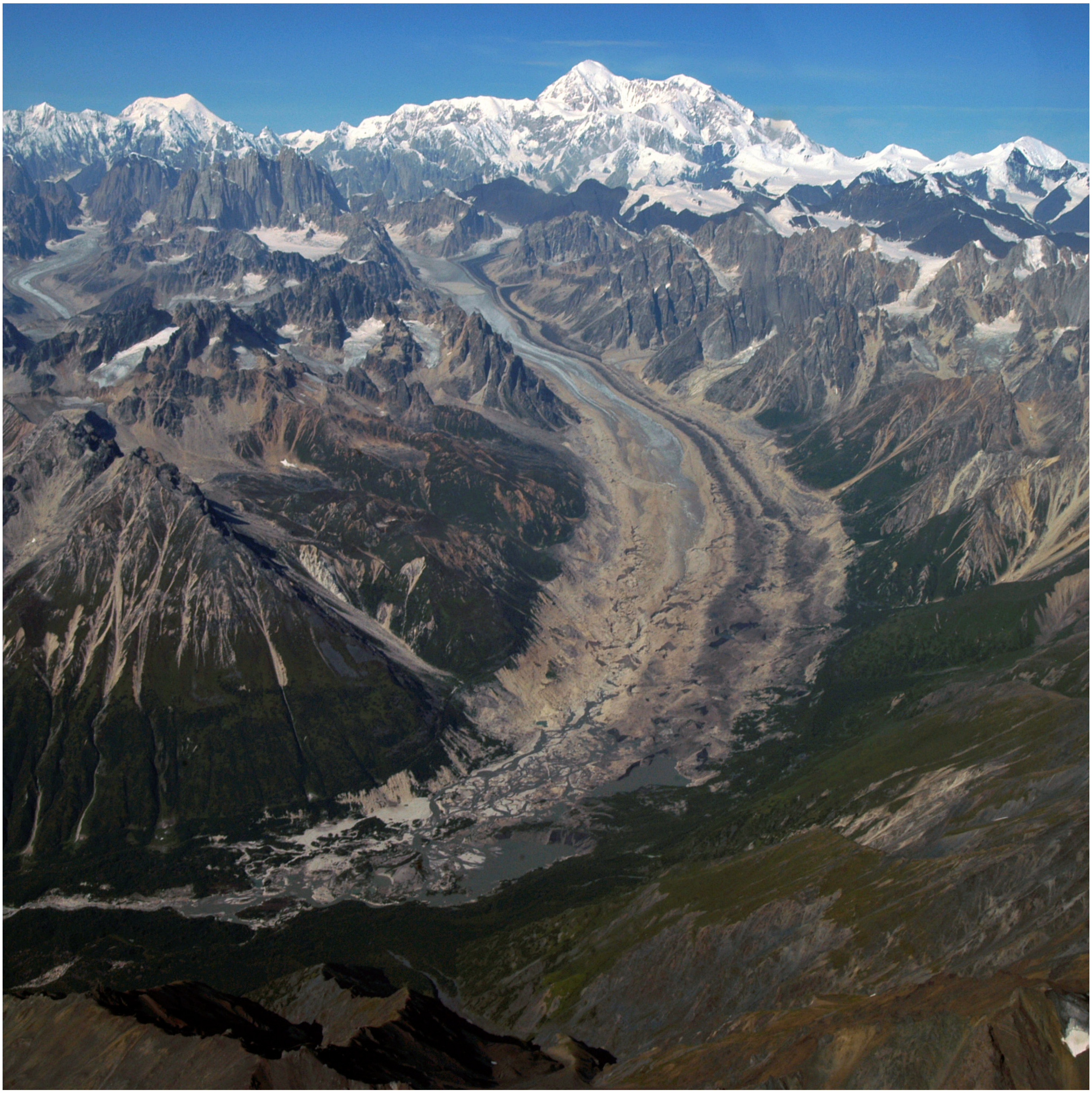
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

# Denali National Park and Preserve

## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRPC/GRD/NRR—2010/244



**THIS PAGE:**
**Mountaineering rangers on backcountry patrol in a land of giants. Ruth Glacier, Denali National Park and Preserve.**

**National Park Service photograph by Tucker Chenoweth, Denali National Park and Preserve.**

**ON THE COVER:**
**View of the terminus of Buckskin Glacier with Mount McKinley (20,320 ft) in the background, Denali National Park and Preserve, Alaska, August 6, 2004.**

**Photo courtesy of Ronald D. Karpilo, Jr., Colorado State University.**

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Ft. Collins, Colorado

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



Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/NRPM).

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# Executive Summary

*This report accompanies the digital geologic map for Denali National Park and Preserve in Alaska, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.*

Denali National Park and Preserve covers more than 6 million acres and features a vast and varied geological landscape. The park protects large portions of the long, arcuate Alaska Range—including Mount McKinley (known as "Denali" ["The High One"] in the native Athabaskan language), which has the greatest vertical relief of any mountain on Earth. The active tectonic processes of southern Alaska are still uplifting the mountains along the Denali fault system. Countering this uplift are weathering and erosion of the highlands by wind and water. Like much of Alaska, the whole of Denali National Park and Preserve is composed of accreted terranes—where the Pacific plate, acting like a conveyor belt, has been bringing bits of islands, the ocean floor, and slivers of other continents northward to for hundreds of millions of years forming a "jigsaw puzzle" of these terranes. The compositions, structures, metamorphic grades, and fossils of these terranes set them apart from neighboring rocks separated by discrete faults. The terranes are covered with more recent sedimentary deposits, and are studded with igneous intrusive rocks. Glacial ice covers a significant amount of the surface area of Denali National Park and Preserve; glaciers carve through thousands of meters of sedimentary, metamorphic, and igneous rocks exposed within the park, creating wide U-shaped valleys and transporting vast amounts of sediment. These glaciers flow over 40 km (25 mi), descending more than 4,500 vertical meters (14,800 ft) from the highest peaks of the range to the lowland hills below. The size, climate, isolation, and complexity of the park's geologic setting create both a challenge to scientists hoping to understand the environment and a valuable target for preservation of a pristine ecosystem.

Understanding the geology in south-central Alaska leads to an appreciation for the unique relationship between geology and the environment. Geologic processes give rise to rock formations, topographic expression, surface and subsurface fluid movement, and soils; thus, geologic units hold clues to the history of the area. Man-made disturbances at the park are also significant. River terraces and channel deposits were reworked during mining periods, locally altering the topographic expression of the landscape and threatening riparian zone health. Human developments may have altered the fragile permafrost regime; as well, glaciers are shrinking due to climate change.

Denali National Park and Preserve's Resource Stewardship Strategy for 2008-2027 identified several geologic processes, values, and components fundamental to achieving the park's goals and maintaining its significance. The following are critical geologic issues for park management:

- Glacier Issues. Today, glacial ice covers approximately 17% of the park. Glacier processes are incredibly dynamic and have far-reaching effects. Resource management concerns include interactions with the changing climate (manifested as glacial thinning or surging glaciers) to visitor safety on glacial surfaces and unstable glacial deposits. The aerial photographic record of glaciers at Denali is extensive, providing an important tool for evaluating glacial changes. Glaciers carved vast valleys and deposited thick mantles of unconsolidated sediment on park slopes, which are vulnerable to slope processes and susceptible to intense erosion. Continual monitoring of the "state of health" of the park's glaciers would help resource managers understand both the past and future conditions of the glaciers.
- Seismicity. Active faults are prevalent on the park's landscape. The large-scale Denali fault system runs through the entire park, extending more than 2,100 km (1,300 mi). Fault processes are active; many fresh fault scarps reveal recent movement, and more than 600 seismic events are measured in the area each year. More than 70% of these events are relatively small—magnitude 1.5 to 2.5—and lie beneath the Kantishna Hills, which is a growing anticline. However, even small-magnitude earthquakes can damage park infrastructure, including buildings and roads, and undermine slope stability throughout the park. On November 3, 2002, a magnitude 7.9 earthquake centered east of the park caused severe local shaking. This event was followed by increased seismic activity, which will require close to 14 years for conditions to return to background level. Seismic and geodetic monitoring provides important knowledge of the tectonic setting, geologic structure, and activity throughout the area. Studies of ancient earthquake history on important faults can yield data on recurrence intervals and past magnitudes.

- Mining and Disturbed Lands. Alaska has long been associated with vast mineral wealth. Gold was discovered in the park area in 1903. Most ore-bearing veins were intruded into brittle faults and fractures within metamorphosed pelitic rocks. Much mining activity focused on the placer gold deposits of the Kantishna Hills region in the northern foothills area of the park. Extensive terrace areas were processed during extraction efforts. Massive tailing piles remain, exposing heavy metal-laden material to weathering and causing acid mine drainage. Concerns include: water quality; long-term riparian zone health; channel and floodplain morphology; and visitor safety. Mining continues in the Kantishna Hills area with strict environmental protection regulations. Studies of the change in the chemistry of the waters near mined or disturbed areas should be considered.

Other geologic issues at the park include permafrost, surface water issues, paleontological resources, geothermal energy, and slope processes. Permafrost is present across the northern portion of the park. Permafrost in Alaska has been warming since the 1970s. Melting permafrost can have dramatic effects on the landscape of the park, including the development of thermokarst. Surface water quality in the park is influenced by the underlying geology. The significant paleontological resources of the park are diverse and span hundreds of millions of years. A Paleontology Management Plan is currently being developed by the park. Geothermal resources are present within the park; however a comprehensive inventory or monitoring plan has not yet been completed. Slope processes (mass wasting) present a geologic hazard in many areas of the park. Seismic activity increases the risk for mass wasting within the park.

The glossary contains definitions of many of the technical terms used in the report. A geologic timescale is provided as figure 21.


# Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Program Center.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Guy Adema (Denali National Park and Preserve) for providing information and images for the report. John Burghardt (NPS Geologic Resources Division) provided substantial comments on the mining and disturbed lands section. Kerry Moss and Julia Brunner of the NPS Geologic Resources Division also provided information.

**Credits**

Author

Trista Thornberry-Ehrlich (Colorado State University)

Review

Peter Haeussler (U.S. Geological Survey)
Will Elder (National Park Service)
Tim Connors (NPS Geologic Resources Division)

Editing

Bonnie Dash (Envirocal)

Digital Geologic Data Production

Jim Chappell (Colorado State University)

Digital Geologic Data Overview Layout Design

Phil Reiker (NPS Geologic Resources Division)


**Dedication**

This report is dedicated to the memory of Phil Brease, Denali park geologist from 1986 until his death in 2010. His passion for geology and geology education continues to be an inspiration to many. Photo courtesy Guy Adema (Denali National Park and Preserve).

# Introduction

*The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Denali National Park and Preserve.*

### Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory web site (http://www.nature.nps.gov/geology/inventory/).

### Park Setting and Establishment

Mount McKinley National Park was established on February 26, 1917 by an act of Congress. The park was intended as "… a public park for the benefit and enjoyment of the people… for recreation purposes by the public and for the preservation of animals, birds, and fish and for the preservation of the natural curiosities and scenic beauties thereof …said park shall be, and is hereby established as a game refuge." (39 Stat. 938). In 1976, the area was declared an International Biosphere Reserve. In 1980, the Alaska National Interest Lands Conservation Act added approximately 3.8 million acres to Mount McKinley National Park (about 1.9 million acres of which were to become the Denali Wilderness); at this point, the park was renamed as Denali National Park and Preserve. Today, the park covers more than 6 million acres, preserving and protecting large portions of the Alaska Range, including the 6,194-m- (20,320- ft)-tall Mount McKinley—known as "Denali" ("The High One")—in the native Athabaskan language). The park is situated approximately 200 km (125 mi) north of Anchorage, Alaska (fig. 1).

### Geologic Setting

Mount McKinley's two peaks tower over neighboring summits, ultimately rising from 61 m (200 ft) at the lowest point in the park (on the Yentna River) to 6,194 m (20,320 ft). The peaks form an east-west-trending 1,000-km- (600-mi)-long line of mountains known as the Alaska Range. This major regional feature forms a topographic barrier and drainage divide between the coastal lowlands around Cook Inlet and the Yukon lowlands of the interior of Alaska (Brease 2004). The Denali fault runs parallel to the length of the central and eastern Alaska Range, and it crosses most of Alaska. Approximately 375 km of right-lateral offset have been documented along the fault since Cretaceous time (Lowey 1998), and the fault remains seismically active.

The Alaska Range has permanent snow cover on northern exposures above approximately 2,100 m (7,000 ft). This snowpack supports several large glaciers. Over 17% of the park's land (more than 1 million acres) is covered with glacial ice. The largest glacier is the 55-km- (34–mi)-long Muldrow Glacier. This glacier flows northward toward the developed road corridor west of the Eielson Visitor Center. Kahiltna Glacier is the longest in the park, at 71 km (44 mi). Ruth Glacier has a thickness of up to 1,160 m (3,850 ft), and moves about 0.95 m (3.1 ft) per day through the deepest gorge in North America (National Park Service 2009).

To the north of the Alaska Range is a series of east-west-trending foothill ridges ranging from approximately 610 to 1,372 m (2,000 and 4,500 ft) in height; the widths of these foothills range from 5 to 11 km (3 to 7 mi). The parallel foothills extend eastward from the Kantishna Hills north of Wonder Lake. They are separated by broad, flat, sediment-filled glacial valleys that drain the region from south to north. Northward-draining rivers include the Foraker, Herron, McKinley, Bearpaw, Toklat, Savage, Teklanika, and Nenana Rivers. To the south, across the divide posed by the Alaska Range, the Chulitna, Susitna, Tokositna, Kahiltna, Yentna, and Kichatna Rivers drain.

Like most of Alaska, the Denali area is composed of a series of accreted terranes (fig. 2). These terranes include bits of islands, oceanic crust, flysch basin deposits, and continental fragments that have been transported from elsewhere by large strike-slip faults and ancient oceanic plates. Because the terranes were too thick to subduct beneath the North American continent into the Aleutian trench, they collided with the edge of the continent, squeezing ocean basins, island arcs, and miniterranes between them in a complex wedge of thickened crust.

Volcanism, mountain building, and orogenesis often accompany terrane accretion. The terranes typically follow an arching pattern that trends roughly east-west, paralleling the Gulf of Alaska coastline. In the park, the terranes are identified as packages of rocks bounded by faults, with distinctly different rock types, fossils, and other physical properties than surrounding terranes.

In the area of Denali, the oldest major accreted terrane is the Yukon-Tanana Terrane. This large mass was added to the continent about 225 million years ago. The Talkeetna Superterrane (Wrangellia, Alexander, and Peninsular Terranes)—also referred to as the Wrangellia composite terrane—slammed into the continent about 110 to 85 million years ago. These two terranes, as well as several smaller terranes (such as the McKinley, Pingston, Windy, and Dillinger Terranes), compose the bulk of the landforms in Denali National Park and Preserve (fig. 3). Smaller accretionary prisms, such as the Chugach, accreted about 67 million years ago; the Prince William accreted by 50 million years ago. The youngest regional-scale terrane, the Yakutat Terrane, is still attached to the Pacific Plate, traveling approximately 5 cm (2 in.) northward per year; thus, accretion is an ongoing process along the coast of southern Alaska.


**Figure 1: Map of Alaska Showing major mountain ranges and rivers. Graphic compiled by Phil Reiker (NPS Geologic Resources Division).**

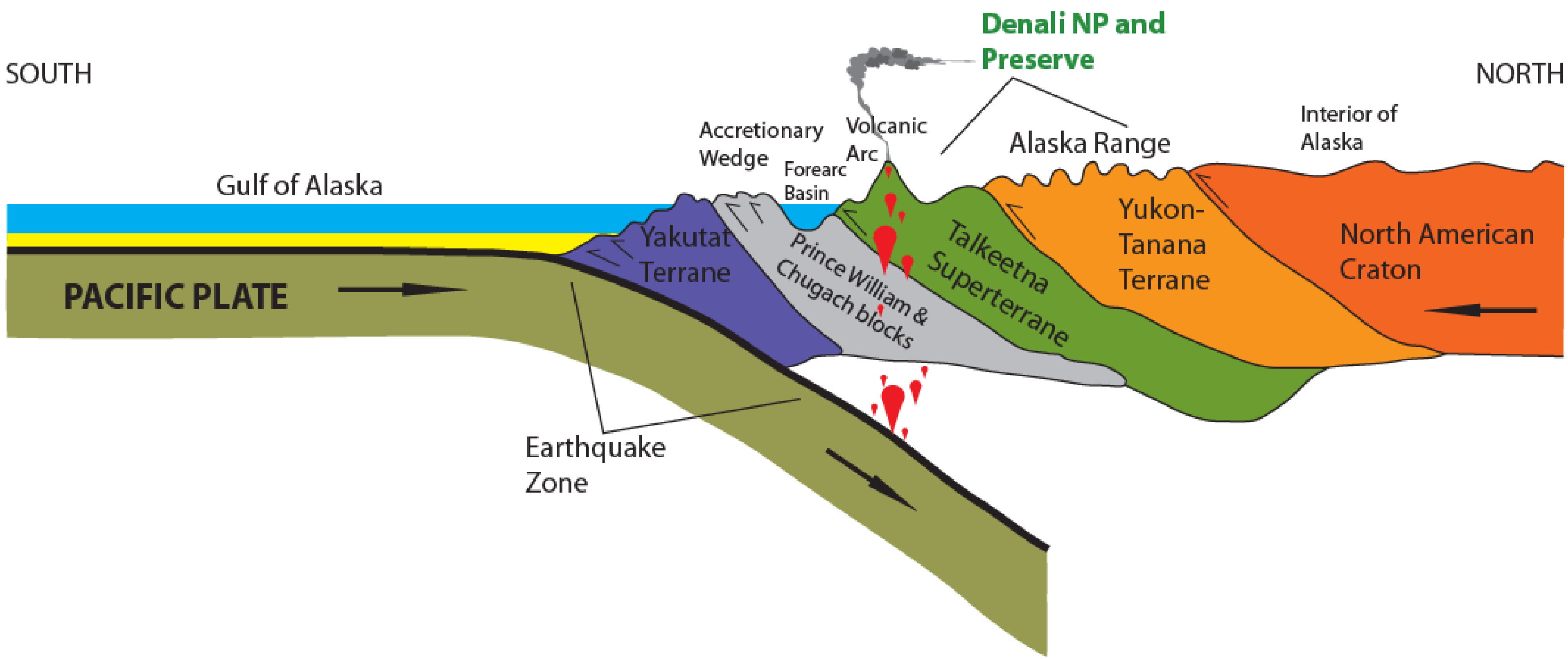


**Figure 2: Generalized cross section from north (south of the Brooks Range) to south (Gulf of Alaska) through central Alaska showing the juxtaposition of accreted terranes over the subduction zone between the Pacific and North American Plates. Note the location of Denali National Park and Preserve. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from Lillie (2005) fig. 11.7.**

# Geologic Issues

*The Geologic Resources Division held a Geologic Resources Inventory scoping session for Denali National Park and Preserve on February 24–26, 2004, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.*

### Introduction

Resource management issues are discussed in relative order of significance, with the most critical listed first. Potential research projects and topics of scientific interest are presented at the end of this section.

### Glacial Issues

#### Glaciers and Glacial Geology

Glaciers are a major feature of the Denali National Park and Preserve landscape. Over 1 million acres (17% of the park's area) is covered with ice. This ice includes more than 400 glaciers, some 40 of which are named. Famed glaciers include the Kahiltna Glacier, which is 71 km (44 mi) long, making it the longest glacier in the Alaska Range. Ruth Glacier is locally the thickest in the park, filling a deep gorge. Eldridge, Traleika, Tokositna, Yentna, and Muldrow Glaciers are among the other well-known glaciers at Denali. Permanent snowpack above 2,100 m (7,000 ft) supports the flow of glaciers from elevations above 6,100 m (20,000 ft) down glacial valleys to elevations as low as 300 m (1,000 ft).

Some of the smaller glaciers at Denali display interesting characteristics. Most of the smaller valley or hanging glaciers in the park are unique because terminal areas are insulated by deep deposits of rock debris and dust. This lessens melting and allows the smaller glaciers to remain stagnant for longer periods of time than larger glaciers. Portions of the larger Muldrow, Ruth, Kahiltna, and Tokositna glaciers are also insulated by deep deposits of rock debris and dust (P. Haeussler, USGS, geologist, written communication, November 2009).

Glaciers have been, and continue to be, powerful agents of landscape change. They carve valleys and gorges out of solid bedrock much faster than rivers and streams. Glaciers leave vast deposits of till and moraines. Glaciers feed outwash flows and streams, and can dam streams to form temporary lakes. At Denali National Park and Preserve, glacially carved features include valley cirques, arête ridges, drumlins, expansive U-shaped valleys, and horns. The widespread glacial deposits include: lateral, medial, and terminal moraines (less than 100 m [325 ft] thick); ablation and lodgement till (less than 10 m [32 ft] thick); eskers and advance and recessional outwash; and rock glaciers (potentially 100s of meters thick).

Rock glaciers are masses of talus that accumulate locally to the point where they retain moisture, freeze, and move slowly downslope (Brease 2004). Blocks of glacial ice left stranded by glacial retreat can become buried by outwash deposits. The ice then melts, forming small, round kettle lakes such as Chilchukabena Lake near the northwest boundary of the park. Wonder Lake, at over 82 m (268 ft) deep, is the largest kettle lake at Denali. Pro-glacial Lake Moody, which formed by the damming action of ice and moraines in front of melting glacial ice, is also a glacial remnant at Denali.

Historical glacial activity in the area is recorded in the rocks, deposits, and vegetation patterns at Denali National Park and Preserve. Four distinct periods of widespread glaciation are recognized in the region of the park. Evidence of former glacial maxima exists on the north side of the Alaska Range, where, beyond the existing glaciers, moraine and outwash deposits extend into the foothills belt and cover large areas of bedrock, possibly filling vast areas underlying present-day river valleys through the unglaciated foothills section. The Wisconsin glaciation (Wisconsinan stage) was the last major advance of glacial ice in North America. Pork Chop Pond, a Wisconsinan kettle lake, contains thick layers of sediment (cored in 1996) that include aeolian sediments, peat, microlaminated muds, tephra (volcanic ash), and other organic deposits. These sediments record late Wisconsin-glacial and following interglacial climate (Axford and Werner 1997).

#### Glaciers and Climate Change

As stated by the Intergovernmental Panel on Climate Change: "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level." (IPCC 2007). This warming is very likely (more than 90% certain) related to anthropogenic greenhouse gas emissions (IPCC 2007).

Alaska has warmed at more than twice the rate of the continental United States. Alaska's annual average temperature has increased 2.0°C (3.4°F) while winters have warmed by 3.5°C (6.3°F) over the past 50 years (Karl et al. 2009). Projections reported by Karl et al. (2009) suggest Alaska's annual average temperature will rise between 2.8 and 7.2°C (5 and 13°F) by 2100, depending on emission scenarios. For more information regarding climate change effects and NPS response, visit the NPS Climate Change Response Program web site (http://www.nature.nps.gov/climatechange/index.cfm).

In response to the warming climate, glaciers are shrinking at the park. Most of the glaciers are consistently thinning, and only about 10% are surging (fig. 4) (P. Haeussler, USGS, geologist, written communication, November 2009). Surging refers to periods of relatively high-speed glacial flow following periods of slow flow. Most surging occurs on glaciers with northern exposure. The photographic record of the glaciers of Alaska spans more than 110 years. The earliest aerial photographs date from 1926 as part of a cooperative arrangement between the U.S. Geological Survey and the U.S. Navy. Systematic vertical aerial photography of Alaskan glaciers began in the 1940s and continues today (Molina and Sfraga 1999). These records provide a comprehensive data set and could be utilized to determine fine-scale glacial changes at Denali.

Glacial monitoring at the park began in earnest in 1991 as part of the National Park Service's Long-term Ecological Monitoring Program. This program initially focused on an "index" method—i.e., single point mass balance monitoring—but has since been supplemented with more detailed mass balance measurements on smaller glaciers, terminus monitoring on multiple glaciers, selected movement monitoring, depth measurements, and extensive photo documentation. Two index monitoring sites exist on Kahiltna and Muldrow Glaciers (Adema et al. 2003)

In 2004, data from past survey and research expeditions were revisited, new digital photographs were taken, and new stations were established for future comparisons of glacial positions (figs. 5, 6). Geographic coordinates, elevation, modern analog aerial images (using helicopters), and other accurate geographic information were incorporated into a parkwide GIS coverage of glacial extent from surveys during the 1950s through 2000s. Information included bidecadal coverages for individual glaciers (Karpilo et al. 2004). Efforts such as this could be expanded on a parkwide scale, incorporating more historic information, photographs, and modern technology to study glacial change at Denali National Park and Preserve. Karpilo (2009) suggested glacier monitoring techniques based on four "vital signs:" glacier mass balance, terminus position, area, and velocity.

#### Glacial Hazards

Glacial issues at the park extend to geologic hazards caused by glacial movement and glacial remnants. Relief in glaciated areas is often very steep and prone to erosion and mass movement depending on rock type. Glacial till often maintains very steep slopes (P. Haeussler, USGS, geologist, written communication, November 2009). Many deformed and altered rock units are present in glaciated areas of the park; these are prone to mass movements when exposed on slopes because of pervasive zones of weakness. When glaciers retreat up a valley, near-vertical walls are left with no structural support or stability. Deep, unstable, unconsolidated glacial deposits are also prone to mass wasting and intense erosion. Glacier terminal areas are attracting increasing numbers of visitors, and these areas could pose icefall and rockfall hazards, as well as unstable trail bases. The vast extent of glaciers and icefields affect the local climate. Glaciers produce microclimates that cause local temperature cells to push moisture-rich air upward, creating localized weather aberrations.

#### Resource Management Suggestions for Glacial Issues

- Perform comprehensive studies on the history of glaciation at Denali. Potential research targets could include glacial debris and deposits, lichen growth, vegetation patterns, striations, and glacial lakes and lake deposits.
- Study glacial change at Denali by developing a glacier "state of health" program within the park (P. Haeussler, USGS, geologist, written communication, November 2009).
- To understand climatic effects on glaciers, conduct glacier dynamics research and perform mass balance studies. Promote contracting with the University of Alaska Fairbanks glaciology group (contact Chris Larsen) for airborne laser altimetry studies on a select group of glaciers to quantify glacier mass balance (P. Haeussler, USGS, geologist, written communication, November 2009).
- Study stability and safety issues related to glacial areas (W. Elder, NPS, geologist, written communication, December 2009).
- Compare glacial response at Denali with other known concentrations of glaciers in Alaska and worldwide to compare and contrast glacial response to global climatic shifts.
- Perform mass balance studies to determine reasons behind glacial surging.
- Perform glacial movement studies to determine differences between glaciers influenced to varying degrees by nonclimatic factors such as rock and dust coverage.
- Cooperate with other government agencies to obtain complete records of historical and ongoing glacial photography and measurement.
- Determine quantitative relationships between glacier size, orientation, location, depth, etc. and the degree of local microclimatic aberrations.
- Study Late Quaternary pollen, plant macrofossils, and insect fossils to determine past glacial and interglacial conditions (climate, vegetation, etc.) (Elias et al. 1996).
- Inventory the named glaciers in the park using 1957 and 1983 aerial and other photography and topographic maps to document spatial changes.
- Increase glacier profiling efforts, including monitoring terminal fronts, glacier thickness, and surge activity.

### Earthquakes and Earthquake Hazards

Faults are prevalent features of the geologic structure at Denali National Park and Preserve. The large-scale Denali fault system runs through the entire park, parallel to the Alaska Range, extending more than 2,100 km

(1,300 mi) from the Yukon-Alaska border to the Bering Sea. The system includes the Denali fault (locally split into the Hines Creek and McKinley strands) and numerous subsidiary faults. Faulting at the park is active, with many fresh fault scarps showing evidence of recent movement. Fission track data indicate that Mt. McKinley is being uplifted along regional faults at rates of ~1 mm/year. More than 600 earthquakes per year are measured in the park area. More than 70% of these events are of magnitude 1.5 to 2.5; they commonly occur at very shallow depths, within 0 to 14 km (0 to 9 mi) below ground surface. The Alaska regional seismic network consisted of approximately 400 monitoring sites operated by various agencies. Seismic waveform data are now recorded digitally. The Alaska Earthquake Information Center (AEIC) is upgrading existing sites with digital broadband sensors (Ratchkovski et al. 2004).

Most earthquakes at Denali are relatively small (too small to be noticed by humans); however, even minor shaking can pose hazards of mass wasting, landslides, and debris flows on undercut, weakened, or unconsolidated geologic units exposed on slopes. On November 3, 2002, a magnitude 7.9 earthquake (consisting of multiple subevents), centered 48 km (30 mi) east of the park, caused severe local shaking. Reports of shaking and "unusual effects" from this earthquake were received from distances up to 3,500 km (2,200 mi) across western Canada (Cassidy and Rogers 2004). For the 30 years prior to this event, only four events greater than magnitude 3 were recorded. Leading up to and following this large earthquake, seismicity in the area increased. It is estimated that close to 14 years will be required for local seismicity rates to return to background level (Ratchkovski et al. 2004). According to the AEIC website (http://www.aeic.alaska.edu/), its system of over 400 sites currently reports about 20,000 earthquakes each year (well over 100 earthquakes in a few days) across the network. The AEUC site lists the location, depth, distance from surrounding communities, and magnitude for each event. The website frequently notes central Alaska for earthquake activity.

The fault rupture associated with the 2002 event was complex, beginning on variably dipping fault segments and continuing along vertical strike-slip segments (Eberhart-Phillips et al. 2003; Aochi et al. 2005). An unusual pattern of landslides and liquefaction resulted from the earthquake. The landslides were concentrated as rockfalls and rockslides in a narrow (~30-km [19-mi]-wide) zone that straddled the more than 340-km (211-mi) rupture zone. This pattern is consistent with strong, low-frequency shaking with only moderate acceleration levels. These rockslides were most visible at Black Rapids Glacier, Gakona Glacier, West Fork Glacier, and McGinnis Glacier (Harp et al. 2003; Schwartz et al. 2005).

Conversely, liquefaction effects (sand blows, lateral spreads, and broad settlement) within alluvial deposits of streams in and adjacent to the central Alaska Range were much more widespread, extending for several hundred km east of Fairbanks (Harp et al. 2003). This pattern is consistent with a long duration of shaking. Most structural damage was focused 160 km (100 mi) east of the park, but the Denali fault system is capable of producing a similar earthquake in or closer to the park. This could have catastrophic effects on visitor use facilities, park infrastructure, the Trans-Alaska pipeline, and geologic landforms.

Widespread aftershocks from the large 2002 earthquake east of Denali increased the number of events recorded by the AEIC—from 1,000 to over 16,000—for a similar period (Ratchkovski et al. 2004). Thus, even if earthquakes are not focused within park boundaries, regional seismic episodes have far-reaching effects that could impact park resources. Future development plans should take into account the earthquake-related hazards of liquefaction, lateral spreading, rockfalls, landslides, and fault ruptures. In addition to these potential problems, the subgrade soils and permafrost (possibility of melting) in the Denali area pose further geotechnical design concerns in the event of an earthquake, so more detailed research is needed to understand their response to intense ground shaking (Adamczak et al. 2004). Braile (2009) suggested the following "vital signs" for seismic monitoring: monitoring earthquakes, analysis and statistics of earthquake activity, analysis of historical and prehistoric earthquake activity, earthquake risk estimation, geodetic monitoring and ground deformation, and geomorphic and geologic indications of active tectonics.

#### Resource Management Suggestions for Earthquakes

- Continue to collaborate on studies by Alaska Earthquake Information Center, universities and the U.S. Geological Survey regarding seismic activity in the region.
- Add seismometers in the park, to augment those put in place by the Geophysical Institute at the University of Alaska, Fairbanks. Present locations include Wickersham Dome in the Kantishna Hills, Thorofare Mountain near the Eielson Visitor Center, and Mount Healy. Cooperate with the AEIC to increase the number of digital broadband seismic stations within park boundaries.
- Continue seismic and geodetic monitoring in the park, as well as the study of ancient earthquakes on knonw important faults, to understand the implications of an event on a particular fault and to establish recurrence intervals (P. Haeussler, USGS, geologist, written communication, November 2009).
- Perform studies to determine the paleoearthquake history along the Denali fault in the ~161-km- (100-mi)-long region west of the 2002 event.
- Perform detailed mapping of the Denali fault and other active fault traces across the park to better understand deformation through time.
- Study paleoseismicity (most recent events) along sections of the park's faults using samples of gouge and radiocarbon dating of offset organic material.
- Support efforts to determine fault slip rates (e.g., Matmon et al. 2006).

- Study geomorphology, tectonic history, and fault orientation relationships, and perform thermochronology studies (apatite fission track, U-Th/He) to determine timing and characteristics of landform development.
- Perform vulnerability assessments of areas in which visitor health and safety are likely to be affected in the event of a large earthquake.
- Incorporate earthquake epicenter data into a GIS, including geologic data, slope data, and trail data, to determine areas susceptible to failure during a moderate earthquake.
- Promote a better GPS geodetic network in the park to provide information about seismic hazards, where active structures lie, and the larger-scale tectonic setting (P. Haeussler, USGS, geologist, written communication, November 2009).
- Promote 3-D ionosphere tomography studies using GPS data to constrain source and propagation of seismic waves in the Denali area (Garcia et al. 2005).

#### Mining and Disturbed Lands

Since the gold rush era of the late 1800s, Alaska has been associated with vast mineral wealth, with approximately 30 million ounces of gold recovered to date. Most ore-bearing veins were intruded into brittle faults and fractures within metamorphosed pelitic rocks, and are composed of quartz with minor chlorite, carbonate minerals, and white mica (Goldfarb et al. 1997). In 1903, gold was discovered in the area of what is now Denali National Park and Preserve (Norris 1998). Past mining activity was focused in the Dunkle Mine area in the Chulitna Terrane of the Alaska Range, the Mt. Eielson/ Copper Mountain district (in the 1940s), and the placer gold deposits of the Kantishna Hills region of the Yukon-Tanana Terrane in the northern foothills area of the park (Van Maanen and Solin 1988; Metz et al. 1989; see summary at www.mindat.org). Mining interests included precious metals such as gold and silver, base metals (copper, lead, antimony, zinc, tungsten, arsenic) and coal (Metz et al. 1989). Abandoned cabins, debris, small tailing piles, assay trenches, adits, and small shafts are historical markers of the hard rock mining history in the region. Most of the historical underground mine features have been closed or have since collapsed (GRI scoping notes 2004).

No new claims have been made since the establishment of Denali National Park and Preserve in 1980. In 1985, litigation was intended to halt mining inside the park, and no legal mining has occurred since (Burghardt 1997; J. Burghardt, NPS Geologic Resources Division, geologist, written communication, May 2010). According to the NPS Abandoned Mine Lands database (maintained at the GRD in Denver, Colorado), as of May 2010, there were 28 patented claims and 9 unpatented claims within the park. The patented claims are underground mine and placer mine sites for commodities such as gold, copper, coal, limestone, and antimony. Many of the claims have been used to establish lodges and cabins rather than mines (J. Burghardt, NPS Geologic Resources Division, geologist, written communication, May 2010). The Abandoned Mineral Lands program also maintains a list of various identified mine-related features within the park, including adits, equipment, surface mines, tailings, buildings, and other structures. Currently (September 2010), this database has 37 listed features, at 28 sites, many of which require remediation. An online mineral database website, www.mindat.org, contains records of nearly 200 mine-related localities within or near the park.

Occasionally, legal disputes arise from the mining claims within the park. The Stampede antimony mine is owned jointly with the University of Alaska, Fairbanks. Several mine areas (Gold King placer claims and Red Top mill) are CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act; "Superfund") sites. This designation involves assessing risks to human health and the environment posed by hazardous waste sites, identifying potentially responsible parties (PRPs), and seeks to find funding for remediation efforts (GRI scoping notes 2004).

Denali National Park and Preserve also contains vast deposits of well-sorted sands and gravels. Small-scale quarries and gravel pits exist within park boundaries for construction and maintenance of park roads and other infrastructure and visitor use facilities. The park's Resource Stewardship Strategy for 2008-2027 lists monitoring and mitigating impacts to fluvial morphology and water quality as a result of park gravel acquisition operations among its resource management goals (Denali National Park and Preserve 2009).

Negative effects from mining are far reaching and long lasting. Impacts include disturbed floodplain areas from extensive placer mining. Placer mining involved removing riparian zone vegetation and topsoil, then sieving valuable minerals from gravels in the stream channel, active floodplain, and old terraces. This process leaves behind barren gravel piles devoid of any soil that would promote natural revegetation. There are channels down to bedrock in some areas (Densmore 2005). A concern of park resource management is that past placer mining activity could result in changes in channel and floodplain morphology, streamflow, and streambed composition facilitated by erosion and/or deposition, that could affect aquatic and riparian ecosystem health (Van Maanen and Solin 1988). Recent regulations require that topsoil be stripped and stockpiled away from the placer mining area, then reincorporated with the sieved gravels so that planted material used in reclamation has a substrate in which to grow (J. Burghardt, NPS Geologic Resources Division, geologist, written communication May 2010). Remediation of old and/or abandoned mines is ongoing. Methods include rebuilding the floodplain areas, restructuring the stream channel (fig. 7), and recontouring terraces, as well as planting species such as *Alnus viridis* (green alder) for nitrogen fixation within new soils. Replanting along Glen Creek watershed (mined from 1906 to the mid 1970s) demonstrated the ability of the *Alnus viridis* species to accelerate the rate of succession by stimulating the growth of woody dominant riparian species such as *Salix alaxensis* (feltleaf willow) (Densmore 2005). For many areas, reclamation is limited by factors such as steep slopes, a lack of a local topsoil source from disturbed areas, an acid-generating sulfide substrate not amenable to revegetation, and remoteness (Burghardt 1997).

Preliminary studies suggest that differences in physical properties of mined and non-mined reaches of several streams were relatively minor; however, the streambed composition below mined areas tended to be enriched in fine-grained material (34 mm average mean particle size vs. 65 mm) and exhibited less variation in mean particle size (Van Maanen and Solin 1988). Along Eldorado Creek, mining and the operation of heavy equipment throughout the area, and particularly at the antimony mine at the headwaters of Slate Creek, have enhanced the flow of natural iron-rich springs (Burghardt 1997).

Placer mining forces larger particles to the streambed surface, which is contrary to natural settling. This could affect spawning habitat for fish as well as aquatic plant distributions. Along Rainy Creek in the Kantishna Hills region, the entire stream had been diverted from its natural channel during mining operations involving the construction of settling ponds. This resulted in extreme erosion of soil and fine-grained floodplain material as well as damage to pre-existing vegetation (Van Maanen and Solin 1988).

Associated with mining are exposures of hazardous materials in mine tailings. Mine tailings and other ground disturbances expose bedrock and crushed rock material to weathering. This leads to water and soil contamination by heavy metals and sulfides due to acid mine drainage. The Banjo Mine (a small-scale gold mine) has 500 cubic yards of mine tailings that contain leachable arsenic and lead, as well as antimony and cadmium that exceed drinking water standards and hazardous waste toxicity limits. Stampede Mine, a 20-acre site, maintains a fine-grained mine tailings dump adjacent to Stampede Creek. This mine is associated with dissolved antimony concentrations in the creek that exceed federal drinking water standards (ADEC 2006).

The Slate Creek antimony deposit, associated with historical mining operations within the park between Moose Creek and McKinley River, has drainage with pH values of 2.7 to 5.8, as well as concentrations of sulfate ions, arsenic, iron, manganese, nickel, antimony, and total dissolved solids that exceed State of Alaska drinking water standards. At the mouth of Slate Creek, some 3 km (2 mi) downstream, manganese and antimony contents exceeded drinking water standards. Stream sediment, soil, and rock samples around the mining area were enriched in arsenic, manganese, and antimony. In addition, sparse to no vegetation exists in the active stream channel and aquatic algae are conspicuously absent (Eppinger et al. 2000).

Mining operations introduce foreign objects and substances to the landscape, including petroleum drums, mercury, and other chemicals for gold extraction. Several areas in the Kantishna Hills region (Gold King #1-15-Area#1; Comstock #1-8-Area#5; Discovery #1-3-Area#7; Trommel Wash Plant-Area#8; Antimony Lode Mining Area#9; Caribou Howtay #11b-24-Area#10; Glacier Assoc.#1-5-Area#12; Caribou Howtay #1-6-Area#13; Rainy Creek #1-3&6-8-Area#2; Liberty #53-Area#3; and Stampede Mine) have petroleum hydrocarbon contamination arising from miscellaneous drums, spills, and soil stains associated with the operations. The Glen Creek area contains mercury and diesel contamination from placer mine operations (ADEC 2006). A project to close a hazardous mine opening within the park was included in the 2009 American Recovery and Reinvestment Act (ARRA).

Resource Management Suggestions for Mining and Disturbed Lands

- Develop a mining history interpretive program focusing on the geology responsible for the valuable mineral resources in the Denali area.
- Continue reclamation efforts, including revegetation and remediation of streams and riparian (floodplain) environments. Increase plantings of *Alnus viridis*, which accelerates the rate of succession by stimulating growth of woody dominants (Densmore 2005).
- Collect continuous records of streamflow that relate changes in channel configuration and bed elevation to sediment transport, erosion, and deposition in mined and non-mined stream reaches for comparison.
- Monitor suspended sediment concentrations and fine bed material in mined and non-mined streams to help determine ecological effects of placer mining.
- Monitor water quality in mine-affected areas to determine degree of improvement, and target areas in need of further restoration. Tracking water chemistry changes through time would help resource managers understand the long-term effects of disturbed lands (P. Haeussler, USGS, geologist, written communication, November 2009).
- Continue to support environmental-geochemical studies of different mining areas, especially those located near springs and/or streams.
- Contact the NPS Geologic Resources Division regarding the history of mining at the park; the current status of mining operations, ore contents, reclamation efforts, and claim litigation and acquisition; and other mine-related queries.

### Permafrost Issues

Unique to high altitudes and latitudes, permafrost is present discontinuously in the arctic climate of Denali National Park and Preserve. This frozen layer can persist to depths of up to 610 m (2,000 ft) below the surface. At Denali, the permafrost is defined as containing soil and rock that have been at a temperature of 0°C (32°F) or colder for two or more years.

Osterkamp and Jorgenson (2009) described the rationale for monitoring permafrost conditions and processes, including examples and case studies from Denali National Park and Preserve. Clark and Duffy (2003) mapped permafrost distribution within the park. Their map shows that permafrost is present across the entire northern side of the park, but only locally south of the Alaska Range. Presenting a more regional perspective, the International Permafrost Association has published a digital map that summarizes the distribution and properties of permafrost and ground ice in the circum-Arctic region (Zhang et al. 1999). Permafrost is a major controlling factor on surface water flow, and therefore on vegetation and habitat. Permafrost exerts an influence on the fluxes of carbon and nitrogen from terrestrial to aquatic ecosystems coincident with fire disturbances (Petrone et al. 1999). It appears that leaching of carbon and nutrients from the burned ash layer is greatest in the active layer over permafrost, and this is marked as increases in these chemical components within the watershed (Petrone et al. 1999). Abundant water is available in the active layer above the permafrost because it cannot seep into the impermeable permafrost below (Brease 2004).

Permafrost also acts as a natural barrier to the downward flow of water, as well as against potentially harmful contaminants such as oil or diesel spilled from fuel storage tanks. Industrial users are interested in this potential use of natural permafrost in lieu of synthetic secondary liners (McCauley et al. 1999). Contaminants could pool atop the surface of the permafrost, causing a local long-standing concentration.

A delicate heat balance exists between permafrost and the layer above it, which freezes and thaws with seasonal temperature change. The balance of this system is sensitive to changes in the vegetative cover and mat and snow depth, and is dependent on the structural and compositional characteristics of the freeze-thaw layer (Brease 2004). These parameters can significantly affect the local thermal regime, resulting in changes at ground level such as frost heaving, polygonal ground patterns, and sags. Extreme conditions or anthropogenic alterations in the right geologic setting can cause melting of permafrost. Geologists are particularly concerned about the effects of global climate change (global warming) on permafrost in subarctic ecosystems. Permafrost is warming throughout Alaska; temperatures have increased throughout the state since the late 1970s as summarized by Karl et al. (2009). Ongoing monitoring is necessary to determine the extent to which this is occurring at the park. Osterkamp and Jorgenson (2009) suggested methods for monitoring permafrost conditions and processes utilizing thermal state and physical conditions “vital signs.”

Melting of permafrost can have dramatic effects on the landscape at Denali. The term “thermokarst” describes a specific landform that develops when permafrost is partially or totally melted. Thermokarst is a highly irregular surface expression that forms variously shaped polygonal depressions (patterned ground), altiplanation (long, smooth, flat ridges), and ice wedges (fig. 8). If melting of ice-rich permafrost (ground ice content greater than 20% by volume) occurs, widespread irregular subsidence of up to 2.0 m (6 ft) of the ground surface could result in significant impacts on the hydrological and ecosystem processes throughout the region. In areas of abundant ice, thawing would result in river bank collapse, creation of thaw lakes, and other thermokarst features (Zhang et al. 1999).

Permafrost is very sensitive to human disturbance. Thermokarst has been created by humans in other parts of Alaska during construction projects. Accompanying thermokarst development, increases in soliflucation, or soil movement, atop the frozen layer are more pronounced when permafrost is melted. This situation can cause heaving, sagging, slope creep, soil slumping, and deep erosion at the surface during successive periods of freeze-thaw heaving in the active layer (periglacial milieu) (Brease 2004). Hillslope stability becomes a safety concern. Like other subsurface movements or disturbances, soliflucation can be detrimental to buried cables, wastewater treatment pipes, sewers, septic systems, utility poles, paved surfaces, trails, buildings, and roadbed foundations. Five large areas of roadway have been affected. Extensive knowledge of permafrost extent, properties, and processes will help resource managers decide where to develop road areas in the future and how best to maintain existing roads.

Resource Management Suggestions for Permafrost Issues

- Increase monitoring and develop a soil temperature monitoring network.
- Work with the National Resource Conservation Service soils mapping program to create a derivative map that includes different types of permafrost. A soil survey geographic database has been completed for the park as part of the NPS Soil Resources Inventory program (National Park Service 2006). Clark and Duffy (2003) produced a permafrost distribution map for the park.
- Increase the installation of thermisters (installed 35 m [115 ft] deep) along road corridors for permafrost monitoring.
- Investigate permafrost and ground ice conditions as well as their relation to the present climatic conditions and potential response to climatic change. Create a model of ground surface response to permafrost thaw to better predict ensuing ecosystem changes.
- Install additional inclinometers and piezometers along roadway slopes, as well as on slope areas near visitor use facilities or other identified vulnerable reaches.

### Surface Water Issues

Snow and rainfall are channeled into three major systems at Denali National Park and Preserve. The first system is the series of glaciers, ice, and perennial snowfields. The second is the groundwater aquifers. The third includes all the streams, rivers, creeks, lakes, and ponds present on the landscape in Denali, including surface ice on lakes, which is a significant ecosystem factor.

There are approximately 400 streams and rivers in the park. Major waterways include the Foraker, McKinley, Kantishna, Toklat, and Teklanika Rivers on the northern slopes, and the Yentna, Kahiltna, and Chulitna Rivers flowing south. The Nenana River marks the eastern boundary of the park. Due to continued regional uplift and plentiful water and sediment supply, these streams are aggrading in some areas and downcutting in the upland areas.

Ecosystem processes on the river floodplains are closely linked to fluvial processes and controlled by climate. Fluvial processes include flooding, sedimentation, and erosion, which interact with biotic processes such as seed dispersal and seedling establishment, and thus determine temporal and spatial development of riparian zones (Adams 1999). Floodplains with regular influxes of fine-grained silt and well-drained river terrace environments are rich ecosystems at Denali, supporting vast forests and lowland species. It is important that resource managers understand the fluvial processes that influence vegetation succession, including silt deposition, erosion, and fiver flow patterns that regulate flood events, as these processes are intimately linked with climate (Adams 1999).

Studies within the Rock Creek watershed targeted for long-term ecological monitoring revealed that streamwater chemical compositions, including elevated levels of $Ca^{2+}$, $Mg^{2+}$, and $SO_4^{2-}$, are directly influenced by underlying geology. In contrast, streamwater concentrations of nutrients and dissolved organic carbon are regulated by biological activity. Vegetation patterns are controlled by soil development, which is strongly related to geologic processes of weathering and alteration in addition to fluvial processes such as erosion and flooding. The productivity of the Rock Creek watershed is limited by physical factors such as unstable channel morphology, increased stream discharge, and organic matter retention (Popovics et al. 1999). Studies of this nature could be applied to many other watersheds at Denali to begin to quantify geologic controls on streamwater quality and riparian zone ecosystem health.

The park contains classic examples of braided streams (fig. 9). These streams typically (but not always) flow from glaciers, and contain choking amounts of sediment, causing them to split and crisscross the landscape. Not all streams at Denali are cloudy glacier-fed streams; clear streams that develop from springs and precipitation contain much lower levels of sediment. Turbidity and suspended sediment are greater in glacier-fed streams from the northern slope than from the southern slope. Levels of pH, alkalinity, conductivity, and ionic concentrations are also elevated in northern streams. These differences in chemical and sediment characteristics of streams at Denali are controlled by bedrock geology; marine sedimentary bedrock yields higher dissolved ion concentrations than resistant granitic bedrock (Edwards et al. 2000).

The wet northern slope area contains a unique wetland hydrology with shallow glacial lakes, bogs, ponds, and taiga. This flat, boggy, tundra area comprises approximately 20% of the park's land area. Some areas developed over millennial timeframes (Mann 1999). Long-term peat development records climatic change over time through pollen, plant debris, and other remains.

Resource Management Suggestions for Surface Water Issues

- Contact the NPS Water Resources Division for assistance with surface water issues. The USGS Water Resources Discipline is an additional source of technical assistance.
- Inventory lakes, ponds, and other small water bodies, including bogs and wetlands.
- Conduct a comprehensive survey determining a vulnerability index for flooding in areas used by backcountry campers, park infrastructure, and other visitor use facilities.
- Identify floodplain areas, such as those around Kantishna lodges, for remediation.
- Perform studies linking spatial variability, climate, and fluvial processes with vegetation patterns and succession.
- Perform studies combining soils characteristics and detailed geologic mapping, soil water flow rate and chemistry, stream retention of organic matter, and streamwater chemistry to understand the relationships between soil, underlying bedrock, channel morphology, and streamwater quality for various watersheds.
- Monitor stream morphology, focusing on areas near gravel mines and damaged floodplain areas (from placer mining). Lord et al. (2009) have suggested techniques for monitoring stream systems.

#### Paleontological Resources

According to the park's Resource Stewardship Strategy for 2008-2027, paleontological resources are important resources for park management and visitors, and the park has a legal mandate to protect such important, nonrenewable resources. The 2009 Paleontological Resources Preservation Act directs the Secretaries of Interior and Agriculture to implement comprehensive paleontological resource management programs. The NPS and other federal land managing agencies are developing joint regulations associated with the Act (J. Brunner, NPS Geologic Resources Division, policy and regulatory specialist, personal communication, May 2010).

Denali National Park and Preserve contains many fossiliferous geologic units. Most of these are from the warm shallow seas present throughout much of the late Paleozoic and Mesozoic eras. Some of the accreted terranes traveled north from lower latitudes where marine life flourished. Fossils include invertebrates (as the dominant type), marine mollusks, insects, plant debris, and abundant trace fossils. A brachiopod, *Myrospirifer breasei,* was named after park geologist Phil Brease. Fossils found outside the park, in the same geologic units that exist in the park, that might also be present at Denali, include dinosaur remains of hadrosaurs, pachycephalosaurs, theropods, tyrannosaurids, ceratopsians, and a variety of vertebrate trace fossils (Gangloff 1999; W. Elder, written communication, December 2009). Paleontological work by Brease et al. (2009) revealed the presence of dinosaur, plants and trace fossils in abundance within certain geologic units in the park (figs. 10, 11). Thousands of trace fossils of fish, pterosaurs, theropods, hadrosaurs, birds, and terrestrial and aquatic invertebrates are preserved in the lower Cantwell Formation, making this one of the best-preserved Late Cretaceous polar continental ecosystems in the global paleontological record (Brease et al. 2009).

At Denali, fossils occur in rocks which span the Paleozoic, Mesozoic, and Cenozoic eras. The boundary between the Cretaceous and Tertiary periods, commonly referred to as the "K-T boundary," is present in the park. This yields a unique opportunity to determine the high-latitude effects on the paleoecosystem during the mass extinction that occurred at the end of the Cretaceous Period.

Paleontology work in the park has been mostly limited to the Healy quadrangle, with some additional fossil finds in the Talkeetna quadrangle on the south side of the range crest by Reed and Nelson (1977) (P. Haeussler, USGS, geologist, written communication, November 2009). Much of the park area remains to be surveyed and inventoried for paleontological resources. Field-based inventories are ongoing. A literature-based paleontological resource summary for the central Alaska Inventory and Monitoring Network is currently underway with expected completion in late 2010 or early 2011. The network summary is part of a national effort to systematically research fossil occurrences in NPS areas Servicewide. Conducting additional large-scale geologic mapping would inevitably reveal additional fossils. The park is currently developing a Paleontology Management Plan to address this vast resource (Brease et al. 2009; G. Adema, NPS, Denali National Park and Preserve, personal communication, July 2010). Santucci et al. (2009) identified "vital signs" for monitoring in situ paleontological resources: geologic and climatic variables affecting natural erosion rates, catastrophic geologic processes or geohazards, hydrology and bathymetry (i.e., changes in water level affecting resources near water bodies), and human impacts.

#### Resource Management Suggestions for Paleontological Resources

- Perform a comprehensive paleontological inventory at the park, including documented locations, abundance, ease of access, risk factors and disturbance, baseline conditions, fragility, and any necessary protection measures (Denali National Park and Preserve 2009).
- Study timing relationships of various deposits across the park using index fossils and locality studies. Focus on the Cantwell Formation for bio-stratigraphic work.
- Cooperate with researchers in creating a paleogeographic atlas of Alaska using invertebrate fossil records, for example.
- Perform palynology studies to research the Cretaceous-Tertiary stratigraphic boundary in the park area.
- Use paleontology to understand the spatial and temporal relationships between the different terranes and subterranes present in the park region.
- Create paleontology interpretive programs to increase visitor awareness of the fossil resources at Denali.
- Increase efforts started by the geoscientist in the parks program to produce a comprehensive paleontological database (using Microsoft Access), expanding on the more than 200 sites already entered. Obtain GPS data for sites, as well as ground truthing, and further description and characterization. Information should be incorporated into the park's GIS.

### Geothermal Activity

Denali National Park and Preserve is located near an active plate margin, above a deep subduction zone, making it a prime area for geothermal activity. It was one of the original 22 national parks considered for geothermal resource management, but was not one of the 16 selected for extensive research (K. Moss, NPS Geologic Resources Division, environmental specialist, written communication, December 2009). Hot and warm springs are present throughout the park area, including Windy Creek and Wigane Creek. Cold meteoric groundwater trickling through the subsurface is heated by rock deep below the earth's surface. This heating causes the water to expand; it is then usually forced upward under intense pressure to emerge as heated pools. There is no inventory of, or monitoring plan for, geothermal features within the park. These are needed data sets for park resource managers.

#### Resource Management Suggestions for Geothermal Activity

- Obtain water chemistry data for geothermal features along the south side of the park, focusing on the Windy Creek area.
- Inventory travertine deposits.
- Perform studies on the hydrogeology of Wigane Creek. This upwelling water feature could be geothermal, but the nature of the system is unknown.
- Inventory all hot spring features in the park. Map locations digitally for incorporation in the park's GIS.

### Slope Processes and Erosion

The geologic processes of erosion are prevalent at Denali National Park and Preserve. Glaciers are remarkable agents of erosion, and sheet runoff, streams, and rivers all carve channels and valleys into the landscape. Topography provides opportunities for erosion (P. Haeussler, USGS, geologist, written communication, November 2009). When unconsolidated sediments—such as slope deposits, glacial till and moraines, and alluvium, as well as altered and/or deformed bedrock—are exposed on moderate slopes, the potential for erosion and mass wasting increases. Some volcanic and sedimentary units are quickly altered to shrink-and-swell clays (minerals that swell when water-saturated and shrink upon drying). This constant change in volume undermines the integrity of the rocks.

The area's earthquake activity increases the risk of catastrophic failure on park slopes. As described above in the seismicity section, ground shaking related to a single large earthquake event can produce widespread effects, including an increase in the intensity and quantity of smaller-scale seismic events that can induce slope failure.

An earthquake in 1912, located near the intersection of the Denali fault and the Richardson Highway, destroyed a climbing route on Mt. McKinley used in the 1910 Sourdough Expedition that allowed quick ascension of the summit of North Peak (Carver et al. 2004; Brease 2004; P. Haeussler, USGS, geologist, written communication, November 2009). On steep, unconsolidated slopes, as well as slopes of deformed rocks with cleavage oriented parallel to the slope, large slumps and slides can be triggered by small seismic events. Vulnerable areas can be assessed and identified based on the composition of the slope forming material, degree of slope, and orientation to known active faults.

Along the entrance road to the park, where it parallels the Hines Creek fault, landslides are relatively common after heavy rainfall. The water-saturated and heavy rocks and soil slide down the slope in slumps of ice-cored, lobe-shaped masses called solifluction lobes (Gilbert 1979). Much of the park road is built on unconsolidated glacial and fluvial deposits that erode easily and slump.

Large landslides often display hummocky topography, which is a very irregular and hazardous trail base for visitor use. Several slides—one older and vegetated, and three younger and unvegetated (not visible on 1949 era aerial photographs)—exist along the trail to Triple Lakes. Another slide, only 1 km (0.6 mi) above the park road, pushed the course of Tattler Creek southward. In 1953, massive landslides of sheared basalt flows dammed Stony Creek, creating Bergh Lake (Gilbert 1979). These slides attest to longstanding and continuous slide activity in the area.

Rockfalls are prominent components to mass wasting at the park. Large rockfalls exist on the south side of the upper Buckskin Glacier and off the east face of the Eye Tooth (fig. 12). Rockfall events are inherent in areas of steep topography, freeze-and-thaw cycles, bare slopes, and rock faces (P. Haeussler, USGS, geologist, written communication, November 2009).

Snow and ice avalanches are a year-round threat to visitor safety, park infrastructure, and backcountry areas. Snow avalanches are a significant hazard at the park. Earthquakes can trigger snow avalanches, much in the same way as rockfalls or landslides. Larger avalanches with longer runouts can be generated with a larger trigger mechanism such as an earthquake (P. Haeussler, USGS, geologist, written communication, November 2009).

Other features at risk for erosion and mass wasting include rock glaciers, glacier fronts, terminal moraine slopes, and eskers (figs. 4, 19). Park resource management attempts to mitigate the effects of erosion and mass wasting along the most vulnerable and exposed areas. Engineering along Lake Moody attempts to alleviate some of the geologic hazards in the area. Areas along park roads and trails subjected to repeated subsurface sliding are targeted for reinforcement. Wieczorek and Snyder (2009) suggested the following "vital signs" for monitoring slope processes: types of landslides, landslide triggers and causes, geologic materials in landslides, measurement of landslide movement, and assessing landslide hazards and risks.

#### Resource Management Suggestions for Slope Processes and Erosion

- Catalog mass failures. As new failures occur, their location and type should be noted and incorporated into the park's GIS. Past mass failures should also be categorized, catalogued, and incorporated in the park's GIS (P. Haeussler, USGS, geologist, written communication, November 2009).
- Perform slope vulnerability studies to identify reaches within the park susceptible to massive landslides in the event of an earthquake. Target unconsolidated deposits and heavily deformed geologic units.
- Determine what effects, if any, social trail development has had on erosion and seasonal runoff in the park.
- Identify areas where park infrastructure is threatened by erosion and mass wasting.
- Incorporate spatial slope data into the park's GIS to correlate with underlying geologic units and structure, as well as vegetation patterns and hydrologic information to determine areas vulnerable to extreme erosion and mass wasting.

### General Geology Issues and Research Possibilities

The remoteness, arctic climate, ruggedness, and sheer size of Denali National Park and Preserve poses significant challenges to geologists and other researchers seeking to study the landscape. However, these same characteristics also serve to preserve a living laboratory and a unique opportunity to study pristine alpine-arctic environments, active glaciers, active seismicity, permafrost, paleontology (fig. 13) and active margin terrane accretion.

#### Resource Management Suggestions for General Geology Issues and Research Possibilities

- Perform larger scale, detailed geologic mapping in a digital format for incorporation in the park's GIS.
- Perform regular surveys and repeated monitoring of soil conditions to determine the lasting impacts of off-road vehicle and snowmobile use on soil compaction and wetland/bog ecosystem health.
- Identify and photograph the park's rare or unique geological features and type sections. Periodically monitor their condition (Denali National Park and Preserve 2009).
- Perform an air quality and visibility change analysis, focusing on the introduction of industrial pollution,

arctic haze, and coal-fired electricity generation. Contact the NPS Air Resources Division (Denver, CO) for technical assistance.

- Cooperate with federal and local agencies for continuing geologic mapping efforts.
- Promote detailed studies of the geologic history and origin of the smaller terranes located along the Denali Fault and throughout the Kahiltna Glacier area.
- Develop additional geologic-themed interpretive programs to increase visitor awareness of the role geology plays in the landscape evolution and ecosystem at the park.
- Map, describe, and characterize the significant loess deposits (windblown, glacially-derived silt) at Denali.
- Determine if caves exist in the Devonian and Silurian age limestones. If caves are present, perform a comprehensive inventory, digitally mapping locations to incorporate into the park's GIS.
- If needed, develop a plan to protect any existing cave resources as well as ensure visitor safety.

**Figure 4: The Straightaway Glacier (shown) is one of many surge-type glaciers which issue from Mt. McKinley. Surging glaciers can move 10-100 times the normal flow rates. NPS Photo/Adema.**

Figure 5: Repeat photography pair showing retreat of a glacier at the head of Hidden Creek in Denali National Park and Preserve. Upper photo was taken in 1911 by USGS geologist Steven R. Capps, lower image was taken on August 7, 2004 by Ronald D. Karpilo, Jr. Photos courtesy of Ronald D. Karpilo, Jr. (Colorado State University).

**Figure 6: Repeat photography pair showing retreat of a glacier in the Teklanika River valley in Denali National Park and Preserve, Alaska. Upper photo was taken in 1919 by USGS geologist Steven R. Capps, lower image was taken on August 9, 2004 by Ronald D. Karpilo, Jr. Photos courtesy of Ronald D. Karpilo, Jr. (Colorado State University).**

**Figure 7: Denali has been steadily restoring abandoned mine lands like this project on Slate Creek. Encapsulated soil lifts guide a new channel away from exposed ore to improve water quality and aquatic habitat. NPS Photo/Adema.**

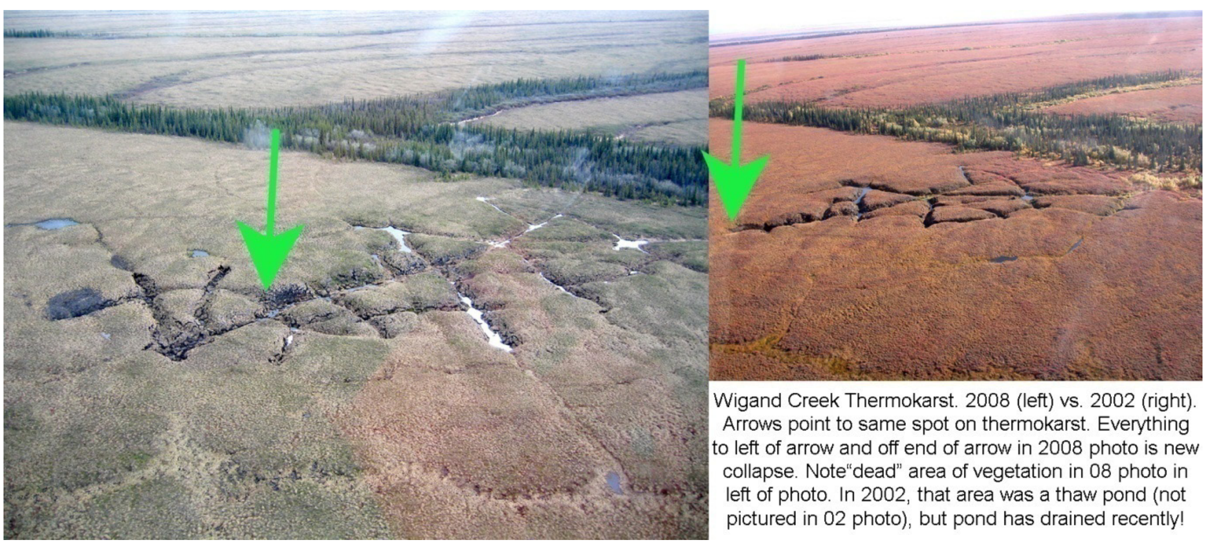


**Figure 8: Thermokarst development, like this example in the Toklat Basin on the north side of Denali, is an indicator of the dramatic and quick change occurring on the base permafrost landscape. NPS Photo/Yocum.**

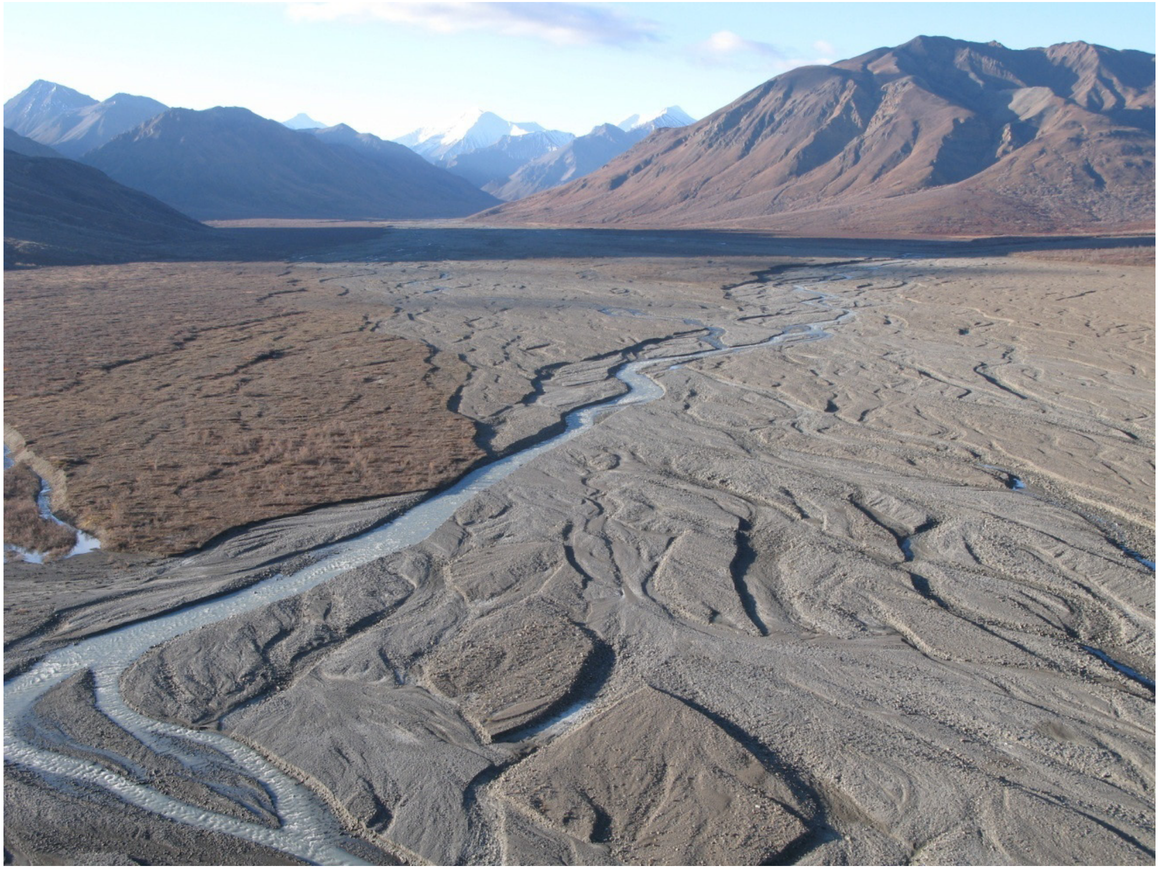

**Figure 9: One of Denali's most dramatic features are the large, braided rivers like the Toklat river. Not only geologically striking, the Toklat provides a renewable source of gravel for maintenance of the Denali Park Road. NPS Photo/Adema.**

**Figure 10: Theropod dinosaur discoveries in the Cantwell Formation have excited considerable paleontological research. A theropod footprint trace fossil is shown here. NPS Photo/Brease.**

**Figure 11: Plant fossils, such as this fern, provide insight to the paleoecology of Denali. NPS Photo/Brease.**

**Figure 12: View of landslide debris on Buckskin Glacier with granite peak named The Moose's Tooth (3,150 m; 10,335 ft) visible in the background, Denali National Park and Preserve, Alaska, August 7, 2004. Photo courtesy of Ronald D. Karpilo, Jr. (Colorado State University).**

**Figure 13: Researchers investigate dinosaur fossils in Denali’s Cantwell Formation. NPS Photo/Brease.**

# Geologic Features and Processes

*This section describes the most prominent and distinctive geologic features and processes in Denali National Park and Preserve.*

### Mt. McKinley (Denali)

Mt. McKinley (known as "Denali" ["The Great One"] in the native Athabaska language) dominates the landscape of Denali National Park and Preserve, towering some 915 m (3,000 ft) above the neighboring peaks in the Alaska Range (figs. 1, 3, 14). Its highest point is 6,194 m (20,320 ft) above sea level, making it the tallest mountain on the North American continent. Mt. McKinley features greater relief than most mountains on Earth. For example, the Wickersham Wall on the northern slope of the mountain has approximately 5,500 m (18,000 ft) of vertical relief. This peak was first scaled in 1913 by a party led by Hudson Stuck. Today, features such as Browne Tower, Karstens Ridge, McGonagall Pass, and Denali Pass, not to mention the numerous icefalls and crevasses posed by the large glaciers in the area, still challenge climbers (Greenwood and Rowell 1980). The American Alpine Journal frequently describes climbing endeavors and routes within Denali National Park and Preserve.

Uplift of the Alaska Range began during the Jurassic and culminated in the Tertiary, some 60 to 30 million years ago. Recent studies suggest that the modern mountain mass in the immediate area of Denali was uplifted rapidly (~1 km/million years [0.6 mi/million years]) beginning ~6 million years ago (Plafker et al. 1989). This uplift was a result of interactions between the right lateral Denali fault (with a local morphology that includes a 22-degree bend) and a series of northeast-striking thrust faults, and changes in motion between the Pacific and North American plates (Haeussler 2005). This caused a space problem that forced crustal blocks upward (Fitzgerald et al. 1993).

Mt. McKinley is still rising approximately 1 mm (0.04 in) per year. Uplift of the range hinged on the convergence of several geologic factors, including subduction, faulting, terrane accretion, and plutonism (Fitzgerald et al. 1993). The emplacement of the Chugach and Prince William accretionary wedges and the Yakutat terranes, as well as assorted smaller terranes, involves extreme shortening (fig. 15) as well as thrust faulting, which thickens the crust and shoves large crustal blocks upward (Dumoulin et al. 1998). The buoyancy of this thickened crust leads to further uplift as it adjusts to approach isostatic equilibrium.

Subduction of the Pacific Plate beneath southern Alaska introduces water into the mantle, which then leads to partial melting and generation of magmas. At Denali, this led to plutonism and volcanism until about 38 million years ago. Since that time, subduction has continued, but there is no magmatism in Denali National Park and Preserve (P. Haeussler, USGS, geologist, written communication, November 2009).

Relatively buoyant and resistant granitic plutons form much of the core of the Alaska Range. These rocks are not easily worn away by erosion and weathering, thus allowing elevations to remain relatively high compared with other mountains of similar ages. The dominant peaks of the range—Mt. McKinley, Mt. Foraker, and Mt. Hunter—are composed of resistant granites. Differential erosion of less competent metasedimentary rocks of the surrounding mountains accentuates the height of these peaks (Fitzgerald et al. 1993). The biotite granite of the so-called McKinley pluton comprises most of the Mt. McKinley massif. It contains quartz, plagioclase, potassium feldspar, biotite, white mica, tourmaline, and other accessory minerals. Nearly 4 km (2.5 mi) of this igneous intrusive body is exposed within Denali National Park and Preserve, rendering it an ideal research target for petrologic and geochemical variations within a large continuous intrusion (West and Swanson 1995).

### Denali Fault System

The Denali fault system is a 2,100-km- (1,300-mi)-long structure, trending from the Yukon border southwest toward the Bering Sea. The entire system connects with the Queen Charlotte fault and the Fairweather fault of southeastern Alaska toward British Columbia, forming a significant piece of the transform fault boundary between the Pacific and North American plates. The great arcuate system of northward-convex transcurrent faults that sweeps across Alaska is one of the most distinctive geologic features within the state (Moore et al. 1994). The Denali fault was first named and described by St. Amand in 1957. The surface trace of the fault is concave to the south, roughly paralleling the shape of the Gulf of Alaska. The curvature of the fault is about 70 degrees between the eastern and western portions. It is one of the largest and topographically best-expressed geologic features of south-central Alaska (Csejtey et al. 1982). This system now accommodates counter-clockwise rotation of accreting terranes by absorbing some of the relative motion between the Pacific and North American plates. The Tintina-Kaltag fault and Iditarod-Nixon Fork fault systems (fig. 16) (other large-scale, right-lateral, strike-slip systems), located north of Denali, accommodate some of this motion; as well, some faults to the south accommodate offsets today (Miller et al. 2002; Ratchkovski et al. 2004; W. Elder, written communication, December 2009). These margin-parallel, strike-slip faults have experienced multiple episodes of dextral motion since approximately 100 million years ago (Miller et al. 2002).

Estimates of right lateral offset along the Denali fault system are as little as several tens of km to as much as 600 km (370 mi) (Csejtey et al. 1982; Redfield and Fitzgerald 1993; Csejtey et al. 1995; Redfield and Fitzgerald 2000). The fault splits into two strands within the Denali region. This split might have been due to a change in relative plate direction during the last ~50 million years from north-south to a more lateral east-west (Gilbert 1979; Cole et al. 1996). The northern branch is the Hines Creek fault; the McKinley fault is the southern strand of the Denali fault. Both faults are right-lateral motion, near vertical strike-slip faults. The northern side of each fault moves eastward relative to the southern block.

The Hines Creek fault traverses the northern reaches of the park. It roughly separates 350-million year old schist, as well as lower and middle Paleozoic metasedimentary rocks of the Yukon-Tanana Terrane from the Pingston and McKinley Terranes. It also bisects portions of the Paleozoic Farewell Terrane (a name used for the combined Dillinger, Nixon Fork, and Mystic Terranes) as well as granites of Mt. McKinley to the south that are Tertiary age (56 million years ago) (Csjetey et al. 1995; Dumoulin et al. 1998; Brease 2004). This fault passes near park headquarters and crosses the Alaska Railroad, extending westward, usually forming valley floors, for 80 km (50 mi). This fault is not considered to be active.

The McKinley strand of the Denali fault is active, and it passes through the central section of the park. It enters the park near Cantwell and trends eastward toward Anderson Pass and then beneath the Muldrow Glacier. (St. Amand 1957). This fault has displaced a pluton of 38 million year old Foraker granite (named for the second highest peak in the park) that is horizontally more than 40 km (25 mi). This corresponds to an average slip rate of 1 mm (0.04 in.) per year for the past 38 million years.

Both strands of the Denali fault are north of Mt. McKinley. The McKinley fault has significant reverse thrust motion associated with it—i.e., the fault surface dips slightly toward the south, with Mt. McKinley being thrust upward and northward along this surface (Ford et al. 2003). The Wickersham Wall on the northwest side of Mt. McKinley reflects the recent vertical component of movement along the fault (Gilbert 1979). Fault scarps along the McKinley strand, as well as local features such as angular grabens, en echelon (overlapped or staggered) ruptures, and "mole tracks," exhibit a reliable history of Holocene movement across the fault system (Redfield and Fitzgerald 1993; Schwartz et al. 2005). These features also demonstrate the partitioned nature of movement between normal, thrust, and lateral (strike-slip) sense throughout such a major structure. The two fault strands coalesce east and west of Denali National Park and Preserve.

As the Alaska Range is being uplifted, reverse and transform motion is accommodated by the Denali fault system and smaller-scale normal faults and thrust faults. On the trail to Triple Lakes, several igneous dikes, intruding the Cantwell Formation, have been offset along several small faults. The hike along Tattler Creek shows evidence of at least 450 m (1,500 ft) of uplift within the Cantwell Formation (Gilbert 1979).

The intensity of deformation within the rocks through which the Denali and other faults pass is variable, but penetrative foliations, well-developed lineations, and strained grains suggest extensive transposition along the strands of the Denali fault, in particular. Locally, the zone of observable fault deformation reaches a width of 5 km (3 mi). Cataclasites and zones of fault gouge from brittle deformation regimes cut mylonitic fabrics, recording earlier ductile deformation along the fault (White 1997). Rocks trapped between shifting fault blocks are pulverized, deformed, and crushed. This renders them easily eroded; thus, most faults are traceable on the surface as linear topographic depressions (Gilbert 1979). Much of the actual fault trace is covered in Quaternary age sediments and/or alpine tundra (White 1997), and is visible east of Anderson Pass (P. Haeussler, USGS, geologist, written communication, November 2009).

#### Kantishna Hills

The Kantishna Hills are tectonically active and among the most interesting geologic features of Alaska (P. Haeussler, USGS, geologist, written communication, November 2009). Precambrian to early Paleozoic crystalline metamorphic rocks (mica schist), intruded by swarms of Cretaceous to Tertiary dikes, underlie the hills (Prindle 1907; Ruppert et al. 2008). The northeast-trending Kantishna Anticline is a growing feature resulting from at least five deformational episodes. High-angle and thrust faults generally follow the trend of the anticlinorium, whereas conjugate folds and faults trend northwest (Bundtzen 1981; Salisbury and Dietz, Inc. 1984; Burghardt 1997). The southern end of the Kantishna Hills anticlinorium marks one of the most prominent areas of seismic activity in all of interior Alaska (Ruppert et al. 2008). It is growing at such a rate as to force rivers to divert around it (P. Haeussler, USGS, geologist, written communication, November 2009). The McKinley River flows around the southern end of the anticlinorium and through the seismic zone. The channel of this river changes from a well-developed braided channel to an incised meander morphology as the river approaches the southwestern part of the structure. North of the Kantishna Hills anticlinorium, the river abruptly reverts to a braided channel morphology (Ruppert et al. 2008). Active deformation, as the structure is propagating southwestward, is also responsible for reaches of convexity along the longitudinal stream profiles of McKinley River and Moose Creek near the Kantishna Hills (Ruppert et al. 2008).

The lode mineralization in the Kantishna Hills appears to be spatially related to the axis of the Kantishna Anticline. This happened where the structure (especially areas of brittle deformation) focused mineralization and the emplacement of locally high-grade mineralized veins (Bundtzen 1981; Salisbury and Dietz, Inc. 1984; Burghardt 1997). Superheated, saturated fluids preferentially flowed through the fracture zones, depositing mineralized veins that would later attract the interest of miners.

### Accreted Terranes

As much as 90% of Alaska's current land mass is not part of the original North American craton, but was instead transported as a series of exotic terranes conveyed atop tectonic plates and accreted onto the continent (Stone 1984). These terranes include bits of islands, volcanic arcs, marine sediments, oceanic crust, and slivers of other continents that either obducted onto the continent or were too thick to subduct into the Aleutian trench. The central part of the Alaska Range in Denali National Park and Preserve is composed of three major separate terranes of varying scale (P. Haeussler, USGS, geologist, written communication, November 2009).

The terranes form long linear belts, and typically follow an arching pattern trending roughly east-west, paralleling the Gulf of Alaska coastline. Each separate terrane is bounded by faults, and is distinguished by differing rock assemblages, metamorphic grade, structural fabric, fossils, etc. Volcanism and mountain building (orogenesis) often accompany terrane accretion; at Denali, pervasive faulting (including strike-slip, thrust, and high-angle reverse faults) have jumbled the terranes, obscuring their chronologic order (Stone 1980). Several faults, including the West Fork, Talkeetna, Denali, Chitina Valley, Castle Mountain, and Totschunda faults, separate terranes in the Denali area (Nokleberg et al. 1994). The contacts between the various accreted terranes are also gave rise to hydrothermal metamorphism and magmatism, which in turn led to the development of gold veins in brittle faults and fractures (Goldfarb et al. 1997). Geologists use stratigraphic correlations, radiometric dating, paleomagnetism, detailed mapping, and other techniques to determine the relative sequence of accretion tectonic history. At least nine widespread magmatic episodes are represented by plutonic rocks scattered across Alaska (Miller 1994).

The names, designations, and numbers of identified terranes in the central Alaska Range have changed with more detailed geologic understanding of the area. Moore et al. (1994) provides one view of the tectonic assembly of the terranes of Alaska (beyond the scope of this report, which presents only a summary). The oldest terrane is the Yukon-Tanana terrane (and the Nixon Fork terrane, located west of Denali) that is composed of sequences of Precambrian through Paleozoic metasedimentary and metavolcanic rocks (Csejtey et al. 1982). This terrane comprises much of central Alaska and is present within the northern areas of the park, north of the Hines Creek fault. Farther south, several smaller terranes were caught between the Yukon-Tanana terrane and the accreting Wrangellia composite terrane or Talkeetna superterrane (Wrangellia, Alexander, Maclaren, and Peninsular terranes) during the Cretaceous collision between the Talkeetna and the continent (figs. 2, 16, 17) (Csejtey et al. 1982).

Farthest north among these smaller "miniterranes" is the Pingston terrane, which contains isoclinally folded, deep water mid-Paleozoic through Mesozoic, silty limestone, slate, and phyllite. The neighboring McKinley, Dillinger, and Windy terranes contain mixed Mesozoic flysch rocks and pillow lavas (McKinley terrane), micaceous sandstone (turbidites), graptolitic shale, deep water limestone (Dillinger terrane), serpentinite, basalt, tuff, chert, limestone, and mixed flysch (Windy terrane).

Farther south, the Mystic terrane is composed of Mesozoic graptolitic shale, pillow basalt, shallow water limestone, sandstone, and chert. The Chulitna Terrane contains Mesozoic ophiolite rocks (oceanic crust), chert, volcanic conglomerate, limestone, and mixed flysch. The ophiolites of this belt were altered to serpentinite and contain clues to crustal suture (Roeske et al. 2005). The West Fork terrane contains chert, sandstone, conglomerate, and tuffaceous argillite. The nearby Broad Pass terrane contains chert, tuff, and blocks of limestone and serpentinite (Jones et al. 1980).

These small terranes are tectonically mixed with intervening Jurassic and Cretaceous flysch, deposited in deep basins that existed between the colliding terranes that collapsed and deformed upon collision (Csejtey et al. 1982). The Kahiltna assemblage is one such flysch sequence. It likely depositionally overlapped the northern margin of the Wrangellia and Peninsular terranes, and is exposed in the northern Talkeetna Mountains and southern Alaska Range (Ridgway et al. 2002). Another noteworthy flysch sequence is the Gravina-Nutzotin belt, which overlies the Wrangellia and Alexander terranes (Nokleberg et al. 1994). These sedimentary basins might record the progressive development of a suture zone between the Talkeetna Superterrane (Wrangellia composite terrane) with the North American continental margin (Ridgway et al. 2002).

Younger large terranes and accretionary prisms, located to the south of Denali National Park and Preserve, include the Chugach and Prince William accretionary blocks and the Yakutat terrane (P. Haeussler, USGS, geologist, written communication, November 2009). The youngest regional-scale terrane, the Yakutat terrane, is still attached to the Pacific Plate, traveling approximately 5 cm (2 in.) northward per year; thus, accretion is an ongoing process along the coast of southern Alaska.

### Glacial Features

Glacial processes carved much of the rugged topography at Denali National Park and Preserve. A glacier is a powerful agent of erosion, capable of profoundly altering the landscape over which it passes. Glaciers primarily erode by two distinct processes: plucking and abrasion (Dyson 1966). In plucking, the glacier actually quarries out distinct masses of rock, incorporates them within the ice, and carries them along; as the glacier moves forward, these blocks of rock are dragged or carried along with it (Dyson 1966). Abrasion involves glacial ice mixed with bits of rock and debris that actually scours the underlying bedrock as it passes over.

#### Cirques

By quarrying headward and downward at its mountain source, the glacier ultimately carves a steep-sided, bowl-shaped basin called a cirque or glacial amphitheatre. The cirque is the first place that ice forms and the place from which it disappears last; thus, it is subjected to intense glacial erosion longer than any other part of the glacial valley. Once the glacial ice melts away, a body of water known as a cirque lake can form in the depression (Dyson 1966). Cirque lakes are not common at Denali because most of the glaciers are still active.

#### U-Shaped Valleys

Rock fragments of various sizes frozen into the bottom and sides of the glacier form a huge file or rasp, which abrades or wears away the bottom and sides of the valley down which the glacier flows. The valley thus attains a characteristic U-shaped cross-section, with steep sides and a broad bottom. This is in contrast to a stream-cut valley and its characteristic narrow, V-shaped profile. Many valleys in the park, once devoid of glacier ice, will possess this distinct U-shaped cross-section. The upper valleys of the Savage, Sanctuary, and Teklanika Rivers are U-shaped (Gilbert 1979).

The topography of the valley floor is not necessarily smooth, as it is usually contoured from erosion controlled by geologic properties of the bedrock. Steep drops or "steps" can mark valleys, between which the valley floor has a comparatively gentle slope. Such a valley floor is called a glacial stairway (Dyson 1966). These features result from the differences of erosional resistance between different rock types of the underlying geologic formations. A glacier will scour more deeply into a weaker rock, such as shale, schist, or altered volcanic rock, forming a "tread" (in contrast to the cliffs or "risers" formed by the erosion of stronger rocks such as massive sandstones, quartzites, or granites).

#### Hanging Valleys

The "tributaries" of glacial valleys, filled with smaller glaciers that feed into the larger ones, are known as hanging valleys. They form as a result of differences in erosional power between the smaller glacier and the larger valley glacier. The thicker the stream of ice, the more capable it is of erosion. Thus, a main valley deepens greatly, while the tributary valleys, with their smaller glaciers, cut down more slowly, leaving them hanging high above the floor of the main valley once the glacier ice melts (Dyson 1966).

#### Arêtes

Conspicuous throughout the Alaska Range are long, sharp ridges forming much of the backbone of the mountains poking above valleys filled with glacial ice. These features are known as arêtes, and owe their origin to glacial processes.

As the long valley glaciers enlarge their source cirques by cutting farther toward the axis of the mountain range, the mountain wall is finally reduced to a very narrow, steep-sided ridge, an arête. In the absence of glacier ice, knife-like ridges separate deep valleys at the park.

In some places, glaciers on opposite sides of a ridge can cut through the ridge, creating a low area known as a col (but usually called a pass) (Dyson 1966). At locations where three or more glaciers have plucked their way back toward a common point, they leave at their heads a sharp-pointed peak known as a horn.

#### Braided Rivers

Most of the major rivers at Denali seem underfit for their valleys. An underfit stream appears to be too small to have eroded the valley in which it flows, commonly the result of drainage changes caused by glaciers. They flow, splitting and intertwining in wide, glacially eroded, U-shaped valleys. They are choked with excess sediment and follow steep gradients. Toklat River, visible from the park road, is a textbook example of such a river (fig. 9) (Gilbert 1979). When one stream channel fills with sediment, other channels form nearby. As streams drop vast piles of poorly sorted sediment, valley trains (long narrow accumulations of glacial outwash confined by valley walls) develop (Brease 2004).

#### Glacial Lakes

Most lakes throughout the park owe their existence directly or indirectly to glaciers and glacial processes. They can be divided into several main types, depending on their origin: cirque lakes, other rock-basin lakes, lakes dammed by glaciers and/or glacial deposits, kettle lakes, or glacial valley lakes.

Cirque lakes fill the depression plucked out of solid rock by a glacier at its source. These are not as common at Denali as in other glaciated parks because glacial activity is still so prevalent at the uppermost parts of most of the river drainages (Gilbert 1979). Other rock-basin lakes fill depressions created where glaciers moved over areas of comparatively weak rock. In all cases of cirque or rock-basin lakes, a bedrock dam contains the water.

Lakes held back by outwash deposits are dammed by mixed sediments and stratified gravel, which were contained in or washed out from glaciers when they advanced into the lower parts of the valleys. Moraine lakes are formed when a moraine deposit blocks a stream outlet. Some lakes at Denali are caused by glaciers acting as dams across pre-existing river valleys or outwash streams from another glacier. Glacial impoundment is recorded in the rock record as varved clay (distinctly laminated sediments including the upper, fine-grained "winter" layer reflecting quiet depositional setting) lacustrine deposits that formed in the transient glacial lakes. Glacial Lake Moody once existed in the Nenana River canyon when the river was dammed by glacial deposits following the Healy Glaciation and during the Riley Creek Glaciation (Gilbert 1979). Glacial valley lakes are often long and finger-like, filling the former U-shaped valleys once occupied by large glaciers. These are large-scale features that could be dammed by moraine deposits.

Kettle lakes and ponds form in response to glacier advance and retreat. Large pieces of ice often calve from the head of a glacier. These pieces are left stranded when the glacier retreats up the valley. When outwash streams deposit sand, clay, gravel, and other sediments around the block of stranded ice, the block is insulated and, once melted, forms a small, typically round, pond in the midst of new thick glacial outwash. West of the Eielson Visitor Center, as well as north of the Teklanika Campground, numerous small lakes and ponds formed by melted blocks of ice in morainal deposits are visible (Gilbert 1979). Wonder Lake, near Kantishna, was formed by a combination of glacial erosion and ice block melting (Brease 2004).

### Glacial Deposits

As the glacier ice moves, rock fragments continually break loose and can entrain into the ice itself. Some of the fragments are ground into powder as they move against each other and scour against the bedrock under the glacier. Many types of rock yield a milky gray powder when finely ground. Melt-water streams issuing from present-day glaciers are cloudy or milky from their load of this finely ground "rock flour." Much of this silt is deposited in lakes where light refracting off the particles imparts a milky turquoise color to the water.

Glacial till is a term used to describe deposits of mixed rock left by glaciers. During glacier advance, huge amounts of rock debris are transported down glacial valleys. When the glacier stops advancing and begins melting and retreating up the valley, a large rock debris deposit, known as a terminal moraine, is dumped at the point of furthest advance (fig. 18). Terminal moraines help constrain the timing of glacial advance and retreat.

The McKinley River area contains one of the most complete glacial deposit sequences along the north flank of the Alaska Range at Denali National Park and Preserve. Included in this sequence are three pre-late Wisconsin age moraines. These are broad ridges formed when the Muldrow and Peters Glaciers coalesced and extended down the valley as a broad lobe approximately 50 km (31 mi) from present margins. Local deposits include a four-fold late Wisconsin moraine sequence (40 km [25 mi] down the valley) and four separate neoglacial moraines. The oldest of the neoglacial deposits is 3,000 years old; the most recent is dated within the past 100 years. These deposits display irregular topography, with some remnant ice present at depth within the deposit and little vegetation cover (Werner et al. 1990).

Terminal moraine deposits throughout the park are susceptible to intense erosion immediately following deposition, as well as the obscuring effects of a vegetative cover. Studies of moraine deposits at Denali reveal at least seven major periods of glacial advance beginning around 2 to 3 million years ago. Locally, these are called (from earliest to latest): the Teklanika (Late Tertiary, >2 million years before present [ybp]); Browne (150,000+ ypb); Bear Creek (125,000 to 150,000 ybp); Dry-Lignite Creek (125,000 ypb); Healy-McLeod Creek (65,000 to 75,000 ybp); and Riley Creek-Wonder Lake (9,000 to 25,000 ybp) glaciations. They are followed by the Carlo Creek readvance of 8,000 ybp (Gilbert 1979; Thorson 1986; Brease 2004). As the Alaska Range was uplifted, subsequent glaciations that did not extend out as far as the previous ones left a record of nested moraines (Gilbert 1979; P. Haeussler, USGS, geologist, written communication, November 2009). Similarly, the various types of rock blocks in glacial deposits can record the distance and direction of the glacial transport from the stone's provenance to present position.

Lateral moraines are the piles of loose fragments and blocks that fall from overhanging cliffs. These blocks accumulate as low ridges of glacial till riding along the edge of the glacier. If two glaciers intersect, adjacent lateral moraines join to form medial moraines (Brease 2004).

Glacier ice supporting large boulders and blocks of rock can be stranded or rafted on glacial lakes. When the ice melts, the largest blocks are known as glacial erratics. A remnant boulder, or erratic, left from the Browne Glaciation sits on a hillside at elevation 1,040 m (3,400 ft) south of park headquarters. A similar granitic erratic, pulled from the crest of the Alaska Range was stranded at 1,280 m (4,200 ft) on the summit of Mt. Fellows, east of park headquarters (Gilbert 1979).

Glacial deposits are cause for resource management concern because of the large proportions of weak rock flour and clays that form the matrix for larger, irregular blocks of rock. In many glacial deposits, the loose material continually slumps, sometimes sliding over a road or trail surface. Knowledge of the location of such deposits is critical for maintenance of park infrastructure and facilities.

### Bergschrunds

Usually a large crevasse, the bergschrund develops in the ice at the head of a glacier as a result of the glacier moving away from the headwall (fig. 19). The size of the bergschrund of many active glaciers in Denali depends on the mass and area of glacier ice. Bergschrunds consist of an arcuate opening between the head of the glacier and the mountain (cirque) wall. The trend of the bergschrund usually parallels the wall. It is at this site that plucking is most active and dominant because water enters the cracks by day and freezes in the rock crevices at night.

## Glaciers

Glaciers are major features on the landscape of Denali National Park and Preserve, covering 17% (~1 million acres) of the total park area. More than 400 glaciers exist at the park, the largest and/or most visible 40 of which are named. The Kahiltna Glacier is 71 km (44 mi) long, making it the longest glacier in the Alaska Range. The Ruth Glacier is the thickest glacier in the park, filling the very deep Ruth Gorge. The Eldridge, Tokositna, Yentna, Peters, Harper, and Muldrow Glaciers are among the other named glaciers at Denali.

Permanent snowpack and abundant precipitation above 2,100 m (7,000 ft) supports the flow of glaciers from elevations above 6,100 m (20,000 ft) down glacial valleys to ~305 m (1,000 ft). The most extensive glaciers and snowfields are concentrated on the southeastern side of the Alaska Range, due to the abundant snowfall from moisture-bearing winds from the Gulf of Alaska. On the drier north side, glaciers are typically smaller and shorter, with the exception of Muldrow Glacier (Brease 2004). Ice within these glaciers moves at varying speeds depending on several factors: glacier thickness, underlying topography, bedrock type and structure, and the presence of water beneath the ice. The average rate in the smallest glaciers is 1.8 to 2.4 m (6 to 8 ft) a year, while the average in the largest glaciers is greater than 70 m (230 ft) a year. Glaciers are never motionless; however, their movement is somewhat slower in winter than in summer. Despite slow speeds, over a period of years, glacial ice transports immense quantities of rock material and debris ultimately to the ends of the glaciers.

#### Short-lived Glacial Surface Features

Countless interesting, short-lived surface features can be seen at various times on any glacier. These include crevasses, moulins (glacier wells), debris cones, and glacier tables (fig. 19). Crevasses are cracks that occur in the ice of all glaciers due to tensions caused by differences in ice velocity throughout the body of the glacier (fig. 20). They can be hidden by skiffs of snow or debris, and thus can pose a hazard problem to visitors.

Debris cones result from the insulating effect of rock debris, usually deposited by a stream running over the glacier's surface, which protects the ice underneath from the sun's rays. As the surface of the glacier is lowered by melting, cones or mounds form beneath the rock-insulated area and grow gradually higher until the debris slides from them. They are seldom higher than 3 to 4 feet, but can pose a hazard to hikers on the glacier. A glacier table is a mound of ice that is capped and insulated by a large boulder. Its evolution is similar to that of the debris cone or mound (Dyson 1966).

Snow that fills crevasses and wells during the winter often melts out from below, leaving thin snowbridges over the cracks in early summer. These snowbridges pose a very real danger to those traveling on glaciers because of their inherent weakness and instability.

### Glacial Retreat and Surging Glaciers

As climate warms (Karl et al. 2009; IPCC 2007), glaciers are shrinking at Denali National Park and Preserve (figs. 5, 6, 18). Most of the glaciers are consistently thinning (see "Geologic Issues" section). Many glaciers appear underfit for their U-shaped valleys (Brease 2004). When the yearly snow accumulation decreases, the ice front of the glaciers seems to retreat, whereas the mass of the glaciers is merely decreasing by melting on top and along the edges (analogous to an ice cube melting on a kitchen counter).

#### Surging Glaciers

When a glacier advances faster than average in one or more seasons, it is said to be surging. The Muldrow Glacier, approaching the park visitor center from the west, has advanced rapidly several times (Brease 2004). The last major surge occurred during the 1956-1957 season. Glacial surging can be the result of periodic water buildup beneath the glacier, lubricating the base of the glacier and facilitating rapid and potentially catastrophic movements of ice (Gilbert 1979). A major tributary to the Muldrow Glacier is the Traleika Glacier. This glacier has flowed at rates of 20 to 70 m (66 to 230 ft) per year since 1991 (Adema et al. 2003).

Presently, only about 10% of glaciers are surging at any one time (fig. 4) (P. Haeussler, USGS, geologist, written communication, November 2009). Most of surging glaciers are located on glaciers of northern exposure along the Alaska Range.

### Other Notable Geologic Features

- Polychrome overlook's multi-colored rocks are the result of weathered rhyolite tuffs and interlayered flows of the Teklanika Formation, deposited 56 million years ago. Similar, colorful volcanics are visible on Cathedral, Double, and Igloo Mountains (Cole 2004). This volcanism was contemporaneous with the formation of Mt. McKinley, suggesting that the volcanic vent source was to the southwest.
- Evidence of more recent volcanism, ~38 million years ago, is conspicuous from the Eielson Visitor Center, and forms much of Mt. Galen with basalt, andesite, dacite, and rhyolite lava flows, tuffs, and breccias (Cole 2004).
- Near Teklanika Campground, the quartz-rich conglomerate of the Cantwell Formation rests atop much older metamorphic rocks, marking a 100- to 65-million year gap (unconformity) in the geologic record. Elsewhere, in the Tolkat River gorge, the Cantwell sits atop pillow basalts that are 135 million years older (Gilbert 1979).
- "Badlands" topography is developed along the gorge of the East Fork River within rhyolite pebble conglomerates of the Nenana Gravel.

**Figure 14: Denali (Mt. McKinley) dominates the ridgeline of the Alaska Range in Denali National Park and Preserve. Wonder Lake (note canoe for scale) is in the foreground. NPS photo.**

**Figure 15: Denali has a rich variety of deformed bedrock, a tribute to the complex geologic history which includes active plate dynamics. NPS Photo/Adema.**

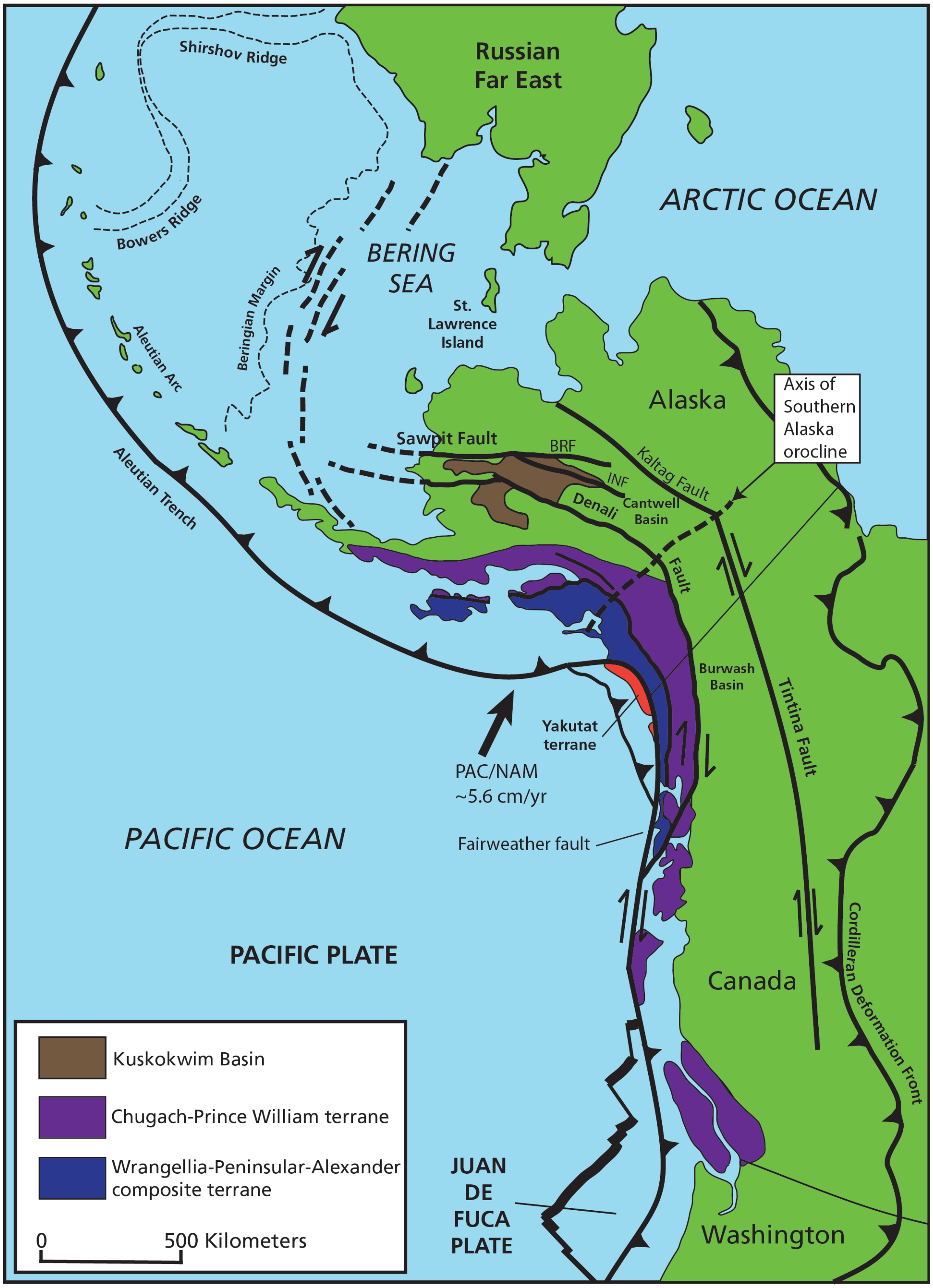


**Figure 16: Map of Alaska showing the Denali fault, Iditarod-Nixon fault (INF), Tintina-Kaltag fault, the Border Ranges fault (BRF - Talkeetna fault), and other regional structures in relation to the southern coast of Alaska and the Aleutian trench subduction zone. Note the location of the Yakutat Terrane. An orocline is an orogenic belt with an imposed curvature or sharp bend. Graphic by Phil Reiker (NPS Geologic Resources Division) after fig 1. from Miller et al. (2002).**

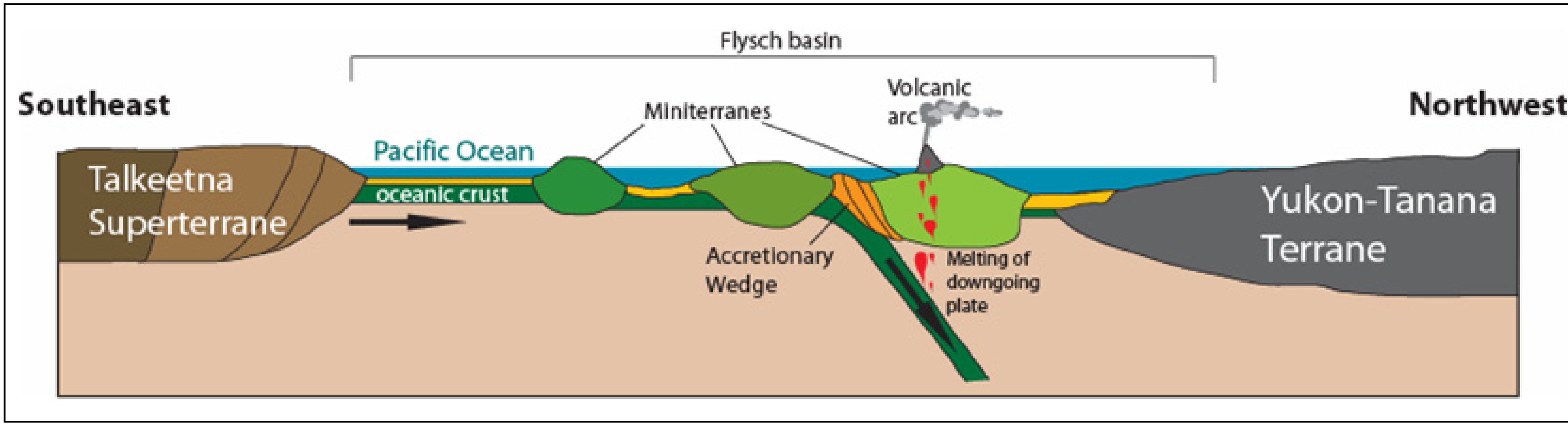


**Figure 17: Cross section of subduction zone between the Talkeetna Superterrane and the Yukon-Tanana Terrane of southern Alaska during early Cretaceous accretion events. Note the location of miniterranes and ocean basins between the two large terranes. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from Csejtey et al. (1982) fig. 9.**

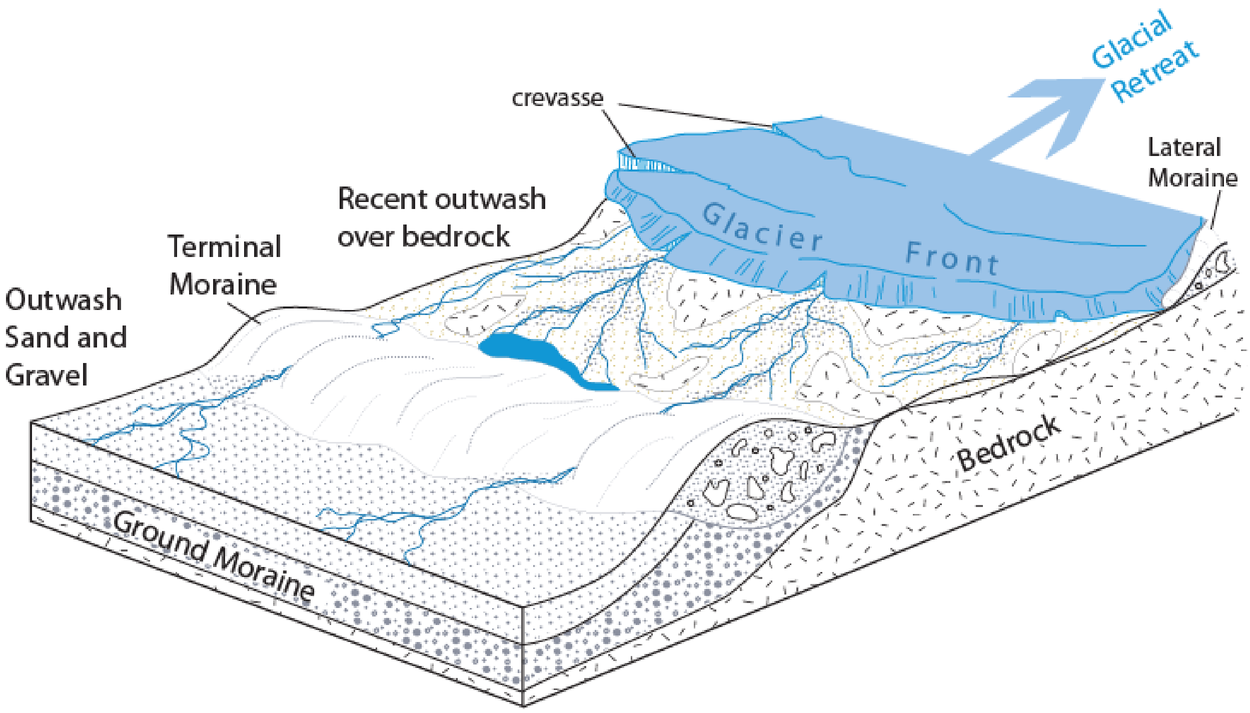


**Figure 18: Diagrammatic view of a retreating glacier with a recent terminal moraine and a broad space between the moraine and the glacier front. Note the variety of glacial deposits. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).**

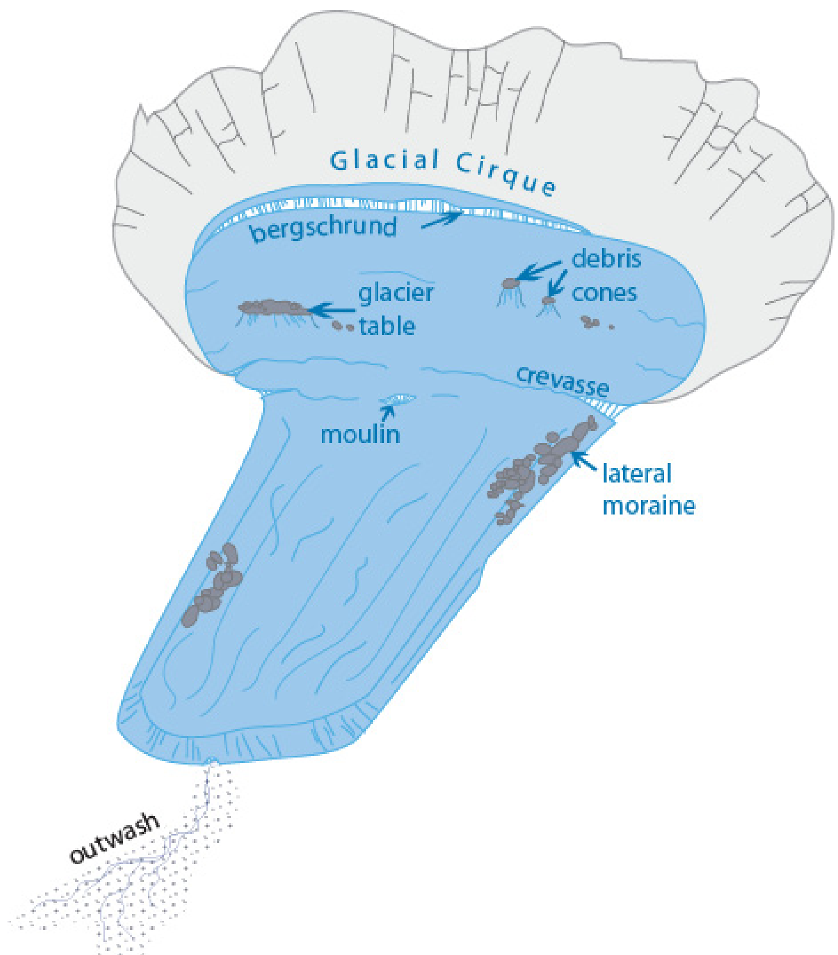


**Figure 19: Short-lived features occurring on the surface of glaciers. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).**

**Figure 20: Ice and crevasses of Eldridge Glacier in Denali National Park and Preserve, Alaska, August 7, 2004. Photo courtesy of Ronald D. Karpilo, Jr. (Colorado State University).**

# Map Unit Properties

*This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Denali National Park and Preserve. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.*

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Denali National Park and Preserve provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions . Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 21) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following references are source data for the GRI digital geologic data for Denali National Park and Preserve:

Clautice, K.H., Newberry, R.J., Blodgett, R.B., Bundtzen, T.K., Gage, B.G., Harris, E.E., Liss, S.A. Miller, M.L., Reifenstuhl, R.R., and D.S. Pinney. 2001. *Bedrock Geologic Map of the Chulitna Region, Southcentral Alaska*. Scale 1:63,360. Report of Investigations RI2001-1A. Fairbanks, Alaska: State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys.

Pinney, D.S. 2001. *Surficial-Geologic Map of the Chulitna Mining District, Southcentral Alaska*. Scale 1:63,360. Report of Investigations RI2001-1C. Fairbanks, Alaska: State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys.

Pinney, D.S. 2001. *Engineering-Geologic Map of the Chulitna Mining District, Southcentral Alaska*. Scale 1:63,360. Report of Investigations RI2001-1D. Fairbanks, Alaska: State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys.

Wahrhaftig, Clyde. 1970. *Geologic Map of the Healy D-4 Quadrangle, Alaska*. Scale 1:63,360. Geological Quadrangle Map GQ-806. Reston, VA: U.S. Geological Survey.

Wahrhaftig, Clyde. 1970. *Geologic Map of the Healy D-5 Quadrangle, Alaska*. Scale 1:63,360. Geological Quadrangle Map GQ-807. Reston, VA: U.S. Geological Survey.

Wahrhaftig, Clyde. 1952. Geologic Map of Part of Healy C-4 Quadrangle, Alaska, Showing Pleistocene Deposits along the Nenana River. Scale 1:63,360. Professional Paper 2933. Reston, VA: U.S. Geological Survey.

Wahrhaftig, Clyde, and R.E. Fellows. 1952. *Geologic Map of Part of Healy B-4 Quadrangle, Alaska, Showing Quaternary Deposits along the Nenana River*. Scale 1:63,360. Professional Paper 2934. Reston, VA: U.S. Geological Survey.

Wilson, F.H., Dover, J.H., Bradley, D.C., Weber, F.R., Bundtzen, T.K., and P.J. Haeussler, compilers. 1998. *Geologic Map of Central (Interior), Alaska*. Open-File Report OF 98-133. Reston, VA: U.S. Geological Survey.

The Map Unit Properties Table is divided into units that are present on larger scale maps (1:63,360; Chulitna region and Healy quadrangle maps) and those on the smaller scale map (1:250,000; Wilson et al. 1998 compilation). The overview of digital geologic data (Appendix A) illustrates the small scale digital geologic data.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, and increases the overall utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase and shapefile GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map and connects the help file directly to the map document. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/). Data will be available on the Natural Resource Information Portal when the portal goes online. As of August 2010, access is limited to NPS computers at http://nrinfo/Home.mvc.

#### Geologic Units of Denali National Park and Preserve

The rock units at Denali National Park and Preserve represent a vast span of geologic history. Because juxtaposed slices of accreted terranes characterize the geology in the Denali area, different rock types and ages form a puzzle of units on the landscape. The oldest rocks are metamorphosed Proterozoic basement rocks of the Nixon Fork sequence. These rocks contain zircon grains dated using uranium-lead isotopes (U-Pb) at 1,250 ± 50 million years ago (Wilson et al. 1998).

Most of the oldest rocks are part of the Yukon-Tanana Terrane, north of the Hines Creek fault (Gilbert 1979). These Late Precambrian to Early Paleozoic age rocks include metamorphosed pelitic and quartzose schists, amphibolite, gritty quartzite, marble, greenstone, phyllitic layers, and other metasedimentary and metaigneous rocks (Gilbert 1979; Wilson et al. 1998). Ordovician rocks include dark chert, slate, argillite, and some greenstone, limestone, and dolostone. Devonian limestone, chert, and volcanic ash fall and lava flows record prolific life and volcanic activity in a marine basin–island arc setting. The Mississippian Moose Creek Member contains metamorphosed basalts and other volcanic rocks (Clautice et al. 2001).

Pennsylvanian and Permian limestones, mudstones, and greywacke sandstones record marine deposition in open basins. During the Mesozoic, granitic magma formed irregular intrusive bodies throughout the region, and mixed schists and amphibolite of the MacLaren Metamorphic Belt underwent several grades of metamorphism and folding (Wilson et al. 1998; Clautice et al. 2001). Triassic greenstones, basalts flows, graywackes, tuffs, and limestones possibly record hotspot activity in a marine basin. These rocks record paleolatitudes of 5 degrees near the equator (Clautice et al. 2001).

Jurassic and Cretaceous age rocks in the map area range from calcareous sandstone and argillite to conglomerates and limestones to vast suites of volcanic rocks of varying compositions, granite-diabase-rhyolite intrusions, mixed mélanges, and mafic igneous rocks (Wilson et al. 1998; Clautice et al. 2001). The vast variety of rocks of this age attests to the tectonic history of the area. Many terranes were accreted with accompanying metamorphism, sedimentation, deformation, and volcanism during this time.

Tectonic processes continued throughout the Tertiary and Quaternary Periods. Tertiary age units include rhyolite, andesite, granite, granodiorite, tonalite, and monzonite intrusive igneous rocks. These units are mixed with fluviatile sedimentary rocks, carbonaceous mudstone, siltstone, conglomeratic sandstone, olivine basalts, volcanics, and coal beds. Named Tertiary units include the Suntrana, Sanctuary, Healy Creek, Lignite Creek, Grubstake, and Cantwell Formations (Wahrhaftig 1970; Wilson et al. 1998).

The intrusive igneous bodies and plutons of hornblende dacite of Jumbo Dome have a relatively young potassium-argon (K-Ar) radiometric date of 2.72 ± 0.25 million years ago (Wahrhaftig 1970). Atop this and other map units at Denali National Park and Preserve are vast and varied unconsolidated Quaternary age rocks of fluvial, colluvial, glacial, lacustrine, and aeolian origin. Older deposits include: rubble from Jumbo Dome; gravels of Late Wisconsin glaciations; high terraces and pediment gravels; rock glaciers; older alluvium (sands, gravels, and silts); glacial erratics up to 2 m (6 ft) in diameter; some varved clays deposited in glacial lakes; and terminal glacial moraine deposits (Wahrhaftig 1970; Clautice et al. 2001).

Younger units include Holocene tills, alluvium, outwash, the end moraine of the Carlo Readvance, extensive terraces above current stream valleys, windblown loess, talus and landslide deposits, and other colluvium. The youngest units at Denali include: boggy peat; stream alluvium; alluvial fans; outwash gravel and drift; some localized debris flows; varved clay and silt in recently dried-up lakes and ponds; swamp deposits; and flood-plain deposits of sand, gravel, silt, mud, and scattered boulders (Wahrhaftig 1970; Clautice et al. 2001).

# Geologic History

*This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Denali National Park and Preserve, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.*

Ongoing research continues to yield new interpretations of the complex geologic history of Alaska and the Denali National Park and Preserve area.

**Precambrian (prior to 542 million years ago)**

The geologic story of Denali National Park and Preserve begins in Precambrian time (fig. 21). The oldest rocks in the park are the metamorphosed and deformed remnants of near shore beach, shallow to deep marine, and volcanic deposits. These rocks were deposited in an ancient ocean basin off the coast of the North American craton. Approximately 1 billion years ago, during the Proterozoic Eon, quartz-rich sands and muds were being shed from the ancient craton and deposited in a shallow sea. During this time, North America was part of a large supercontinent known as Rodinia (Condie and Sloan 1998).

**Paleozoic Era (542 to 251 million years ago)**

During the early Paleozoic, volcanic activity began in the marine basin, possibly accompanying the breakup of Rodinia, spreading basaltic lava and erupting volcanic ash to mix with the terrigenous sediments. In shallow sea areas, during the Cambrian, Silurian, and Devonian periods, marine animals (including corals) thrived, creating layers of limy muds mixed with the quartz-rich sands and volcanic layers in the park (Gilbert 1979).

Following deposition, these early deposits experienced several episodes of folding deformation and metamorphism under extreme temperature and pressure conditions. Metamorphism is bracketed between the middle Paleozoic age of the youngest protoliths and the widespread mid-Cretaceous granitic intrusions (Dusel-Bacon et al. 1993). Deformation under conditions that produce greenschist and amphibolite rocks resulted in northwest-trending folds. A second episode at lower greenschist-facies conditions overprinted these folds with northeast trending folds during the Cretaceous (Dusel-Bacon et al. 1993). During greenschist to amphibolite-facies conditions, quartz sand deposits were hardened into quartzites; mixed sand, mud, and volcanic layers were converted to micaceous schists, gneisses, and phyllites; and limy mud deposits were metamorphosed into marble.

This assemblage of rocks forms much of the widespread Yukon-Tanana terrane, which creates the basement complex of much of interior Alaska (Gilbert 1979; Moore et al. 1994). It is separated from younger terranes toward the south within the park by the Hines Creek fault, the northern branch of the Denali fault system. Timing of deformation for the rocks north of the Hines Creek fault is poorly constrained between fossil ages from the middle Paleozoic protoliths and undeformed Mesozoic age granitic igneous intrusions (Dusel-Bacon et al. 1993).

As early as the Middle Silurian, intermittent periods of tectonic collision and subduction of oceanic crust and occasional island arcs were occurring west of the North American continent, slowly adding pieces to the continental land mass. At least two subduction zones were present during the Mississippian, Pennsylvanian, and Permian periods. There is no evidence of significant mountain building (orogenesis) during this time in the Denali area. In the western conterminous United States, however, the Antler terrane was accreted during the Mississippian Antler orogeny (Condie and Sloan 1998).

**Mesozoic Era (251 to 65.5 million years ago)**

The Antler orogeny started a long sequence of accretions along the western edge of the continent as the plates (Kula-Farallon-Pacific and North American plates) collided and slid past each other. The accretion of the metamorphosed and deformed ocean basin and volcanic flows of the Yukon-Tanana terrane onto the North American craton in the Denali area was possibly completed by about 225 million years ago in the early Triassic or prior to the Jurassic (Moore et al. 1994). Several large terranes, including Sonomia (Middle Triassic) and Stikinia (Late Triassic), were added to western Canada.

South of the Hines Creek fault, part of other tectonic terranes (Pingston, Windy, Dillinger, and McKinley terranes) are belts of metamorphic rocks containing gray slate, marble, metamorphosed intrusive mafic rocks (gabbros), and greenstones (altered basalts) (Gilbert 1979; Lillie 2005). These rocks are part of a complex suture zone disrupted by strike-slip faulting along the Denali fault system (described below) and thrust or normal bounding faults (Coney et al. 1980). These rocks were deposited in the latter half of the Paleozoic and beginning of the Mesozoic Era as muds, sand, and fossil debris in a deep ocean basin at tropical latitudes. Marine environments dominated the area for hundreds of millions of years. Some early minor deformation created fissures, allowing basaltic magma to intrude as plutons and extrude as flows (Gilbert 1979).

As the Peninsular and Wrangellia segments of the composite Talkeetna superterrane (elsewhere called the southern Alaska or Wrangellia composite terrane) were being dragged toward the southern boundary of the continent, the sediments trapped between the approaching terrane and the continent were squeezed, metamorphosed, and deformed to form a northeastward tapering wedge of rocks (Farewell terrane?) called flysch. This accompanied an eastward-increasing metamorphic grade sequence during the Late Mesozoic (Dusel-Bacon et al. 1993). The Upper Jurassic-Cretaceous Kahiltna assemblage records a basin that persisted between the terranes and now contains flysch (Ridgway et al. 2002). Some portions of the flysch wedge are exposed in mountains of the eastern portion of the park, such as Mt. Pendelton and Scott Peak. Masses of accreted island arcs, forming portions of the Pingston and McKinley terranes, were also caught between southern Alaska and the Talkeetna superterrane about 200 million years ago. The culmination of this event involved the emplacement of structurally interleaved tectonic fragments and low- to medium-grade metamorphism, creating the Maclaren metamorphic belt.

In the Jurassic, the block of rocks that eventually became the Brooks Range in northern Alaska collided with North America, producing high-pressure metamorphism, deformation, and thrusting along the southern margin of the continental terranes (Moore et al. 1994). In the Early Jurassic, northward thrusting off the coast of central Alaska caused terranes to "telescope" together. Large nappes and thrusts were forced onto the southern and western edges of the older accreted terranes (Condie and Sloan 1998). The Nevadan orogeny of the western conterminous United States also occurred during this time. Extreme crustal thickening along the plate margins led to partial melting at depth and the emplacement of Jurassic age igneous batholiths (granite, granodiorite, quartz diorite, and tonalite) of the Alaska-Aleutian Range (Wilson et al. 1998). Between the Denali fault system and the Border Ranges to the south, a medium-grade metamorphic event occurred across most of the southern Peninsular and Wrangellia terranes prior to final accretion onto the continent. This metamorphism accompanied local intrusions of tonalitic to granodioritic plutons of Early to Middle Jurassic age in the Peninsular terrane and of Late Jurassic age in the Wrangellia terrane (Dusel-Bacon et al. 1993). Jurassic age plutons are present in the Talkeetna Mountains (Miller 1994).

Metamorphism within the Chugach accretionary wedge, south of the park, was associated with north-directed underthrusting beneath the Peninsular and Wrangellia terranes beginning in the Early to Middle Jurassic. This event created metabasalts, metachert, and other metasedimentary rocks under greenschist to high-pressure blueschist metamorphic facies conditions (Dusel-Bacon et al. 1993).

Starting in the Jurassic, strong orogenic activity began the formation of the Alaska Range. This was in response to subduction of the Kula Plate beneath southern Alaska. Accompanying subduction was terrane accretion, thrust faulting, crustal thickening, isostatic adjustment, and plutonism (Dumoulin et al. 1998). As the subducting Kula Plate (described below) descended farther into the crust beneath southern Alaska, dewatering of the oceanic crust as well as increasing heat caused local melting. This melting created magma plumes that rose to form relatively buoyant granitic plutons that now compose the core of the Alaska Range. Some of the oldest plutons are dated at 149 million years ago, whereas the younger plutons are 29 million years old (Wilson et al. 1998).

Intense deformation, plutonism, metamorphism, and volcanism continued in the Denali area in response to subduction and subsequent terrane accretion during the Cretaceous (fig. 22) (Condie and Sloan 1998). During most of the accretion events, rising crustal temperatures led to massive gold vein formation (Goldfarb et al. 1997). Movement along the Denali fault might have started during this time. Accretion of the Talkeetna super-terrane—transported from the south along the margin of western Canada by dextral strike-slip movement—was complete by 110 to 85 million years ago during the Cretaceous (Hickman et al. 1990; Miller et al. 2002).

Prior to regional uplift, much of the Denali area was composed of continental lowlands, similar to the areas north of the Alaska Range today. Streams flowed predominantly south toward the coast, depositing alluvial sand, gravel, and silt. During the early stages of uplift, streams began diverting to northerly courses (fig. 23). A pull-apart asymmetrical basin graben developed in the area between the Hines Creek and southern fault strands of the Denali fault system. This so-called Cantwell Basin filled with as much as 4,000 m (13,000 ft) of southward thickening sediments (Hickman et al. 1990).

#### Cenozoic Era (the past 65.5 million years)

Intense regional volcanism peaked around 56 and 38 million years ago, leading to vast igneous intrusions and deposits of red, yellow, and brown basalts, rhyolites, andesites, and other volcanic rocks (Teklanika Formation). Some of these extrusive rocks are present at Polychrome Pass (older event) and Mt. Galen (younger event) (Cole 2004). Contemporaneous granitic igneous intrusions formed Mt. Eielson and Mt. Foraker (Gilbert 1979). Hydrothermal activity increased as well, leading to the development of gold-bearing quartz vein systems (fig. 24) (Goldfarb et al. 1997). Extensive volcanic flows covered the stream sediments that ultimately became the shale, sandstone, coal beds, and pebble conglomerate of the Tertiary lower Cantwell Formation (Wahrhaftig 1970; Gilbert 1979; Hickman et al. 1990).

During the Jurassic and Cretaceous, three major plates existed west of the North American continent separated by mid ocean spreading ridges: the Kula, Farallon, and Pacific plates. Most remnants of the Kula and Farallon plates were lost to subduction beneath northeastern Asia and western North America, respectively.The Juan de Fuca and Cocos plates in the eastern Pacific basin are remnants of the otherwise subducted Farallon plate. Subduction of the Farallon plate drove the Laramide orogeny spanning from Mexico to Canada from the Late Cretaceous into the Tertiary.

By the mid-Tertiary, the Pacific plate dominated the basin. Dated volcanic layers (53.9 ± 1.6 million years ago based on argon isotopes [$^{40}Ar/^{39}Ar$]) in the upper

Cantwell Formation are cut by younger high angle, northwest-trending, right-lateral shear zones, suggesting that the once collisional boundary between Alaska and the Pacific plate was changing to a more translational ("side-swiping") boundary by this time (Cole et al. 1996).

Once the Farallon spreading ridge (East Pacific Rise) was consumed, the margin between the Pacific and western North American plates became more transform in nature, around 30 million years ago (creating the San Andreas fault), and the Pacific plate continued to travel northwestward, subducting beneath Alaska, and dragging terranes with it (Condie and Sloan 1998).

From the Cretaceous to early Tertiary, accompanying the accretion of the Chugach accretionary prism to the south, the southern edge of the Talkeetna superterrane was exposed to further deformation and overprinting of a lower-grade metamorphic event (Dusel-Bacon et al. 1993). The Chugach split into a sequence of accretionary prisms and mélange complexes that underthrust each other sequentially from south to north, each accompanied by pervasive deformation and metamorphism throughout the Cretaceous into the early Tertiary. The accretionary wedge in its entirety was part of southern Alaska by about 67 million years ago, followed by the accretion of the Prince William accretionary prism at approximately 50 million years ago (Lillie 2005). Between these large terranes, forearc basins, narrow volcanic arcs, and small-scale marine basins received alluvial, volcanic, and shallow marine sediments that record uplift to the north and subsequent erosion of vast amounts of sediments, as well as thrust faulting to the south associated with continued accretion in the Talkeetna area (Trop et al. 2003).

As accretion of the Yakutat Terrane that started ~20 million years ago persists today, low-pressure, amphibolite facies metamorphism and deformation is occurring on the southern coast of Alaska (Dusel-Bacon et al. 1993; Lillie 2005). The Pacific plate continues to move northwestward at a rate of approximately 5 cm (2 in.) per year. This active margin has lead to extensive faulting throughout the region over the past 100 million years. Some of this deformation is accommodated along the right-lateral Denali fault system running parallel to the Alaska Range. Fresh fault scarps and offset stream gravels attest to recent movement along the fault (Wahrhaftig 1970), as well as the magnitude 7.9 Denali fault earthquake in 2002 (Eberhart-Phillips et al. 2003). Maximum local uplift rates in Denali are estimated at ~1 km/million years (0.6 mi/million years) beginning in the late Tertiary as a result of changes in motion of the Pacific plate relative to North America. This, in conjunction with the geometry (bend) along the Denali fault, caused local crustal blocks to be rapidly forced upward (Fitzgerald et al. 1993).

Block faulting during the mid-Tertiary created downfaulted inland basins, which collected vast deposits of sediments, including the coal-bearing Suntrana Group (30 to 5 million years ago) (Wahrhaftig 1970; Gilbert 1979). The Tertiary basin coal-bearing rocks record terrestrial cyclic sequences of siltstone, claystone, mudstone, shale, pebbly sandstone, subbituminous coal and lignite, and minor amounts of pebble conglomerate (Wilson et al. 1998). These basins supported vast forests and swampy bog environments (Gilbert 1979). The coal-bearing rocks were covered by sand and gravel shed from erosion of further uplift of the Alaska Range during the Pliocene Epoch (5.3 to 2.6 million years ago). These thick sediments comprise the poorly consolidated Nenana Gravel (Gilbert 1979; Wilson et al. 1998).

Erosion kept pace with exhumation of the Alaska Range until the beginning of Pliocene time. Around 6 million years ago, the Alaska Range began to uplift rapidly, causing most major streams of the central portions of the range to flow north (Gilbert 1979). During the Pliocene–Pleistocene, several global ice age events also occurred. Glacial ice covered vast extents of the Alaska Range, carving U-shaped valleys. Interglacial period climates supported the growth of open boreal woodland, dense alder shrub vegetation, open taiga, graminoid tundra, and birch shrub tundra through at least the past 50,000 years. Holocene coniferous forests only became established after 6,500 years before present (Elias et al. 1996). This vegetation is recorded in recent peat, swamp, bog, and other organic deposits in the Quaternary unconsolidated sediments in the foothills north of the Alaska Range in the park.

Between four and seven major glacial advances altered the landscape at Denali between 2 million and 10,000 years ago (Gilbert 1979; Brease 2004), starting with the Teklanika glacial advance, which began possibly in the late Pliocene to early Pleistocene. Other advances, including the Browne, Bear Creek, Dry-Lignite Creek, Healy-McLeod Creek, and Riley Creek, are also locally recorded in the glacial deposits at Denali. The Carlo Creek Readvance began in the early Holocene, 8,000 years ago (Brease 2004). End units from this advance form lakes that trap fine-grained sands and other lacustrine deposits today (Wahrhaftig 1952). The past glacial advances left ice erosional and glacial depositional features in most of the river valleys within the park. U-shaped valleys are present in the Savage, Toklat, Thorofare, Sanctuary, Teklanika, and McKinley Rivers' drainages. Large glacial erratic deposits are located throughout lower areas of the park (Brease 2004). Glacial processes continue today as smaller glaciers cover more than 1 million acres within Denali National Park and Preserve. Table 1 summarizes the geologic history in the Denali area of Alaska.

| Eon | Era | Period | Epoch | Ma | | Life Forms | North American Events |
|---|---|---|---|---|---|---|---|
| Phanerozoic | Cenozoic | Quaternary | Holocene | 0.01 | Age of Mammals | Modern humans | Cascade volcanoes (W) |
| | | | Pleistocene | 2.6 | | Extinction of large mammals and birds | Worldwide glaciation |
| | | Tertiary: Neogene | Pliocene | 5.3 | | Large carnivores | Sierra Nevada Mountains (W) |
| | | | Miocene | 23.0 | | Whales and apes | Linking of North and South America |
| | | Tertiary: Paleogene | Oligocene | 33.9 | | | Basin-and-Range extension (W) |
| | | | Eocene | 55.8 | | Early primates | Laramide Orogeny ends (W) |
| | | | Paleocene | 65.5 | | | |
| | Mesozoic | Cretaceous | | 145.5 | Age of Dinosaurs | **Mass extinction**<br>Placental mammals<br>Early flowering plants | Laramide Orogeny (W)<br>Sevier Orogeny (W)<br>Nevadan Orogeny (W) |
| | | Jurassic | | 199.6 | | First mammals | Elko Orogeny (W) |
| | | Triassic | | 251 | | **Mass extinction**<br>Flying reptiles<br>First dinosaurs | Breakup of Pangaea begins<br>Sonoma Orogeny (W) |
| | Paleozoic | Permian | | 299 | Age of Amphibians | **Mass extinction**<br>Coal-forming forests diminish | Supercontinent Pangaea intact<br>Ouachita Orogeny (S)<br>Alleghanian (Appalachian) Orogeny (E) |
| | | Pennsylvanian | | 318.1 | | Coal-forming swamps<br>Sharks abundant | Ancestral Rocky Mountains (W) |
| | | Mississippian | | 359.2 | | Variety of insects<br>First amphibians<br>First reptiles | Antler Orogeny (W) |
| | | Devonian | | 416 | Fishes | **Mass extinction**<br>First forests (evergreens) | Acadian Orogeny (E-NE) |
| | | Silurian | | 443.7 | | First land plants | |
| | | Ordovician | | 488.3 | Marine Invertebrates | **Mass extinction**<br>First primitive fish<br>Trilobite maximum<br>Rise of corals | Taconic Orogeny (E-NE) |
| | | Cambrian | | 542 | | Early shelled organisms | Avalonian Orogeny (NE)<br>Extensive oceans cover most of proto-North America (Laurentia) |
| Proterozoic | | Precambrian | | 2500 | | First multicelled organisms<br>Jellyfish fossil (670 Ma) | Supercontinent rifted apart<br>Formation of early supercontinent<br>Grenville Orogeny (E)<br>First iron deposits<br>Abundant carbonate rocks |
| Archean | | | | ≈4000 | | Early bacteria and algae | Oldest known Earth rocks (≈3.96 billion years ago) |
| Hadean | | | | 4600 | | Origin of life? | Oldest moon rocks (4–4.6 billion years ago)<br>Formation of Earth's crust |
| | | | | | | Formation of the Earth | |

**Figure 21: Geologic timescale. Included are major life history and tectonic events occurring on the North American continent with an emphasis on events affecting Alaska. Red lines indicate major unconformities between eras. Isotopic ages shown are in Ma. Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/, with additional information from the International Commission on Stratigraphy, http://www.stratigraphy.org/view.php?id=25.**

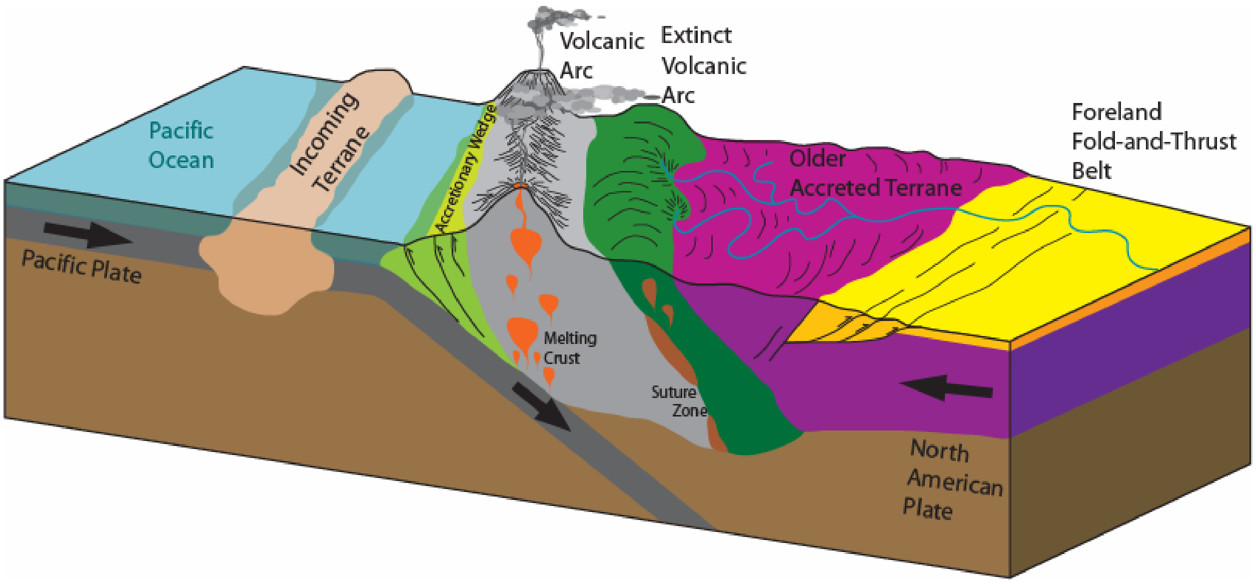


**Figure 22: Three-dimensional model of an active margin setting with successive terrane accretion, uplift, volcanism, and subduction. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from Lillie (2005) fig. 11.8.**

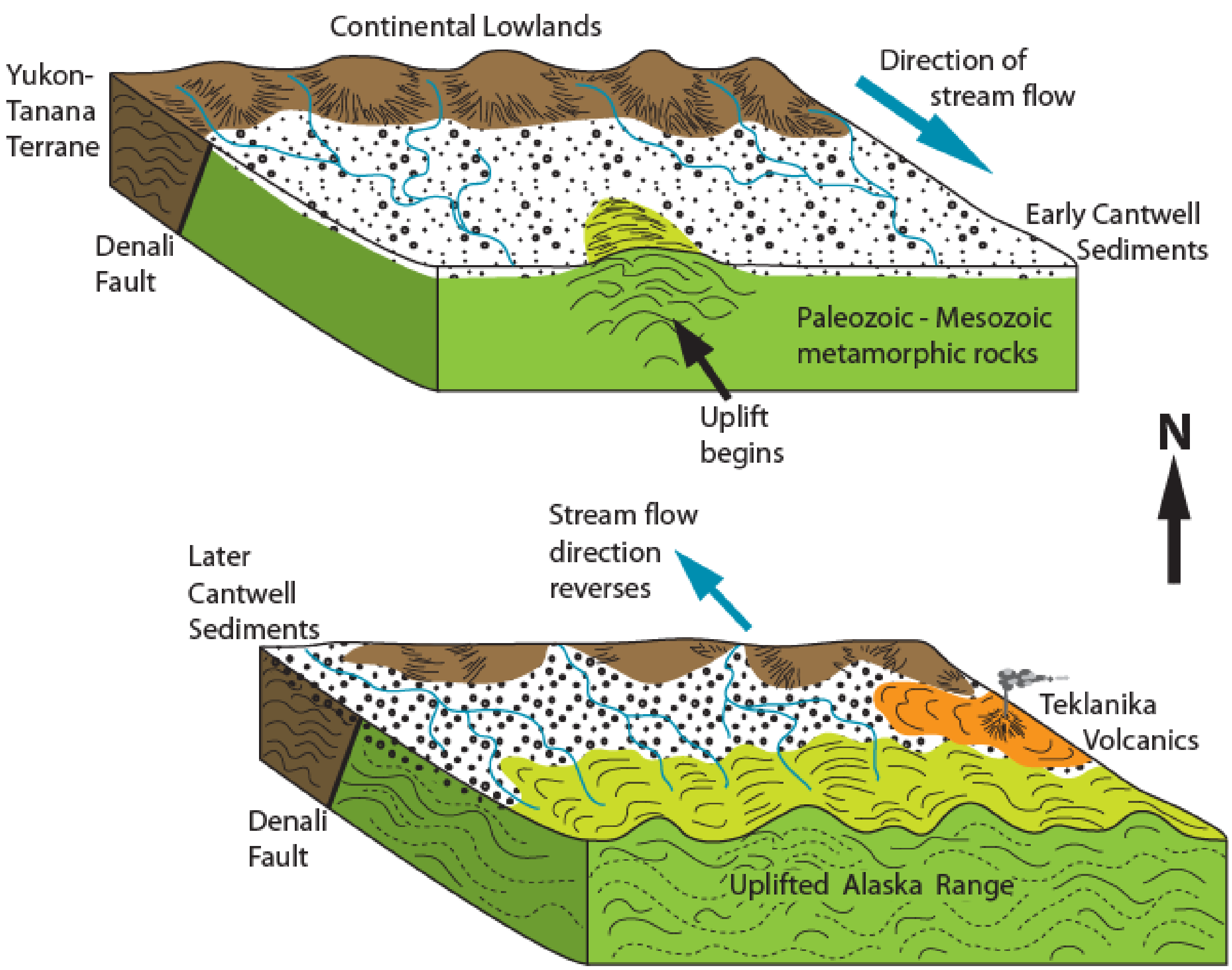


**Figure 23: Reversal of stream direction from southward to northward accompanying uplift of the Alaska Range in the early Cenozoic. Graphic is by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from Gilbert (1979) fig. 13.**

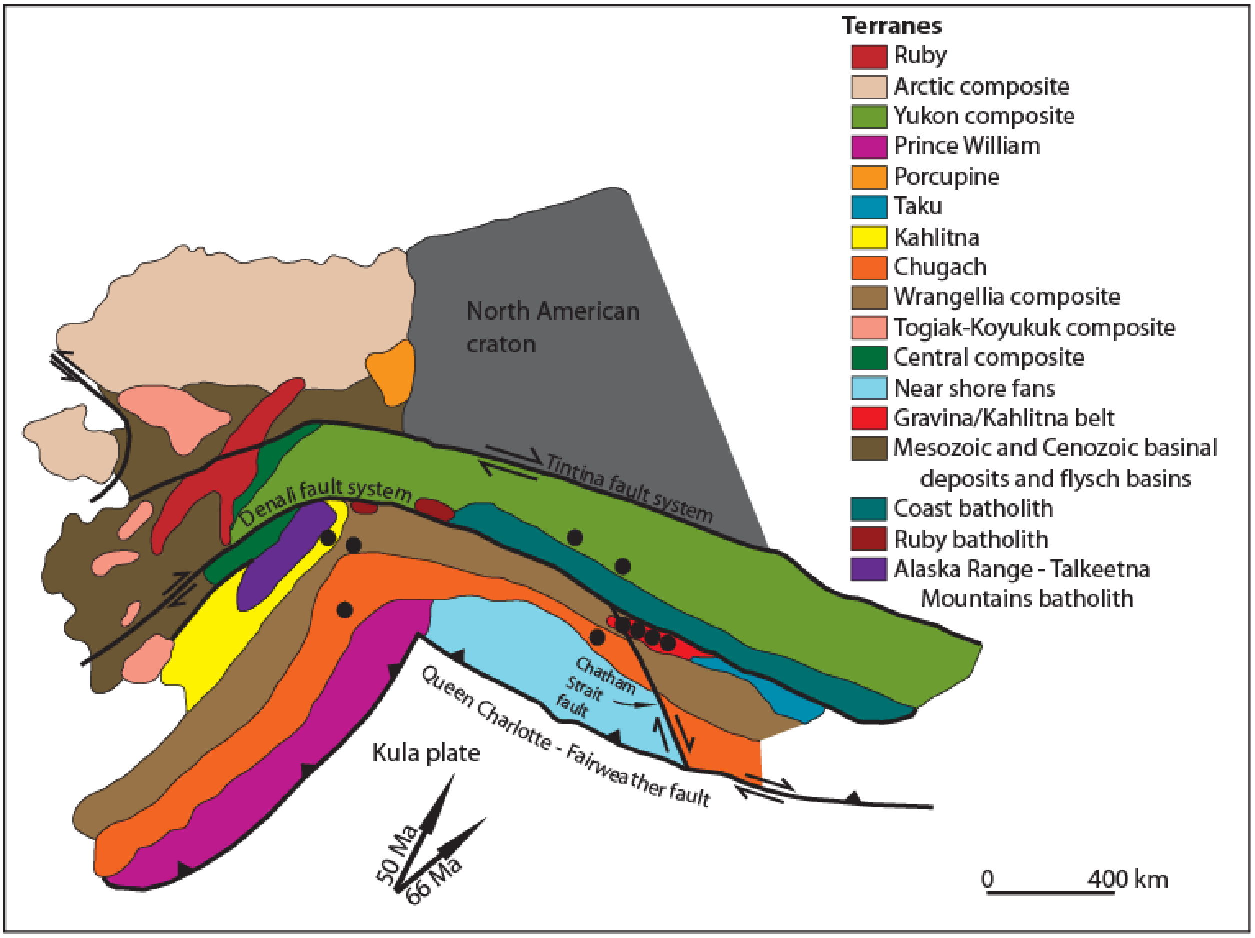


**Figure 24: Map of Alaska during the Paleocene and Eocene epochs showing generalized locations of major terranes, faults, as well as significant gold districts (black circles). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from Goldfarb et al. (1997) fig. 7.**

**Table 1: Summary of geologic events in the Denali area. Ma = million years ago; ybp = years before present. Colors (also used on the Map Unit Properties Table) according to the Commission for the Geological Map of the World. Table modeled after Brease (2004) table 34.1.**

| Eon | Era | Period | Epoch | Geologic Events |
|---|---|---|---|---|
| PHANEROZOIC | CENOZOIC | QUATERNARY | HOLOCENE | Cantwell ash fall with volcanism from southerly source (~3,700 ybp) and multiple glaciation events. |
| | | | PLEISTOCENE | Multiple glacial advances starting ~2 Ma to 8,000 ybp; intense glacial erosion of rapidly uplifting Alaska Range. |
| | | TERTIARY – NEOGENE | PLIOCENE | Deposition of Nenana Gravel shed from uplifting Alaska Range; units include sandstone, conglomerates, claystone, and lignite. Uplift and exhumation of Mt. McKinley. Movement along Denali fault system likely resumes. |
| | | | MIOCENE | Deformation and thrust faulting cause a surge in uplift of the Alaska Range; beginning of Yakutat terrane accretion. Regional subsidence due to crustal thickening and continued sedimentation and coal deposits of the Tanana foreland. |
| | | TERTIARY – PALEOGENE | OLIGOCENE | Deposition in subsidence basins north and south of the Alaska Range; several phases of igneous intrusion and volcanism at 38 Ma. |
| | | | EOCENE | Cantwell volcanism and McKinley intrusive sequence from 41 to 57 Ma results in flows, breccias, and tuffs, as well as granodiorite intrusion with some sulfide mineralization; Prince William wedge accretes. |
| | | | PALEOCENE | Emergent Alaska Range continues to shed sediments into foreland pull-apart basin, leading to piles of sandstone, siltstone, shale, tuff layers, coal, and conglomerates of the Cantwell Formation; strike-slip movement along Denali fault. Continued intrusion of granites in the Alaska Range, including the McKinley and Ruth plutons. |
| | MESOZOIC | CRETACEOUS | | Multiple phases of igneous intrusive activity (granites and granodiorites), volcanism, and orogenesis as the Chugach wedge accretes to the continent; continued flysch deposition in shallow basins; pervasive deformation and metamorphism at 115 to 106 Ma, 74 Ma, and 65 to 60 Ma; uplift of Alaska Range continues. Final closer of ocean between Talkeetna Superterrane, and previously accreted terranes to the north. |
| | | JURASSIC | | Orogenic activity increases as Talkeetna superterrane is accreting, pushing miniterranes within the intervening basin toward the continent; intense deformation and metamorphism; continued deposition of Mesozoic flysch in segmented, forearc, and backarc basins |
| | | TRIASSIC | | Final accretion of Yukon-Tanana terrane; abundant submarine basalt flows form Nikolai Greenstones; continued deposition of redbed sandstones, conglomerates, tuffs, argillites, and limestones; Pingston, McKinley, and Chulitna terranes are pushed toward the margin of North America. |
| | PALEOZOIC | PERMIAN | | Deposition of alternating limestone and argillite beds of the Eagle Creek Formation, as well as massive marine limestone, mudstone, and greywacke. |
| | | PENNSYLVANIAN | | Widespread volcanism forms andesitic Tetelna Volcanics, later metamorphosed to greenschist; continued marine deposition of cherts, pillow basalts, shales, fossiliferous limestones, sandstones, and argillites. |
| | | MISSISSIPPIAN | | Moose Creek Member basaltic to intermediate volcanism, later metamorphosed to greenschists (Totatlanika Schist). |
| | | DEVONIAN | | Andesitic tuff from island arc volcanism, red and brown chert deposits, and shallow marine basin limestone. |
| | | SILURIAN | | Marine deposition and coral growth; intermittent volcanic activity. Continued deposition of turbidites, sandstones, argillites, dolomitic limestones, cherts, volcanic flows and ash falls, shales, and conglomerates; intermittent igneous activity, including mafic dike intrusions; multiple phases of deformation and metamorphism change sediments to quartzites, phyllites, slates, marbles, gneisses, meta-volcaniclastic schists, and greenstones. |
| | | ORDOVICIAN | | |
| | | CAMBRIAN | | |
| PRECAMBRIAN | | | | Shallow marine basins covered large area south of ancient North American continent; resulted in deposition of quartz-rich sediments interlayered with volcanic flows and ash and limestone. Formations include Keavy Peak Formation and Birch Creek Schist. |

# Glossary

*This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).*

**accretionary prism.** A wedge-shaped body of rock consisting of rocks scraped off of subducting oceanic crust at a subduction zone. Rocks consist of trench-fill turbidites, seamounts and surrounding reefs. Accretionary prisms form in the same manner as a pile of snow in front of a snowplow.

**active margin.** A tectonically active margin where lithospheric plates converge, diverge or slide past one another (also see "passive margin"). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism.

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

**alluvium.** Stream-deposited sediment.

**alpine glacier.** A glacier occurring in a mountainous region on the sides of a mountain.

**altiplanation.** Soliflucation and related mass movements that tend to produce flat or terrace-like surfaces, especially at high elevation and latitudes where periglacial processes predominate.

**andesite.** A dark-colored, fine-grained extrusive rock that, when porphyritic, contains phenocrysts composed primarily of zoned sodic plagioclase and one or more of the mafic minerals with a groundmass composed generally of the same minerals as the phenocrysts.

**angular unconformity.** An unconformity where the strata above and below are oriented differently; generally caused by structural deformation and erosion prior to deposition of the upper bed.

**anticline.** A convex-upward ("A" shaped) fold. Older rocks are found in the center.

**anticlinorium.** A large, regional feature with an overall shape of an anticline. Composed of many smaller folds.

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

**arête.** A rocky sharp-edged ridge or spur, commonly present above the snowline in rugged mountains sculptured by glaciers, and resulting from the continued backward growth of the walls of adjoining cirques.

**argillite.** A compact rock, derived from mudstone or shale, more highly cememted than either of those rocks. It lacks the fissility (easily split) of shale or the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

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

**asthenosphere.** Earth's relatively weak layer or shell below the lithosphere.

**axis (fold).** A straight line approximation of the trend of a fold, that divides the two limbs of the fold.

**base flow.** Stream flow supported by groundwater flow from adjacent rock, sediment, or soil.

**base level.** The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist.

**basement.** The undifferentiated rocks, commonly igneous and metamorphic, that underlie the rocks exposed at the surface.

**basin (sedimentary).** Any depression, from continental to local scales, into which sediments are deposited.

**basin (structural).** A doubly-plunging syncline in which rocks dip inward from all sides (also see "dome").

**batholith.** A massive, discordant pluton, greater than 100 $km^2$, (40 $mi^2$) often formed from multiple intrusions.

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

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

**bedrock geology.** The geology of underlying solid rock as it would appear with the sediment, soil, and vegetative cover stripped away.

**bergschrund.** The crevasse occurring at the head of an alpine glacier, which separates the moving snow and ice of the glacier from the relatively immobile snow and ice adhering to the headwall of a cirque.

**block (fault).** A crustal unit bounded by faults, either completely or in part.

**blueschist.** A schistose metamorphic rock with a blue color due to the presence of sodic amphibole, e.g. the minerals glaucophane or crosstie, and commonly mottled bluish-gray lawsonite. Often associated with high pressure, relatively low temperature metamorphic conditions.

**braided stream.** A stream, clogged with sediment that forms multiple channels that divide and rejoin.

**breccia.** A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

**brittle.** Describes a rock that fractures before sustaining deformation.

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

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

**cataclasite.** A fine-grained rock formed by pervasive fracturing, milling, crushing, and grinding by brittle deformation, typically under conditions of elevated pressure.

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

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

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

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

**cirque.** A deep, steep-walled, half-bowl-like recess or hollow located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier. It often contains a small round lake.

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

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

**cleavage.** The tendency of a rock to split along parallel, closely spaced planar surfaces. It is independent of bedding and is produced by deformation or metamorphism.

**concordant.** Strata with contacts parallel to the attitude of adjacent strata.

**congeliturbate.** Mass of soil or other unconsolidated material moved or disturbed by frost action.

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

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

**continental shield.** A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone only gentle warping compared to the intense deformation of bordering crust

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

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

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

**crevasse.** A deep fissure or crack in a glacier, caused by stresses resulting from differential movement over an uneven surface. Crevasses may be as much as 100 m (330 ft) deep.

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

**cross-bedding.** Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions (e.g., direction and depth).

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

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

**dacite.** A fine-grained extrusive rock with the same general composition as andesite, but having a less calcic plagioclase and more quartz.

**debris cone.** A cone or mound of ice or snow on a glacier, covered with a veneer of debris thick enough to protect the underlying material from ablation.

**debris flow**. A rapid and often sudden flow or slide of rock and soil material involving a wide range of types and sizes.

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

**dike.** A tabular, discordant igneous intrusion.

**dip.** The angle between a bed or other geologic surface and horizontal.

**dip-slip fault.** A fault with measurable offset where the relative movement is parallel to the dip of the fault.

**disconformity.** An unconformity at which the bedding of the strata above and below are parallel.

**discordant.** Having contacts that cut across or are set an angle to the orientation of adjacent rocks.

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

**drainage basin.** The total area from which a stream system receives or drains precipitation runoff.

**drift.** All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier.

**ductile.** Describes a rock that is able to sustain deformation before fracturing.

**eolian.** Formed, eroded, or deposited by or related to the action of the wind.

**extrusive.** Of or pertaining to the eruption of igneous material onto the surface of Earth.

**facies (metamorphic).** The pressure-temperature regime that results in a particular, distinctive metamorphic mineralogy (i.e., a suite of index minerals).

**facies (sedimentary).** The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

**fan delta.** An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

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

**fault gouge.** Soft, uncemented, pulverized, clay-like material found along some faults formed by friction as the fault moves.

**felsic.** Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

**flysch.** A marine sedimentary facies characterized by a thick sequence of poorly fossiliferous, thinly bedded, graded marls and sandy and calcareous shales and muds, rhythmically interbedded with conglomerates (rare), coarse sandstones, and graywackes. Typically deposited in deep ocean basins near convergent plate boundaries and rising mountains.

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

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

**fracture.** Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

**frost wedging.** The breakup of rock due to the expansion of water freezing in fractures.

**gelifluction.** Progressive lateral flow of earth material under periglacial conditions.

**geology.** The study of Earth, including its origin, history, physical processes, components, and morphology.

**graben.** A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

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

**graywacke.** A term commonly used in the field for a dark gray to dark green, very hard, dense sandstone of any composition but with a chlorite-rich matrix; these rocks have undergone deep burial.

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

**hanging valley.** A tributary glacial valley whose mouth is high above the floor of the main valley, which was eroded by the main body of the glacier.

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

**horn.** A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.

**horst.** Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

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

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

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

**isostasy.** The process by which the crust "floats" at an elevation compatible with the density and thickness of the crustal rocks relative to underlying mantle.

**isostatic adjustment.** The shift of the lithosphere to maintain equilibrium between units of varying mass and density; excess mass above is balanced by a deficit of density below, and vice versa.

**joint.** A semi-planar break in rock without relative movement of rocks on either side of the fracture surface.

**laccolith.** A mushroom- or arcuate-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers. Common on the Colorado Plateau.

**lacustrine.** Pertaining to, produced by, or inhabiting a lake or lakes.

**lamination.** Very thin, parallel layers.

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

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

**lignite.** A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

**limbs.** Either side of a structural fold.

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

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

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

**loess.** Windblown silt-sized sediment, generally of glacial origin.

**mafic.** Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

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

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

**matrix.** The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

**meander.** Sinuous lateral curve or bend in a stream channel.

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

**mélange.** A mappable body of jumbled rock that includes fragments and blocks of all sizes, both exotic and native, embedded in a fragmented and generally sheared matrix.

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

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

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

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

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

**migmatite.** Literally, "mixed rock" with both igneous and metamorphic characteristics due to partial melting during metamorphism.

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

**monocline.** A one-limbed flexure in strata, which are usually flat-lying except in the flexure itself.

**monzonite.** A group of plutonic rocks containing approximately equal amounts of alkali feldspar and plagioclase, little or no quartz, and commonly augite as the main mafic mineral. Intrusive equivalent of latite.

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

**mole track.** A small, geologically short-lived ridge, formed by the humping up and cracking of the ground where movement along a large strike-slip fault occurred in heavily alluviated terrain.

**moulin.** A roughly cylindrical, nearly vertical hole or shaft in the ice of a glacier, scoured out by swirling meltwater as it pours down from the surface.

**mylonite.** A fine-grained, foliated rock typically found in localized zones of ductile deformation, often formed at great depths under high temperature and pressure.

**nappe.** A sheetlike, allochthonous (manufactured elsewhere) rock unit that has moved in a predominantly horizontal surface. The mechanism may be thrust faulting, recumbent folding, or gravity sliding.

**nonconformity.** An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks.

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

**obduction.** The process by which the crust is thickened by thrust faulting at a convergent margin.

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

**orogeny.** A mountain-building event.

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

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

**overbank deposits.** Alluvium deposited outside a stream channel during flooding.

**overburden.** Non-economic, often unconsolidated, rock and sediment overlying an ore, fuel, or sedimentary deposit.

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

**paleontology.** The study of the life and chronology of Earth's geologic past based on the fossil record.

**Pangaea.** A theoretical, single supercontinent that existed during the Permian and Triassic periods (also see Laurasia and Gondwana).

**parent (rock).** The original rock from which a metamorphic rock was formed. Can also refer to the rock from which a soil was formed.

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

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

**periglacial.** Describes processes, climates, and features at the margin of former or existing glaciers or icesheets influenced by the cold temperatures of the ice.

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

**phenocryst.** A coarse crystal in a porphyritic igneous rock.

**placer.** A surficial mineral deposit formed by mechanical concentration of mineral particles from weathered debris. The mineral concentrated is usually a heavy mineral such as gold, cassiterite, or rutile.

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

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

**plutonic.** Describes igneous rock intruded and crystallized at some depth beneath Earth's surface.

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

**porphyry.** An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

**potassium feldspar.** An alkali feldspar rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

**Principal of Original Horizontality.** The concept that sediments are originally deposited in horizontal layers and that deviations from the horizontal indicate post-depositional deformation.

**Principle of Superposition.** The concept that sediments are deposited in layers, one atop another, i.e., the rocks on the bottom are oldest with the overlying rocks progressively younger toward the top.

**progradation.** The seaward building of land area due to sedimentary deposition.

**protolith.** The parent or unweathered and/or unmetamorphosed rock from with regolith or metamorphosed rock is formed.

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

**radioactivity.** The spontaneous decay or breakdown of unstable atomic nuclei.

**radiometric age.** An age in years determined from radioisotopes and their decay products.

**red beds.** Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric oxide (hematite) coating individual grains.

**regolith.** General term for the layer of rock debris, organic matter, and soil that commonly forms the land surface and overlies most bedrock.

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

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

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

**rhyolite.** A group of igneous rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

**rift valley.** A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

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

**roundness.** The relative amount of curvature of the "corners" of a sediment grain, especially with respect to the maximum radius of curvature of the particle.

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

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

**scarp.** A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

**seafloor spreading.** The process in which tectonic plates diverge and new lithosphere is created at oceanic ridges.

**seamount.** An elevated portion of the sea floor, 1,000 m (3,300 ft)or higher, either flat-topped or peaked.

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

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

**sequence.** An informal rock-stratigraphic unit that is traceable over large areas and defined by a major sea level transgression-regression sediment package.

**serpentinite.** A rock consisting almost wholly of serpentine-group minerals, e.g. antigorite and chrysotile, commonly derived from the alteration of peridotite. Accessory chlorite, talc, and magnetite may be present.

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

**sill.** A tabular, igneous intrusion that is concordant with the surrounding rock.

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

**siltstone.** A variable-lithified sedimentary rock with silt-sized grains.

**slickenside.** A smoothly polished and often striated surface representing deformation of a fault plane.

**slope.** The inclined surface of any geomorphic feature or measurement thereof. Synonymous with gradient.

**slump.** A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

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

**soliflucation.** The slow downslope movement of waterlogged soil, normally at 0.5–5.0 cm/year (0.2–2 in/year), especially the flow occurring at high elevations in regions underlain by frozen ground that acts as a downward barrier to water percolation, initiated by frost action and augmented by meltwater resulting from alternate freezing and thawing of snow and ground ice.

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

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

**stratigraphy.** The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

**stream.** Any body of water moving under gravity flow in a clearly confined channel.

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

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

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

**subbituminous.** A black coal, intermediate in rank between lignite and bituminous coal. It is distinguished from lignite by higher carbon and lower moisture content.

**subsidence.** The gradual sinking or depression of part of Earth's surface.

**suture.** The linear zone where two continental landmasses become joined due to obduction.

**system (stratigraphy).** The group of rocks formed during a period of geologic time.

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

**terraces (stream).** Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

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

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

**terrigenous.** Derived from the land or a continent.

**theory.** A hypothesis that has been rigorously tested against further observations or experiments to become a generally-accepted tenet of science.

**thermokarst topography.** An irregular land surface containing cave-in lakes, bogs, caverns, pits, and other small depressions formed in a permafrost region by the melting of ground ice.

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

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

**tonalite.** A plutonic rock with the composition of diorite, but with an appreciable amount of quartz (between 5 and 20 percent of the light-colored constituents).

**topography.** The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

**trace (fault).** The exposed intersection of a fault with Earth's surface.

**trace fossils.** Sedimentary structures, such as tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

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

**travertine.** A limestone deposit or crust, often banded, formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves.

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

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

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

**uplift.** A structurally high area in the crust, produced by movement that raises the rocks.

**vent.** An opening at Earth's surface where volcanic materials emerge.

**volcanic.** Related to volcanoes. Igneous rock crystallized at or near the Earth's surface (e.g., lava).

**water table.** T The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

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

**xenolith.** A foreign rock entrained in magma as an inclusion.

# Literature Cited

*This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.*


Adamczak, S., Jr., R. D. Abbott, and F. J. Wuttig. 2004. “Earthquake Hazards: Geotechnical Design Concerns. A Review Based on the November 3, 2002 Alaska Earthquake.” In *It's a Cool World,* eds. Daniel W. Smith, David C. Sego, and Charles A. Lendzion. Proceedings of the International Symposium on Cold Regions Engineering 12: unpaginated.

Adams, P. C. 1999. “Fluvial Geomorphic Processes and Succession on the Tanana River Floodplain.” In *Arctic Science Conference Program and Abstracts* 50: 161.

Adema, G. W., P. Brease, and A. Bucki. 2003. “Glacier Monitoring in Denali National Park and Preserve.” In *Geological Society of America Abstracts With Programs* 35 (6): 132.

Alaska Department of Environmental Conservation (ADEC). 2006. *Contaminated Sites Program – Database Results*. Division of Spill Prevention and Response, Contaminated Sites Program http://www.dec.state.ak.us/SPAR/csp/ (accessed August 30, 2006).

Aochi, H., O. Scotti, and C. Berge-Thierry. 2005. “Dynamic Transfer of Rupture Across Differently Oriented Segments in a Complex 3-D Fault System.” In *Geophysical Research Letters* 32 (21): 4 pp.

Axford, Y. L. and A. Werner. 1997. “A Lacustrine Record of Late-Glacial/Holocene Environmental Change: Pork Chop Pond, Denali National Park, AK.” In *Geological Society of America Abstracts With Programs* 29 (6): 35, 1997

Braile, L. W. 2009. Seismic monitoring. In *Geological Monitoring*, eds. R. Young and L. Norby, 229-244, Boulder, CO: Geological Society of America.

Brease, P. 2004. “Denali National Park and Preserve: South Central Alaska.” In *Geology of National Parks*, eds. A. G. Harris, E. Tuttle, and S. D. Tuttle: 477-504.

Brease, P., L. Stromquist, A. Fiorillo, and S. T. Hasiotis. 2009. “Cretaceous Dinosaurs in Denali—A Newly Discovered Resource Requires a New Management Plan.” In *Geological Society of America Abstracts With Programs* 41 (7): 150.

Bucki, A. K. and V.B. Valentine. 2003. “Thickness Changes of the Muldrow Glacier Near the Traleika Confluence, Denali National Park, Alaska.” In *Arctic Science Conference Program and Abstracts* 54: 199.

Bundtzen, T. K. 1981. Geology and Mineral Deposits of the Kantishna Hills, Mt. McKinley Quadrangle, Alaska. MS Thesis. Anchorage, AK: University of Alaska.

Burghardt, J. E. 1997. Mineral Report: Validity Examination of the Comstock #1 Lode, Comstock #2 Lode, Comstock #5 Lode, and Comstock #6 Lode Mining Claims. Unpublished report. Denver, CO: Geologic Resources Division, National Park Service.

Capps, S. R. 1933. *The Eastern Portion of Mount McKinley National Park [Alaska].* Bulletin B 0836-D: 219-300. Reston, VA: U. S. Geological Survey.

Carver, G., G. Plafker, M. Metz, L. Cluff, B. Slemmons, E. Johnson, J. Roddick, and S. Sorensen. 2004. “Surface Rupture on the Denali Fault Interpreted From Tree Damage During the 1912 Delta River Mw 7.2-7.4 Earthquake: Implications for the 2002 Denali Fault Earthquake Slip Distribution.” In *Bulletin of the Seismological Society of America* 94 (6B): S58-S71.

Cassidy, J. F. and G. C. Rogers. 2004. “The M (sub w) 7.9 Denali Fault Earthquake of 3 November 2002: Felt Reports and Unusual Effects across Western Canada.” In *Bulletin of the Seismological Society of America* 94 (6): Part B 53-57.

Clague, J. J. 1979. “The Denali Fault System in Southwest Yukon Territory: A Geologic Hazard?” In *Paper - Geological Survey of Canada* (79-1A): 169-178.

Clark, M. H. and M. S. Duffy. 2003. *Soil survey of Denali National Park area, Alaska.* Palmer, AK: Natural Resource Conservation Service. http://soildatamart.nrcs.usda.gov/Manuscripts/AK651/0/DenaliPark.pdf. Accessed 10 September 2010.

Clautice, K. H. and R. J. Newberry. 1999. “Geology and Geophysics of the Healy A-6 Quadrangle, Chulitna Mining District.” In *Arctic Science Conference Program and Abstracts* 50: 207-208.

Clautice, K. H., R. J. Newberry, R. B. Blodgett, T. K. Bundtzen, B. G. Gage, E. E. Harris, S. A. Liss, M. L. Miller, R. R. Reifenstuhl, and D. S. Pinney. 2001. Bedrock Geologic Map of the Chulitna Region, South-Central Alaska. RI2001-1A, 1C, 1D. State of Alaska Department of Natural Resources: Division of Geological and Geophysical Surveys.

Cole, R. B. 2004. “Dynamics of Tertiary Volcanism in Denali National Park, Alaska.” In *Geological Society of America Abstracts With Programs* 36 (5): 54-55.

Cole, R. B., K. D. Ridgway, P. W. Layer, and J. Drake. 1996. "Volcanic History, Geochronology, and Deformation of the Upper Cantwell Formation, Denali National Park, Alaska: Early Eocene Transition Between Terrane Accretion and Strike-Slip Tectonics." In *Geological Society of America Abstracts With Programs* 28 (7): 313.

Cole, R. B., W. M. Brewer, and B. P. Hooks. 2002. "Melange and Late Paleozoic-Triassic(?) Chert, Limestone, and Pillow Basalt Along a Terrane Suture Zone South of the Denali Fault, Reindeer Hills, Alaska." In *Geological Society of America Abstracts With Programs* 34 (6): 44.

Condie, K. C. and R.E. Sloan. 1998. *Origin and Evolution of the Earth, Principles of Historical Geology*. Dubuque, IA: Prentice-Hall, Inc.

Coney, P. J., N. J. Silberling, and D.L. Jones. 1980. "Accretionary Tectonic Styles in the Alaska Range." In *Eos, Transactions, American Geophysical Union* 61 (46): 1114.

Csejtey, B., Jr., D. P. Cox, R. C. Evarts, G. D. Stricker, and H. L. Foster. 1982. "The Cenozoic Denali Fault System and the Cretaceous Accretionary Development of Southern Alaska." In *Journal of Geophysical Research*. B 87 (5): 3741-3754.

Csejtey, B., Jr., A. B. Ford, C. T. Wrucke, J. T. Dutro, Jr., A. G. Harris, and P. F. Brease. 1995. "Geological Correlations across the Denali Fault in South-Central Alaska: Implications for Cenozoic Fault Displacement." In *Geological Society of America Abstracts With Programs* 27 (5): 12-13.

Denali National Park and Preserve. 2009. *Denali National Park and Preserve Resource Stewardship Strategy 2008-2027 Summary*. http://www.nps.gov/dena/naturescience/rss.htm. Denali Park, AK: Denali National Park and Preserve. Accessed December 2009.

Densmore, R. V. 2005. "Succession on Subalpine Placer Mine Spoil: Effects of Revegetation with Alnus Viridis, Alaska, U.S.A." In *Arctic, Antarctic, and Alpine Research* 37 (3): 297-303.

Dumoulin, J. A., D. C. Bradley, and A. G. Harris. 1998. Sedimentology, Conodonts, Structure, and Regional Correlation of Silurian and Devonian Metasedimentary Rocks in Denali National Park, Alaska. U. S. Geological Survey Professional Paper P 1595: 71-98.

Dusel-Bacon, C., B. Csejtey, Jr., H. L. Foster, E. O. Doyle, W. J. Nokleberg, and G. Plafker. 1993. Distribution, Facies, Ages, and Proposed Tectonic Associations of Regionally Metamorphosed Rocks in East and South-Central Alaska. U. S. Geological Survey Professional Paper P 1497-C: C1-C72.

Dyson, J. L. 1966. *Glaciers and Glaciation in Glacier National Park*. Glacier Natural History Association, in cooperation with the National Park Service.

Eberhart-Phillips, D., P. J. Haeussler, J. T. Freymueller, A. D. Frankel, C. M. Rubin, P. Craw, N. A. Ratchkovski, G. Anderson, G. A. Carver, A. J. Crone, T. E. Dawson, H. Fletcher, R. Hansen, E. L. Harp, R. A. Harris, D. P. Hill, S. Hreinsdóttir, R. W. Jibson, L. M. Jones, R. Kayen, D. K. Keefer, C. F. Larsen, S. C. Moran, S. F. Personius, G. Plafker, B. Sherrod, K. Sieh, N. Sitar, and W. K. Wallace. 2003. "The 2002 Denali Fault Earthquake, Alaska: A Large Magnitude, Slip-Partitioned Event." In *Science* 300 (5622): 1113-1118.

Edwards, P., M. Tranel, P. Brease, and P. Sousanes. 2000. "Stream and River Water Quality in Denali National Park and Preserve, Alaska." In *American Water Resources Association Technical Publication Series* TPS 00-1: 203-207.

Elias, S. A., S. K. Short, and C. F. Waythomas. 1996. "Late Quaternary Environments, Denali National Park and Preserve, Alaska." In *Arctic* 49 (3): 292-305.

Eppinger, R. G., P. H. Briggs, J. G. Crock, A. L. Meier, S. J. Sutley, and P. M. Theodorakos. 2002. Environmental-Geochemical Study of the Slate Creek Antimony Deposit, Kantishna Hills, Denali National Park and Preserve, Alaska. Professional Paper P 1662: 123-141. Reston, VA: U. S. Geological Survey.

Fitzgerald, P. G., E. Stump, and T. F. Redfield. 1993. "Late Cenozoic Uplift of Denali and its Relation to Relative Plate Motion and Fault Morphology." In *Science* 259 (5094): 497-499.

Ford, A. B., B. Csejtey, Jr., and C. T. Wrucke. 2003. "Denali Fault Geologic Relations at Gunsight Pass, Denali National Park, Alaska." In *Geological Society of America Abstracts With Programs* 35 (6): 561.

Gangloff, R. A. 1999. "Arctic Dinosaurs and Their Cretaceous Record in Alaska." In *Arctic Science Conference Program and Abstracts* 50: 288-289.

Garcia, R., F. Crespon, V. Ducic, and P. Lognonne. 2005. "Three-Dimensional Ionospheric Tomography of Post-Seismic Perturbations Produced by the Denali Earthquake from GPS Data." In *Geophysical Journal International* 163 (3): 1049-1064.

Gilbert, W. G. 1979. A Geologic Guide to Mount McKinley National Park. Anchorage, AK: Alaska Natural History Association.

Goldfarb, R. J., L. D. Miller, D. L. Leach, and L. W. Snee. 1997. "Gold Deposits in Metamorphic Rocks of Alaska." In *Economic Geology Monographs* 9: 151-190.

Gough, L. P. and J. G. Crock. 1997. Distinguishing Between Natural Geologic and Anthropogenic Trace Element Sources, Denali National Park and Preserve. Professional Paper P 1574: 54-71. Reston, VA: U. S. Geological Survey.

Greenwood, S. M. and G. Rowell. 1980. "Mount McKinley." In *America's Magnificent Mountains*, pref. Sterling B. Hendricks, 90-103, Washington, DC: National Geographic Society Special Publications Division.

Haeussler, P. J. 2005. "What made Denali so Tall? Structural Geology of the High Peaks of the Alaska Range." In *Geological Society of America Abstracts With Programs* 37 (7): 79.

Harp, E. L., R. W. Jibson, R. E. Kayen, D. K. Keffer, B. L. Sherrod, G. A. Carver, B. D. Collins, R. E. S. Moss, and R. N. Sitar. 2003. "Landslides and Liquefaction Triggered by the M 7.9 Denali Fault Earthquake of 3 November 2002." In *GSA Today* 13 (8): 4-10.

Hickman, R. G., K. W. Sherwood, and C. Craddock. 1990. "Structural Evolution of the Early Tertiary Cantwell Basin, South-Central Alaska." In *Tectonics* 9(6): 1433-1449.

IPCC, 2007, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Geneva, Switzerland, Intergovernmental Panel on Climate Change, 104 p. (http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html, accessed March 6, 2010.)

Jones, D.L., N. J. Silberling, W. G. Gilbert, and P. J. Coney. 1980. "Age, Character, and Distribution of Accreted Terranes in the Central Alaska Range, South-Central Alaska." In *Eos, Transactions, American Geophysical Union* 61 (46): 1114.

Karl, T. R., Melillo, J. M., and Peterson, T. C. 2009. *Global climate change impacts in the United States.* New York, NY: Cambridge University Press. http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts. Accessed 17 September 2010.

Karpilo, R. D., Jr. 2009. Glacier monitoring techniques. In *Geological Monitoring*, eds. R. Young and L. Norby, 141-162, Boulder, CO: Geological Society of America.

Karpilo, R. D, Jr., G. W. Adema, and B. F. Molina. 2004. "Documenting Glacier Change in Denali National Park and Preserve, Alaska." In *Geological Society of America Abstracts With Programs* 36 (5): 229.

Lillie, R. J. 2005. Parks and Plates: The Geology of our National Parks, Monuments, and Seashores. New York: W.W. Norton and Company.

Lowey, G. W. 1998. "A New Estimate of the Amount of Displacement on the Denali Fault System Based on the Occurrence of Carbonate Megaboulders in the Dezadeash Formation (Jura-Cretaceous), Yukon, and the Nutzotin Mountains Sequence (Jura-Cretaceous), Alaska." In *Bulletin of Canadian Petroleum Geology* 94: 4333-4359.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. In *Geological Monitoring*, eds. R. Young and L. Norby, 69-103, Boulder, CO: Geological Society of America.

Mann, D. H. 1999. "Development of Taiga Vegetation and Soils over Millennial Time Scales in Denali National Park." In *Arctic Science Conference Program and Abstracts* 50: 229.

Matmon, A., D. Schwartz, H. Stenner, J. Lienkamper, T. Dawson, P. J. Haeussler, L. Staft, and R. C. Finkel. 2004. Determining Holocene and Late Pleistocene Slip Rates Along the Denali Fault Using Cosmogenic (Super 10) Be Analysis of Boulders on Displaced Moraines." In *Geological Society of America Abstracts With Programs* 36 (5): 137.

Matmon, A., D. P. Schwartz, P. J. Haeussler, R. Finkel, J. J. Lienkamper, H. D. Stenner, and T. E. Dawson. 2006. "Denali Fault Slip Rates and Holocene-Late Pleistocene Kinematics of Central Alaska." In *Geology* 34: 645-644.

McCauley, C. A., M. R. Lilly, D. M. Nyman, and D. M. White. 1999. "Measuring the Potential of Permafrost as an Environmental Barrier by a Diesel/Jet Fuel In-situ Infiltration Test in Bethel, Alaska." In *Arctic Science Conference Program and Abstracts* 50: 275-276.

Meisling, K. E., M. C. Gardner, G. W. Cushing, and S. C. Bergman. 1987. "A Reconstruction of Southern Alaska at 75 Ma." In *Geological Society of America Abstracts With Programs* 19 (7): 769.

Metz, P. A., C. J. Freeman, D. D. Adams, and J. C. Balla. 1989. "Late Proterozoic Precious Metal Bearing Sequences in Interior Alaska." In *Geological Society of America Abstracts With Programs* 21 (5): 116-117.

Miller, M. L., D. C. Bradley, T. K. Bundtzen, and W. C. McClelland. 2002. "Late Cretaceous through Cenozoic Strike-Slip Tectonics of Southwestern Alaska." In *Journal of Geology* 110 (3): 247-270.

Miller, T. P. 1994. "Pre-Cenozoic Plutonic Rocks in Mainland Alaska." In *The Geology of Alaska*, eds. G. Plafker and H. C. Berg., 535-554 Boulder, CO: Geological Society of America.

Molina, B. F. and M. Sfraga. 1999. "Measuring and Monitoring Changes in Alaska's Glaciers with Ground, Aerial, and Space Photography: A History." In *Arctic Science Conference Program and Abstracts* 50: 78-79.

Moore, T. T., A. Grantz, and S. M. Roeske. 1994. "Continent-Ocean Transition in Alaska: The Tectonic Assemblage of Eastern Denalia." In *Phanerozoic Evolution of North America Continental-Ocean Transition,* ed. R. C. Speed. Geological Society of America, DNAG Continental-Ocean Transect Volume: 399-441.

National Park Service. 2006. Soil Survey Geographic (SSURGO) database for Denali National Park and Preserve, Alaska. Denver, CO: National Park Service Geologic Resources Division. http://science.nature.nps.gov/nrdata/datastore.cfm?ID=48854. Accessed 10 September 2010.

National Park Service. 2009. Glaciers/Glacial Features. Online feature. Denali Park, AK: Denali National Park and Preserve. http://www.nps.gov/dena/naturescience/glaciers.htm. Accessed 16 September 2010.

Newkirk, S. R. 2005. "Tectonic Setting and Lithogeochemical Characteristics of Metavolcanics and Metabasite Sills of the Delta District, East-Central Alaska Range, Alaska." In *Geological Society of America Abstracts With Programs* 37 (2): 35.

Nixon, G. T. 2003. "Use of Spinel in Mineral Exploration: The Enigmatic Giant Mascot Ni-Cu-PGE Deposit - Possible Ties to Wrangellia and Metallogenic Significance." In *Geological Fieldwork 2002: A Summary of Field Activities and Current Research*. Geological Fieldwork, Report: 2003-1: 115-128. Victoria, BC: British Columbia Ministry of Energy and Mines, Resource Development Division, Geological Survey Branch.

Nokleberg, W. J., G. Plafker, and F. H. Wilson. 1994. "Geology of South-Central Alaska." In *The Geology of Alaska*, eds. George Plafker and Henry C. Berg., 311-366 Boulder, CO: Geological Society of America.

Norris, F. 1998. "Gold Rush-Era Mining Sites in Alaska's National Parks." In *CRM (Washington, D.C.)* 21 (7): 30-31.

Osterkamp, T. E. and M. T. Jorgenson. 2009. Permafrost conditions and processes. In *Geological Monitoring*, eds. R. Young and L. Norby, 205-227, Boulder, CO: Geological Society of America.

Petrone, K. C., L. D. Hinzman, and R. D. Boone. 1999. "The Influence of Permafrost and Fire Disturbance on Nitrogen and Carbon Concentrations in Three Subarctic Streams." In *Arctic Science Conference Program and Abstracts* 50: 202.

Pfeiffer, T. J., and S. L. Bednarz. 2000. "The Influence of Structural Geology on a Massive Landslide in Denali National Park, Alaska." In *Annual Meeting - Association of Engineering Geologists* 43 (4): 107.

Plafker, G., W. J. Nokleberg, and J. S. Lull. 1989. "Bedrock Geology and Tectonic Evolution of the Wrangellia, Peninsular, and Chugach Terranes Along the Trans-Alaska Crustal Transect in the Chugach Mountains and Southern Copper River Basin, Alaska." In *Journal of Geophysical Research, B, Solid Earth and Planets* 94 (4): 4255-4295.

Popovics, L. M., A. M. Milner, and C.L . Ping. 1999. "The Effect of Soil and Stream Water Quality on Primary and Secondary Productivity of Rock Creek, Denali National Park and Preserve, Alaska." In *Arctic Science Conference Program and Abstracts* 50: 194-195.

Prindle, L. M. 1907. *The Bonnifield & Kantishna Regions, Alaska*. Bulletin 314-L. Reston, VA: U.S. Geological Survey.

Ratchkovski, N. A., S. Wiemer, and R. A. Hansen. 2004. "Seismotectonics of the Central Denali Fault, Alaska, and the 2002 Denali Fault Earthquake Sequence." In *Bulletin of the Seismological Society of America* 94 (6): Part B 156-174.

Redfield, T. F. and P. G. Fitzgerald. 1993. "Denali Fault System of Southern Alaska: An Interior Strike-Slip Structure Responding to Dextral and Sinistral Shear Coupling." In *Tectonics* 12 (5): 1195-1208.

Redfield, T. F. and P. G. Fitzgerald. 2000. "Plate Kinematics, Escape Tectonics, and the Denali Fault System of Cenozoic South Central Alaska." In *Eos, Transactions, American Geophysical Union* 81 (48): Suppl. 1123.

Redfield, T. F., D. W. Scholl, M. E. Beck, and P. G. Fitzgerald. 2005. "Escape Tectonics and Plate Kinematics in the South-Central Alaskan Orocline." In *Geological Society of America Abstracts With Programs* 37 (7): 79.

Reed, B.L and S. W. Nelson. 1977. *Geologic map of the Talkeetna Quadrangle, Alaska*. Miscellaneous Field Studies Map 870-A. Reston, VA: U.S. Geological Survey.

Richter, D. H. and D. L. Jones. 1973. "Structure and Stratigraphy of Eastern Alaska Range, Alaska." In *Arctic Geology Memoir - American Association of Petroleum Geologists* 19: 408-420.

Ridgway, K. D., J. M. Trop, W. J. Nokleberg, C. M. Davidson, and K. R. Eastham. 2002. "Mesozoic and Cenozoic Tectonics of the Eastern and Central Alaska Range: Progressive Basin Development and Deformation in a Suture Zone." In *Geological Society of America Bulletin* 114 (12): 1480-1504.

Roeske, S. M., B. A. Hampton, K. D. Ridgway, and G. E. Gehrels. 2005. Cryptic Strike-Slip Faults and Dismembered Ophiolites: Potential Tracers of the Alaska Range Suture Zone." In *Geological Society of America Abstracts With Programs* 37 (4): 80.

Roush, J., and P. Brease. 1997. Glacier Monitoring in Denali National Park and Preserve, Alaska: Integrating Field Study and Remote Sensing. Open-File Report 98-0031. Reston, VA: U.S. Geological Survey.

Ruppert, N.A., K.D. Ridgway, J.T. Freymueller, R.S. Cross, and R.A. Hansen. 2008. Active tectonics of interior Alaska: Seismicity, GPS geodesy, and local geomorphology. In *Active Tectonics and Seismic Potential in Alaska,* eds Freymueller, J.T., et al., *Geophysical Monograph Series,* 179: 109-133.

Salisbury and Dietz, Inc. 1984. *Kantishna Hills and Dunkle Mine Areas,Denali National Park and Preserve, Alaska*. 1983 Mineral Resource Studies, Contract S0134031. Washington, DC: U.S. Bureau of Mines.

Santucci, V. L., J. P. Kenworthy and A. L. Mims. 2009. Monitoring in situ paleontological resources. In *Geological Monitoring*, eds. R. Young and L. Norby, 189-204, Boulder, CO: Geological Society of America.

Schwartz, D. P, P. J. Haeussler, A. Matmon, T. E. Dawson, G. Seitz, H. Stenner, S. Bemis, E. Molhoek, B. Sherrod, A. J. Crone, S. Personius, P. A. Craw, and J. Beget. 2005. *Earthquake Geology of the Denali Fault System, Alaska*. Open-File Report 2005-1131: 25-29. Reston, VA: U. S. Geological Survey.

Seraphim, R. H. 1975. "Denali: A Monmetamorphosed Stratiform Sulfide Deposit." In *Economic Geology and the Bulletin of the Society of Economic Geologists* 70 (5): 949-959.

St. Amand, P. 1957. Geological and geophysical synthesis of the tectonics of portions of British Columbia, the Yukon Territory and Alaska. *Geological Society of America Bulletin* 68: 1343-1370.

Stone, D. B.. 1980. "Timing of Accretion of Alaskan Tectonostratigraphic Terranes." In *Eos, Transactions, American Geophysical Union* 61 (46): 1114.

Stone, D. B. 1984. "Alaska: Geology and Tectonics." In *Biennial Report - Geophysical Institute, University of Alaska* 1983-84: 1-19.

Symons, D. T. A., M. J. Harris, J. E. Gabites, and C. J. R.Hart. 2000. "Eocene (51 Ma) End to Northward Translation of the Coast Plutonic Complex: Paleomagnetism and K-Ar Dating of the White Pass Dikes." In *Tectonophysics* 326 (1-2): 93-109.

Thorson, R. M. 1986. "Late Cenozoic Glaciation of the Nenana Valley." In *Glaciation in Alaska–The Geologic Record,* eds. T. D. Hamilton, K. M. Reed, and R. M. Thorson: 99-122. Fairbanks, AK: Alaska Geological Society.

Trop, J. M., K. D. Ridgway, and T. L. Spell. 2003. "Sedimentary Record of Transpressional Tectonics and Ridge Subduction in the Tertiary Matanuska Valley-Talkeetna Mountains Forearc Basin, Southern Alaska." In *Special Paper - Geological Society of America* 371: 89-118.

Van Maanen, J. L. and G. L. Solin. 1988. Hydraulic and Channel Characteristics of Selected Streams in the Kantishna Hills Area, Denali National Park and Preserve, Alaska, 1982-84. U. S. Geological Survey Open-File Report 88-0325.

Wahrhaftig, C. 1952. Geologic Map of Part of Healy C-4 Quadrangle, Alaska, Showing Pleistocene Deposits Along the Nenana River. U.S. Department of Interior: Geological Survey.

Wahrhaftig, C. 1970. Geologic Map of the Healy D-4 Quadrangle, Alaska. Geologic Quadrangle Map GQ-806. Reston, VA: U.S. Geological Survey.

Werner, A., R. M. Thorson, and N. W. Ten Brink. 1990. "Geology of the McKinley River Area, Denali National Park and Preserve, Alaska." In *Geological Society of America Abstracts With Programs* 22 (7): 176.

West, A. W., M. Keskinen, and S. Swanson. 1995. "Petrology of the Mt. McKinley Pluton, Denali National Park, Alaska." In *Geological Society of America Abstracts With Programs* 27 (5): 83-84.

White, J. C. 1997. "Deformation Processes Along the Denali Fault System." In *Lithoprobe Report* 56: 143-145.

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. In *Geological Monitoring*, eds. R. Young and L. Norby, 245-271, Boulder, CO: Geological Society of America.

Wilson, F. H., J. H. Dover, D. C. Bradley, F. R. Weber, T. K. Bundtzen, and P. J. Hauessler (compilers). 1998. *Geologic Map of Central (Interior) Alaska.* Open-File Report 98-133. Reston, VA: U.S. Geological Survey.

Zhang, T., R. G. Barry, and K. Knowles. 1999. "Characteristics of Permafrost and Ground Ice Distribution in the Northern Hemisphere." In *Arctic Science Conference Program and Abstracts* 50: 117-118.

# Appendix A: Overview of Digital Geologic Data

*The following page is an overview of the digital geologic data for Denali National Park and Preserve. For a poster-size PDF of this map and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).*

The overview incorporates the small scale (1:250,000) data set that encompasses the entire park and preserve. Larger scale (1:63,360) data is available for Chulitna region and Healy quadrangle.

# Appendix B: Scoping Session Participants

*The following is a list of participants from the GRI scoping session for Denali National Park and Preserve, held on February 24–26, 2004. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.*

| LAST NAME | FIRST NAME | AFFILIATION | TITLE | PHONE | E-MAIL |
|---|---|---|---|---|---|
| Adema | Guy | Denali National Park and Preserve | physical scientist | 907-683-6356 | guy_adema@nps.gov |
| Blodgett | Robert | U.S. Geological Survey | paleontologist | 907-786-7416 | rblodgett@usgs.gov |
| Brease | Phil | Denali National Park and Preserve | geologist | | phil_brease@nps.gov |
| Claudice | Karen | Alaska Division of Geological and Geophysical Surveys | geologist | 907-451-5023 | karen@dnr.state.ak.us |
| Connors | Tim | NPS, Geologic Resources Division | geologist | 303-969-2093 | tim_connors@nps.gov |
| Dickison | George | NPS, Alaska Regional Office | GIS coordinator | 907-644-3546 | george_dickison@nps.gov |
| Fiorillo | Tony | Dallas Museum of Natural History | paleontologist | 214-421-3466 x 234 | tfiorillo@dmnhnet.org |
| Gamble | Bruce | U.S. Geological Survey | geologist | 907-786-7479 | bgamble@usgs.gov |
| Giffen | Bruce | NPS, Alaska Regional Office | geologist | 907-644-3572 | bruce_giffen@nps.gov |
| Halloran | Jim | NPS, Alaska Regional Office | geologist | 907-644-3574 | jim_halloran@nps.gov |
| Heise | Bruce | NPS, Geologic Resources Division | geologist | 303-969-2017 | bruce_heise@nps.gov |
| Kucinski | Russell | NPS, Alaska Regional Office | geologist | 907-644-3571 | russ_kucinski@nps.gov |
| Liebsher | Tom | Yukon-Charley Rivers National Preserve | chief, natural resources | 907-455-0620 | thomas_liebsher@nps.gov |
| Norby | Lisa | NPS, Geologic Resources Division | geologist | 303-969-2318 | lisa_norby@nps.gov |
| Rosenkrans | Danny | Wrangell-St. Elias National Park and Preserve | geologist | 907-823-7240 | danny_rosenkrans@nps.gov |
| Sharp | Devi | Wrangell-St. Elias National Park and Preserve | chief, natural resources | 907-822-7212 | devi_sharp@nps.gov |
| Spencer | Page | NPS, Alaska Regional Office | ecologist | 907-644-3448 | page_spencer@nps.gov |
| Stevens | Deanne | Alaska Division of Geological and Geophysical surveys | geologist | 907-451-5014 | deanne@dnr.state.ak.us |
| Stromquist | Linda | NPS, Alaska Regional Office | geologist | 907-644-3576 | linda_stromquist@nps.gov |
| Wesser | Sara | NPS, Central Alaska Network | network coordinator | 907-644-3558 | sara_wesser@nps.gov |
| Wilder | Doug | NPS, Central Alaska Network | data manager | 907-455-0661 | doug_wilder@nps.gov |
| Wilson | Ric | U.S. Geological Survey | geologist | 907-786-7448 | fwilson@usgs.gov |

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National Park Service
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**Natural Resource Program Center**
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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