Glacier, Shamrock Glacier, and Double Glacier. Loso et al. (2014) noted that the trend of warmer summers and wetter winters will continue within Alaska for at least the next 50 years, and that warming will accelerate. Recent glacier trends of negative mass balance, diminished ice cover, and reduced ice volume are predicted to intensify as climate changes. A focused condition assessment was funded for Fiscal Year 2020 to repeat the Loso et al. (2014) study and assess the change in glacier extent in Alaska parks since 2010.

Coastal Issues

Surficial poster units: **Qtf, Qmt, Qbd, Qes, Qdl**

Bedrock poster units: **Qmd** (see Table 3)

The park's coast stretches along the western side of lower Cook Inlet, from Redoubt Point in the north to Chinitna Bay in the south, encompassing surficial deposits such as tidal flat and estuarine deposits (**Qtf**), beach deposits (**Qbd**), landslide deposits (**Qls**), outwash deposits (**Qno**), alluvium (**Qal**), colluvial deposits (**Qcf**) and glacial deposits (**Qwg**) (see the surficial poster). Coastal areas of the park host a variety of paleontological, archaeological, and biological resources. Additionally, the coast receives relatively high visitation, with recreational activities including fishing, boating, camping, and nature and wildlife viewing. The coast is a dynamic area, constantly evolving as the coast gains sediment (accretion) or loses sediment (erosion), and as sea level changes.

Geomorphic coastal change is one of the "vital signs" monitored by the Southwest Alaska Inventory and Monitoring Network, however this vital sign is currently on hold. Coastal surveys of seven localities in 1992 and 2005 found that erosion occurred at five of the sites and accretion occurred at two (Cusick and Bennett 2005; see the "Coastal Features and Change" section for more details). These shoreline profiles were measured again in 2011, but a report on the findings of that work has not been published. Data from the 1992 and 2005 surveys suggests that beaches are accreting and growing between the Red River and the west entrance to Tuxedni Channel; and erosion of the shoreline is occurring between Chisik Island and Polly Creek in the north, and between West Glacier Creek and Spring Point in the south (Cusick and Bennett 2005). Nearshore currents are one of the main factors that contribute to erosion and accretion patterns, however the nearshore currents along the park's coast are not currently known. An ongoing project is mapping the park's nearshore coastal currents, which will provide important baseline data for understanding the park's current and future coastal change (Tahzay Jones, NPS Alaska Regional Office, coastal oceans coordinator, personal communication, 28 September 2020). This project is also establishing a tide gauge on Gull Island that will aid in understanding sea level change.

Relative sea level along the coast of the park is changing in response to several factors, including isostatic rebound, tectonic forces, and global sea level rise due to climate change. While there is no tide gauge along the coast of the park, or even on the western side of Cook Inlet, the nearest tide gauge in Seldovia records a decreasing sea level of -10 mm/yr (-0.4 in/yr) between 1964 and 2019 (https://tidesandcurrents.noaa.gov/sltrends/, accessed 29 September 2020). Considering nearby tide gauges and the fact that the uplift measured by Freymueller et al. (2008) is outpacing global sea level rise, it is likely that sea level along the park's coast is going down. Large-scale relative sea level change can happen almost instantaneously during a large megathrust earthquake. During the magnitude 9.2 1964 Great Alaska Earthquake, significant uplift and subsidence occurred in Prince William Sound and on the Kenai Peninsula, while the west side of Cook Inlet underwent slight uplift of 0.3–0.7 m (1–2.5 ft; Plafker 1969). If another significant earthquake occurred again, especially if the epicenter was closer to the park than the 1964 earthquake, there is the potential that sea level could change dramatically in a very short time. Rapid changes of sea level could have a significant impact on coastal ecosystems and patterns of erosion and accretion.

Cook Inlet is home to an extensive oil and gas industry, which has the potential to impact coastal park resources (Figure 44). Oil and gas development within 3 miles of the park's coast is managed by the Alaska Division of Oil and Gas (DOG), while the area beyond 3 miles from the coast is part of the Cook Inlet Planning Area, managed by the Bureau of Ocean Energy Management (BOEM). Most of the oil and gas leases in Cook Inlet managed by the Alaska DOG are in Upper Cook Inlet or on the eastern short of Lower Cook Inlet. The closest Alaska state leases to the park are found on Klagin Island, while land on the Iniskin Peninsula and in the Cook Inlet Planning area contain non-state oil and gas leases. As of 2017, 14 oil and gas leases exist in the Cook Inlet Planning area, all of which were issued as a result of Lease Sale 244 (BOEM 2018). An additional lease sale (Lease Sale 258) in the upper part of the Cook Inlet Planning area is scheduled for 2021, so the number of oil and gas leases offshore the park may increase (https://www.boem.gov/ak258 accessed 3 August 2020). Jones et al. (2019) conducted an assessment of nearshore habitats adjacent to the Lease Sale 244 area (including the coast of Lake Clark National Park and Preserve and Katmai National Park and Preserve), which provides information on the physical and biological resources that could potentially be impacted by oil and gas development.

The NPS coastal adaptation handbook (Beavers et al. 2016) provides climate change adaptation guidance to coastal park managers in parks that are potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts. Case studies of the many ways that park managers are implementing adaptation strategies for threatened resources are available in Schupp et al. (2015). An additional reference manual that guides coastal resource management is NPS Reference Manual #39-1: Ocean and Coastal Park

Jurisdiction, which can provide insight for managers in parks with boundaries that may shift with changing shorelines; this manual is available at https://home.nps.gov/applications/npspolicy/DOrders.cfm. For more information on monitoring coastal resources, see Bush and Young (2009). The NPS Water Resources Division, Ocean and Coastal Resources Branch website (https://www.nps.gov/orgs/1439/ocrb.htm) has additional information about servicewide programs and resources.

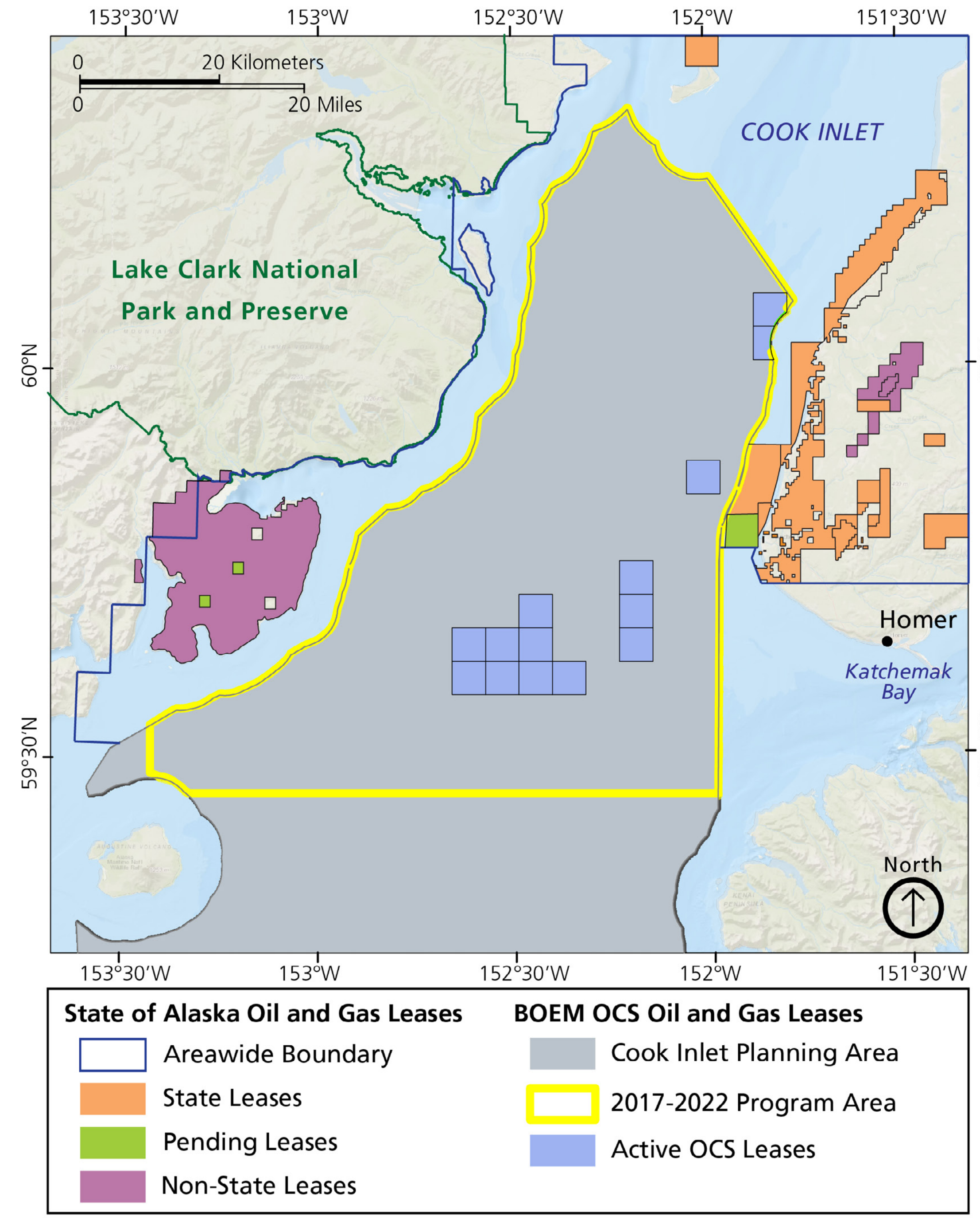


Figure 44. Map of the oil and gas leases in Cook Inlet.
Oil and gas development within 3 miles of the park's coast is managed by the Alaska Division of Oil and Gas, while the area beyond 3 miles from the coast is part of the Cook Inlet Planning Area, managed by the Bureau of Ocean Energy Management (BOEM). State oil and gas leases are labeled in orange, pending leases in green, and non-state leases in purple. The Cook Inlet Planning Area is shown in grey, the 2017-2022 program area is outlined in yellow, and active outer continental shelf (OCS) oil and gas leases are in blue. Map created using data from BOEM (2020) and Alaska DOG (2020).

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Additional References

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

Alaska Geology

- 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 and Geophysical Surveys (and Alaska USGS) publications: https://dggs.alaska.gov/pubs/pubs

Climate Change Resources

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS sea level change: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- US Global Change Research Program: http://www.globalchange.gov/home

Geological Surveys and Societies

- Alaska Division of Geological & Geophysical Surveys: http://dggs.alaska.gov/
- Alaska Volcano Observatory: https://avo.alaska.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

Landslides

- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/
- The "Monitoring Slope Movements" chapter (Wieczorek and Snyder 2009) of *Geological Monitoring* (Young and Norby 2009): https://www.nps.gov/articles/monitoring-slope-movements.htm

NPS Geology

- NPS Alaska Regional Office (Anchorage, Alaska) Active Geology Website: https://www.nps.gov/subjects/aknatureandscience/activegeology.htm.
- Alaska Park Science Understanding and Preparing for Alaska's Geohazards: https://www.nps.gov/subjects/aknatureandscience/geohazards.htm
- Alaska National Parks Geology Sketchfab Website: https://sketchfab.com/alaska_nps_geology
- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Division geoscience concepts: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Scientists-In-the-Parks (SIP) internship and guest scientist program: https://www.nps.gov/subjects/science/scientists-in-parks.htm

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural Resource Inventory and Monitoring Guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS *Management Policies 2006* (Chapter 4: Natural Resource Management): http://www.nps.gov/policy/mp/policies.html
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

Offshore and Coastal Geology

- COAST NPS SharePoint site: https://doimspp.sharepoint.com/sites/nps-coast (available on NPS computers only). COAST is a Community of Practice (CoP) for people interested in meeting the challenges confronting oceans and coasts. Information about the Benthic Habitat Mapping and other priority projects can be found here.
- Natural Resource Conservation Service (NRCS) subaqueous soil surveys: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcseprd1343022
- NPS benthic habitat mapping, data availability: https://www.nps.gov/gis/storymaps/mapseries/v2/index.html?appid=90f695c68cc648b7980a151eafd9d9b7
- NPS Submerged Resources Center: https://www.nps.gov/orgs/1635/index.htm. Although the center focuses on cultural resources, it may be able to provide guidance for collecting offshore data because it embraces an interdisciplinary approach to resource management issues and works actively across disciplines to provide science-based recommendations to park managers and partners in line with the preservation mandate of the National Park Service.
- NPS Ocean and Coastal Resources Program (OCRP), part of the Water Resources Division: https://www.nps.gov/orgs/1439/ocrb.htm

Tsunamis

- NOAA, Deep-Ocean Assessment and Reporting of Tsunamis (DART) stations: https://www.ndbc.noaa.gov/dart/dart.shtml
- Tsunami warning centers: https://www.weather.gov/safety/tsunami-twc

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: History of Geologic Exploration

The following timeline summarizes the early history of geologic exploration in the Lake Clark area, up until 1961. This information has been compiled because many of the earliest publications have only short references to geology, which are often buried in much longer narratives. References cited in this appendix are included in "Literature Cited."

Pre-European contact – Ancestors of the Dena'ina Athabascan people occupied and explored the Lake Clark region for thousands of years before European contact and possessed intimate knowledge of the geography and natural resources of the area. Their relationship with the natural world is reflected in the descriptive Dena'ina place names throughout the region (Gaul 2007).

1741 – This part of Alaska was first visited by Europeans during the early voyage of discovery in 1741, when a Russian expedition led by Danish navigator Vitus Bering caught a glimpse of the coast or islands, probably near the mouth of Cook Inlet (Lauridsen 1889).

1778 – The first charting in this region was conducted by British Captain James Cook, when he entered the inlet (now named Cook Inlet) and spent more than 10 days exploring and mapping the shores. Cook noted the presence of a volcano (Redoubt Volcano) on the west side of the inlet (Cook 1821).

1779 – A Spanish expedition investigating the Russian and British presence in Alaska and searching for a possible passage to the Atlantic entered Cook Inlet on 1 August. The expedition was led by Ignacio Arteaga y Bazan and Lieutenant Juan Francisco de la Bodega y Quadra aboard two newly built frigates: the Favorita and the Princesa. They incorrectly thought the Kenai Peninsula was an island and named it, "Isla de la Regla" (Island of the Rule). On 2 August, they went ashore and claimed the land for Spain, built a rock cairn, erected a cross, and held a mass. During their brief visit, Iliamna Volcano on the west shore of Cook Inlet was sighted and named Miranda (Unrau 1994).

1786 – British Captains Nathaniel Portlock and George Dixon (both served as officers under Cook), returned to Cook Inlet on a venture for King George's Sound Company to investigate the economic possibilities of fur trade on the northwest coast of North America. The expedition entered Cook Inlet on 19 July where they spent several days and noted the presence of a volcano (Redoubt Volcano) and added considerable detail to the mapping of the area (Portlock 1789).

1788 – A Spanish expedition led by Esteban José Martinez, aboard the frigate La Princesa, and second in command Gonzalo Lopez de Haro, aboard the packetboat San Carlos visited Prince William Sound, Cook Inlet, and the surrounding area. For several weeks the expedition traded with the local inhabitants and claimed possession of land for Spain by burying bottles, erecting crosses on shore, and distributing Spanish silver coins. The expedition sighted the Iliamna Volcano on 13 June (Unrau 1994). Days after the Spanish expedition left the area, John Meares, a British officer aboard the Iphigenia commanded by Captain William Douglas, visited the northwest coast of North America hoping to capitalize on trade in sea otter pelts. On 17 June, Meares entered Cook Inlet and left on 2 July (Meares 1791).

1790 – Lieutenant Salvador Fidalgo led a three-ship Spanish expedition that sailed to Cook Inlet and Prince William Sound to continue the exploration of Alaska, monitor Russian activities, and search for the Northwest Passage. Fidalgo sailed from Nootka Sound on 4 May and arrived at Prince William Sound on 24 May. He entered Cook Inlet in early July and noted a thick column of smoke emanating from Volcano Miranda (Iliamna) and eventually left Alaskan waters in late October (Unrau 1994).

Early 1790s – A winter expedition of Russian fur traders headed by Vasilii Ivanov and accompanied by several Dena'ina people, was sent north from Iliamna Lake to investigate the fur trade potential in the Kuskokwim and Yukon valleys. It is believed that Ivanov's route led from Iliamna Lake across Lake Clark to the upper Mulchatna River valley and from there to either the Holitna or Stony rivers (Unrau 1994).

1794 – The next noteworthy expedition to the region was led by George Vancouver, another of Cook's officers, who on 11 April returned to Cook Inlet in search of the Northwest Passage and completed the mapping of the shores of the inlet (Vancouver and Vancouver 1801).

1797 – Alexander Baranov of the Shelikhov Company sent Vasilii Grigorevich Medvednikov and Filipp Kashevarov to explore the Lake Iliamna area. The expedition may have been the first Euroamericans to encounter Lake Clark (Unrau 1994).

1818 – The Russian-American Company commissioned Petr Korasakorsky to explore the Lake Clark region to expand fur trade operations and examine mineral potential of the area. In late July he ascended the Kvichak River to Iliamna Lake and from there to Lake Clark and the upper reaches of the Mulchatna River. Korsakovsky did not leave a map, so it is difficult to fully gauge the geographical contributions of his travels (Smith 1917; Unrau 1994).

1829 – The Northern Land Expedition explored the area adjacent to the Lake Clark region. The venture was led by Ivan Vasilev, an ensign in the Russian Corps of Fleet Navigators. Vasilev along with Lukeen, his interpreter, left Alexandrov and traveled upstream on the Nushagak River, portaged to the Holitna River, followed that river to its mouth, then traveled down the Kuskokwim River to the Bering Sea. The objectives of the trip were to collect topographical and ethnographic data and establish relations with Native tribes (Smith 1917; Unrau 1994).

1832 – The governor of the Russian settlements in Alaska, Ferdinand von Wrangell, sent Fedor Kolmakov to follow Vasilev's route and further explore the area. About 100 miles below the mouth of the Holitna River on the Kuskokwim River, the interpreter of the expedition, Lukeen, stayed behind and established a trading post. This post became known as Lukeen's Fort and served as the primary interior trading post for the Russians (Smith 1917).

1834 – In the winter, Andrei K. Glazunov traveled to Lukeen's Fort. In February, he went up the Kuskokwim River to a river then called Tchalochuk, now known as Stony River. At the mouth of that river the Alaska Native guides left the expedition. Glazunov and the rest of the Russians in his party continued for about 50 miles to a point near the Lime Hills. The winter expedition covered approximately 1,400 miles in 104 days (Smith 1917; Unrau 1994).

1839 – Baron Ferdinand P. Wrangell, who possessed an intense interest in geographical and scientific topics, published his work "Russian America Statistical and Ethnographic Information." The book was a synthesis of his observations and material he collected during his time in Alaska. The chapter titled "Notes On Two High Mountains On the West Coast of Cook's Inlet and the Effect of Subterranean Fires on the Island of Unimak," records some of the earliest detailed data on Iliamna and Redoubt Volcanoes, providing precise geographic and elevation information (Wrangel and Pierce 1980).

1842 to 1844 – The Russian-American Company commissioned Lieutenant Lavrentiy A. Zagoskin to lead an expedition investigating the Kuskokwim and Yukon regions. Zagoskin made statistical, ethnographical, geological, and botanical observations. He also surveyed 600 miles of the Yukon River and 250 miles of the Kuskowim River. In 1844, he visited Kolmakovsk Redoubt on the Kuskowim River and the Lime Hills region (Unrau 1994).

1851 – The Russian-American Company sent Petr Doroshin, a mining engineer, to Alaska to begin investigating the geological and mineral potential of the region. After spending two years looking for gold on the Kenai Peninsula, in 1851 he turned his attention to evaluating the coal potential of the area. Doroshin and his companions traveled along the eastern shore of Cook Inlet and then down the western shore to Kamishak Bay. At this point they left the boat and went on foot over the mountains to Iliamna Lake, making geologic notes along the way. From Iliamna Lake they went down the Kvichak River to Bristol Bay and from there up the Naknek and Mishket Rivers (Unrau 1994).

1852 – Captain M. D. Teben'kov of the Russian Navy published his "Atlas of the Northwest Coasts of America" in St. Petersburg. The atlas was based on data gathered from his own voyages as well as other resources. The work contains a detailed map of Cook Inlet that includes topographical features such as Redoubt and Iliamna Volcanoes and the Alaska Range (Pierce 1981).

1853 – Signs of petroleum potential were discovered in the Cook Inlet region around this time (Martin 1921).

1869 – Two years after the United States purchased Alaska from Russia, the steamer Fideleter visited Cook Inlet with Major General George H. Thomas aboard for an inspection tour of army posts in Alaska. Thomas' aide-de-camp, Captain Alfred Lacey Hough, recorded details about the Cook Inlet area, including the presence of volcanoes Elamna (Iliamna) and St. Nicholas (Redoubt) and observations of mountains with glaciers or ice fields (Athearn 1949).

1871 – The first detailed information related to the geology of the Lake Clark region was published by Karl Eduard von Eichwald, a German scientist attached to a Russian exploration party. He noted sandstone and shale containing ammonites at Chisik Island and Fossil Point (Eichwald 1871).

1872 – Alphonse Louis Pinart extensively explored the coast of the Alaska Peninsula and Bering Sea, including ascending the Kvichak River to Iliamna Lake (Pinart 1875).

1881 – Under orders issued on 11 April, the US Army Signal Service sent C. L. McKay, a trained naturalist, to establish a station at Fort Alexander. McKay made numerous trips into the interior region surrounding

Bristol Bay. McKay reportedly visited Lake Iliamna, Lake Clark, and crossed the Chulitna Portage (Osgood 1904).

1882 – The first known samples of oil were collected in the Oil Bay area by a Russian named Paveloff (Martin 1921).

1883 – During an expedition sponsored by the Museum für Völkerkunde in Berlin, Captain J. Adrian Jacobsen, a Norwegian ethnological collector, visited the Kuskokwim, Togiak, and Nushagak delta regions and traveled between Bristol Bay and Cook Inlet via Iliamna Lake (Unrau 1994).

1891 – Early in the winter, A. B. Schanz of Frank Leslie's Magazine and J. W. Clark of the Alaska Commercial Company ascended the Nughhagak and Mulchatna rivers and explored the lower ends of Lake Clark and Iliamna Lake. They traversed portions of the region east of the Mulchatna River. They were the first non-Alaska Native party to definitively confirm the existence of Lake Clark, which had been noted on some early Russian charts. This expedition brought back important geographic information, but no geologic data about the area (Martin and Katz 1912).

1892 – Edelman staked petroleum claims near the heads of the creeks entering Oil and Dry bays, but quickly abandoned the claims (Martin 1921).

1894 – Around this time, gold was first discovered at several places in the upper Cook Inlet area, mainly on the streams draining into Turnagain Arm. News of these discoveries brought an influx of prospectors into this part of Alaska (Capps 1930a).

1895 – George F. Becker, C. W. Purington, and W. H. Dall visited Tuxedni Bay, collected fossils, and made brief descriptions of the rocks in the area (Dall 1896). The fossils were described by Alpheus Hyatt (1896).

1896 – Pomeroy and Giffin staked petroleum claims at Oil Bay, organized the Alaska Petroleum Company in 1897, and began drilling work in 1898 (Martin 1921).

1897 to 1898 – Hugh Rodman, a lieutenant in the US Navy and an assistant with the US Coast and Geodetic Survey, prospected for gold on the west coast of Cook Inlet and in the Lake Clark region. The first summer, Rodman and a companion explored from Chinitna Bay to Kamishak Bay traveling inland at many points along the route. The next summer Rodman returned with five men and made a base camp on the south shore of Iliamna Lake. From this camp they explored as far as possible in all directions but found only iron pyrite (Unrau 1994).

1898 – A US Geological Survey (USGS) reconnaissance expedition led by geologist J. E. Spurr and topographer W. S. Post traveled down the Kuskokwim River from the Alaska Range to the Bering Sea. A. E. Harrell, Oscar Rohn, George Hartman, and F. C. Hinckley served as camp hands. Rohn assisted with the geology and topographic work and Hinckley made natural history observations. The party landed at Tyonek on 26 April with three canoes and went up the Susitna River and then up the Skwentna River to its headwaters. At this point they crossed the Alaska range into the Kuskokwim basin and traveled down that river to its mouth. They then traveled along the shore and by river to Nushagak and crossed the Alaska Peninsula. After traveling a total of 1,425 miles they were finally picked up at the village of Katmai by the last steamer of the season on 31 October. During this remarkable journey, the expedition acquired a great amount of important information about the geology and geography of a wide territory on each side of the route of travel (Spurr 1900).

1899 – The next organized exploration of this region was the Cook Inlet Exploring Expedition, led by Lieutenant Joseph S. Herron of the US Army. Herron, an assistant surgeon, two enlisted men, two packers, two Native guides, and a pack train landed at Tyonek on 14 May. They proceeded by boat up the Yentna River and on 1 July up the Kichatna River, eventually crossing the Alaska Range at Simpson Pass. The party arrived at the junction of the Yukon and Tanana rivers on 1 December. No accurate surveys were made during the expedition, but Herron's sketch map added considerably to the knowledge of the area he traversed (Herron 1901).

1901 – In this year and several subsequent years, a route for a railroad line from Iliamna Bay to Anvik (on the Yukon) was explored. It seems that a rough survey was made nearly as far as the Mulchatna River. The effort was later abandoned and the railroad was not completed (Smith 1917).

1902 – The Biological Survey of the US Department of Agriculture sent W. H. Osgood, with A. G. Maddren as assistant and Walter Fleming as camp hand, to conduct a biological reconnaissance of a portion of the Alaska Peninsula that included the Lake Clark region. The party landed at Iliamna Bay on 10 July, crossed the mountains to Iliamna Lake and then moved to Lake Clark. On 10 August the party traveled up the Chulitna River and then on 27 August crossed to Swan Lake and began their descent of the Swan, Kakhtul, and Nushagak rivers, arriving at Nushagak on 12 September. Along with detailed descriptions of the flora and fauna, Osgood published a brief account of the region and a rough map of the area (Osgood 1904). Another noteworthy expedition conducted that same year was the USGS party that explored and mapped portions of the Alaska Range. The expedition was led by geologist Alfred H. Brooks and included topographer D. L. Reaburn and assistant geologist L. M. Prindle. The group landed with pack horses and supplies at Tyonek and traveled overland, crossing the Skwentna River and ascending the Kichatna River. They crossed the Alaska Range at Rainy Pass, proceeded northeastward along the face of the range to the Nenana River, and then continued to Rampart on the Yukon River. The results of this expedition provided the first detailed geologic information about the Mount McKinley region and the Alaska Range (Brooks 1911). Prospector William R. Buckman visited the Holitna basin in 1902 and 1903 in search for gold and other minerals. The maps he made using compass and paced surveys were later used by the USGS during their expeditions (Smith 1917).

1903 – Geologist G. C. Martin (USGS) visited Oil Bay from June to August and conducted geologic and topographic reconnaissance of the supposed oil fields between Iniskin and Chinitna bays. He noted that drilling for oil was in progress in the area (Martin 1905).

1904 – The next summer Martin returned with T. W. Stanton to examine the geology of the west coast of Cook Inlet and the Alaska Peninsula from Tuxedni Bay to Cold Bay, including a detailed focus on Chinitna, Iniskin, and Oil Bay (Martin 1905, Stanton and Martin 1905). In mid-July, H. P. Gallagher arrived at Tyonek by steamer from Seward with C. G. Van Houk and Amos Palmer. The trio spent the rest of the summer unsuccessfully prospecting for gold on both the western and eastern shores of Cook Inlet. Gallagher mentioned that there were reports of gold in what was likely the Crescent River, but their panning efforts at the mouth yielded nothing (Unrau 1994).

1906 – Charles Brooks and Count Charles von Hardenburg located a copper-iron prospect on Kasna Creek about 1.5 or 2 miles from the south shore of Kontrashibuna Lake (Martin and Katz 1912). O. B. Millett located claims on the copper prospect at Millett Point on the north shore of Iliamna Lake (Rutledge and Mulligan 1952).

1907 – A US Coast and Geodetic Survey party aboard the steamer McArthur, under the command of H. W. Rhodes, completed a detailed chart of Iliamna Bay on 19 July. The following year additional topographic, hydrographic, and triangulation was conducted on the west coast of Cook Inlet (Capps 1935).

1908 – In response to the influx of gold prospectors in the northern part of the Lake Clark-Central Kuskokwim region, the USGS dispatched a small party in charge of A. G. Maddren to the Innoko region to investigate mining activities and assess the mineral potential of the area (Maddren 1911).

1909 – The USGS conducted a topographic and geologic reconnaissance expedition in the Lake Clark region. The field party consisted D. C. Witherspoon and C. E. Giffin, topographers, and G. C. Martin, F. J. Katz, and Theodore Chapin, geologists, and seven packers and camp hands. The party landed and began field work at IIiamna Bay on 16 May. The expedition utilized a pack train of eight horses and three Peterborough canoes. From Iliamna Bay, the group worked their way to Iliamna Lake. At this point they broke into two smaller parties, with Witherspoon and Katz mapping the area north of Iliamna Lake and east of Lake Clark. Giffin and Martin paddled the shorelines of Iliamna Lake and Lake Clark, where they mapped the topography and geology that could be reached on foot and made an exploratory trip down Kvichak River to Koggiung. Field work was concluded at Iliamna Bay on 28 September. During the four months in the field, the topographers mapped 6,150 square miles and the geologists mapped 3,000 square miles (Martin and Katz 1912).

1910 – USGS geologist A. G. Maddren returned to the Innoko-Iditarod region with a larger topographic and geologic party to conduct a more thorough investigation of the area (Maddren 1911). Gold miners were active in the Mulchatna region during this year and for several subsequent years. One party consisted of J. W. Walker, Otis M. "Doc" Dutton, and Joe Kackley, who were based at Tanalian Point on Lake Clark. It is reported that they found coarse gold on Bonanza Creek. Others active in the area included Chris Hansen who was placer mining on Tom Creek, a tributary of Bonanza and O. B. Millett of Iliamna running a hand drill in the area. Many claims were staked in the area and a little gold was recovered, but no ground was found to be profitable at the time (Capps 1932, Unrau 1994).

1914 – The USGS sent a combined topographic and geologic reconnaissance team to explore and map the Lake Clark-Central Kuskokwim River region. The effort was led by geologist Philip S. Smith and topographer R. H. Sargent with five supporting expedition members. The party, along with a pack train of 20 horses, arrived at Iliamna Bay in Cook Inlet on 4 June aboard a steamer arriving from Seattle. The group traveled to Iliamna Village, and split into two smaller field parties. The group led by Smith took the majority of the supplies and traveled by boat down the Iliamna River and along Iliamna Lake to the Newhalen portage. From there he moved up the Newhalen River valley to Sixmile Lake. The other group led by Sargent advanced overland skirting the east slopes of Roadhouse Mountain and then to Sixmile Lake. On 20 June the expedition left the lake heading in a northwestward direction. The men eventually made their way to the Kuskokwim River and then to Iditarod where the fieldwork ended on 10 September. The mission gathered data regarding the geologic and physiographic character of the region and covered a distance of 280 miles from Sixmile Lake to Iditarod, topographically surveying 4,800 square miles of previously unmapped territory (Smith, 1917).

1915 – Nine claims of the Kasna Creek copper deposit near Kontrashibuna Lake were patented to Richard M. Edwards of Houghton, Michigan on 10 August. The claims were known as Cyanide, Gilt Edge, Kindall, Barnes, Peary, Cook, King, Platsburg, and Belle Lode and covered 175.292 acres (Warfield and Rutledge 1951).

1920 – USGS geologist F. H. Moffit, geologic assistant Herbert Insley, and topographer C. P. McKinley conducted a detailed geologic and topographic reconnaissance survey of the Tuxedni Bay region. The work took place between 10 June and 10 September and covered 380 square miles. One objective of the work was to better understand the geology in relation to the petroleum production potential of the area (Moffit 1922). That same year and continuing into the following year, Roy A. Trachsel of Anchorage worked and assayed a magnetite deposit on Magnetic Island in Tuxedni Bay (Moffit 1927).

1921 – Moffit and McKinley returned to the Iniskin-Chinitna Peninsula to continue the USGS project of mapping the topography and geology of the area. McKinIey led the topographic party with topographic assistant Gerald Fitzgerald and a field support staff consisting of T. E. Johnson, Ellison Morris, A. H. Armstrong, and Ray Russell. Moffit conducted the geologic mapping with geologic aid Auther A. Baker, and with camp and logistical support from C. C. Tousley, Volney L. Gray, and C. P. Dyer. The topographic party and two members of the geologic party, including Baker, arrived at the Snug Harbor cannery on 2 June and were taken by the cannery tender to Camp Point in Chinitna Bay the next day. Due to a marine engineer strike, Moffit, the remaining members of the party, and the 11 pack horses, were delayed in Seattle and did not arrive arrived in Snug Harbor until 2 July. The expedition returned to Snug Harbor on 29 August to catch the last ship of the season to Seattle (Moffit 1927).

1923 – The USGS dispatched a joint geologic and topographic mapping expedition to the Kamishak Bay area and the unmapped country south of Lake Iliamna. The party consisted of topographic engineer R. H. Sargent, geologist K. F. Mather, and four assistants and camp hands. The group arrived at Iliamna Bay on 16 June. The mapping of the area was completed on 28 August (Mather 1925).

1926 – This year the first of an ambitious series of four USGS expeditions led by geologist S. R. Capps was launched to map the rugged country between the Skwentna River to the north, the Iliamna-Lake Clark region to the south, Cook Inlet to the east, and the Mulchatna-Kuskokwim lowland to the west (Figure 45). The 1926 effort was unorthodox in that William N. Beach, a sportsman and wildlife photographer from New York, approached the USGS with an offer to share expenses and cooperate in a joint expedition into the headwaters of the Skwentna River and parts of the Kuskokwim Basin. Beach provided a pack train of 17 horses and additional equipment and services; his total contribution was approximately half the cost of the expedition. Under this arrangement the survey party was led by Capps, with K. W. Trimble serving as topographer, William T. Mulkey as recorder, Seward Old and Alfred H. Norman as packers, and Thomas R. Farrell as cook. They arrived in Anchorage early in June and the pack horses and a portion of supplies were landed at Beluga and taken overland to the Skwentna River. A larger quantity of the provisions and equipment were taken by launch to the mouth of the Skwentna and then upriver to the mouth of the Happy River in a small boat that used a combination of an outboard motor and manually lining the boat upstream. At that point, the two parties were reunited and traveled by pack train to conduct the fieldwork for the season. The expedition returned via the same route in the fall. An area of about 1,200 square miles was geologically and topographically mapped on a scale of 1:180,000 (Capps 1929).

1927 – USGS geologist S. R. Capps and topographer R. H. Sargent planned to enter the Chakachatna River basin from the east and connect with the work of the previous field season in the Skwentna Basin. Without any firm information about a feasible route for pack horses, they decided to start from the west shore of Cook Inlet a few miles south of Tyonek with the hope that they could find a valley on the southside of Mount Spurr that would allow passage into the Alaska Range. The field party convened in Anchorage early in June. Capps and Sargent were supported by recorder Ray C. Russell, packers C. C. Tousley and G. W. Pearson, cook Edgar Booker and 15 pack horses. The outfit was taken by launch and barge to Trading Bay and on 10 June the arduous trip into the mountains began. The expedition followed a ridge from the beach for about 24 miles then dropped down into the brushy lowlands of the Chakachatna River valley south of Mount Spurr. Cutting the trail for the pack horse through the thick alder in this area slowed progress to less than a mile

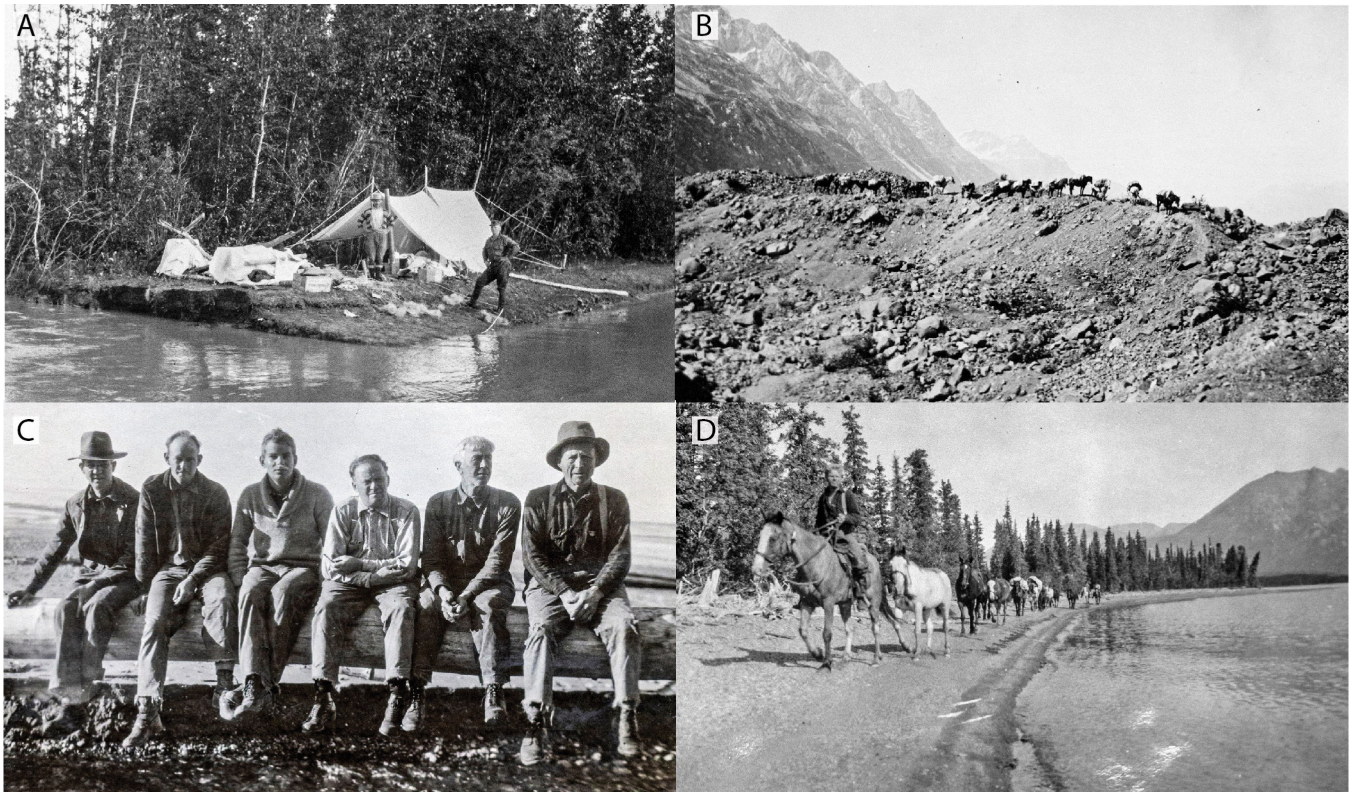

Figure 45. Photographs of USGS expedition in the Lake Clark region.
This expedition lasted four years and was led by geologist S. R. Capps. (A) Photograph taken in 1926 of the first campsite of the season on the Skwentna River. USGS photograph by S. R. Capps. (B) Photograph taken in 1927 of the USGS expedition pack train crossing Barrier Glacier. USGS photograph by S. R. Capps. (C) Photograph taken in 1928 of USGS expedition members at Trading Bay at the end of the field season. From left to right, the photograph shows Stephen R. Capps, Gerald FitzGerald, William A. Spurr, Jim Brown, R. A. Francis, and C. C. Tousley. USGS photograph by S. R. Capps. (D) Photograph taken in 1929 of the USGS pack train traveling on the shore of Lake Clark. USGS photograph by S. R. Capps.

a day. They struggled up the valley, crossed Barrier Glacier and then skirted the northeast corner of Chakachamna Lake and headed up the valley of the Nagishlamina River. Six miles up the valley they crossed Pothole Glacier and about 4 miles farther they crossed Harpoon Glacier. They then went over a high pass into the basin of Chilligan River and turned southwestward through another pass to the Igitna River. At this point the lateness of the season forced the party to return to the coast via the trail the expedition established in the spring. The effort of this work resulted in geologic and topographic mapping of a previously unexplored area of about 2,000 square miles. In the fall, the new geographic knowledge about the existence of a large river valley and substantial lakes on the backside of Mount Spurr motivated Russell H. Merrill, a pioneer of aviation in Alaska to explore the area for a quicker route (later named Merrill Pass) by plane between Anchorage and points on the Kuskokwim River (Capps 1930a, Capps 1935).

1928 – Based on aerial observations by Merrill of a pass that seemed passable for pack horses, the USGS planned to continue mapping work in the head of the Chakachatna Basin and westward across the Alaska Range into the basin of the Stony River. In the spring of 1928, Capps returned to Alaska with topographer Gerald FitzGerald, recorder William A. Spurr, packer C. C. Tousley, assistant packer R. A. Francis, and cook Jim Brown. To maximize the brief Alaskan field season, the three technical members of the party and about a ton of supplies were flown by airplane from Anchorage on 10-11 June to the head of Kenibuna Lake in the Chakachatna Basin. The pack train, remaining supplies, two packers, and cook traveled overland from Trading Bay following the trail established the previous year. The pack train took three weeks to arrive at the Kenibuna Lake base camp, while the trip for the members transported by plane took just over an hour. On 30 June, the expedition proceeded westward to the head of Another River, toward Merrill Pass. Considerable effort was expended by the men to fill the voids between large talus blocks and build a passable trail for the pack train over the pass. Once across, the expedition moved westward down a valley to the Necons River and then to Two Lakes. A well-worn game trail was followed from the head of Two Lakes westward across a divide to the valley of the Stony River. The Stony River was followed upstream to an easy pass that led northward into the basin of the Hartman River. At this point the majority of the field season was expended and the party returned to Trading Bay by way of the overland trail used in June by the packers. An area of about 1,000 square miles was topographically and geologically mapped, and a better understanding of the drainage systems of the Skwentna, Chakachatna, and Kuskokwim Rivers and Lake Clark was gained (Capps 1930b).

1929 – The next year, the USGS conducted a fourth combined geologic and topographic reconnaissance survey in the Lake Clark-Mulchatna region. The objective of this effort was to connect the earlier USGS surveys conducted west and northwest from Iliamna Bay with the work by led by Capps in the three preceding years. This expedition was led by Capps, with topographer Gerald FitzGerald, recorder Fred M. Bullard, packers G. W. Pearson and L. W. Oules, and Thomas Owens as cook. In early June, the men along with 15 pack horses landed at the mouth of Iliamna Bay. From there they proceeded over the trail and road to Iliamna Village, where three members of the party and the majority of the provisions were sent by boat to Severson's trading post. The horses were taken around the north shore of Iliamna Lake to rejoin the party waiting at the trading post. The expedition then traveled to Sixmile Lake and the horses were swum across the Newhalen River. Supplies for the last portion of the season were sent up Lake Clark to be cached at Brown Carlson's cabin, a few miles above the mouth of the Kijik River. Following an old Alaska Native trail, the party moved northwestward to the Chulitna River. Field work began in the hills north of Long Lake, connecting with the 1914 work of Sargent and Smith. From there they worked in a northeasterly direction through the foothills of the Alaska Range to Telaquana Lake, where they joined their mapping with the 1928 surveys by Capps and FitzGerald in the basin of the Stony River. The return trip was made from Telaquana Lake to Lake Clark over the Telaquana trail. From Carlson's cabin, the pack train and three men followed the northwest shore of Lake Clark and Sixmile Lake to the head of the Newhalen River, while the rest of the party traveled down the lakes by boat. From that point the party retraced their route back to Iliamna Bay. An area of approximately 1,400 square miles was mapped topographically and geologically connecting the surveys of 1909, 1914 and 1926 to those conducted in 1928 (Capps 1932, Capps 1935).

1934 to 1939 – During this period, oil company geologists explored the Iniskin Peninsula (Detterman and Hartsock 1966). The Iniskin Drilling Company drilled test wells but no commercially viable petroleum pools were found and drilling efforts were abandoned in 1939 (Smith 1941).

1940 – Harry Townsend made an examination of the Millett copper prospect on the north shore of Iliamna Lake for the Anaconda Copper Company (Rutledge and Mulligan 1952).

1941 – From 20 May to 10 June, mining engineer J. C. Roehm (Alaska Territorial Department of Mines) visited Iliamna and Iniskin Bays to investigate mining activities. Roehm examined the Millett prospect on 9-10 June (Roehm 1941).

1944 – As part of a USGS effort to investigate war-related mineral resources, Lewis B. Kellum and Helmuth Wedow, assisted by Warren Gilman and Spencer Schoonover, mapped approximately 20 square miles on Fitz Creek and the south shore of Chinitna Bay (Kirschner and Minard 1949).

1946 – From 23 May to 11 September, USGS geologists C. E. Kirschner and D. L. Minard with the assistance of D. R. Clark, mapped the structure and stratigraphy of the southern portion of the Iniskin Peninsula (Kirschner and Minard 1949). In that same year, the US Bureau of Mines reported that there were a number of copper deposits in the Iliamna Lake district, including the nine Kasna Creek claims near Kontrashibuna Lake, as well as several claims and prospects in the Iliamna Lake and Kamishak Bay area (Bain 1946).

1948 to 1951 – In 1948 and 1949, the US Bureau of Mines (in cooperation with the St. Eugene Mining Corp., Ltd., of Vancouver, British Columbia), examined the Kasna Creek deposit as part a US Department of the Interior program for the development of critical and strategic minerals (Warfield and Rutledge 1951). During 1949 and 1950, mining engineers F. A. Rutledge and J. J. Mulligan (US Bureau of Mines) investigated the Millett copper deposit on the north shore of Iliamna Lake. Field work was conducted 8 August to 28 November 1949 and resumed 28 May to 3 July 1950. The work included topographic surveying, machine and hand trenching, diamond drilling, and sampling the zones of mineralization (Rutledge and Mulligan 1952). Also in 1948, USGS geologists Don J. Miller, Ralph W. Imlay, and John K. Hartsock with assistance from J. S. T. Kirkland and D. B. Snodgrass began studying and mapping the geology of the Iniskin-Tuxedni region. The next year Arthur Grantz and assistants R. Werner Juhle, Richard Hoare, William Cunningham, Anthony Fetler, and David Hill joined Hartsock and continued the work until completion in 1951 (Detterman and Hartsock 1966). From 8-10 September 1951 Arthur Grantz and R. Werner Juhle of the USGS investigated and mapped the magnetite deposits on Chisik Island in Tuxedni Bay (Grantz 1956). From mid-July through August 1949 USGS geologists R. M. Moxham and A. E. Nelson with camp support from J. C. Whitaker and Henry Bender conducted a reconnaissance for radioactive deposits in the Iliamna Lake-Lake Clark region. This project was on behalf of the Division of Raw Materials of the US Atomic Energy Commission. The field party studied four copper prospects, one copper iron prospect, two silver-lead prospects, ore from a molybdenum prospect, and one placer-gold mine. They collected 14 placer samples and conducted approximately 240 miles of radiometric surveys by boat, 40 miles by truck, and 30 miles on foot (Moxham and Nelson 1952).

1953 to 1958 – During this period, several oil companies explored the Iniskin Peninsula and surrounding area (Detterman and Hartsock 1966).

1961 – From 22-26 May, mining engineer Martin W. Jasper (Alaska State Division of Mines and Minerals) conducted fieldwork in the Bonanza Creek area to determine the effect that glaciation had on the preglacial gold bearing stream sorted gravels (Jasper 1961).

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed Table 5 to summarize 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 protection of a particular resource or when other, more specific laws are not available. Information is current as of July 2021. Contact the NPS Geologic Resources Division for detailed guidance.

Table 5. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1) Archaeological Resource—** nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law. **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource—**the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2 requires NPS to protect geologic features from adverse effects of human activity.** **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Table 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/ Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/ disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2 requires NPS to protect geologic features from adverse effects of human activity.** **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
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. **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. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **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.

Table 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq.** as amended in 1988, states -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). -NPS is required to monitor those features. -Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.		**Section 4.8.2.3** requires NPS to -Preserve/maintain integrity of all thermal resources in parks. -Work closely with outside agencies. -Monitor significant thermal features.

Table 5, continued. Geologic resource laws, regulations, and policies.

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

Table 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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. **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. **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. **American Indian Lands Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108,** all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and… leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **Regulations re: Native American Lands within NPS Units:** **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62** and **§§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. **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 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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**.
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.
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	None Applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.

Table 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Table 5, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Table 5, continued. Geologic resource laws, regulations, and policies.

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

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

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