National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

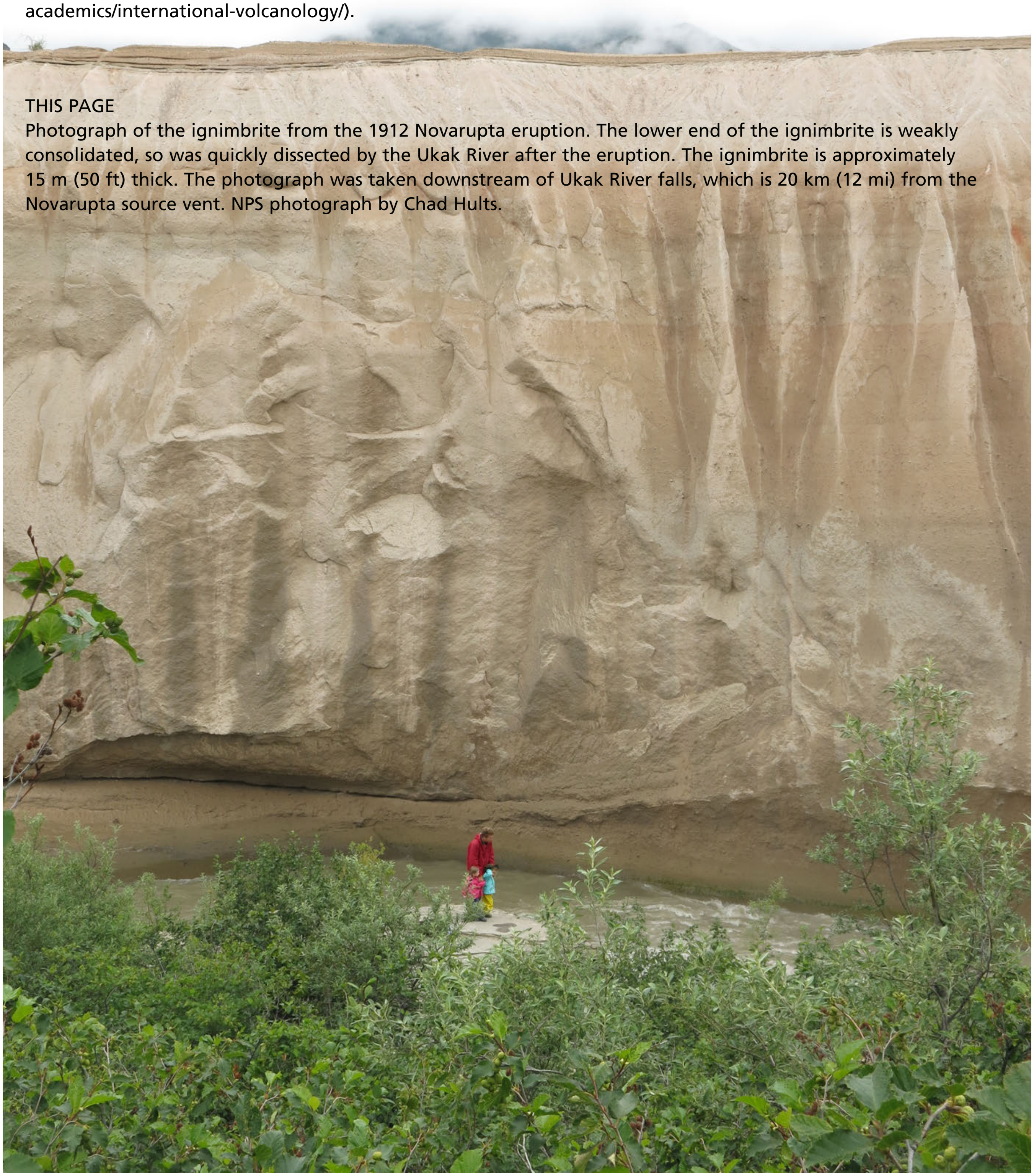
Katmai National Park and Preserve and Alagnak Wild River

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1314

ON THE COVER

Photograph of the Baked Mountain huts, a shelter for hikers and a temporary home for scientists, with Mount Griggs in the background. The huts were built by the University of Alaska Fairbanks (UAF) Geophysical Institute in 1965. At 2,330 m (7,650 ft) above sea level, Mount Griggs is the highest peak in Katmai National Park and Preserve. It lies 12 km (7 mi) behind the main volcanic front and has superheated, sulfur-precipitating fumaroles near its summit. The flanks of the volcano are covered with ash from the 1912 Novarupta eruption. Ignimbrite from the 1912 eruption fills the Knife Creek arm of the Valley of Ten Thousand Smokes. Alaska Volcano Observatory (AVO)/UAF Geophysical Institute photograph by Pavel Izbekov taken in 2008 during the International Volcanology Field School held annually in Katmai National Park (https://www.uaf.edu/geology/academics/international-volcanology/).



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Photograph of the ignimbrite from the 1912 Novarupta eruption. The lower end of the ignimbrite is weakly consolidated, so was quickly dissected by the Ukak River after the eruption. The ignimbrite is approximately 15 m (50 ft) thick. The photograph was taken downstream of Ukak River falls, which is 20 km (12 mi) from the Novarupta source vent. NPS photograph by Chad Hults.

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September 2016

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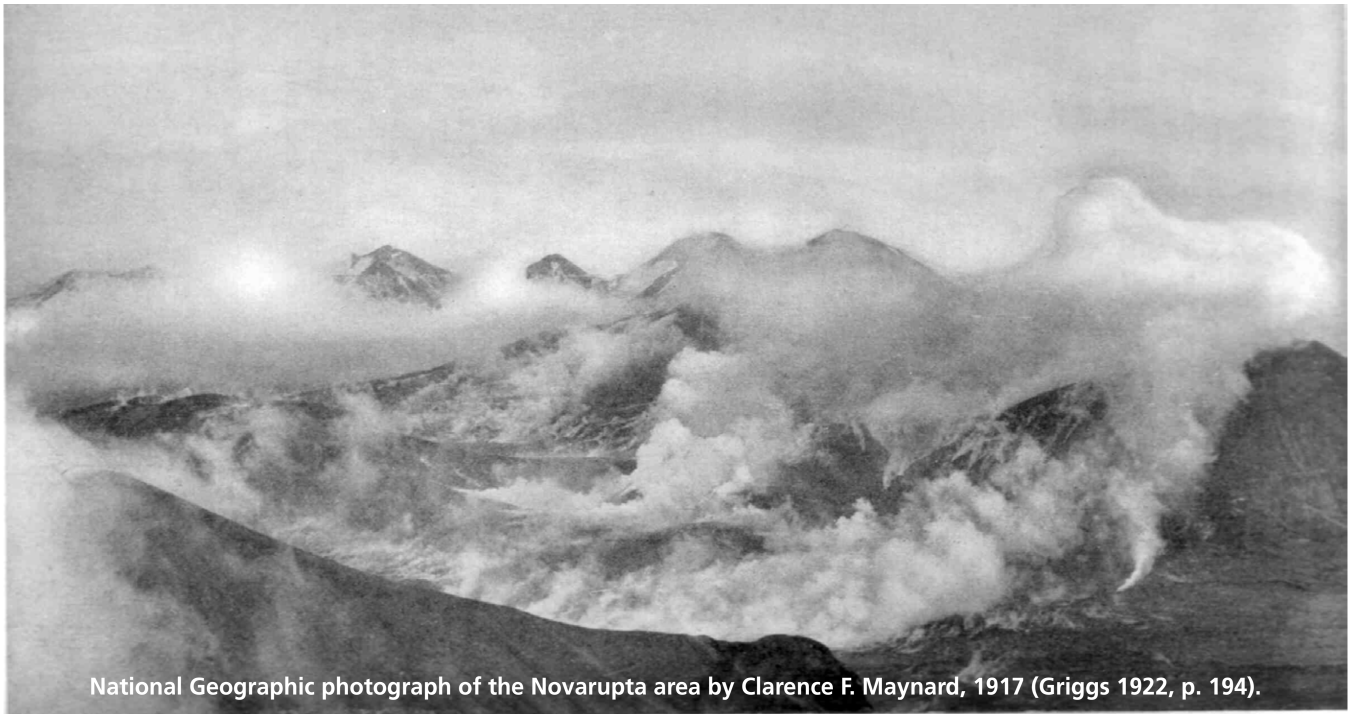

National Geographic photograph of the Novarupta area by Clarence F. Maynard, 1917 (Griggs 1922, p. 194).

The sight that flashed into view as we surmounted the hillock was one of the most amazing visions ever beheld by mortal eye. The whole valley as far as the eye could reach was full of hundreds, no thousands—literally, tens of thousands—of smokes curling up from its fissured floor.

From our position they looked as small as the little fumaroles nearby, but realizing something of their distance we knew many of them must be gigantic. Some were sending up columns of steam which rose a thousand feet before dissolving.

After careful estimate, we judged there must be a thousand whose columns exceeded 500 feet. A dozen miles away the valley turned behind a blue mountain in the distance. Plainly the smokes extended that far. How much farther we could not tell…

It was as though all the steam engines in the world, assembled together, had popped their safety valves at once and were letting off surplus steam in concert.

—Griggs (1922, p. 191)

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

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

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

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Hults, C. P. and J. Fierstein. 2016. Katmai National Park and Preserve and Alagnak Wild River: Geologic Resources Inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1314. National Park Service, Fort Collins, Colorado.

NPS 127/134578, September 2016

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information. Chapters of the report discuss distinctive geologic features and processes, describe the geologic history leading to the present-day landscape, highlight geologic issues facing resource managers, and provide information about the associated GRI geologic map data. A poster (Plate 1, in pocket) illustrates these data.

The largest volcanic eruption of the 20th century exploded 6 June 1912, from a new volcanic vent, Novarupta, creating the Katmai caldera and the Valley of Ten Thousand Smokes. The magnitude and volume of the eruption at Novarupta in 1912 were exceptional, far larger than any other historical eruption in North America. Katmai National Monument was established in 1918 to preserve the volcanic features formed by this eruption, and provide for the scientific study of these features and how the landscape recovers from the eruption. The monument was greatly expanded and redesignated as Katmai National Park and Preserve in 1980. Alagnak Wild River was also established in 1980 to protect the Alagnak River system, which is an important sockeye (red) salmon fishery, and critical to the economy, culture, recreation, and history of southwest Alaska. In this report the term "Katmai area" refers to Katmai National Park and Preserve, Alagnak Wild River, and the immediate surrounding area on the geologic map (see Plate 1, in pocket).

The primary geologic features and processes within the Katmai area are associated with the 1912 eruption and formation of the Valley of Ten Thousand Smokes. Two dozen volcanoes in the park have erupted in the past 2.6 million years.

- **Eruption Episodes.** The 1912 Novarupta-Katmai eruption consisted of three main explosive episodes originating from the Novarupta vent. Episode I, on 6 June, produced widespread fallout and ash flows from a high eruption column. Episodes II and III, on 7 and 8 June, were similar to each other; each began after an eruptive lull, and deposited widespread fall layers. These three episodes formed the ignimbrite (pumice rich ash flow deposit) of the Valley of Ten Thousand Smokes. The explosive episodes were followed by extrusion of three lava domes. Although the eruption took place at the Novarupta vent, the bulk of the magma was sourced from a chamber under Mount Katmai. As the magma chamber was depleted, the summit of the mountain collapsed and formed the Katmai caldera.
- **Landscape Changes Caused by the 1912 Eruption**. The eruption deposited 13 to 15 km^3 (3.1 to 3.6 mi^3) of mostly loose volcanic material on the surrounding landscape, which increased the sediment supply in streams. The valley of the River Lethe was filled with the ignimbrite sheet, which changed the valley from U-shaped and heavily vegetated to flat and nearly barren of vegetation. The accumulation of warm ash fall on snow caused rapid melting, which formed lahars that flowed down drainages surrounding Novarupta. Numerous, large landslides were caused by concurrent earthquakes, most notably the Katmai Canyon landslide, and the great Mageik Landslide. The Katmai Canyon landslide dammed the river for three years. The geomorphic and biologic processes in the first few years following the eruption were documented by the Griggs expeditions, but many of the processes observed then are continuing and evolving today.
- **Global Climate Effects of the 1912 Eruption**. Volcanic ash, more than from all other historical eruptions in Alaska combined, devastated areas hundreds of miles away, and the huge eruption column rose greater than 30,000 m (100,000 ft), where stratospheric winds carried the ash around the world. The ash shrouded most of southern Alaska and the Yukon Territory, and haze was noticed within a day of the eruption as far away as British Columbia, and in Europe two weeks later. The ash and aerosols shielded the sun's rays and lowered average temperatures about 1°C (2°F) in the Northern Hemisphere for more than a year.

- **Volcanoes**. The Katmai area contains the most active and dense group of stratovolcanoes of any national park. Katmai has 24 volcanoes that erupted in the last 2.6 million years (the Quaternary Period) with 36 volcanic vents. Ten of the Katmai volcanoes are considered active (Douglas, Fourpeaked, Kukak, Snowy, Griggs, Katmai, Novarupta, Trident, Mageik, Martin), and five of the volcanoes erupted during historic time (Fourpeaked, Kukak, Katmai, Novarupta, Trident). Trident Volcano erupted intermittently for 21 years between 1953 and 1974, forming lava flows and a lava dome on the southwest flank of the volcano. Fourpeaked volcano was thought to be dormant, so the small eruption on 17 September 2006 was a surprise. The eruption caused a glacial outburst flood and debris flow, and fumaroles emitted gases near the summit for a year after the eruption.

In addition to features and processes associated with volcanic eruptions and their deposits, the Katmai area contains other significant geologic features and processes, including the following:

- **Geothermal Features**. Katmai National Park and Preserve is one of 16 units of the National Park System with significant thermal features as designated by the Geothermal Steam Act of 1970 (amended in 1988).
    - **Fumaroles**. Fumaroles of the Valley of Ten Thousand Smokes made the Katmai area famous and prompted the formation of a national monument to preserve these unique features. Groundwater in the Valley of Ten Thousand Smokes interacted with the hot ignimbrite and steam escaped through fractures, forming the "smokes." As the ignimbrite sheet cooled, the smokes of the valley slowly extinguished. The fumaroles that are active today, at the summits and along the flanks of the volcanoes, expel volcanic gases, which are sourced from magma within the active volcanic systems. Active fumaroles exist on the following volcanoes: Novarupta dome, Trident, Martin, Mageik, Griggs, Kukak, Snowy, Fourpeaked, Douglas, and under the crater lakes of Katmai and Kaguyak.
    - **Warm Springs and Warm Ground**. Warm springs are present throughout the volcanic area of Katmai. In particular, warm springs still issue from the 1912 ignimbrite sheet and the Trident Volcano 1953–1960 lava flows. Warm ground has been documented near Novarupta dome and on Mount Griggs.
    - **Crater Lakes**. Six of the volcanoes in the Katmai area (Mageik, Martin, Katmai, Kaguyak, Douglas, and Savonoski) contain crater lakes. Mageik and Martin have shallow, very warm lakes fed by numerous fumaroles. The Katmai crater lake formed after the top of the mountain collapsed as a result of the 1912 eruption. The lake has progressively filled since the eruption.
- **Glaciations.** The Katmai area contains abundant, well preserved glacial moraines and other landforms created by past glacial advances. During the Pleistocene Epoch (2.6 million–0.01 million years ago [MYA]), the Alaska Peninsula held the western extent of the continental ice sheet that spanned northern North America. During the last glacial maximum, the entire Katmai area was covered by glacier ice, except for the highest peaks. Three major glaciations are recognized in the Katmai area: Johnson Hill glaciation (>43,000 years ago); Mak Hill glaciation (>43,000 years ago); and Brooks Lake glaciation (30,000–20,000 years ago). The Brooks Lake glaciation is divided into four stades: Kvichak; Iliamna; Newhalen; and Iliuk. Glacial deposits, Ukak drift and Katolinat till, from two younger (17,000–10,000 years ago) advances, are present near the Valley of Ten Thousand Smokes. Beach ridges and wave-cut terraces are found tens of meters above the present lake levels. The ridges and wave-cut terraces were formed by proglacial lakes that were larger and deeper than the present day lakes.
- **Modern Glacier Features and Changes**. Katmai contains an estimated 300 glaciers that more-or-less cover the volcanoes. Glacial area has decreased 14% since the 1950s. Most glaciers in the Katmai area are retreating, including notable retreats of up to 4 km (2.4 mi) for glaciers on Fourpeaked Mountain and Mount Douglas, and Hallo Glacier and others on Kukak Volcano. Some of the glaciers, however, have advanced, for example those that were covered by thick deposits of 1912 ash. Additionally, two glaciers have formed in the Katmai crater since the 1912 eruption.
- **Permafrost Features.** Although the average annual temperature at King Salmon is above freezing, isolated permafrost is present in the western

portion of the park unit, namely on the coastal plain under areas insulated by peat and thick vegetation mats. The presence of the permafrost is possibly due to the thermal properties of overlying peat, or remnants of the Pleistocene (2.6–0.01 MYA) glaciations. Polygonal ground is present at higher elevations on a pass near Kaguyak Crater. Climate scenarios indicate a rise in average annual temperature of 2.6°C (4.7°F) by 2040 in the Katmai area, and permafrost melting was identified as a potential major change to the park. Periglacial features in the Katmai area also include patterned ground, solifluction deposits, and rock glaciers.

- **Coastal Features.** The Katmai coast is a mix of rugged wave-eroded sea cliffs on the headlands and protected bays.
  - **Beach Berms**. Beach berms are present in many of the protected bays, including some places with stranded shorelines far inland from the modern shoreline.
  - **Raised marine terraces and sea caves**. Raised marine terraces are present along the coast of Shelikof Strait and Katmishak Bay at 15 m (50 ft), 27 m (90 ft), and between 40 and 45 m (130 and 150 ft) above the modern high tide line. Relict beaches, sea caves, and sea cliffs are found well above modern sea level, as a result of ongoing uplift. The uplift rate of the coast is approximately 3–8 mm/yr (0.1–0.3 in/yr).
- **Modern Surficial Deposits and Processes.** Modern surficial deposits have formed in the last few thousand years, and many are still forming today. They include swamp deposits in bogs and ponds, alluvium along modern rivers, alluvial fans along mountain fronts, landslide and colluvium below cliff faces and along steep slopes, and dunes in the Valley of Ten Thousand Smokes and near beaches along the coast.
- **Mesozoic Bedrock.** Katmai contains a nearly complete sequence of rocks that spans the Mesozoic era (252–66 MYA). Triassic (252–201 MYA) greenstone is overlain and intruded by Lower Jurassic (201–174 MYA) plutonic and volcanic rocks of the Talkeetna volcanic arc. Sedimentary rocks formed predominately along a narrow shelf at the edge of the eroding Talkeetna volcanic arc. Many of the Jurassic and Cretaceous sedimentary rocks contain abundant marine fossils. The Mesozoic rocks formed offshore in the proto-Pacific Ocean.
- **Tertiary Sedimentary Rocks**. Tertiary sedimentary rocks crop out along the Katmai coast and on the west side of the mountains north of Naknek Lake. The Oligocene (34–23 MYA) or, possibly, earliest Miocene (23–20 MYA) Hemlock Conglomerate crops out on the Katmai coast and is a fluvial (river) sandstone and conglomerate deposited in a braided fluvial system with highly sinuous channels. The Eocene (56–34 MYA) and possibly upper Paleocene (60–56 MYA) Copper Lake Formation crops out near Kukaklek Lake on the north and around Fourpeaked Mountain and Mount Douglas. It consists of fluvial conglomerate and interbedded sandstone and siltstone that represent predominantly braid-plain fluvial deposits. The Ketavik Formation is an upper Paleocene to lower Eocene (59–49 MYA) fluvial sandstone and conglomerate that crops out in small, obscure exposures along Naknek Lake west of Brooks Camp and at Brooks Falls. The Tertiary sedimentary units contain abundant and well-preserved plant fossils.
- **Tertiary Igneous Rocks**. Four groups of Tertiary (66–2.6 MYA) igneous rocks are recognized throughout the map area: (1) the Meshik Volcanics north of Naknek Lake, (2) the Gibraltar Lake Tuff on the most northern edge of the map area, (3) volcanic rocks of the Barrier Range near Katmai and Snowy mountains, and (4) undivided intrusive rocks underlying Fourpeaked Mountain and Mount Douglas. The rocks range in age from the late Eocene to Pliocene epochs (40–2.6 MYA) and represent an episodic period of volcanism that started in the early Tertiary and continues today.
- **Faults and Folds.** The major geologic structure of the Katmai area is the inactive Bruin Bay fault, which runs through the middle of the park and extends nearly the entire length of the Alaska Peninsula from near Aniakchak National Monument and Preserve through Lake Clark National Park and Preserve. It is a major reverse fault that dips to the northwest with the upthrown side on the northwest. The fault was active during deposition of the Upper Jurassic to Lower Cretaceous (145–100 MYA) marine sedimentary rocks. The magmatic arc rocks on the northwest side of the fault were uplifted and eroded, which provided sediment to a shallow marine shelf on the southeast side of the fault.

- **Terrane Translation and Accretion.** The Mesozoic rocks belong to a group of rocks called the Peninsular terrane, which is thought to have originated far to the south and to have been added to southern Alaska in late Mesozoic time. Evidence from paleomagnetism, fossil assemblages, and depositional environments suggests that the Mesozoic rocks formed originally in tropical waters in the Late Triassic (237–201 MYA), were transported to polar (boreal) environments by the Late Jurassic (164–145 MYA), back down to low latitudes in the mid-Cretaceous (110–90 MYA), then slid northward to its present location. Plate tectonics has played a major role in the formation of the rocks of Katmai, transporting across the proto-Pacific Ocean, and causing the deformation and uplift that is still ongoing today.

Three meetings were held to discuss GRI products, geology of the park units, and resource management issues. These meetings were held with NPS natural resource managers, NPS Southwest Alaska Network staff, NPS Alaska Region specialists, and geologists with experience in the Katmai area. At these meetings, participants discussed the following geologic resource management issues:

- **Preservation of Katmai's Natural Features for Inspiration and Study**. The primary purpose of establishing Katmai National Monument was to preserve the spectacular volcanic features of the 1912 eruption, specifically for inspiration and research. The Katmai area is ideal for studying volcanic processes and monitoring the regeneration of ecosystems after a catastrophic eruption.
- **Geohazards.** The Katmai area has a very high potential for natural hazards. It contains many active volcanoes and adjacent active volcanoes could impact the area. Strong wind events frequently re-suspend ash from the 1912 eruption. Hydrothermal processes produce acidic waters (such as crater lakes) that can cause ecological harm to sensitive riverine or lacustrine ecosystems. The area overlies the tectonically active Aleutian megathrust, and movement on this thrust causes frequent and large earthquakes. The steep slopes in the mountainous areas are prone to landslides and rockfall. The coastal areas are exposed to tsunamis originating from earthquakes or volcanic mass flows.
    - □ **Dynamic Volcanic Landscapes**. Volcanic landscapes are constantly changing. The intermittent addition of volcanic materials and gases affects streamflow, lakes, glacial processes, and atmospheric conditions. Volcanic eruptions can disturb ecosystems, and in very large eruptions, like the 1912 Novarupta-Katmai eruption, can bury or sterilize landscapes.
    - □ **Crater Lake Explosions and Acidic-Water Flooding**. Lakes in the active volcanic craters of Mounts Douglas, Martin, Mageik, and Katmai create the potential hazard of lake water and magma violently mixing to generate an explosive eruption. The water-magma interaction acts as an intensifier for the eruption. The violence of the interaction is controlled by a number of factors, including magma type, volume, rate of extrusion, degree to which the magma is fragmented by expanding internal gas bubbles, and water depth. The disruption of such acidic lakes also increases the possibility of local acid rainfall and of sending acid-water-rich lahars and debris flows downhill from those summits. Acidic volcanic lake water can have catastrophic effects on riverine and lake ecosystems.
- **Geothermal Features Inventory and Monitoring.** The Geothermal Steam Act of 1970, as amended in 1988, lists Katmai National Park and Preserve as containing significant geothermal features. The act prohibits geothermal leasing in parks, and authorizes the Secretary of the Interior to mitigate or not issue geothermal leases outside parks that would have a significant adverse impact on notable thermal features within the park. The act also requires inventorying and monitoring significant geothermal features of the park.
- **Coastal Issues.** The rugged Katmai coast is dynamically changing. Uplift of the coast in the last few thousand years is evident by raised marine terraces and stranded sea caves. Climate change may lead to sea level rise, increased storm strength, and ocean acidification, which could alter the current coastal geomorphic processes and coastal ecosystems. Intergovernmental Panel on Climate Change (IPCC) models predict that absolute sea level in the region will increase about 37 cm (1.2 ft) by the end of the century, but the uplift rate of the

Katmai coast is projected to outpace the rise in sea level. The uplift of the coastline is primarily caused by plate tectonic forces, but isostatic rebound from the melting of the glaciers from the last ice age may be a contributor. The uplift has preserved archeological sites from inundation and erosion. However, increased erosion from increasing storm frequency should also be expected in the future.

- **Fluvial Erosion.** Fluvial erosion along steep river banks is a threat to archeological sites, especially along the Brooks and Alagnak Rivers. As the rivers naturally change their courses, erosion will continue to impact the shoreline and associated cultural resources. This is of particular concern along braided sections of the rivers where change can occur over relatively short amounts of time.
- **Glacier Changes.** About 915 km^2 (350 mi^2) of the Katmai area is covered in ice. Glaciers are affected by temperature and precipitation, so they are indicators of long-term climate change. The overall coverage of glacial ice in Katmai has decreased 14% since 1950. Most glaciers in the Katmai area are receding, like most glaciers in Alaska, but glaciers that were covered by thick deposits of 1912 ash are not receding and some have advanced.
- **Paleontological Resource Inventory, Monitoring, and Protection.** The Katmai area contains more than 550 fossil localities. The Mesozoic sedimentary rock units contain mostly invertebrate marine fossils, and the Tertiary sedimentary rock units contain well-preserved plant fossils and petrified wood. The units with the most abundant fossils are the Ketavik Formation, Copper Lake Formation, Hemlock Conglomerate, Herendeen Formation, Kaguyak Formation, and the Naknek Formation. Fossil bone material was found in the Naknek Formation near Ukak Falls and adjacent to the park. Dinosaur tracks have been found in the Naknek Formation outside the park boundary, so dinosaur tracks or bones could be present within the park units. The abundance of fossils in the wide-spread sedimentary units in the park provides that potential for unauthorized collection and a need for a paleontological survey and field site assessment and monitoring plan.
- **Abandoned Mineral Lands (AML).** The Katmai area contains 31 locations with notable mineral resources. Between the early 1900s and the 1980s, small-scale mining and prospecting took place at 11 of these sites. Mineral occurrences and prospected mineral resources included pumicite from the 1912 eruption, placer gold, coal, and copper. No known safety issues exist at any AML sites within Katmai. Diesel-contaminated soil at one site is the only documented resource issue that has been associated with AML in the park and preserve. In 2011, after several years of soil treatment, the Alaska Department of Environmental Conservation (DEC) declared the site to be adequately cleaned up. The abandoned mine structures on the site are unsightly but pose no known safety or environmental threat.
- **Potential Petroleum Development.** The Katmai area is surrounded by oil and gas reservoirs. The Cook Inlet area contains reserves of oil and natural gas. More than a century of petroleum exploration has occurred in the Iniskin Peninsula area of the Alaska Peninsula. Offshore exploration wells have been drilled less than 25 km (16 mi) from the northeastern coast. The Bureau of Ocean Energy Management (BOEM) is preparing an environmental impact statement for a potential lower Cook Inlet lease sale. The Katmai coast supports a complex ecosystem that was impacted by the Exxon Valdez oil spill. Oil spills from exploration or production activity in Cook Inlet have the potential to severely harm the coastal ecosystems of Katmai.
- **Soils and Permafrost.** Soil temperature and permafrost were listed as important physical elements of the Southwest Alaska Network vital signs monitoring plan. Climate scenarios indicate a rise in average annual temperature of 2.6°C (4.7°F) by 2040 in the Katmai area, and permafrost melting was identified as a potential major change to the park due to climate change.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix C provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

This compilation was built from over a century of research in the Katmai area and could not have been completed without the efforts of the many geologic explorers and writers. Two of these geologists that have extensive experience with Alaskan geology provided thorough technical reviews of this report: **Wes Hildreth** (research geologist, USGS-California Volcano Observatory) and **Will Elder** (interpreter, NPS Golden Gate National Recreation Area; and former USGS paleontologist). We thank all the people that attended the pre-report meetings that pointed the authors to sources of information that may not have been obvious, and ideas for topics to include. In particular, we thank **Troy Hamon** (chief of resources, NPS Katmai/Aniakchak) for taking time to discuss the resource management issues. The clarity of the manuscript was improved by informal reviews by **Mike Fitz** (visual information specialist, NPS Katmai/Aniakchak). We greatly appreciate the thorough edits completed by **Katie KellerLynn** (research associate, Colorado State University). **Katie Meyers** (collections manager, NPS Katmai/Aniakchak) was a great help sleuthing through the archives in the Alaska Regional Office Curatorial Center to provide many interesting documents about the geologic exploration history. **Thomas Hamilton** (former USGS research geologist) provided unpublished manuscripts from his geologic explorations in the 1960s. The paleontology information provided in the report was compiled by **M. Mark Turner** (Geoscientists-in-the-Parks intern, Alaska Regional Office). Sea level change scenarios were provided by **Maria Caffrey** (research associate, University of Colorado and Geologic Resources Division) and **Rebecca Beavers** (geologist, Geologic Resources Division and Climate Change Response Program). **Sarah Venator** (geologist, Alaska Regional Office) provided information about AML sites. Some of the graphics were provided by **Trista Thornberry-Ehrlich** (research associate, Colorado State University). The lead author greatly appreciates the many reviews of this document by **Jason Kenworthy** (geologist, Geologic Resources Division) and his persistent efforts to keep up the momentum.

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List of Abbreviations

For a geologic glossary with simplified definitions, refer to http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.

- AVO: Alaska Volcano Observatory
- BOEM: Bureau of Ocean Energy Management
- CalVO: California Volcano Observatory
- cal. yr BP: calibrated years before present
- GRD: Geologic Resources Division
- GRI: Geologic Resources Inventory
- K/Ar: potassium/argon (an isotopic ratio used to determine the age of volcanic rocks)
- MYA: million years ago
- NASA: National Aeronautics and Space Administration
- NOAA: National Oceanic and Atmospheric Administration
- NPS: National Park Service
- UAF: University of Alaska Fairbanks
- USGS: United States Geological Survey
- VABM: vertical angle bench mark
- VEI: Volcanic Explosivity Index (see Table 1)
- yr BP: years before present

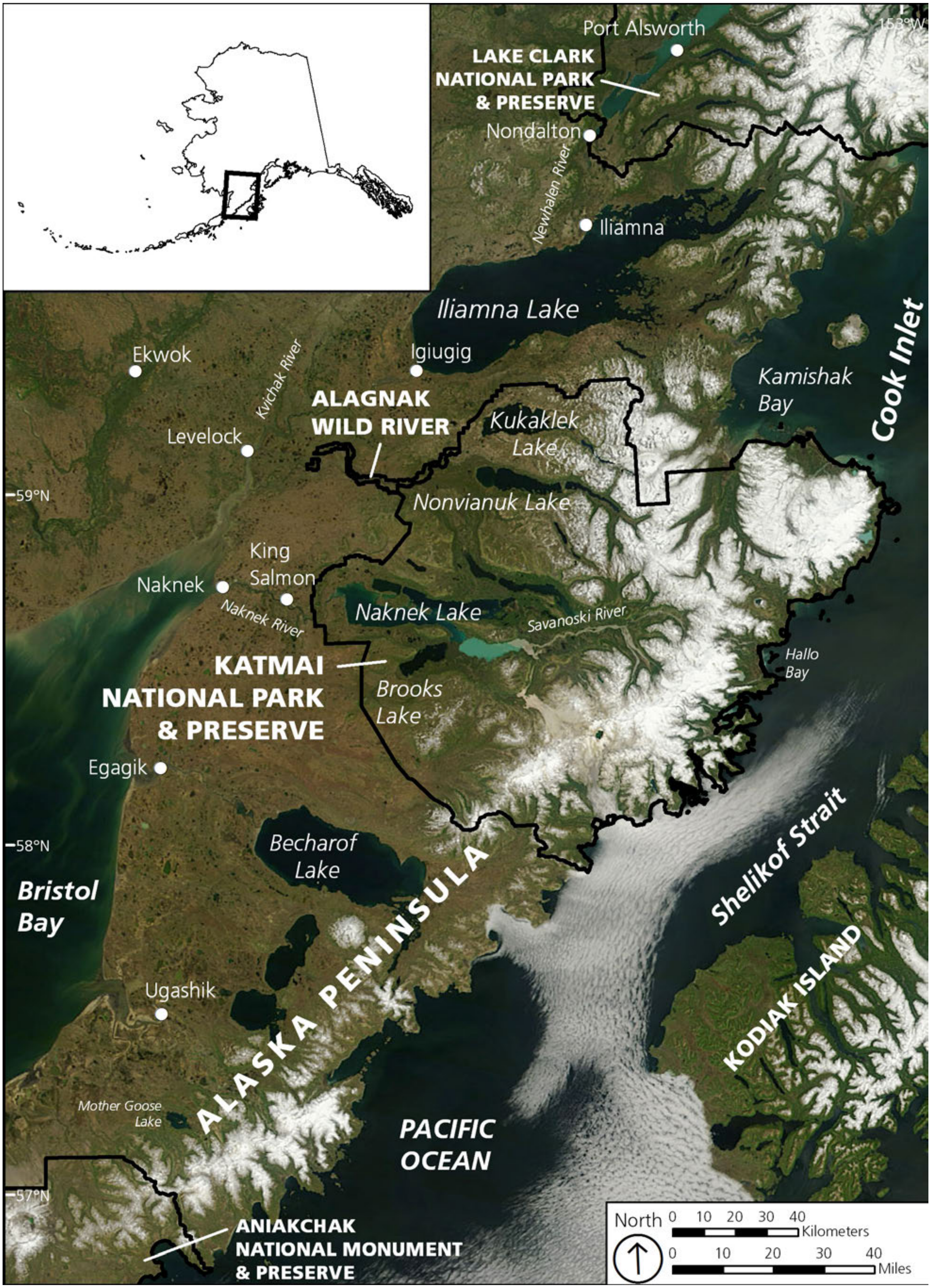


Figure 1. Map showing the location of Katmai National Park and Preserve and Alagnak Wild River. The Katmai area spans the northern Alaska Peninsula from Cook Inlet to Bristol Bay MODIS satellite imagery from 2013.

Geologic Setting and Significance

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

Katmai National Park and Preserve and the contiguous Alagnak Wild River encompass an active geologic landscape shaped by the dynamic forces of volcanoes, glaciers, rivers, waves, currents, wind, and plate tectonics. In this report the term "Katmai area" refers to Katmai National Park and Preserve, Alagnak Wild River, and the immediate surrounding area on the geologic map (see Plate 1, in pocket). Located along the Alaska Peninsula, the Katmai area spans from the Pacific Ocean nearly to Bristol Bay (Figure 1). The principal geologic feature of the Katmai area is the spectacular landscape created by the 1912 Novarupta-Katmai eruption, which formed the Valley of Ten Thousand Smokes. The valley so impressed its first explorer, Robert F. Griggs, that he urged President Wilson's administration to preserve it for posterity, and Katmai National Monument was established in 1918. The monument was created with the dual intention of both protecting the scenic wonders and preserving possibilities for continued scientific study of phenomena related to the 1912 eruption. Expansion of the protected area and redesignation as a national park and preserve in 1980 validated and supported both values. The volcanoes of Katmai National Park and Preserve have provided geologists and other scientists with many opportunities for exploring and understanding volcanic phenomena and their ecological effects.

The preserved area encompasses 1,656,405 ha (4,093,067 ac) or 16,564 km^2 (6,395 mi^2) and Katmai National Park and Preserve is the fourth largest unit in the National Park System. The Katmai area consists of a rugged volcanic spine; long lakes and rivers draining to the west; and steep, short river valleys flowing to the complex, dynamic coast on the east. The 13 highest mountains, which rise more than 1,500 m (5,000 ft) above the coast, are heavily glaciated volcanoes. The Katmai area is home to 24 Quaternary volcanoes (active in the last 2.6 million years), more than any other national park. Ten of the volcanoes are considered active, and five had eruptions in historic time. Nearly 300 glaciers cap the mountain crest that covers 915 km^2 (353 mi^2). These glaciers are the source of turbulent braided rivers that flow down U-shaped valleys that were sculpted by glacial action during the last ice age. Glacier advances left numerous terminal moraines that dam the many lakes of the region. Naknek Lake is the largest of these lakes and, at 627 km^2 (242 mi^2), is the largest lake in the National Park System. Notably, the lake was much larger during the Pleistocene (2.6–0.01 MYA) glaciations.

The Alagnak River flows northwest for 119 km (74 mi) from Kukaklek Lake (in Katmai National Park and Preserve) to where it joins the Kvichak River then flows to Bristol Bay. The Alagnak Wild River area encompasses 12,409 ha (30,741 ac) or 124 km^2 (48 mi^2). The Alagnak Wild River protects a pristine river system, which hosts significant Bristol Bay sockeye (red) salmon runs, as well as artifacts that preserve the history of habitation in southwest Alaska. The river changes from braided to meandering as it flows through subdued terrain that was formed during some of the oldest Pleistocene glaciations.

The Katmai area is known best for the 1912 Novarupta-Katmai eruption and many active volcanoes. The dominant geologic feature, and principal reason Katmai National Park and Preserve was established, is the Valley of Ten Thousand Smokes ignimbrite (pumice rich ash flow deposit) that was emplaced during the 1912 eruption; the largest volcanic eruption of the 20th century. Lesser known is the eruption from a new vent on the southwest flank of Trident Volcano, which lasted from 1953 to 1974 and produced numerous lava flows.

These volcanoes are part of a dense cluster of 24 volcanoes that are the most tightly spaced line of stratovolcanoes in Alaska (Figure 2). Crater-to-crater spacing between adjacent (commonly contiguous) edifices is typically 5 km (3 mi) or less. The volcanoes of the Katmai area are part of the larger Aleutian volcanic arc that spans 2,500 km (1,600 mi) from the Alaska Range to the far western Aleutian Islands (Figure 2). The volcanoes of the Aleutian arc are the result of subduction of the Pacific oceanic plate under Alaska. Subduction occurs where denser oceanic crust moves toward and sinks below less dense continental crust (Figure 3). The subducting Pacific oceanic plate under

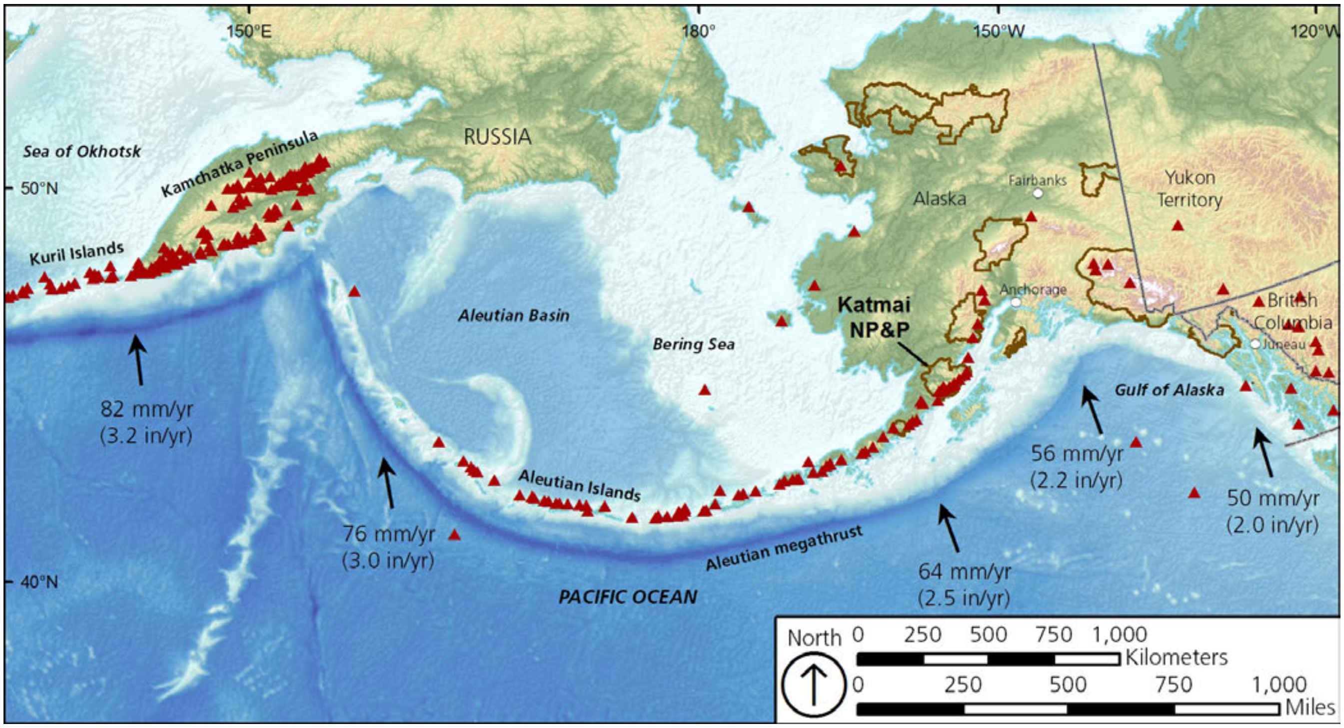


Figure 2. Map of Holocene volcanoes along the Aleutian volcanic arc, Kamchatka Peninsula, and Kurile Islands. Red triangles are volcanoes (Smithsonian Holocene volcano list: http://www.volcano.si.edu/list_volcano_holocene.cfm). Arrows show the direction of motion of the Pacific plate relative to the North American and Asian continents (Haeussler and Plafker 2004). National Park System units in Alaska are outlined in brown.

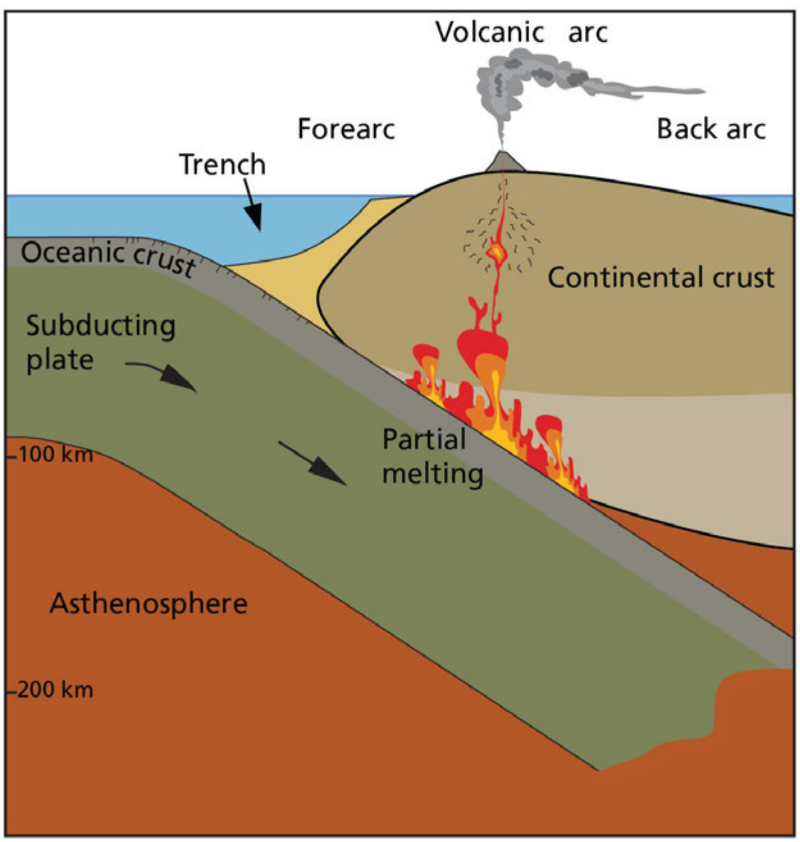


Figure 3. Schematic cross section of oceanic crust subducting under continental crust. Water in the subducting plate reacts with the dry mantle, which causes melt to form and rise into the overlying plate. Volcanoes form where this melt reaches the surface of the earth and erupts as lava. "Arcs" are linear features. Fore arcs are areas of a subduction zone between the trench and the volcanic arc. Back arcs are on the opposite side of a volcanic arc from the subduction-related trench. Graphic modified from original provided by Trista Thornberry-Ehrlich (Colorado State University).

Alaska is denoted by the earthquakes that progressively get deeper under the Aleutian volcanic arc as the plate sinks deeper into the mantle (Figures 4 and 5). The boundary between the plates is called the Aleutian megathrust and is the focus of frequent earthquakes, some of which can be very large and cause tsunamis.

The Katmai area was mostly covered by glaciers during the last glacial maximum, during the Pleistocene Epoch (2.6 million–11,700 years ago), so the landscape was shaped by glacial processes. The gently sloping western side of the Alaska Peninsula contains many glacial moraines that define the maximum reach of the glaciers during glaciations and intermediate stades (advances). The lakes of the Katmai area are dammed by glacial moraines, and abundant evidence shows that the lakes were higher and more expansive in the past. Post-glacial mass wasting (slope movement) has eroded the highest peaks and is more common near the range crest and along the foothills. The many lakes and streams support extensive runs of anadromous fish that were a source of food for human populations for thousands of years. As a result of deglaciation, dropping water levels of the greater Naknek Lake stranded salmon, creating the endemic Kokanee populations. Dropping water levels also allowed post-glacial erosion to form the famous

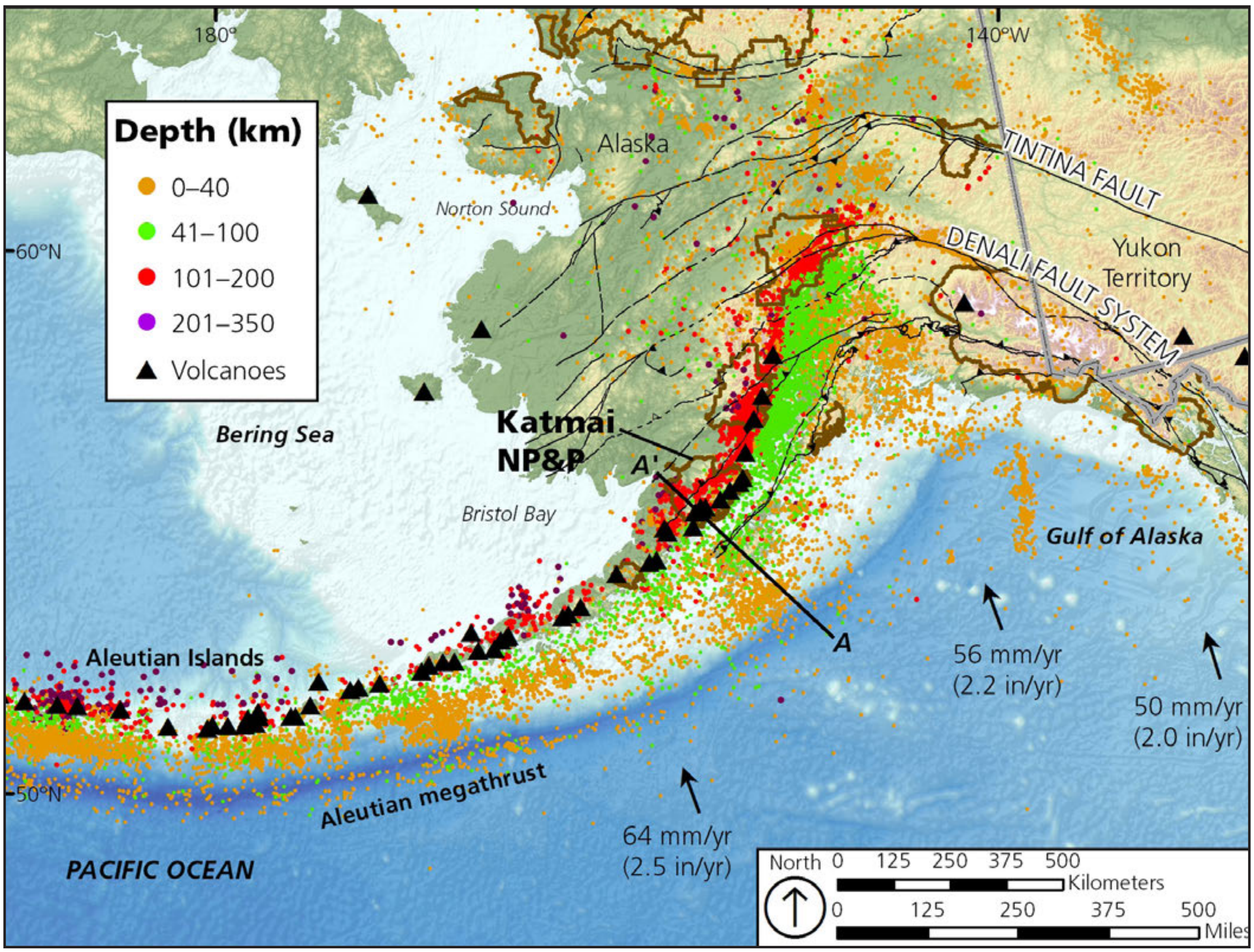


Figure 4. Map showing earthquake epicenters. Only earthquakes greater than magnitude 3.0 are shown from 1889 to present (http://www.aeic.alaska.edu). The Aleutian arc volcanoes (black triangles) form where the subducting Pacific plate reaches 100 km deep (where the earthquake epicenters transition from green to red dots). At this depth, the water retained within the subducting plate reacts with the dry mantle to form magma. The Pacific plate motion relative to the North American plate is shown with arrows. The Pacific plate is subducting under Katmai at a convergence rate of about 60 mm/yr (2.4 in/yr). A cross-section in Figure 5 shows the location and depth of earthquakes along the line A–A'.

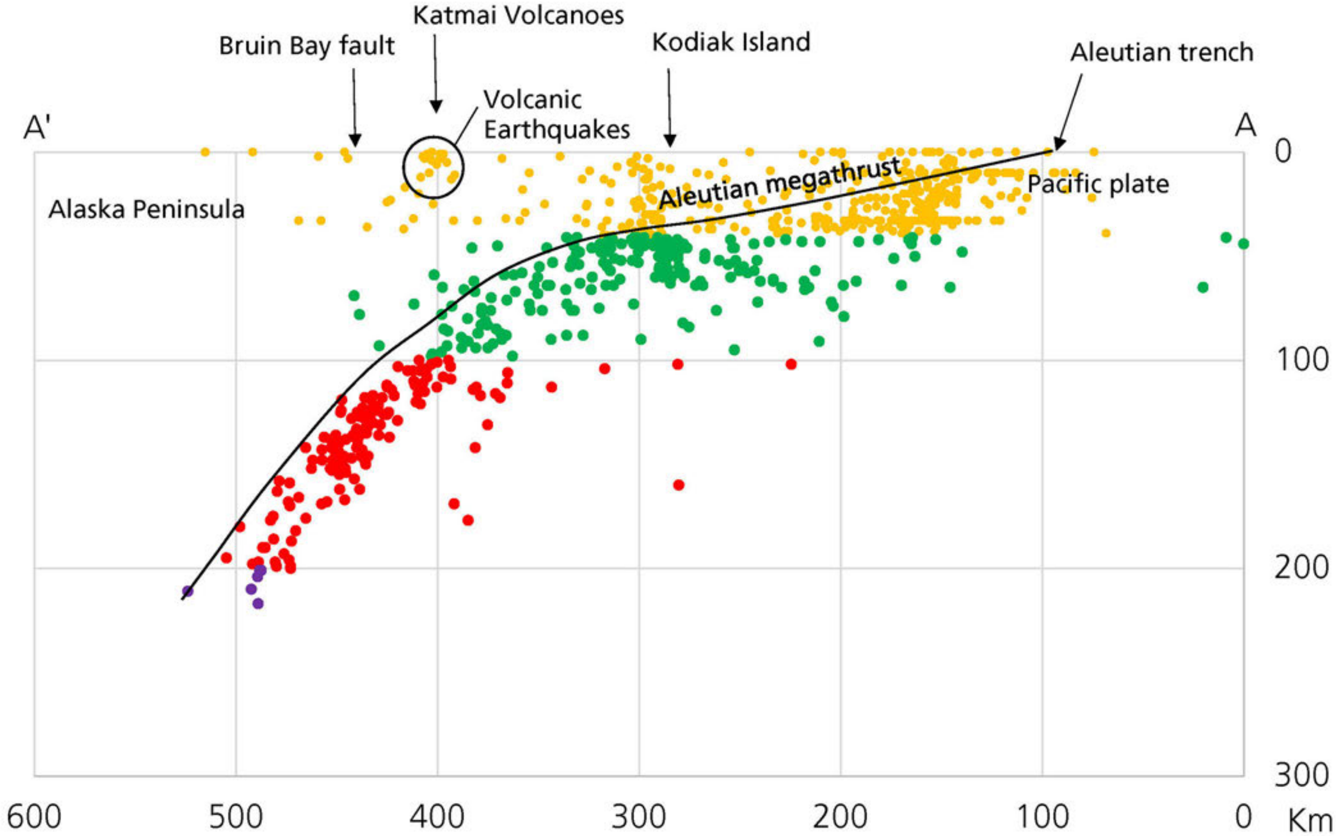


Figure 5. Chart showing a cross section of earthquakes along line A–A' in Figure 4. The colors correspond to earthquake depth ranges shown in Figure 4. The Aleutian trench, which is 5–6 km (3–4 mi) below sea level, is 300 km (190 mi) southeast of the Katmai volcanoes. The inclined seismic zone shows where the Pacific Plate subducts under Alaska and is defined by an area of earthquakes that is 20–30 km (12–19 mi) wide (Kienle et al. 1983; Page et al. 1991). It dips about 10° NNW for some 300 km, then steepens to about 45° beneath the present-day volcanic arc. The plate is about 100 km deep under the Katmai area volcanoes, and continues behind the volcanoes to depths as great as 220 km. The cluster of shallow earthquakes in the Katmai area were generated from magma movement under the volcanoes (Ward et al. 1991; Moran 2003; Dixon and Power 2009).

Brooks Falls. Low passes, like Katmai Pass, formed by glacier erosion, were ancient and historic trade/migratory routes that provided a pathway for travel and trade across the Alaska Peninsula between the Pacific coast and Bristol Bay.

Underlying the volcanic carapace are ancient sedimentary and volcanic rocks (Plate 2) that have been uplifted by tectonic forces and carved by glaciers. The east half of the Katmai area is mostly made up of Mesozoic (252–66 MYA) marine sedimentary rocks that are gently folded (Plate 3). The Bruin Bay fault cuts across the center of the park from northeast to southwest (Plate 1). Movement along the fault uplifted rocks to the southwest of the fault, and erosion exposed Mesozoic plutonic (intrusive) and metamorphic (altered) rocks that formed deep in the crust. Overlying the Mesozoic rocks northeast of the fault are Tertiary (66–2.6 MYA) sedimentary, volcanic, and minor plutonic rocks that formed on land at or near the surface. The Mesozoic rocks include rocks of the Talkeetna arc, which formed in the Early Jurassic Period just after the start of the breakup of Pangea (Figure 6).

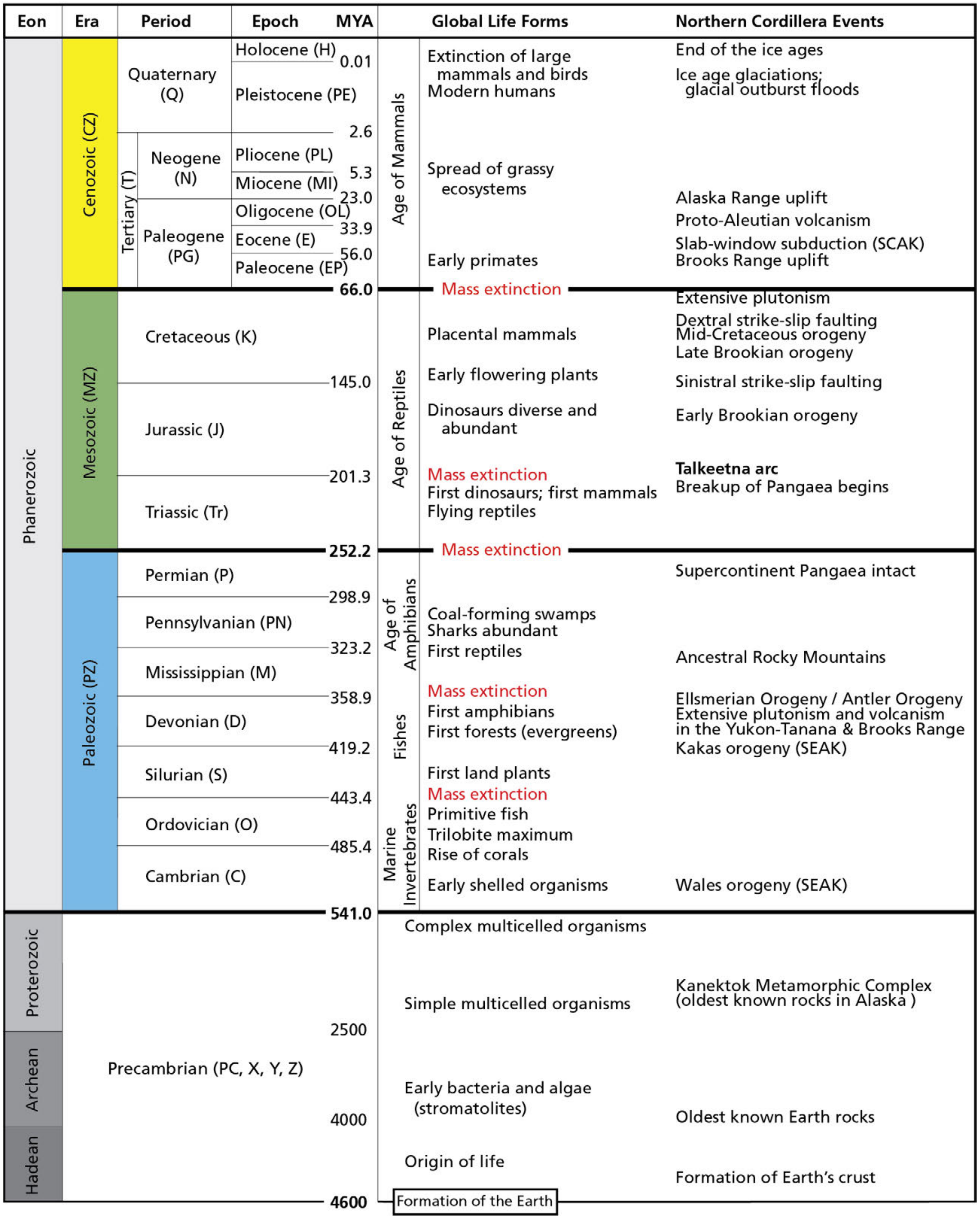


Figure 6. Geologic time scale showing the onset of major global evolutionary events and tectonic events of the North American continent and the Northern Cordillera. SCAK = south-central Alaska. SEAK = southeast Alaska. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Plate 2 (in pocket) shows the ages of rock types within the Katmai area. Ages are millions of years ago (MYA) from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

Geologic Features and Processes

This section describes and explains the formation of the distinctive geologic features of Katmai National Park and Preserve and Alagnak Wild River, and describes the processes of their formation. The geologic features are presented generally from youngest to oldest. The formation of the volcanic features is presented first, starting with the 1912 Novarupta-Katmai eruption and the features formed during the eruption. The many volcanoes that make up the mountain crest are listed and described. Surficial features, including glacial, coastal, and alluvial; and processes that shaped the landscape are discussed. The underlying bedrock units are then presented from oldest to youngest.

Much has been written about the 1912 Novarupta-Katmai eruption and the volcanoes of the Katmai area because they are features that formed in historic time and have potentially large impacts on human and natural resources. Instead of re-writing these works, much of the text for the following volcanic features section was taken from three sources: Fierstein (2012a), Fierstein (2012b), and the centennial report by Hildreth and Fierstein (2012).

1912 Eruption and Formation of the Valley of Ten Thousand Smokes

Map units: **Qpd** (in part), **Qhvd** (in part), and **Qafd** (in part)

The largest volcanic eruption of the 20th century began on 6 June 1912 from a new volcano, Novarupta. The great eruption of 1912 lasted for three days and consisted of three explosive episodes. The eruption created Katmai caldera and the Valley of Ten Thousand Smokes (Figure 7). Volcanic ash, more than from all other historical eruptions in Alaska combined, devastated areas hundreds of kilometers away, and the huge eruption column rose so high that stratospheric winds carried the ash around the world.

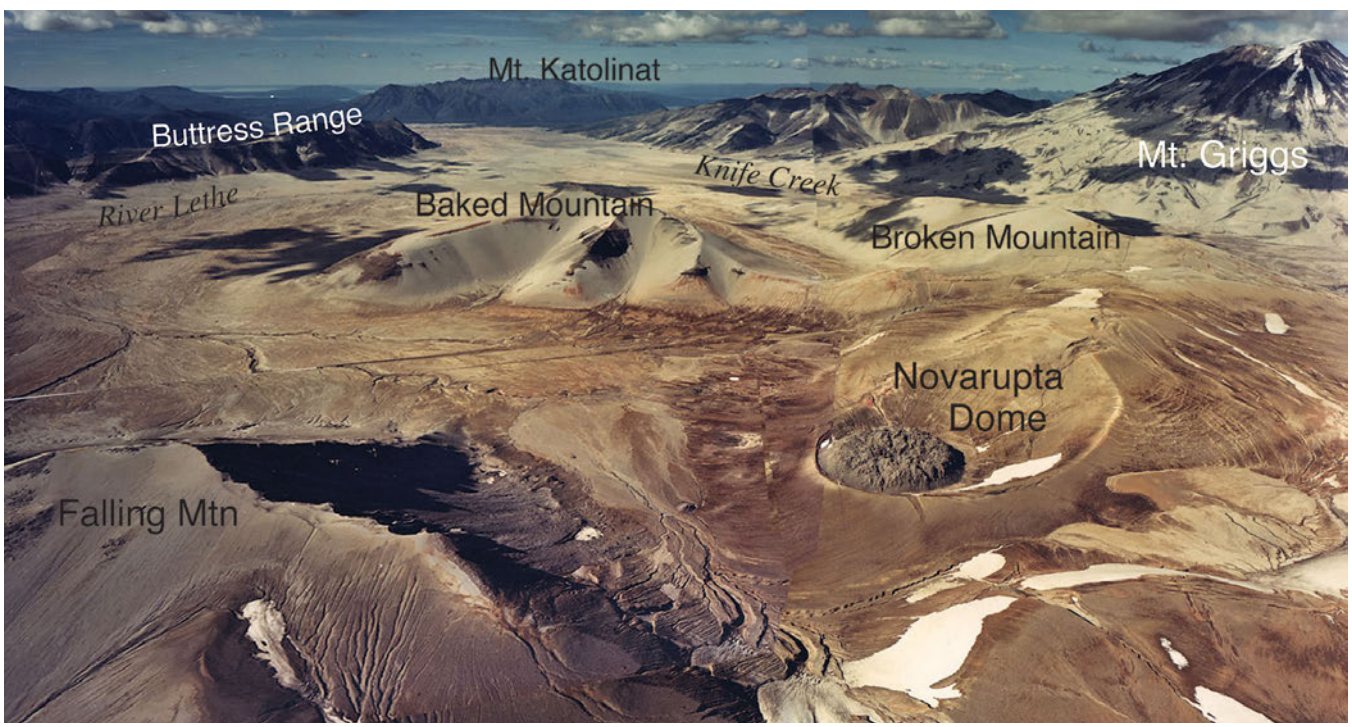


Figure 7. Aerial photograph of the Valley of Ten Thousand Smokes extending 20 km (13 mi) northwest from vent at Novarupta to distant Mount Katolinat. Novarupta dome is encircled by an asymmetrical ring of accumulated pumice from eruptive Episodes II and III. USGS California Volcano Observatory (CalVO) photograph.

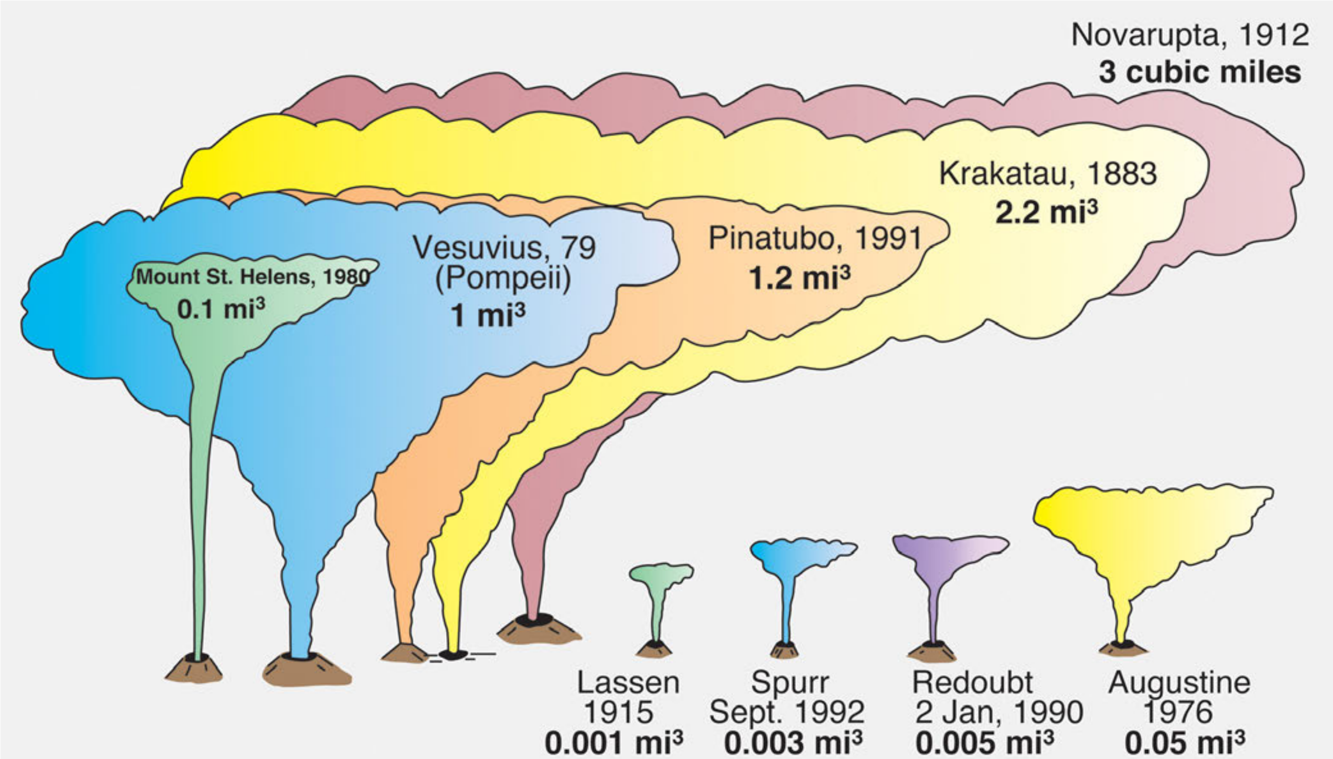


Figure 8. Diagram showing comparisons of the 1912 Novarupta erupted magma volume to other historic eruptions in North America and the world. Figure 2 from Fierstein (2012a).

The magnitude and volume of the eruption at Novarupta in 1912 were exceptional, far larger than any other historical eruption in North America (Figure 8; Table 1). This fueled early US Geological Survey and National Geographic Society scientific investigations that helped to shape thinking about volcanoes and magmas (Martin 1913; Griggs 1922). For the first time in recorded history, a great explosive eruption deposited its pyroclastic flows on land rather than in the sea (as at Krakatau in 1883), so that they could be studied in detail. It was also one of the few places where scientists recognized a wide range of magma compositions having erupted together. Over the past three decades, detailed studies of Novarupta deposits have contributed to a better understanding of how volcanoes work, how explosive pumice and ash erupt and are emplaced, how calderas collapse, and what happened at the vent during

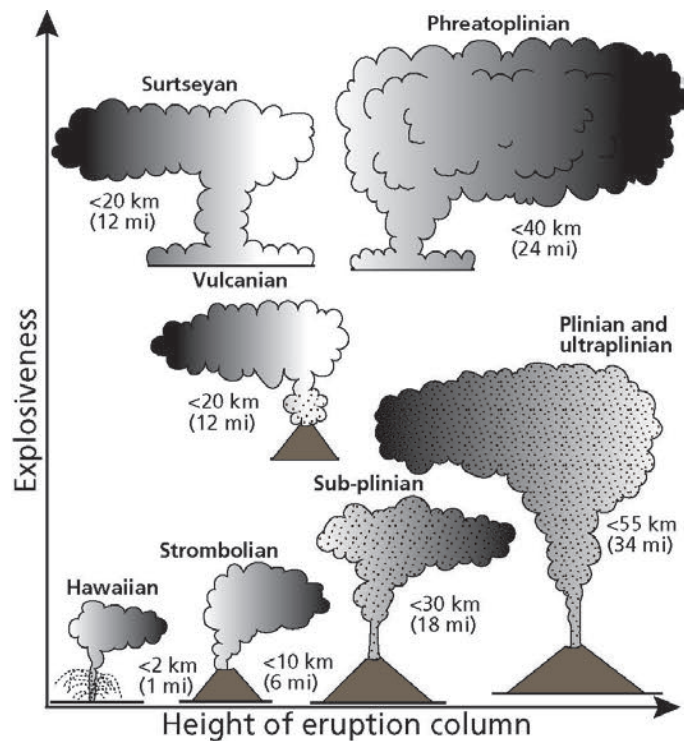


Figure 9 (right). Diagram showing the explosiveness and eruption column heights of different types of eruptions. The “colossal” Novarupta eruption is considered Plinian to Ultra-Plinian eruption. See Table 1 for how these classifications fit into the volcanic explosivity index. Graphic by Trista Thornberry-Ehrlich (Colorado State University), modified from Cas and Wright (1988).

Table 1. Volcanic explosivity index (VEI).

VEI	Ejecta Volume in km³ (mi³)	Column Height in km (mi)	Classification	Description	Examples
0	0.00001 (0.000002)	<0.1 (0.06)	Hawaiian	Effusive	Kilauea (ongoing)
1	0.001 (0.0002)	1 (0.6)	Hawaiian/Strombolian	Severe	Stromboli (numerous)
2	0.01 (0.002)	5 (3)	Strombolian/Vulcanian	Explosive	**Fourpeaked** (2006), **Cleveland** (ongoing), Shishaldin (ongoing)
3	0.1 (0.02)	15 (9)	Vulcanian/Sub-Plinian	Catastrophic	**Katmai** (1912), **Redoubt** (1989, 2009), **Trident** (1953–1974), **Augustine** (2003), Lassen Peak (1915)
4	1 (0.2)	25 (16)	Sub-Plinian	Cataclysmic	**Aniakchak** (1931), Eyjafjallajökull (2010), **Crater Peak** (1992), **Kasatochi** and **Okmok** (2008)
5	10 (2)	>25 (16)	Plinian	Paroxysmal	Mount St. Helens (1980), Vesuvius (1979)
6	100 (20)	>25 (16)	Plinian/Ultra-Plinian	Colossal	**Aniakchak I and II** (approximately 9,000 and 3,700 years ago), **Novarupta** (1912), Krakatoa (1883), Pinatubo (1991)
7	1,000 (200)	>25 (16)	Ultra-Plinian	Mega-colossal	Mount Mazama (7,550 years ago), Tambora (1815)
8	>1,000 (200)	>25 (16)	Ultra-Plinian	Apocalyptic	Yellowstone (640,000 years ago),

Modified from Newhall and Self (1982).

For eruption classification descriptions see Figure 9. Alaska volcanoes in **bold** and NPS volcanoes in green. The VEI scale is logarithmic, and each interval on the scale indicates a tenfold increase in erupted volume, except for VEI 0–2 events Modified from Newhall and Self (1982).

Find GRI reports for descriptions of eruptions of Kilauea (Hawaii Volcanoes NP), Lassen Peak (Lassen Volcanic NP), Aniakchak (Aniakchak NM&P), and Mount Mazama (Crater Lake NP) at http://go.nps.gov/gripubs.

the three day eruption (Hildreth 1983, 1987, 1991; Fierstein and Hildreth 1992; Fierstein and Nathenson 1992; Fierstein et al. 1997; Hildreth and Fierstein 2000, 2012; Houghton et al. 2004; Fierstein and Wilson 2005). These unusual conditions and fascination with the "Ten Thousand Smokes" led President Wilson to establish Katmai National Monument in 1918.

Reports of an Eruption

Initial signs of an impending eruption began with severe earthquakes felt at Katmai village on the Shelikof Strait coast "for at least 5 days prior to the eruption" (Martin 1913). More were felt on 4 and 5 June, including as much as 250 km (160 mi) to the northeast, prompting the few inhabitants at Katmai village to evacuate by canoe down the coast toward Cold Bay (now Puale Bay). Unrest continued, as explosions were heard 230 km (140 mi) away on the morning of 6 June. Not until 1 pm (Alaskan time) was the first towering eruption cloud witnessed by crew members of the steamer SS *Dora*, then in Shelikof Strait. Two hours later darkness abruptly enveloped the vessel as it was overtaken by the choking ash. Lightning flashed from the black cloud overhead as Captain McMullen changed course from the intended stop at Kodiak and headed toward the open Gulf of Alaska. Even "full steam ahead," the *Dora* remained under the ash cloud until early the next day.

At Kodiak, 160 km (100 mi) southeast of the eruption center, the air became thick with ash and, for 60 hours, darkness was so complete that a lantern held at arm's length could scarcely be seen. The terrified townspeople, some temporarily blinded by the sulfurous gas, crowded onto the US Revenue Cutter *Manning* docked in Kodiak harbor, while 30 cm (1 ft) of ash smothered their town with three closely spaced periods of ash fall. The weight of the ash collapsed roofs in Kodiak; buildings were wrecked by ash avalanches that rushed down from nearby hill slopes; other structures burned after being struck by lightning from the ash cloud; water became undrinkable.

By midnight of the first day, 11 hours into the eruption, about 5 km³ (1.2 mi³) of the Mount Katmai summit collapsed. The collapse resulted in a 2.5 km (1.5 mi) wide caldera, which has since accumulated a lake about

CHRONOLOGY OF THE 1912 ERUPTION

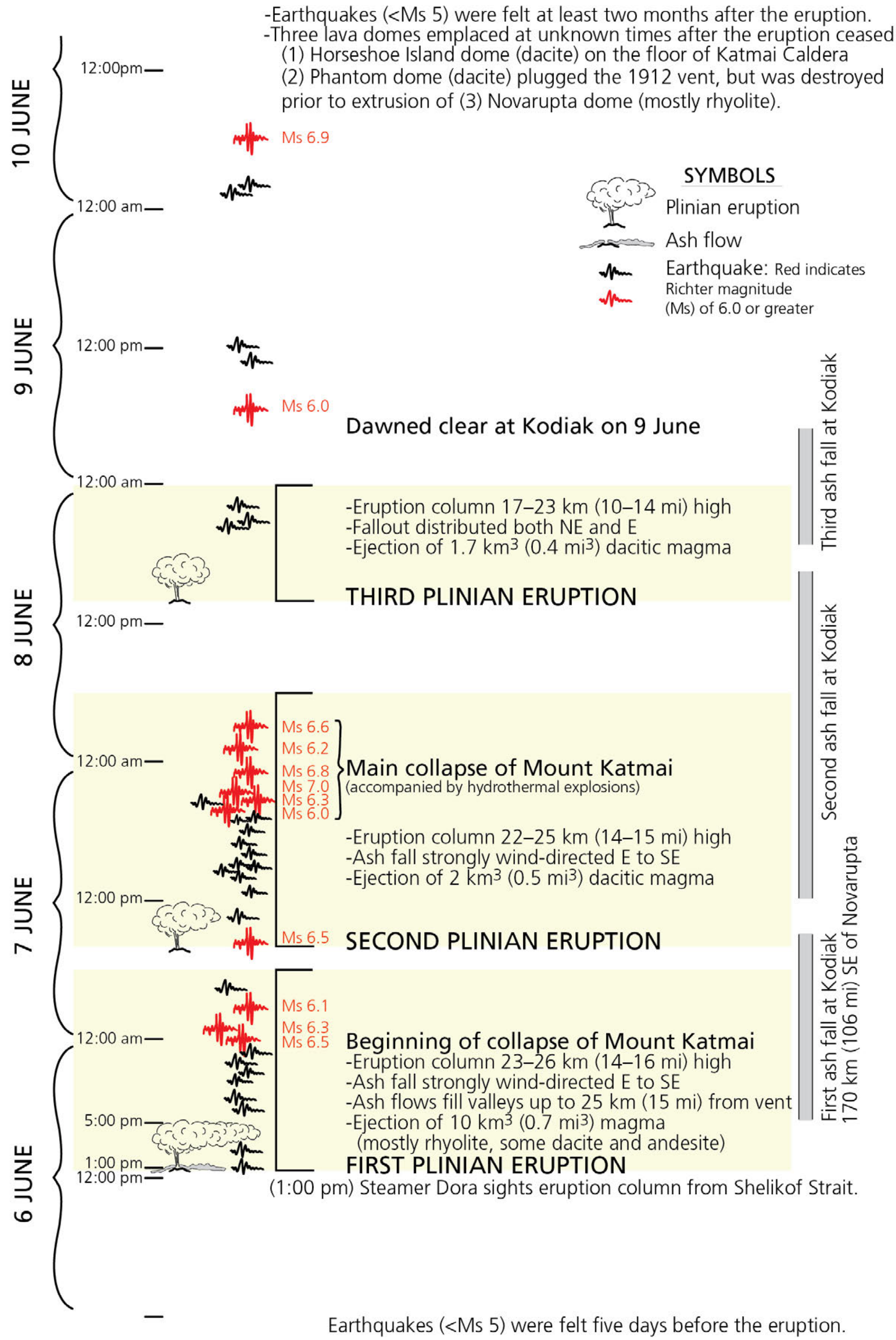


Figure 10 (facing page). Chronology of 1912 eruption. Earthquakes felt by local residents during the five days before the eruption prompted evacuation to what they hoped were safer havens. Ms = earthquake surface-wave magnitude as measured on the Richter scale (Abe 1992). Although only one seismograph was operating in Alaska at the time of the eruption, many of the earthquakes were big enough to be recorded by instruments in Europe, Asia, Japan, Hawaii, North Africa, and North America. Modifed from Figure 5 of Fierstein (2012a)

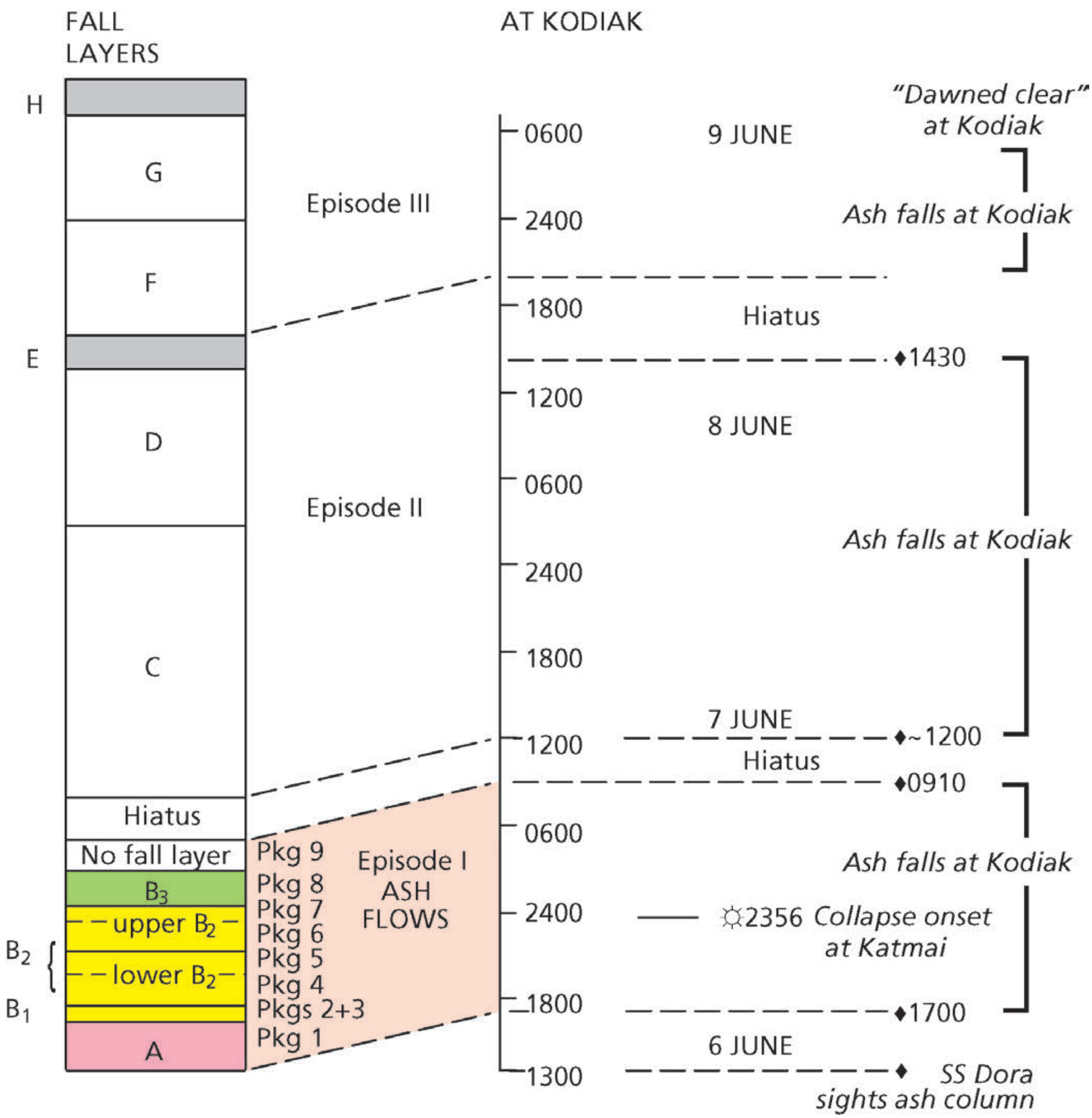


Figure 11 (above). Generalized 1912 eruptive sequence and chronology of ash fall recorded at Kodiak village, about 170 km (100 mi) downwind. Four hour offset at base represents time between initial sighting of eruption column by SS *Dora* and the beginning of ash fall at Kodiak. All of the tephra fall layers are mapped on Plate 1 as Qpd. Figure 2 from Hildreth and Fierstein (2012).

250 m (800 ft) deep. Caldera collapse was accompanied by 14 earthquakes of magnitudes 6 to 7, 100 earthquakes greater than magnitude 5, and countless smaller earthquakes (Figure 10). By 9 June, when the main outpouring finally ceased at Novarupta and the day dawned clear at Kodiak, the advancing ash cloud had begun dropping sulfur-permeated fallout on Puget Sound in Washington State. On the following day, the cloud passed over Virginia, and by 17 June it reached Algeria.

The 60-hour-long explosive sequence at Novarupta consisted of three discrete episodes (Figure 11) separated by lulls of at most a few hours (Martin 1913; Hildreth 1983; Fierstein and Hildreth 1992). During Episode I, the volume and rate at which the pumice and ash were ejected from the vent were so great that some of it went upward into the towering eruption column to be distributed as ash fall, while some flowed down the surrounding valleys forming ash flows. The ignimbrite (pumice rich ash flow deposit) remained hot for several decades, earning the name "Ten Thousand Smokes" for the many steaming cracks and fissures on the ignimbrite (see Figure 18). Episode I left a depression 2 km (1.3 mi) wide, filled with pumice and ash from its own eruption. Fault scarps caused by collapse and subsidence in 1912 encircle the area that provided the vent for the first day of eruption (Figure 7). Within this large vent, the subsequent eruptions (Episodes II and III) bored through the partly consolidated deposits of Episode I through a smaller vent that produced the ash falls of the next two days. Eruption episodes II and III also built a ring of pumice-rich ejecta around their smaller vent, which was plugged by the Novarupta lava dome that developed following the explosive episodes.

The deposits from these three eruption episodes are distinguishable by the ratios of the three pumice types they contain: white rhyolite with few phenocrysts (mineral crystals); white to gray dacite with abundant phenocrysts; and brown to black andesite, also with abundant phenocrysts (see Table 2 for an explanation of volcanic rock classifications). Although ejected together throughout much of the eruption, their relative proportions varied with time. These variations are used to track the dispersal, character, and thickness of each layer, both around the vent and in more distant locations. That information was used to piece together

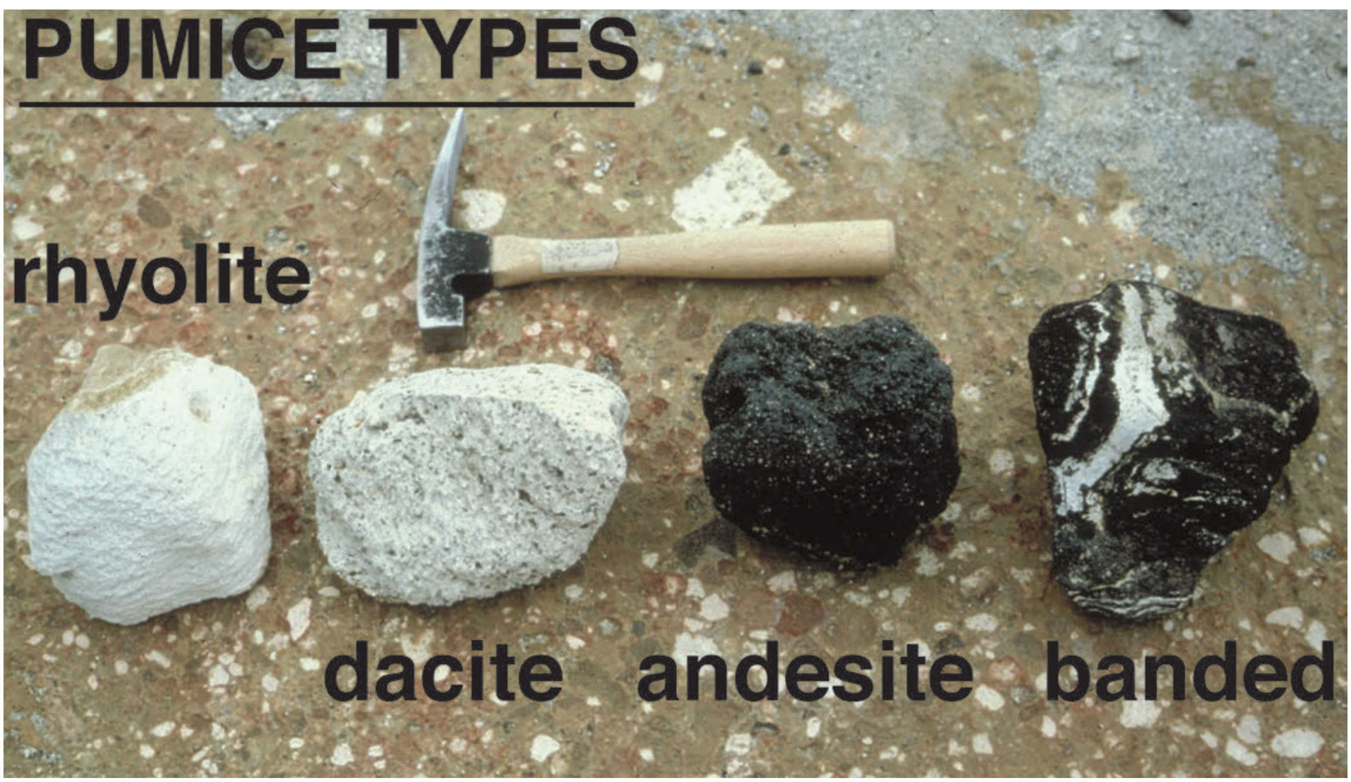


Figure 12. Photograph showing representative pumices from 1912 eruption. From left to right, the pumice from the 1912 eruption included white crystal-poor rhyolite, pale gray crystal-rich dacite, black crystal-rich andesite, and rhyolite-andesite banded pumice. USGS-CalVO photograph by Wes Hildreth.

Table 2. Simplified volcanic rock classification and characteristics.

Name	Percent Silica (SiO_2)*	Viscosity	Typical Explosiveness	1912 Eruption Products
Rhyolite	>72%	Viscosity ranges from high for rhyolite to low for basalt.	Explosiveness ranges from high for rhyolite to low for basalt.	Yes
Rhyodacite	68%–72%			Yes
Dacite	63%–68%			Yes
Andesite	57%–63%			Yes
Basaltic andesite	53%–57%			No
Basalt	<53%			No

* From Clynne and Muffler (2010).

what happened during those three days in 1912 (Hildreth 1983; Fierstein and Hildreth 1992).

Episode I

Episode I began with widespread dispersal of purely rhyolitic fallout (Layer A) and synchronous emplacement of rhyolitic ash flows from the same high eruption column. After ejection of approximately 3 km^3 (0.7 mi^3) of rhyolitic magma over the course of a few hours, small amounts of andesitic and dacitic magma began contributing to the eruption column, marking the onset of Plinian Layer B (Figure 11). Pumice proportions in Layer B change from more than 99% rhyolite at its base to only about 15% rhyolite at its top, matching the progressive shifts in (rhyolite/dacite/andesite) pumice proportions in the main sequence of pulses, or packages, emplaced concurrently in the Valley of Ten Thousand Smokes (Fierstein and Hildreth 1992; Fierstein and Wilson 2005). Rhyolite, dacite, and andesite magmas (each containing different amounts of silica; see Table 2) swirled together to create white and black "banded" pumice (Figure 12), an unusual occurrence that instigated debates about how these evolved together in the underground plumbing system. Banded pumice is most abundant in Layer B and in the layers that make up the ignimbrite. By 9:10 am on 7 June, emplacement was over and ash fall stopped at Kodiak for a short time. Episode I lasted about 16 hours and produced almost all of the Valley of Ten Thousand Smokes ash flows, which cover 11 km^3 (2.6 mi^3), and roughly half of the ash-fall deposits, covering 8.8 of 17 km^3 (2.1 of 4 mi^3; Figure 13).

Episodes II and III

Episodes II and III were similar to each another; each began after an eruptive hiatus (see Figure 9) then erupted from a smaller vent nested inside the larger one of Episode I. Each deposited widespread fall layers (Layers C–D and F–G, respectively), which were almost entirely dacitic. As with the preceding ash falls, Layers C and D were strongly dispersed east-southeastward, but the wind relented and the subsequent ash falls were less strongly directed toward Kodiak (Figure 14). Layers E and H are mostly accumulations of fine ash that settled regionally in the relative calm after each eruptive episode. Almost all of the deposits from these two episodes are widespread ash falls, but near the vent, short-traveled ash flows are preserved as well. Some of these proximal deposits were from small explosions during the lull between the Episode II and III eruption columns, which indicate the vent still remained unsettled during this lull.

Three Lava Domes

The explosive episodes were followed by extrusion of three lava domes. Compared to the explosive violence of 6–9 June, the growth of the domes was an uneventful expulsion of molten rock that was largely rid of its former gas content and slowly squeezed out of the vent. Though the exact timing is not known, these domes may have formed within days or as long as a year after the Plinian events. One small dacite lava dome that plugged the Episode III vent was destroyed by small explosions; all that remains are lava blocks scattered around the Novarupta dome (Adams et al. 2006). The same vent was plugged again by the rhyolitic Novarupta dome, which survives today. The third one is a dacite lava dome extruded on the floor of the Katmai caldera, then partially disrupted explosively. Photographed by Griggs in 1916 and sampled by Fenner in 1923, it is now covered by a crater lake. Figure 15 shows a conceptual cross section of the Novarupta vent area.

Landscape Changes Caused By the 1912 Eruption

The landscape of the Katmai area was forever changed by the 1912 eruption. The geomorphic and biologic processes in the first few years following the eruption were documented by the Griggs expeditions, but many of the processes observed then are continuing and evolving today. The eruption occurred in early summer when snow was still covering some areas. The accumulation of warm pumiceous tephra fall on this snow led to lahars down drainages surrounding Mount Katmai (Hildreth and Fierstein 2012). Numerous slope

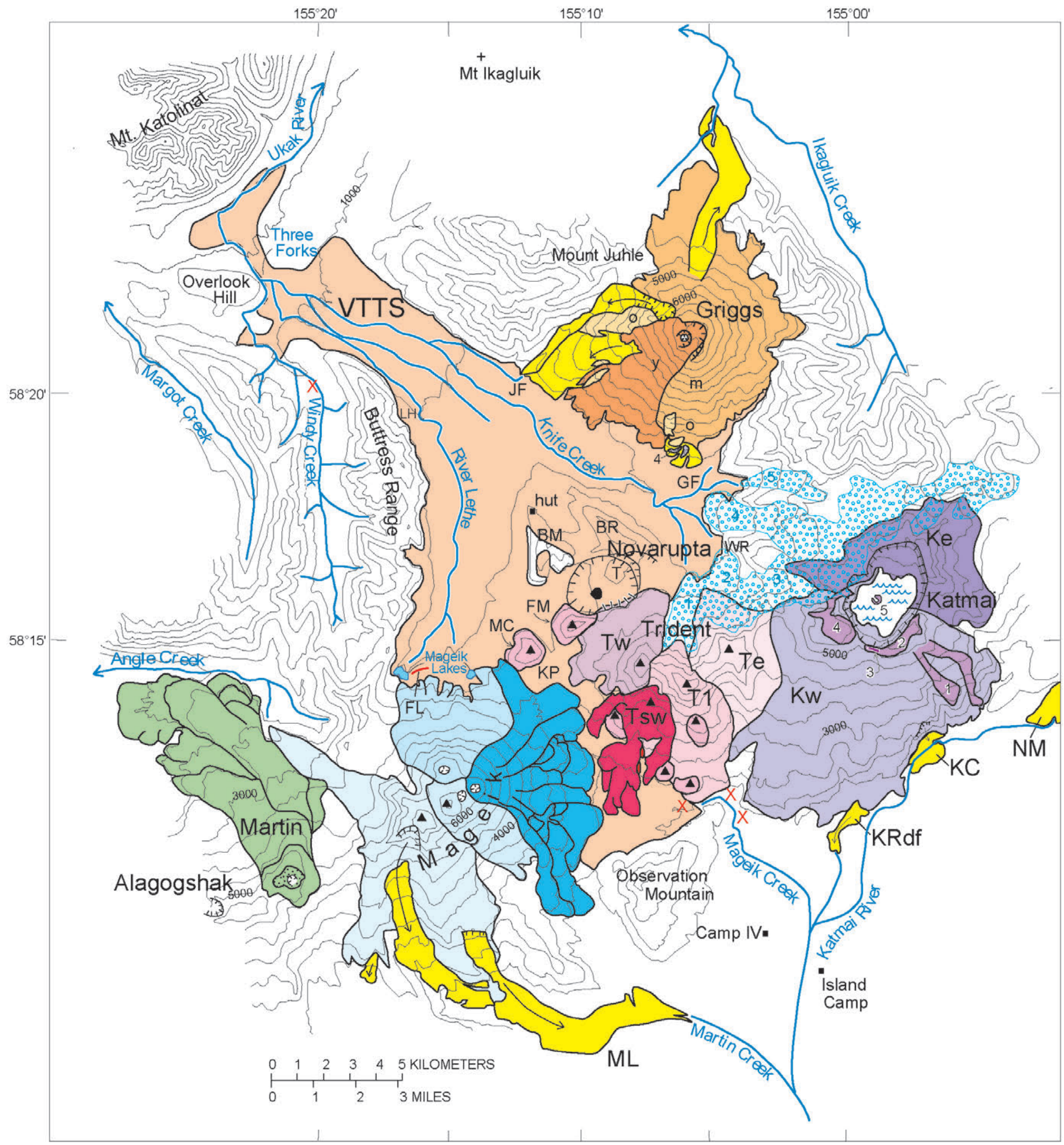


Figure 13. Simplified geologic map of the Valley of Ten Thousand Smokes and volcanoes of the Katmai cluster. The map shows the volcanic rocks by source volcano. The Valley of Ten Thousand Smokes ignimbrite (VTTS, tan) extends northwest 20 km from the Novarupta lava dome (hachured vent depression) and across Katmai Pass (KP) for 10 km down Mageik Creek. Knife Creek Glaciers (blue stippled areas) are numbered 1–5; other glaciers are omitted for clarity. The Alagogshak volcano, long extinct, is indicated only by its eroded crater. Mount Mageik consists of four overlapping centers (in shades of blue); only the youngest and easternmost center (for which individual lava flows are indicated) is Holocene. Mount Martin (green), entirely Holocene, consists of a small fragmental summit cone and several overlapping flows. The Trident group of volcanoes (pink) consists of three Pleistocene (2.6–0.01 MYA) cones: East Trident (Te), Trident 1 (T1), and West Trident (Tw), as well as the historical [*caption continues on next page*]

[*caption continued from previous page*] (1953–1974) Southwest Trident (Tsw, dark pink) lavas and fragmental cone; several peripheral Pleistocene lava domes (also pink), comagmatic with Trident, include Mount Cerberus (MC) and Falling Mountain (FM). Mount Katmai consists of two overlapping centers, Northeast Katmai (Ke) and Southwest Katmai (Kw), both truncated by the 1912 collapse of Katmai caldera (hachured), which is now partly filled by a lake (white with blue "waves"). The five youngest eruptive units of Mount Katmai are numbered (1–5): 1, leveed dacite lava flows; 2, south-rim rhyodacite lavas; 3, scoria fall atop unit 2; 4, dacite flow on caldera rim and at Knife Creek; and 5, Horseshoe Island dacite dome. Remnants of the 22,500-year-old rhyodacite pumice-fall deposits (and ignimbrite) in Windy and Mageik creeks (sites indicated by red X) are related to the most evolved lava of unit 2. Products of Mount Griggs are subdivided by age into older (o, middle Pleistocene), middle (m, late Pleistocene), and younger (y, postglacial) exposures. Holocene debris-avalanche deposits are in bright yellow; those emplaced in 1912 are labeled KC, Katmai Canyon landslide; KRdf, Katmai River pumiceous debris flow; ML, Mageik Landslide; NM, Noisy Mountain landslide. Uncolored basement rocks are the Naknek Formation or undivided intrusions. Miscellaneous features: BM, Baked Mountain; BR, Broken Mountain; FL, site of Fissure Lake; GF, Griggs Fork of Knife Creek; JF, Juhle Fork of Knife Creek; T, Turtle; WR, Whiskey Ridge; hut, Baked Mountain Hut research shelter. Island Camp and Camp IV were way stations between Katmai Bay and the Valley of Ten Thousand Smokes. Refer to Hildreth and Fierstein (2003) for a detailed map of the volcanic units by source volcano, as the volcanic rocks are not differentiated by source on the GRI geologic map in Plate 1. Figure 5 in (Hildreth and Fierstein 2012).

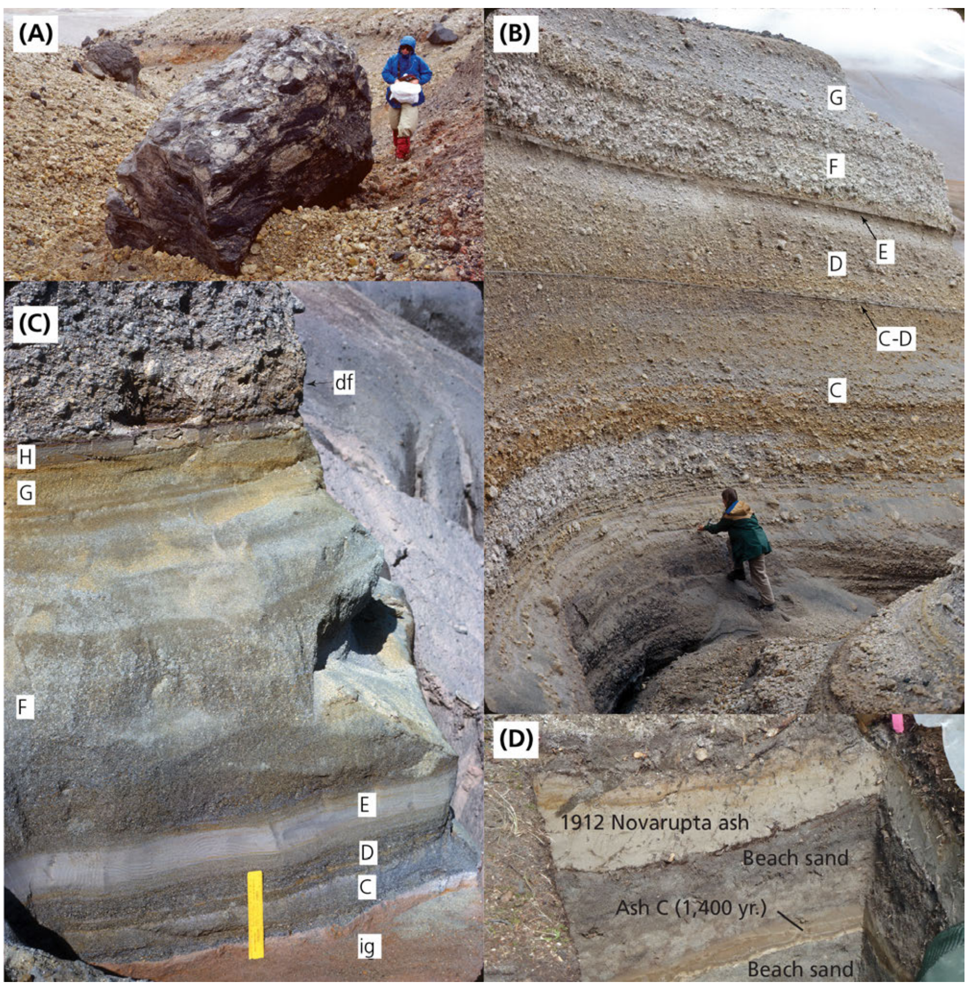


Figure 14. Photograph of fall deposits at different distances from vent. Deposits are coarsest and thickest closest to vent, and get finer and thinner with distance. (A) Large block about 1 km (0.6 mi) from Novarupta dome never went into the high eruption column. (B) Coarse dacite pumice fall deposits of Episodes II and III 4 km (2.5 mi) northeast of Novarupta are 12 m (36 ft) thick. Fall layers are labeled C–G. (C) Complete section of dacite fall deposits of Episodes II and III about 11 km (7 mi) northwest (upwind) of Novarupta are about 1 m (3 ft) thick. Fall layers are labeled C–H. Episode I ignimbrite (ig) underlies the fall layers. Debris flow (df) on top is a flood deposit that covered the 1912 fall soon after the eruption. (D) Structureless fine white ash about 50 km (30 mi) upwind northwest of Novarupta at Brooks Camp is about 20 cm (8 in) thick. This distal ash layer includes contributions from all three eruptive episodes. Photographs A–C: USGS-CalVO photographs by Judy Fierstein and Wes Hildreth; D: NPS photograph by Mike Fitz.

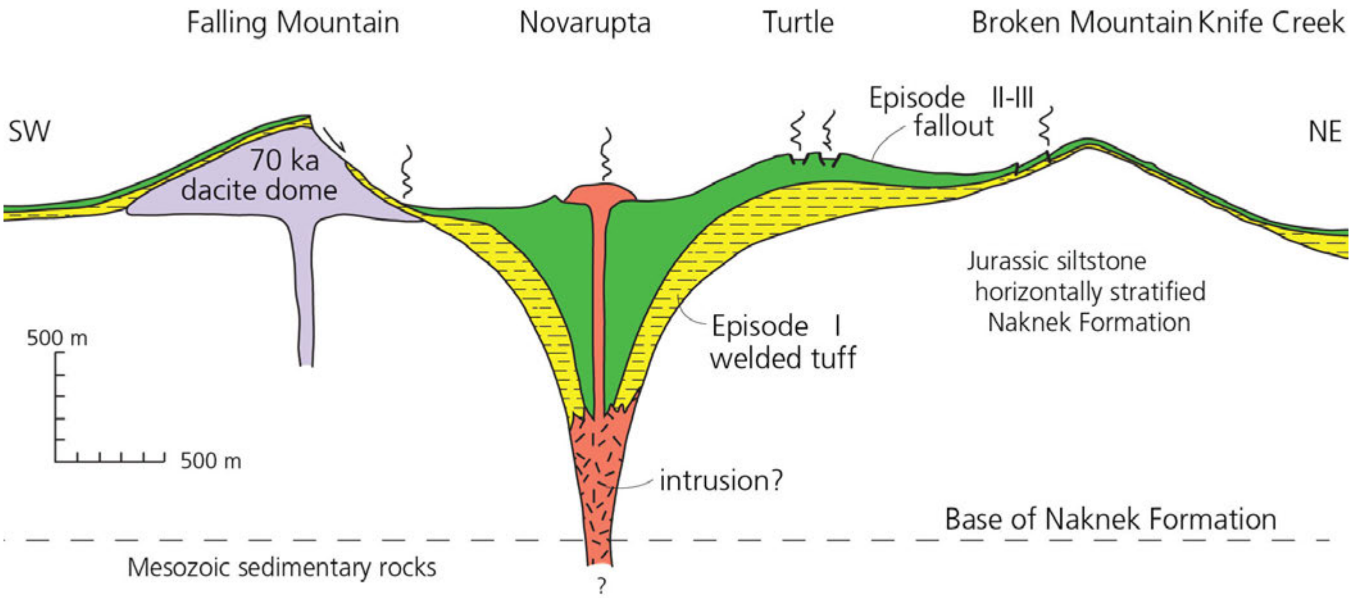


Figure 15. Inferred cross section of Novarupta vent area. Representation is based on surface exposures, geophysical interpretations, regional Mesozoic stratigraphy, and estimates of volumes of basement lithic ejecta and recycled welded ejecta. Beneath the Katmai volcanic cluster and adjacent to the Valley of Ten Thousand Smokes, exposed basement rocks belong exclusively to the Naknek Formation, which supplied all the non-volcanic lithic fragments ejected at Novarupta, including sparse granitoid cobbles from its conglomerate members. No vertical exaggeration. Figure 96 in Hildreth and Fierstein (2012).

failures were caused by the concurrent earthquakes; one of which dammed the Katmai River resulting in a large, subsequent flood in 1915. Systematic documentation of these geomorphic changes was not a primary focus of the initial studies, but some key geomorphic features and processes were discovered during those explorations.

Landslides during the Eruption
Map units: **Qls** (in part)

During the night of 6–7 June 1912, the Katmai Canyon landslide (unit KC in Figure 13; Figure 16) was triggered by earthquakes associated with collapse of the Katmai volcano. Rhyolitic fallout layer A is missing from the ash overlying the landslide debris, indicating that the landslide occurred early during the eruption (Hildreth and Fierstein 2012). Major seismicity probably shook the landslide loose. Griggs (1922) surmised that water was dammed by the landslide deposit, which breached catastrophically in 1915, causing flooding down the Katmai River valley three years after the eruption. Griggs found evidence of high water marks downstream of the landslide that indicated the flood waters flowed over a rock promontory forming a waterfall 30 m (100 ft) high and 300 m (1000 ft) wide at the end of Katmai Canyon, and that the flood filled the mouth of the Katmai River 3 m (10 ft) deep where the floodplain is 10 km (6 mi) wide. The Mageik Landslide (unit ML in

Figure 16. Photograph showing the Katmai Canyon landslide. The hummocky area on both sides of the Katmai River is the landslide deposit, marked by a dashed line, with the crest of the scarp shown with a solid black line. The landslide dammed the river, creating a temporary lake that flooded in 1915. Subsequently, the river has cut down through the landslide deposit. USGS-CalVO photograph by Wes Hildreth.

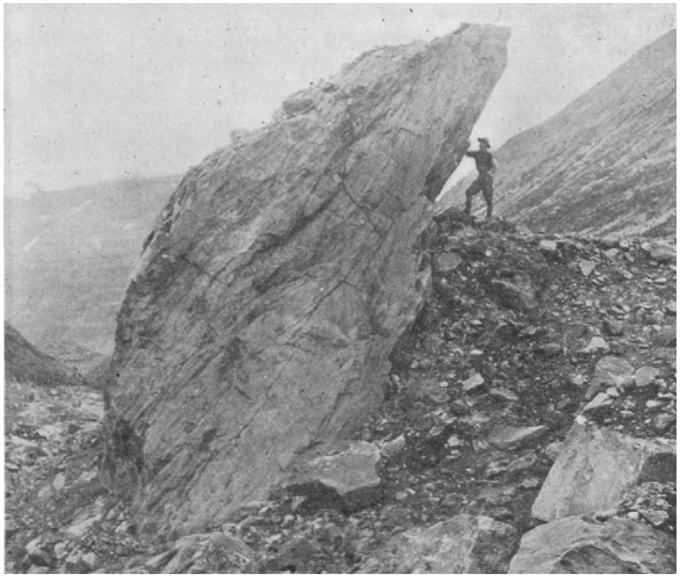


Figure 17. Photograph of a very large boulder in the Mageik Landslide. National Geographic Society photograph by Robert Griggs from Griggs (1920, p. 326).

Figure 13; Griggs 1920, 1922) consists mostly of angular blocks (Figure 17) of fresh dacite that broke loose from a stack of lava flows low on the Southwest Summit flank evidently triggered by shaking that accompanied caldera collapse at neighboring Mount Katmai. Leaving behind a scarp 120 m high, the deposit extends 6 km (4 mi) down valley and is 5–30 m (15–100 ft) thick. The Noisy Mountain landslide, in upper Katmai Canyon (unit NM in Figure 13), is avalanche debris consisting of andesite from Noisy Mountain; the headwall scarp extends as high as 900 m (3,000 ft) above the valley floor on the south slope of the mountain. Large parts of this avalanche broke loose during eruptive Episode I. Griggs (1922) noted that when his party camped there in 1917, rockfalls large and small had continued on the scarp every few minutes, inspiring the name Noisy Mountain. It was quiet when USGS scientists Wes Hildreth and Judy Fierstein investigated the area in the 1990s. The deposit impounded Upper Katmai Lake, which was approximately 2 km (1.5 mi) across in 1917 (Griggs 1922), but is only a shallow pond today.

Figure 18. Photographs of the Valley of Ten Thousand Smokes. Top: In 1917, the northwest arm of the valley was filled with steaming fumaroles. The view is looking northwest toward the Buttress Range on the left side of the photograph. National Geographic Society photograph by Robert Griggs (Griggs 1922, p. 234). Bottom: The photograph, taken in 2013, shows the same area but devoid of fumaroles. Fog is visible at the end of the valley. AVO-UAF Geophysical Institute photograph by Taryn Lopez.

Changes in the Valley of Ten Thousand Smokes

The eruption inundated Knife Creek, the River Lethe, and upper Mageik Creek with ignimbrite. Today, the once steaming ignimbrite that formed the Valley of Ten Thousand Smokes (Figure 18) only contains a handful of fumaroles (vent from which gases and vapors are emitted). Voids left by the fumaroles are filling up with sediment from material that is frequently transported by the strong winds (Figure 19).

The River Lethe, Knife Creek, and other small creeks in the valley incised (cut) rapidly into the ignimbrite soon after it was deposited. The River Lethe, Knife Creek, and other small creeks in the valley have changed little since they were first explored in 1917. The emplacement of the ignimbrite changed the valley from a U-shaped valley shaped by ice age glaciers to a relatively flat-bottomed valley abutting steeper slopes (Figure 20). The amount of downcutting relates to the amount of welding or sintering of the ignimbrite with rapid downcutting in nonwelded ("softer") deposits and slower downcutting in stronger sintered deposits (Figure 20). The nonwelded, stratified fall deposits of Episodes II and III had been eroded away along the main stream channels by 1917, and incision of the underlying ignimbrite was generally only a few meters in the upper valley but about 20 m (70 ft) in the central valley. No quantitative measurements of erosion rates has been made, but erosion slowed greatly after the first few years. A century after the eruption, streams in the upper River Lethe and Knife Creek arms of the valley have eroded steep-sided gorges only 2–8 m (7–25 ft) deep into sintered ignimbrite. In the lower valley, where the tuff is nonwelded, the underlying bedrock (10–20 m, 33–66 ft deep) is exposed, but for only 2 km (1.2 mi) upstream from the toe of the ignimbrite. Today the gorges are deepest in the central Valley of Ten Thousand Smokes, where the ignimbrite grades from sintered to nonwelded. The greatest depths are 30–35 m (100–115

Figure 19. Photograph of an inactive fumarolic fissure. This fumarole formed along a fracture that is near the edges of the ignimbrite (see Figure 20). Deposits at the top of fissure are windblown accumulations of pumice, with colorful alteration from steam and hot gases that deposited their dissolved minerals in and around the pieces of pumice. When this photograph was taken in 1982, a weak vapor plume was still coming through this fumarole, but it is now filled in by windblown pumice and ash. USGS-CalVO photograph by Wes Hildreth.

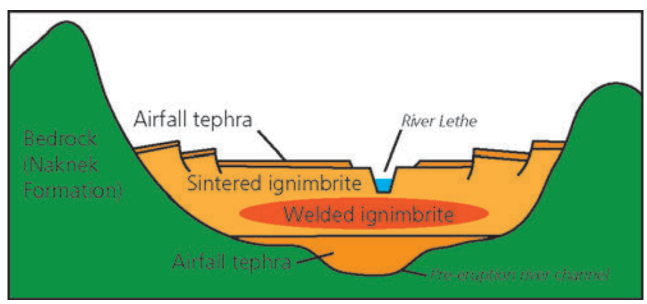
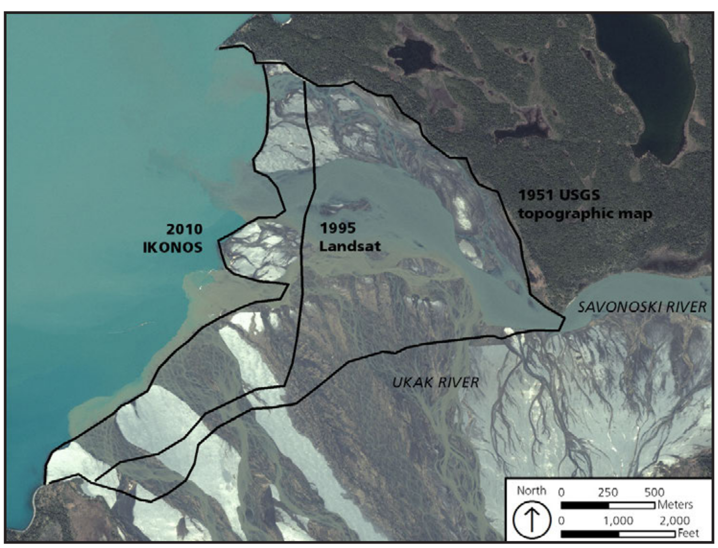


Figure 20. Simplified cross section of a glacial valley filled with a thick pyroclastic flow followed by rapid incision of streams. The depth and rate of down-cutting relates to the amount of sintering or welding of the ignimbrite. The initial thickness of the ignimbrite was about 240 m (790 ft). After cooling and welding of the ignimbrite, it compacted in the center portion to about 170 m (560 ft) thick, which left terraces on the edges of the valley that are about 70 m (230 ft) above the central portion of the ignimbrite (Kienle 1991). Fumaroles are aligned along the fractures on the edges of the terraces. Re-drafted from figure 3 of Waythomas (2015).

Figure 21. Photograph of deep incisions by creeks into the ignimbrite. Gorges are approximately 30 m (100 ft) across. NPS photograph.

Figure 22. Photograph of the Ukak River and Savonoski River deltas showing the brown waters of the sediment laden rivers. NPS photograph by Kaiti Critz.



ft), along the gorges of the main and Juhle forks of Knife Creek, 1–2.5 km (0.6–1.5 mi) above their confluence (Figure 21).

Glaciers were somewhat more advanced during the time of the 1912 eruption than they are today and some of the glacier termini were overtopped by the hot ash flow (Hamilton 1973). This caused rapid ice melt that formed explosive generation of steam. Pits from the phreatic eruptions are present around the toes of the glaciers at the upper reaches of the Valley of Ten Thousand Smokes (see map by Hildreth and Fierstein 2003). Ice melt following subsidence of the ignimbrite formed closed basins ringed concentric fault scarps. A lake formed in one of these depressions at the base of Mount Mageik that has since drained (see repeat photographs in figure 89 of Jorgenson et al. 2008).

Sediment Output in Katmai and Savonoski Rivers

Map unit: **Qaf** (in part)

The 1912 eruption deposited pumice-rich tephra 10–15 km (6–9 mi) from the caldera and ash beyond. This massive amount of mostly loose material has had a major impact on the sediment flux of the rivers and melting rates of the glaciers. Griggs (1922) noted that the streams were choked with sediment in the Katmai River valley. The influx of sediment caused fluvial aggradation (deposition of sediment) of the Ukak, Ikagliuk, Rainbow, Savonoski, and Katmai rivers. The abundant sediment (Figure 22) caused the Ukak River and Savonoski River deltas to grow 1–2 km (0.5–1.5 mi) into Naknek Lake from 1951 to 2010 (Figure 23).

Vegetation Changes

The 1912 eruption has provided opportunities for integrated biological research for understanding disturbance ecology. Griggs was a botanist who, before the eruption, was studying colonization of marginal habitats in Alaska. After the eruption he was sent to the Katmai area by the National

Figure 23 (left). Map showing the progradation (growth) of the Ukak River and Savonoski River delta from 1951 to 2010. The abundant loose material produced by the 1912 eruption has inundated the rivers with sediment, which has been transported downstream and is being deposited at the mouths of the rivers. Satellite (IKONOS) imagery from 2010.

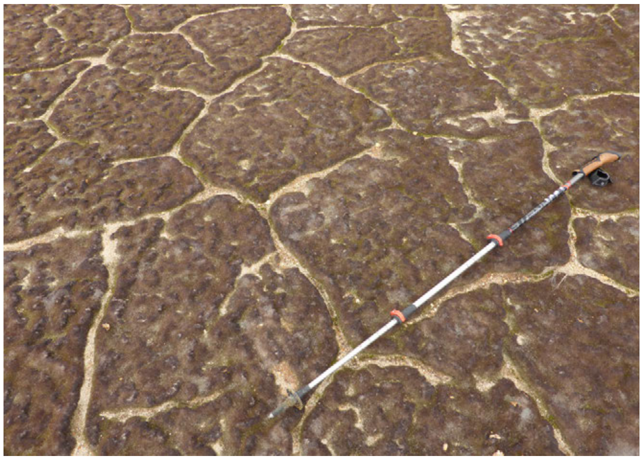
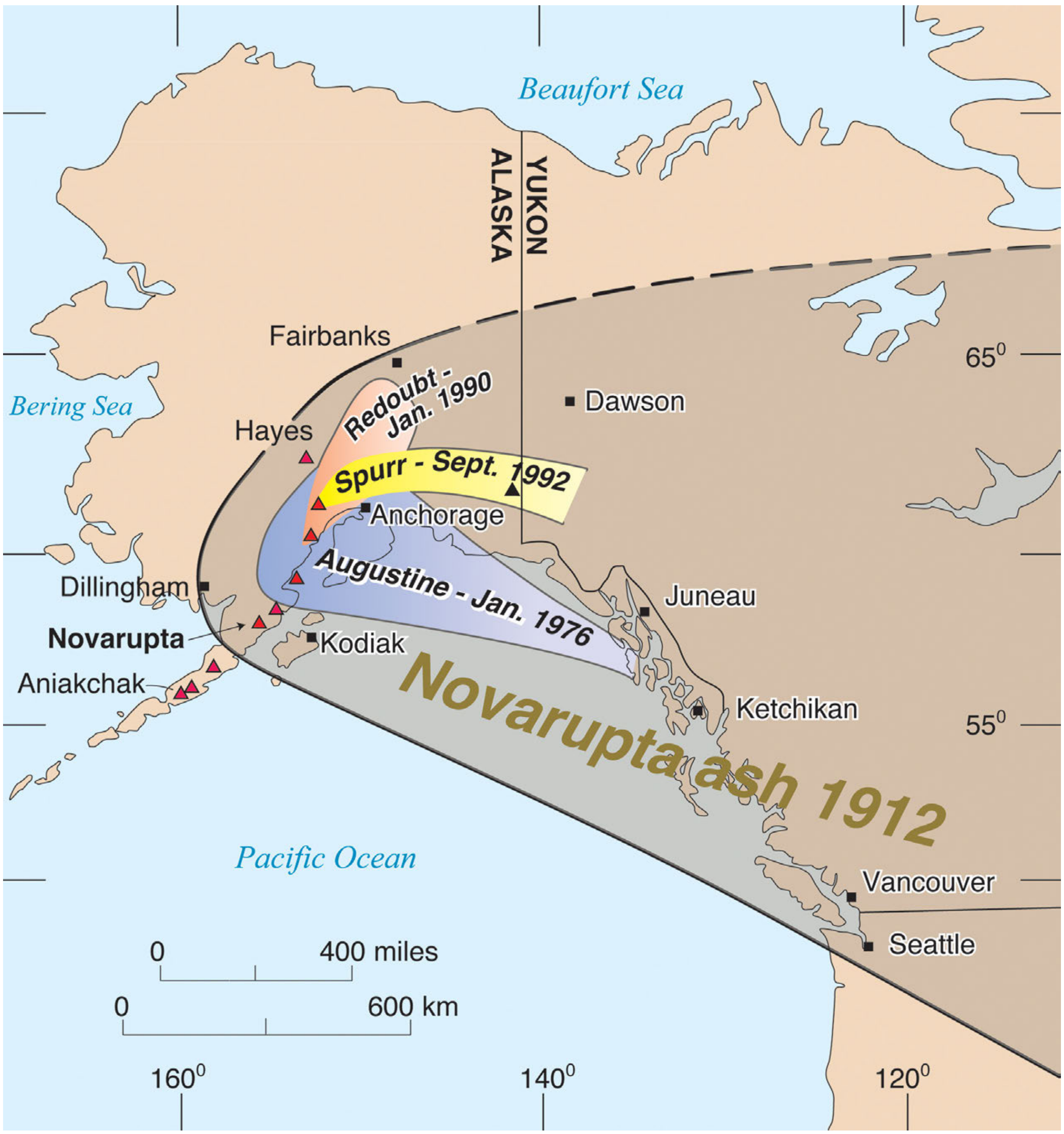


Figure 24 (left). Photograph of biological soil crust. In places less exposed to high winds, biological soil crusts have formed. This is a living crust that can be made up of bacteria, cyanobacteria, fungus, moss, and other organisms. Trekking pole is approximately 130 cm (50 in) long. NPS photograph by Mike Fitz.

Figure 25 (below). Map of Alaska and adjacent parts of North America showing the location of Novarupta and the region impacted by ash fall. Within a few days after the 1912 eruption, the ash was carried by winds across the North American continent. The limited distribution from other recent Alaska eruptions is shown for comparison. Figure 2 in Fierstein (2012c).



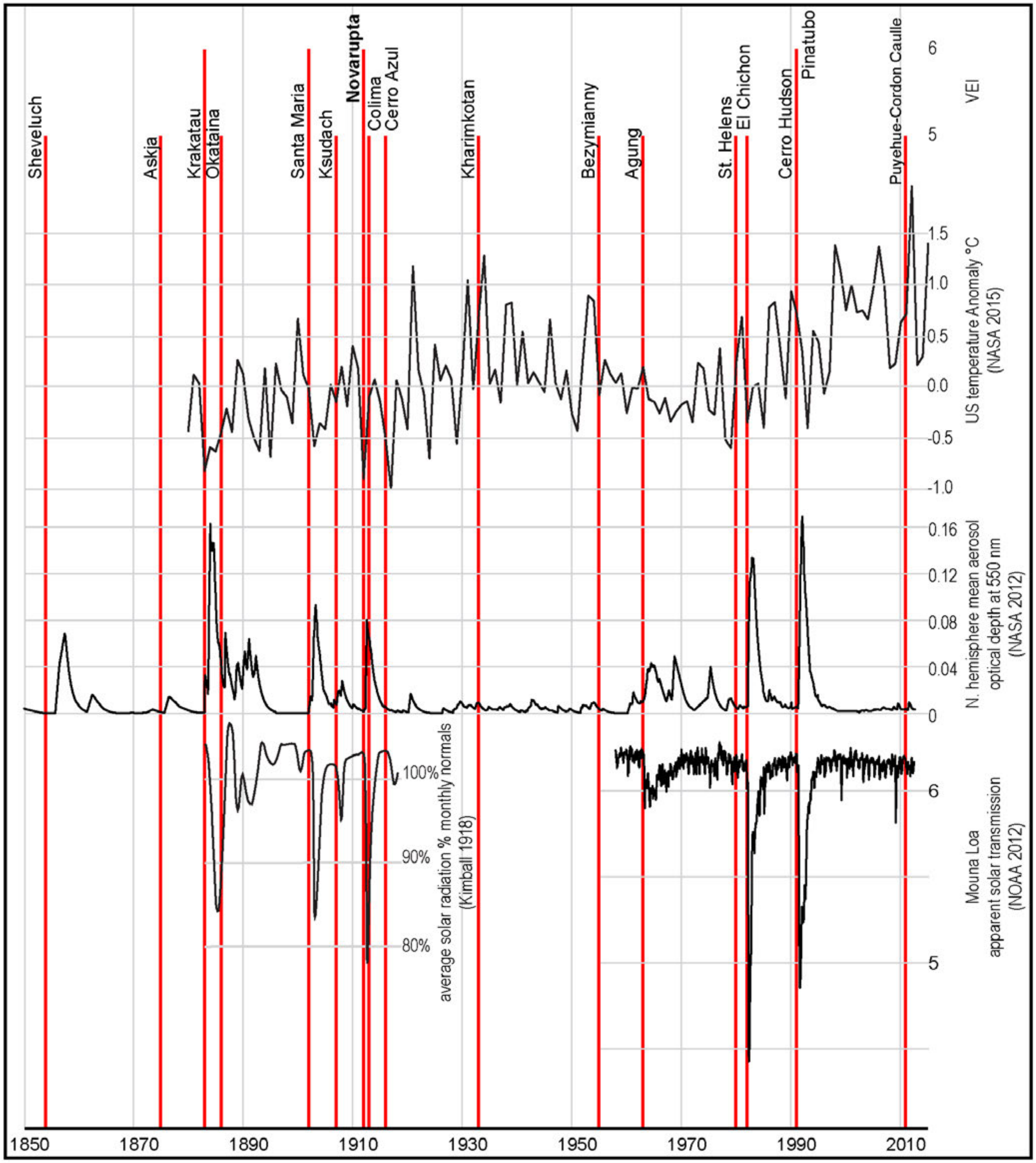


Figure 26. Graph showing the timing of major volcanic eruptions compared to Northern Hemisphere climate records. The timing of eruptions since 1850 with a VEI≥5 are compared with changes to Northern Hemisphere solar radiation, aerosol optical depth ("haze"), and the US temperature anomaly. The eruptions produce aerosols that increase the aerosol optical depth (haze), which decreases the solar radiation. This decrease in solar radiation commonly reduces temperatures. The 1912 Novarupta-Katmai eruption is correlated with the second lowest measured temperature anomaly measured across the United States. Graph incorporates data from Kimball (1918), NASA (2012, 2015), and NOAA (2012); also see Antón et al. (2014) and Sigl et al. (2015).

Geographic Society to document the volcanic features of the eruption and the effects of the eruption on the ecology of the area. During these expeditions to Kodiak and the Katmai area, he found that plants recovered well in places where the accumulated ash was less than 1 m (3 ft) thick, but thick, windswept surfaces remained barren (Griggs 1917, 1918a, 1919, 1922, 1933). He tested the fertility of the ash and found that it was severely depleted in the necessary nutrients, especially nitrogen, for plant growth. This lack of nutrients and the constantly shifting surface are why vegetation has been slow to return where there were thick deposits of ash in and near the Valley of Ten Thousand Smokes. Where fallout was thin, the ash acted like mulch preventing some plants from growing (Griggs 1918a). Plants that were able to sprout through the ash flourished because of the lack of competition. On the thick, barren surface of the ignimbrite, in 1917 Griggs witnessed moss and algae growing around the fumaroles (Griggs 1922). By 1930, a surface made up exclusively of liverworts developed in thick areas of the ignimbrite that are protected from the strong winds (Griggs 1933). When the area was visited by V. Cahalane in 1953–54 the extensive mats of liverworts had vanished; whereas, in places of moderate stability and on the slopes surrounding the valley seed plants had multiplied (Cahalane 1959).

Today's sparse vegetation on the ignimbrite provides little cover and meager food for the few animals that do venture into the Valley of Ten Thousand Smokes. Meager vegetation and thin biological soil crusts (Figure 24) have grown on the thick ignimbrite in places protected from the winds that constantly scour much of the surface with blowing sand. Comparing photographs taken during the Natural Geographic expeditions to those of today, Jorgenson et al. (2007) noted very slow succession in the valley, with exception of the growth of a few plants only in a few areas near Novarupta and near the Knife Creek Glaciers.

Global Climate Effects of the 1912 Eruption

Large Plinian eruptions produce atmospheric aerosols (fine particles in air) that reduce the solar radiation reaching the Earth's surface, which can cause global cooling (Sigl et al. 2015). Effects of the ash from the 1912 eruption were felt across the Northern Hemisphere. From the vent at Novarupta, the towering column of ash jetted skyward with only two short interruptions for 60 hours. Concurrently, it distributed ash flows that filled the valley of the River Lethe and fed a cloud more than 1,600 km (1,000 miles) wide that shrouded most of southern Alaska and the Yukon Territory. The ash cloud rapidly rose to more than 30 km (100,000 ft), where the jet stream carried much of it eastward (Figure 25). Strongly aided by winds blowing east-southeastward, ash fall began at Kodiak within 4 hours and by the next day had spread 1,000 km (630 miles) east and at least 100 km (60 miles) west. Atmospheric effects (haze, smoke, red twilights) had been observed downwind, beginning in British Columbia on 6 June, and in Europe two weeks later. The great quantity of ash and aerosol not only caused unusually brilliant sunsets, but, by shielding the sun's rays, lowered average temperatures by about 1°C (2°F) in the Northern Hemisphere for more than a year (Figure 26; Griggs 1922).

Volcanoes

Map units: **Qv**, **Qvd**, **Qpd**, **Qafd**, and **QTv**

Katmai contains the most active and dense group of stratovolcanoes of any unit in the National Park System. The explosive eruption of Novarupta on 6–8 June 1912 was the world's most voluminous of the 20th century and made the remote Katmai region famous. The Novarupta volcanic vent is part of the Aleutian volcanic arc, which is one of the most active volcanic regions in the world (Simkin and Siebert 1994). Novarupta is one of 24 Quaternary (erupted in the last 2.6 million years) volcanoes in Katmai that trend northeast to southwest (Table 3, Figure 27). Together, the volcanoes form 36 volcanic vents (Cameron and Nye 2014). Ten of the Katmai volcanoes are considered active (Madden et al. 2014). Five of the volcanoes erupted during historic time (CE 1760–present). "Active" refers to volcanoes with historical (CE 1760–present) eruptions, or considered hazardous because of plausible historical eruptions, vigorous fumarolic activity, intense earthquake swarms, or volcanic deformation (Madden et al. 2014). Geologic studies in the last three decades have identified more than 50 discrete volcanic vents in Katmai; 35 of these have been named (Cameron and Nye 2014). Most of these vents form a narrow line of ice-clad stratovolcanoes on the drainage divide of the Alaska Peninsula, which makes up the Aleutian arc segment that stretches from Mount Douglas on the north, south to Alagogshak. What follows is a brief geologic summary of the volcanoes in Katmai National Park and Preserve.

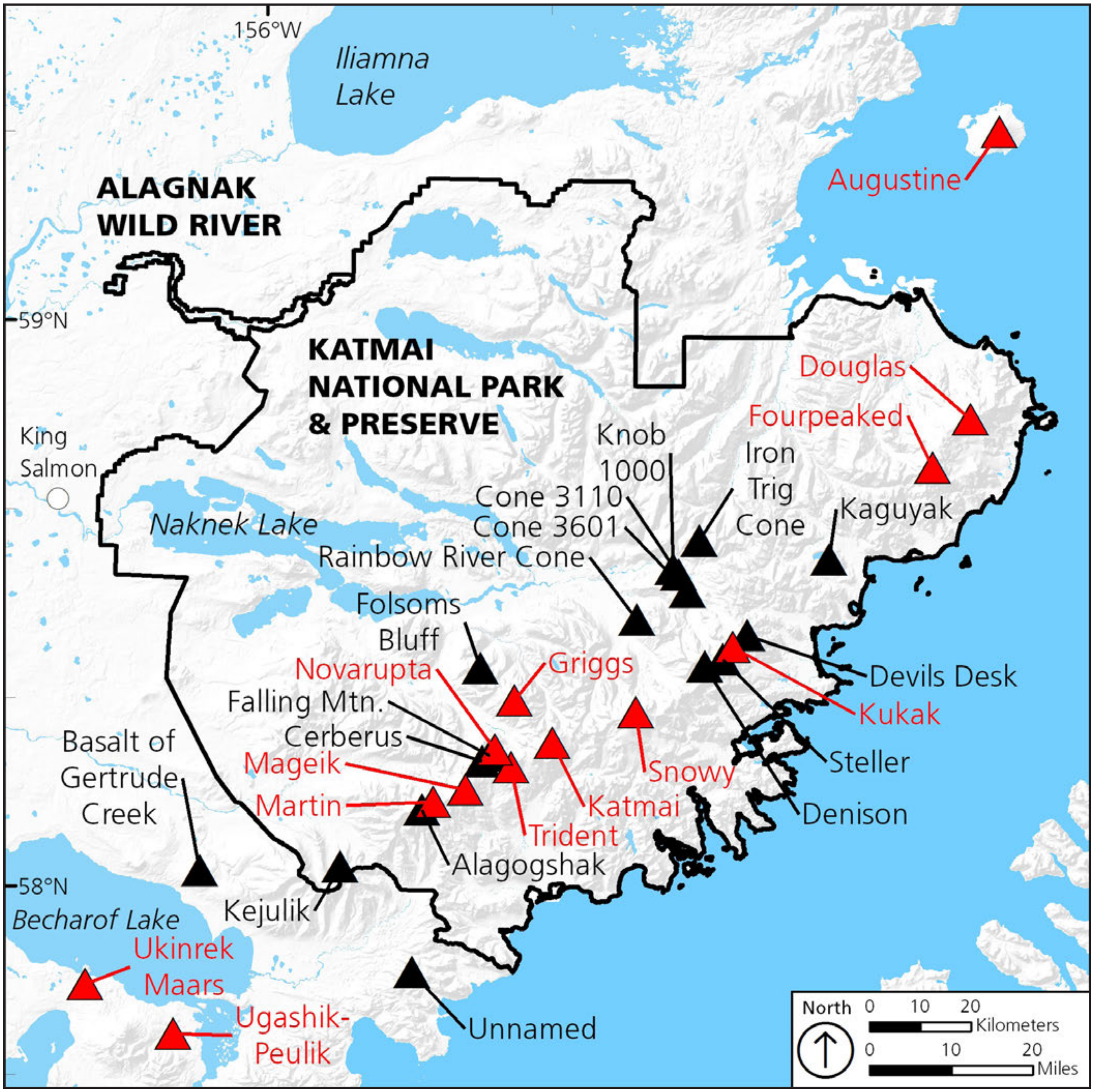


Figure 27. Map showing the locations of Quaternary (<2.6 MYA) volcanoes in the Katmai area. Active volcanoes are shown in red as identified in the Alaska interagency operating plan for volcanic ash episodes (Madden et al. 2014). See Table 3 for information about Quaternary volcanoes within Katmai National Park and Preserve.

Katmai Cluster

Twenty of the volcanic vents in the park are within 15 km (9 mi) of Novarupta (Hildreth and Fierstein 2003; Cameron and Nye 2014). This unusually dense grouping around Novarupta, informally referred to as the Katmai cluster, includes six stratovolcanoes Snowy, Katmai, Griggs, Mageik, Martin, and Alagogshak; the cluster of volcanic vents making up Trident Volcano; and the three lava domes Novarupta, Cerberus, and Falling Mountain.

The Katmai cluster is very active, with fumaroles and steam vents on all of the stratovolcanoes but Alagogshak. The most recent eruptions were from

Table 3. Volcanoes within Katmai National Park and Preserve.

Volcano[1]	Active[2]	Historic[2]	Last eruption (yr BP)[3]	History and Notes
Douglas	Yes	No	<11,700	Ice-clad stratovolcano with a small crater lake and active fumarole field on north side of crater.
Fourpeaked	Yes	Yes	CE 2006	17 September 2006 eruption formed a 6,100 m (20,000 ft) high plume from phreatic explosions (VEI 2). Unusual radar cloud height was measured at 6 km (4 mi). Volcanic steam was observed through 2007.
Kaguyak	No	No	1,060	A stratovolcano with a 3 km (2 mi) wide caldera and lake with CO_2 bubbling up from the bottom. Pyroclastic flows from the caldera-forming eruption filled surrounding valleys with over 30 m (100 ft) thick.
Iron Trig Cone	No	No	88,000±27,000	Mafic scoria cone of the Savonoski River Cluster of volcanoes.
Cone 3110	No	No	235,000±30,000	Partly erupted under a glacier.
Cone 3601	No	No	132,000±27,000	Mafic cone of the Savonoski River volcanic cluster.
Knob 1000	No	No	Unknown	Remnant of a volcanic cone and part of the Savonoski River cluster of volcanoes.
Rainbow River Cone	No	No	390,000±39,000	Small basaltic volcano of radially dipping stacks of thin lavas and breccia that is part of the Savonoski River cluster of volcanoes.
Devils Desk	No	No	<11,700	Ice-clad volcanic neck of a stratovolcano.
Kukak	Yes	Yes?	CE 1889	Ice-clad stratovolcano that contains a vigorous fumarole field near the northern summit. Report of an eruption in 1889.
Steller	No	No	<11,700	Ice-clad stratovolcano
Denison	No	No	<11,700	Ice-clad stratovolcano.
Snowy	Yes	No	<11,700	Ice-clad stratovolcano with fumaroles on the peak.
Folsoms Bluff	No	No	Unknown	Andesitic vent complex with a mass of curving glassy lava columns indicative of ice-contact emplacement.
Griggs	Yes	No	<11,700	Numerous fumaroles. 10 km (6 mi) behind (northwest of) the volcanic front defined by Martin, Mageik, Trident, Katmai, and Snowy Mountain centers
Katmai	Yes	Yes	CE 1912	A stratovolcano with a 10km (6 mi) diameter caldera formed by collapse during the 1912 Novarupta eruption (VEI 3).
Novarupta	Yes	Yes	CE 1912	Vent source of the 1912 eruption that is plugged with a 400 m (1,300 ft) in diameter dome (VEI 6).
Trident	Yes	Yes	CE 1953–1974	Volcanic complex consisting of four stratovolcanoes and numerous domes. 1953–1960 intermittent eruptions formed numerous lava flows and a volcanic dome (VEI 3). Numerous steam eruptions until 1974.
Cerberus	No	No	114,000±46,000	Andesite to dacite peripheral dome of Trident.
Falling Mountain	No	No	70,000±8,000	Andesite to dacite peripheral dome of Trident.
Mageik	Yes	No	Unknown	A stratovolcano with a phreatic crater on the northeast side that contains a crater lake and has vigorous fumarolic activity.
Martin	Yes	No	<11,700	A stratovolcano with a 300 m (1,000 ft) diameter crater that has intense fumarolic activity, and an ephemeral lake.
Alagogshak	No	No	2,600,000–11,700	Several eruptions spread intermittently over at least 600,000 years.
Kejulik	No	No	Unknown	Heavily eroded remnant of a stratovolcano.

[1]The order of the volcanoes is presented from northeast to southwest. See Figure 27 for a location map of Quaternary volcanoes. See Table 1 for description of Volcanic Explosivity Index (VEI) values in "History and Notes" column. AVO information for each volcano is available at https://www.avo.alaska.edu/volcanoes/ (volcano names in table are linked to this website).

[2]"Active" refers to volcanoes with historical (CE 1760–present) eruptions, or considered hazardous because of plausible historical eruptions, vigorous fumarolic activity, intense earthquake swarms, or volcanic deformation (Madden et al. 2014). Historic and last eruption data is from the Global Volcanism Program global list of volcanoes (Smithsonian Institution 2015). List of active volcanoes is from Madden et al. (2014, Appendix A).

[3]CE (Common Era; preferred to "AD") years are given for historic eruptions. All other dates are in years before present (yr BP).

a new vent on Trident Volcano (Southwest Trident, 1953–1974), but ash deposits indicate that at least eight other explosive events in the past 10,000 years are associated with the volcanoes of this area. Activity continues in the northeast corner of the park as well, including steam explosions from Fourpeaked Mountain in 2006, prolonged vigorous steaming that has coated snow-covered Kukak Volcano with yellow sulfur, and gas bubbling up through the Kaguyak crater lake. All of these rugged and active volcanoes contribute to spectacular scenery in this remote and sparsely inhabited wilderness on the Alaska Peninsula.

The eruptive history for each of the Katmai volcanoes was derived by mapping the distribution of eruptive products, and by describing in detail both lava flows and ash layers (Hildreth and Fierstein 2003; Fierstein 2007). Combined with the mapping, information about the ages of the deposits constrains the timing and frequency of past eruptions, which was used to make a volcano-hazard assessment for the Katmai cluster (Fierstein and Hildreth 2001).

Katmai Cluster: Mount Katmai

Mount Katmai, centered 10 km (6 mi) east of Novarupta, is a stratovolcano that once consisted of a pair of large cone-shaped volcanoes with interfingered lava flows, which had been active for more than 70,000 years. Both cones caved in during the caldera collapse of 1912 (Figure 28). Thick stacks of lava flows and sequences of pyroclastic deposits from at least 20 explosive eruptions are exposed in the caldera walls. Mount Katmai has a varied volcanic history, erupting products with a wide compositional range (basalt to rhyodacite).

One of the largest and most explosive events ever to occur at the Katmai volcanic cluster originated from Mount Katmai about 23,000 years ago. Rhyodacite pumice-fall and deposits from that eruption were widely distributed but have since been largely scoured away by glaciers. Remnants of the pumice fall preserved in nearby creeks are so thick that it seems likely the eruption was more voluminous than that of Novarupta in 1912.

Figure 28. Aerial view looking northwestward of Katmai caldera with Mount Griggs and the Valley of Ten Thousand Smokes in the background and part of Trident Volcano on the left. NPS photograph by Chuck Lindsay.

Since 23,000 years ago, Mount Katmai has erupted at least four more times, with both lava flows and ash falls. The largest of these is an explosive eruption thought to have occurred sometime between 16,000 and 12,000 years ago. Because pumice that fell near the vent landed on glaciers that occupied the valleys at that time, no undisturbed fall deposits remain near the volcano (Hildreth and Fierstein 2000, 2003), but a fine ash layer on the Kenai Peninsula, 225 km (140 mi) away, is probably equivalent (Reger et al. 1996; Fierstein 2007). Clearly, Mount Katmai has had a history that includes more explosive eruptions than any of the other stratovolcanoes in the cluster.

Katmai Cluster: Alagogshak Volcano

Alagogshak volcano, the most southwestern member of the Katmai volcanic cluster, is marked by hydrothermally altered remnants of the summit crater of a severely eroded vent complex (Figure 29). Such rocks, when permeated by acidic hot water and gas from the volcano's core, turn into colorful red, white, yellow, and orange remnants rich in clay minerals. Lava flows extending as much as 10 km (6 mi) in most directions are all glacially ravaged. Alagogshak, oldest by far of all the Katmai cluster volcanoes, is made of lavas as old as 680,000 years and no younger than 40,000 years (Hildreth et al. 1999). This is the only Katmai cluster volcano that is not considered active.

Figure 29. Photograph of the glacially eroded summit of Alagogshak volcano (center), about 3 km (2 mi) southwest of Mount Martin (left cone). USGS-CalVO photograph by Wes Hildreth.

Katmai Cluster: Mount Martin

Mount Martin, southwest of Mount Mageik, consists of a small volcanic cone and ten overlapping blocky lava flows that stretch northwestward for10 km (6 mi). The cone is smaller than it seems, for although its summit exceeds 2,030 m (6,100 ft) in elevation, it is built

Figure 30. Photograph of the fumarolically active Mount Martin summit cone and shallow lake. USGS-AVO photograph by Cyrus Read.

on a high ridge of sedimentary rocks of the Naknek Formation. Several ash-fall layers from Mount Martin are preserved in soils nearby and suggest that at least three eruptive episodes separated by at least a thousand years to as much as several thousand years built Mount Martin between about 6,000 and 2,800 years ago (Fierstein 2007). Still active, the cone is marked by a persistent steam plume that coalesces from as many as 20 fumaroles that precipitate sulfur around a shallow lake on the floor of its 100-m- (300-ft-) wide summit crater (Figure 30). Since seismic monitoring of the volcano was initiated in the early 1990s, the volcano has had five spikes in seismicity due to volcanic activity deep within the volcano (Dixon and Power 2009; Neal et al. 2009).

Katmai Cluster: Mount Mageik

Mount Mageik (Figure 31) is a compound stratovolcano just higher than 2,370 m (7,100 ft); it rivals Mount Katmai as the largest edifice in the Katmai cluster (Hildreth et al. 2000). Each of its four ice-mantled summits is a discrete eruptive center, and each is the source of numerous lava flows. Three of the eruptive centers are severely eroded by glaciers, indicating that they are older than the fourth. The three eroded centers each made up of sets of lava flows piled on top of one another that erupted during intervals 10,000 to 20,000 years long with some as old as 93,000 years. The eruptions at these three centers were long over by the time the fourth, youngest eruptive center formed.

The east summit was the only part of Mount Mageik built during the last 10,000 years. It erupted a dozen lava flows and seven explosive ash fall–producing events, the youngest of which is about 4,000 years old. Soil has developed on some of the lava flow surfaces but not on others in the sequence, indicating that at least hundreds, if not thousands, of years has passed between eruptive episodes. The youngest Mageik eruption about 2,500 years ago was an explosion that formed a crater between two of the summits. Evidently, no magma erupted from this vent, but the crater is filled with a yellow-green acid lake that sends up curls of steam often mistaken for eruption plumes.

Katmai Cluster: Trident Volcano

Trident Volcano (Figure 32) is a group of four overlapping stratovolcanoes and several lava domes as old as 150,000 years (Hildreth et al. 2003a). Although more deeply eroded by glaciers and in part older than the adjacent Mageik and Katmai volcanoes, Trident Volcano produced the area's most recent eruptive episode, from 1953 to 1974 (see Coombs et al. 2000; and Hildreth et al. 2003a). The eruption was intermittent over the 21-year span, and National Park Service photographs show that the cone had attained nearly its full height by 1960, although explosive showers of blocks continued to augment the cone until 1974. The central and highest cone is considerably eroded and certainly inactive over the last 10,000 years, but nonetheless supports a vigorous field of sulfur-producing fumaroles on its lower southeast flank, first

Figure 31. Photograph of ice-clad Mount Mageik from Baked Mountain. Mount Cerberus is in the foreground and the small plume on the right flank of the mountain is actually from Mount Martin, which is behind Mount Mageik. Photograph by Alexander Prusevich (University of New Hampshire).

Figure 32. View of the Trident Volcano from Baked Mountain. Although named Trident, the peak is made up of four eroded andesite and dacite cones. The Novarupta lava dome is visible at the bottom, center. Photograph by Alexander Prusevich (University of New Hampshire).

Figure 33. Photograph of the early stages of the Southwest Trident eruption taken 21 February 1953, showing a small lava flow and ash plume. Mount Griggs is on the left and Mount Katmai is on the right under the ash plume. US Navy photograph.

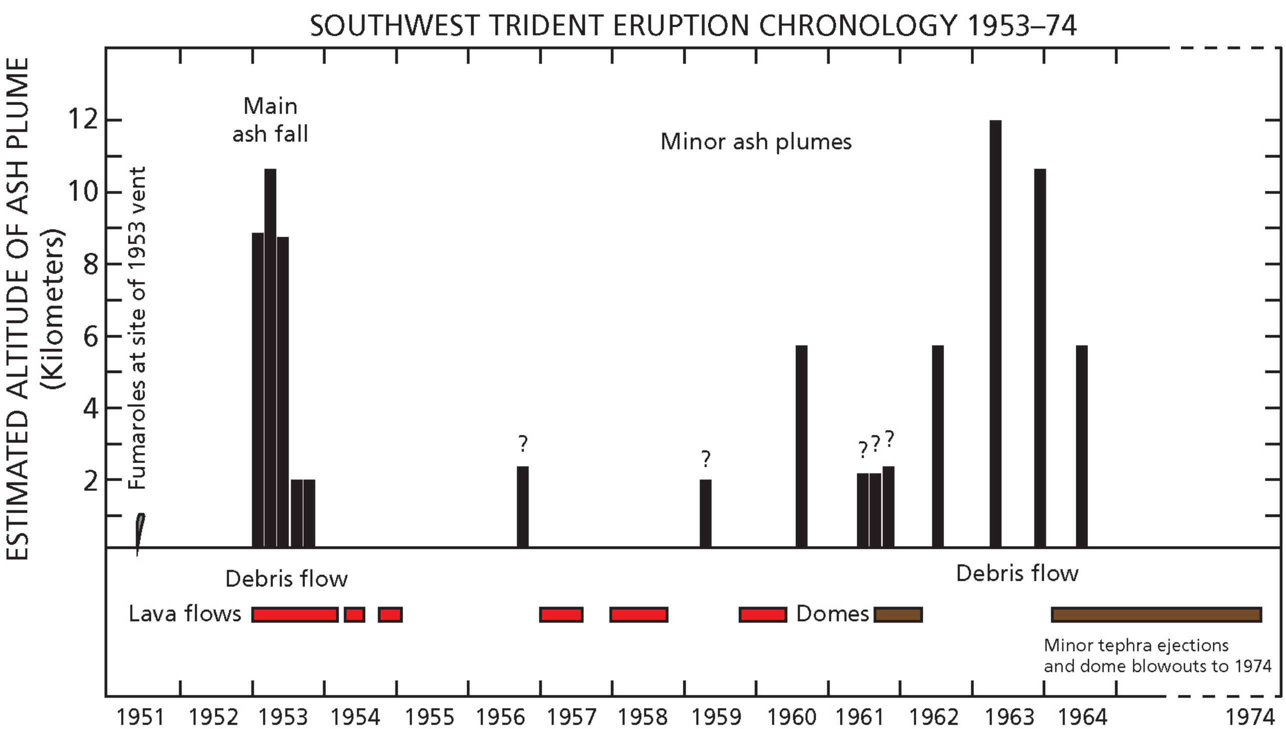


Figure 34. Time series showing the chronology of the Southwest Trident 1953–1964 eruptions. The eruption started in 1953 with the main eruption and the lava flows formed up until 1959, and then minor ejections of tephra continued intermittently until 1974. Modified from Figure 14 in Fierstein and Hildreth (2001).

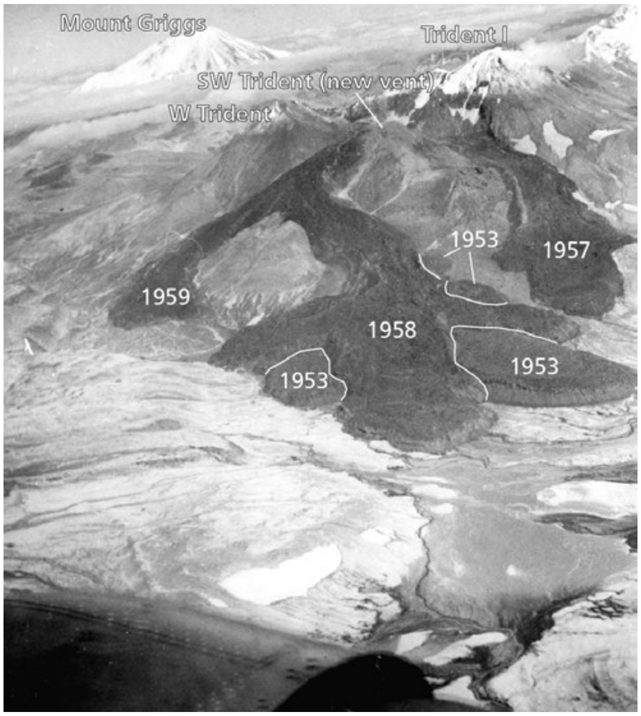


Figure 35. 1960 photograph showing the lava flows of Southwest Trident that formed from 1953 to 1959. NPS photograph by Robert Peterson, accession number KATM-399.

recorded in 1916 by botanist R. F. Griggs (Griggs 1922). Another fumarole, visible in 1951 aerial photographs as a 60-m- (200-ft-) wide steaming pit on the southwest ridge of the central cone, became the vent site for the new volcanic cone (Southwest Trident) that began to grow in 1953 (Figure 33). The eruption lasted intermittently for 21 years with the last episode in 1974 (Figure 34). In contrast to Mount Katmai, no large explosive deposits have come from any of the Trident peaks, although a few small remnants of pyroclastic flow deposits south of the peaks are evidence of some minor explosive activity. Most of the eruptions of Trident Volcano have been lava domes and short-traveled blocky lava flows (Figure 35) accompanied sporadically by small ash plumes.

Katmai Cluster: Mount Griggs

Mount Griggs (formerly Knife Peak Volcano) is the tallest peak in the Katmai area, rising to 2,530 m (7,600 ft) in elevation on the eastern margin of the Valley of Ten Thousand Smokes (Figure 36). A relatively symmetrical cone, it has three nested summit craters and several small glaciers radiating from its summit. Mount Griggs is largely armored by young lava flows,

Figure 36. Photograph of Mount Griggs, the highest peak in the Katmai cluster. The slopes of the volcano are coated with ash fall from the 1912 eruption. The hikers shown in the photograph are walking on the 1912 eruption ignimbrite that fills the Knife Creek valley. The toe of one of the ash-covered Knife Creek Glaciers is visible on the right. USGS-AVO photograph by Game McGimsey.

but a few remnants of older lavas show that the volcano has existed for at least 290,000 years. Much of the volcano was built by dozens of overlapping lava flows between 85,000 and 10,000 years ago. Within the last 10,000 years, collapse of the southwest part of the volcano left an amphitheater near the summit and shed a large debris avalanche (rapidly moving mass of rock and debris) into the river valley below. Subsequent andesite lava flows nearly filled this scoop-shaped depression and covered the southwest slope of the volcano with a fan of blocky lava flows. Small-volume lavas have characterized most of the activity of Mount Griggs, and the volcano has had no recognized large ash fall-producing explosive events (Hildreth et al. 2002). Yellow sulfurous fumaroles discharging vigorously near its summit show the volcano is still active.

Katmai Cluster: Snowy Mountain

Snowy Mountain, the most northeastern volcano of the Katmai cluster, is largely ice covered (Figure 37) and has active fumaroles that create holes in the glaciers (Figure 38). It is made of a contiguous pair of small, deeply glaciated volcanic cones as well as a young lava dome that fills what was the summit crater for the northeastern cone. The youngest dacite lava dome was emplaced less than 490 cal. yr BP (calibrated ^{14}C age in years before 1950; Fierstein 2007). The other two peaks are eroded remnants of lava flows from the two cones that are as much as 200,000 years old. The young lava dome sits in a scoop-shaped amphitheater created by collapse of the upper part of the northeastern cone that had been weakened by persistent hydrothermal activity in the volcano's core. The collapse produced a 22 km^2 (9 mi^2) debris-avalanche deposit that came down in the last 1,500 years (Hildreth et al. 2001); the lava dome, therefore, is younger still.

Figure 37. Photograph of Snowy Mountain. The tallest peak, 2,161 m (7,090 ft) above sea level, has an active fumarole field. The dome at the summit was formed in the Holocene Epoch (<11,700 yr BP) following creation of the amphitheater below it, which formed from a sector collapse (flank collapse, like the 1980 Mount Saint Helens eruption). USGS-CalVO photograph by Judy Fierstein.

Denison, Steller, Kukak, and Devils Desk

Denison, Steller, Kukak, and Devils Desk (Figure 39, Figure 40, Figure 41, Figure 42) make up a heavily glaciated cluster of closely spaced volcanoes at the headwaters of the Savonoski River. This poorly known cluster has only been studied at the reconnaissance level (Hildreth et al. 2003b, 2004). Mount Denison has lava flows and cross-bedded tephra, but the precise age of volcanic activity is not known (Smithsonian Institution 2015). Mount Steller is suspected to have erupted in the Holocene Epoch (Nye 1998), but the precise age of activity and the location of source vents are not known (Smithsonian Institution 2015). Kukak Volcano has a vigorous summit fumarole field and abundant subglacial fumaroles (Hildreth et al. 2003b, 2004), which suggests that it is an active volcano. Kukak Volcano may have erupted as late as 1889, but the effects were insignificant and signs of the eruption were gone in a few years (Erskine 1962). Devils Desk is a 2 km (1.2 mi) wide by 900 m (2,950 ft) high mafic andesite cone that resembles a great lectern surrounded by glaciers (Figure 42; Hildreth et al. 2004). Three dikes extend outward from the peak toward the east (Wood and Kienle 1990). Using potassium/argon (K/Ar) dating, Hildreth et al. (2003b) established an age of 245,000±42,000 years old for Devils Desk. Also, they suggested that the eruption that formed the peak was short lived.

Figure 38. Photograph of the Snowy Mountain "Snowy Hole." The hole formed on the south flank of the volcano as a result of melting and collapse of glacial ice over a fumarole. USGS-AVO photograph by Cyrus Read.

Figure 39. Photograph of the volcanic peaks Mount Denison (right) and Mount Steller (left). USGS-CalVO photograph by Judy Fierstein.

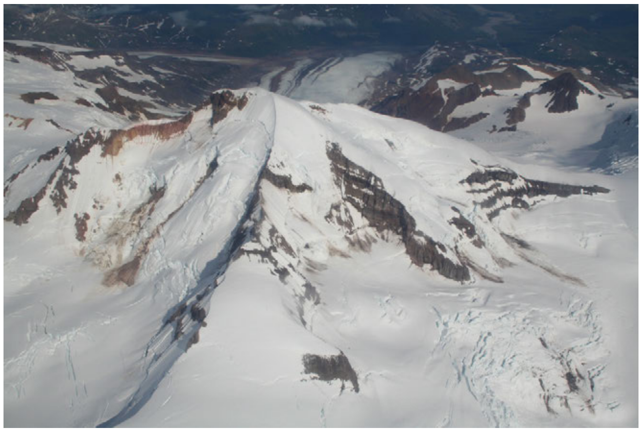


Figure 40. Photograph of the summit of Mount Steller. NPS photograph by Chuck Lindsay.

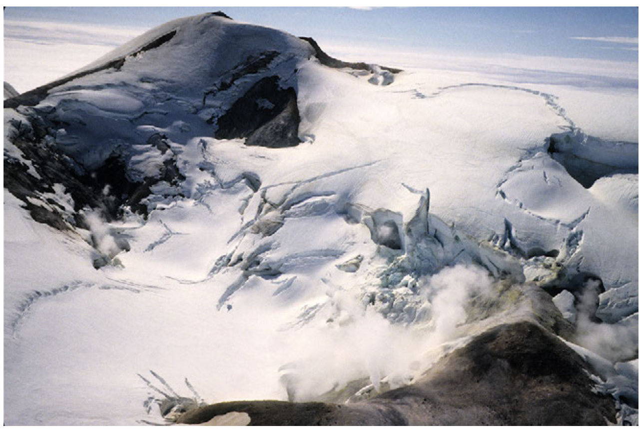


Figure 41. Photograph of the summit of Kukak Volcano. Steam from fumaroles rises in the bottom center of the photograph. USGS-CalVO photograph by Judy Fierstein.

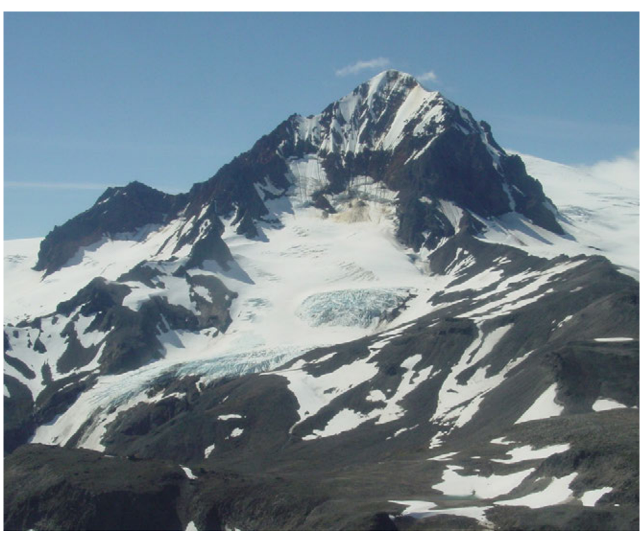


Figure 42. Photograph of Devils Desk volcanic neck. A volcanic neck is intrusive rock that solidified within the vent of a volcano. NPS photograph by Chuck Lindsay.

Savonoski River Cluster

The Savonoski River cluster includes six volcanoes located in the headwaters of the Savonoski River and behind (west of) the main trend of the Denison to Devils Desk volcanoes (Figure 27). Five of the volcanoes formed during the Quaternary Period (2.6–0.01 MYA); one is somewhat older, forming during the Pliocene Epoch (5.3–2.6 MYA). The descriptions of the Savonoski River cluster volcanoes below are abridged from Hildreth et al. (2004).

Savonoski River Cluster: Rainbow River Cone

The Rainbow River Cone along the Rainbow River valley, (Figure 43), also known as “Peak 3980,” is a small basaltic stratocone with a lava-flow apron perched on a ridge. The peak is labeled with 3980 feet elevation on the USGS topographic maps; hence, “Peak 3980”. The cone and a lava plateau that extends 1 km (0.6 mi) from the cone are glacially scoured. Rocks on the plateau yielded a K/Ar age of 390,000±39,000 years old.

Figure 43. Photograph of the Rainbow River Cone. USGS-CalVO photograph by Wes Hildreth.

Savonoski River Cluster: Cone 3601

Cone 3601, near the toe of the Hook Glacier on the west side of the Savonoski River, is the largest mafic cone at 2.5 km (1.6 mi) wide (Figure 44). It is made up of blocky columnar lavas, breccia (cemented angular fragments) sheets, and scoria (lava with a frothy texture). A K/Ar age on the lava indicates the cone is 132,000±27,000 years old.

Savonoski River Cluster: Dome 2115

Dome 2115, situated near the toe of the Hook Glacier and is across (east of) the Savonoski River from Cone 3601, is a dacite lava dome approximately 1 km (0.6 mi) across and 300 m (1,000 ft) tall. The cone is glacially scoured and is ringed by vertically jointed cliffs. Although not a Quaternary (2.6 MYA or younger) volcano, a K/Ar age of 4.77±0.18 MYA indicates that it erupted during the Pliocene Epoch (5.3–2.6 MYA).

Figure 44. Photograph of Cone 3601. USGS-CalVO photograph by Wes Hildreth.

Savonoski River Cluster: Cone 3110

Cone 3110 (Figure 45), 3.5 km (2 mi) north of Cone 3601, is a pile of basaltic breccia, scoria, and columnar lava that is about 2 km (1.5 mi) wide and 675 m (2,210 ft) tall. The K/Ar age of the cone is 235,000±30,000 yr BP.

Figure 45. Photograph of Cone 3110. USGS-CalVO photograph by Wes Hildreth.

Savonoski River Cluster: Knob 1000

Knob 1000, 1.5 km (1 mi) northwest of Cone 3110, is a small, 400 m (1,310 ft) wide, glacially scoured basaltic cone consisting of vesicular (frothy) lava, layered breccia, and scoria rubble. Textures and jointing suggest that the lava was emplaced in contact with ice, referred to as "ice-contact emplacement." No age was reported for the cone.

Savonoski River Cluster: Iron Trig Cone

Iron Trig cone (Figure 46), on the north side of the Savonoski River, is a glacially scoured mafic scoria cone that is 800 m (2,620 ft) across and 250 m (820 ft) high. It consists of thin lava sheets cut by a small intrusion. A lava-flow apron associated with the cone yielded a K/Ar age of 88,000±27,000 yr BP.

Figure 46. Photograph of Iron Trig Cone. USGS-CalVO photograph by Wes Hildreth.

Savonoski River Cluster: Savonoski Crater

The Savonoski crater, 8 km (5 mi) southwest of the confluence of the Rainbow and Savonoski Rivers, is a curiously circular depression 520 m (1,700 ft) in diameter formed on a ridge of marine sedimentary bedrock (Figure 47). The feature formed either as a meteor impact crater or by volcanic processes. Reconnaissance geologic and geophysical study of the crater in the 1960s did not find clear evidence for either genesis (French et al. 1972). Neither distinctive shock-metamorphic features nor volcanic features were observed. Dikes were found near the rim, but they are not clearly related to the crater. Moreover, the feature was glacially scoured so much of the primary evidence of formation has been removed by erosion. The crater's position between (in-line with) the Saddlehorn Creek and Savonoski River clusters suggests that it may be a rear-arc volcanic feature (volcanic feature set back from the main line of volcanoes making up the volcanic arc).

Figure 47. Photograph of the Savonoski crater. The circular depression, now filled by a lake, may have been formed by a meteor impact or is a volcanic crater behind the main trend of volcanoes. NPS photograph by Kaiti Critz.

Saddlehorn Creek Cluster

Saddlehorn Creek cluster, northwest of Mount Griggs, is made up of five small volcanic remnants surrounding the forks of Saddlehorn Creek (Hildreth et al. 2004). The remnants consist of deeply eroded vent complexes and lava flows of uncertain source; ages straddle the Pliocene-Quaternary boundary (2.6 MYA). The following descriptions of the volcanoes are paraphrased from Hildreth et al. (2004). Only Folsoms Bluff is listed as a Quaternary volcano in Table 3 and included in the Quaternary volcanoes map in Figure 27.

Saddlehorn Creek Cluster: Mount Juhle

Mount Juhle is made up of a dacite lava-flow remnant 30–80 m (100–260 ft) thick that has a K/Ar age of 2.97±0.03 MYA. No vent has been identified.

Saddlehorn Creek Cluster: Maynard Crag

Maynard Crag (Peak 4800) is a 600 m (1,970 ft) wide, 250 m (820 ft) high, shallow basaltic plug (dome intrusion) that formed 2.6±0.05 MYA.

Saddlehorn Creek Cluster: Sayre Mesa

Sayre Mesa (Plateau 4500) is a mafic lava-flow remnant that is 20–50 m (70–160 ft) thick and 1.3 km (0.8 mi) long. A K/Ar age of 2.64 ±0.04 MYA was derived from plagioclase crystals separated from the lava.

Saddlehorn Creek Cluster: Fenners Saddlehorn

Fenners Saddlehorn (Crag 3200) is a 250- by 400-m- (820- by 1,300-ft-) wide, 200-m- (660-ft-) high basaltic remnant that forms a horn-like feature, the Saddlehorn Creek namesake. The lava contains horizontal and inclined columns in ten tiers that are 5–20 m (16–66 ft) thick. It probably formed 2.27±0.11 MYA as magma intruded at shallow depths below the surface.

Saddlehorn Creek Cluster: Folsoms Bluff

Folsoms Bluff (Knob 3800) is an andesitic funnel-shaped vent complex that is a multi-lobed mass of glassy lava, 500 m (1,600 ft) wide and 200 m (660 ft) high. The lava contains flow foliation and inclined to subhorizontal curving glassy columns that are indicative of ice-contact emplacement. The base is brecciated and overlies 8 to 15 m of proximal fallout of scoria bombs and blocks of basement granitoid rocks. No age is reported.

Northeast Volcanoes

Northeast Volcanoes: Kaguyak Crater

Kaguyak Crater (Figure 48), in the northeast corner of the park, is a steep-walled collapse caldera filled with a 150-m- (500-ft-) deep lake that was created approximately 5,800 years ago in a large explosive eruption. Once thought to be a collapsed stratovolcano, work by Fierstein and Hildreth (2008) showed that ancestral Kaguyak was, instead, nine closely spaced but discrete clusters of lava domes. The domes, ranging from basalt to rhyolite in composition, are each stacks of short-traveled lava flows. Kaguyak Crater is a good example of the episodic nature of volcanic activity. The earliest lava flows are as much as 300,000 years old. An especially active eruptive period between 60,000 and 30,000 years ago built five multi-component lava domes where the lake is now. All that activity was followed by a quiescent interval more than 20,000 years long. Then, about 6,000 years ago, another dome was extruded near the center of the cluster. This triggered explosions and culminated in the big event 200 years later that produced ash flows and ash falls, erupted enough magma that an area 2.5 km (2 mi) wide collapsed to form the caldera, and truncated the field of lava domes. Fine ash, largely winnowed out of the ash flows, is now found as a distinctive orange ash-fall layer preserved widely in soils as far as the Valley of Ten Thousand Smokes, 80 km (50 mi) to the southwest. Some activity continued after the caldera-forming eruption, with emplacement of two more domes inside the new caldera that are now islands in the lake. Gas seeps still bubble up to the lake surface, some with a strong sulfurous smell.

Figure 48. Photograph of Kaguyak Crater with its 150 m (490 ft) deep lake. Nine separate dome complexes once made up the area in and around the lake until a large explosive eruption formed the crater about 5,800 years ago. NPS photograph by Chuck Lindsay.

Northeast Volcanoes: Fourpeaked Mountain

Fourpeaked Mountain, adjacent to Mount Douglas, emitted a small eruption on 17 September 2006, which surprised AVO staff and residents of south-central Alaska. Before this eruption, the volcano was not considered active (Neal et al. 2009). Late in the day, a large ash cloud was observed, which reached a minimum altitude of 6,100 m (20,000 ft). The ash drifted 20 km (12 mi) downwind and deposited a dusting of very fine ash at the Nonvianuk Lake outlet, 110 km (70 mi) west northwest of Fourpeaked Mountain, and near Homer 150 km (90 mi) northeast of Fourpeaked Mountain. When AVO scientists visited the area by helicopter on 24 September, the vent area had nine craters or pits (Figure 49, Figure 50), with three to five of them venting steam and volcanic gas. Ash deposits were thickest west of the vent area at 1–2 mm (less than 0.1 in) thick, and the other flanks of the volcano received a dusting (Neal et al. 2009).

A glacial outburst and debris outflow originated at about 1,500 m (5,000 ft) from underneath an unnamed glacier (Figure 51, Figure 52). The flood scoured a canyon more than 100 m (330 ft) deep in places, and blocks of ice up to 5 m (16 ft) were rafted in a mixture of water and debris for about 6 km (4 mi) down slope, where the material continued off the end of the glacier down the Douglas River drainage (Neal et al. 2009). A similar outburst flood could occur in association with any volcanic eruption in the Katmai area (see "Geohazards" section).

Analysis of the seismic stations in the Katmai area revealed a swarm of earthquakes between 11:48 am and 3:50 pm ADT on 17 September (Michael West, State Seismologist, UAF Geophysical Institute, personal communication, 2006, in Neal et al. 2009). A plume was observed at this time in radar images of the area and the UAF infrasound array detected a signal (Steve McNutt, Research Professor, AVO-UAF Geophysical Institute, personal communication, 2006, in Neal et al. 2009). A temporary seismic array of three stations was installed following the eruption, and they recorded low-level activity through the end of the year with a few volcanic earthquakes on most days (Neal et al. 2009).

AVO scientists concluded that the eruption was most likely caused by new magma rising to fairly shallow (less than a few kilometers) levels, which accounted for the seismicity and the degassing, and provided a heat and gas source for a phreatic explosion (Neal et al. 2009).

Through the remainder of 2006 and into 2007, volcanic gas and vapor discharged from a chain of pits in the glacier ice. No other ash emissions observed, although yellow sulfurous deposits stained the snow around the summit.

Figure 49. Photograph of fumaroles on the west side of Fourpeaked Mountain, 24 September 2006. USGS-AVO photograph by Cyrus Read.

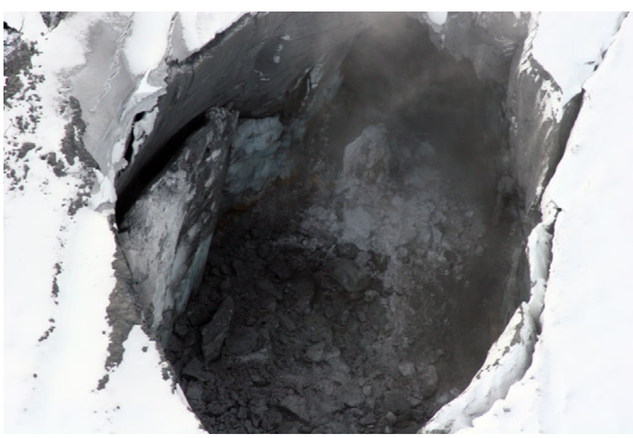


Figure 50. Photograph of a non-venting fumarole pit in glacier ice on the summit of Fourpeaked Mountain. The diameter of this pit is about 50 m (160 ft), and the floor is made of ash-covered blocks of ice. USGS-AVO photograph by Kristi Wallace.

Figure 51. Photograph of the debris outflow (black areas) below the canyon and the deep chasm formed below the eruption site at Fourpeaked Mountain. Steam from the summit fumaroles are visible. USGS-AVO photograph by Rick Wessels, 25 September 2006.

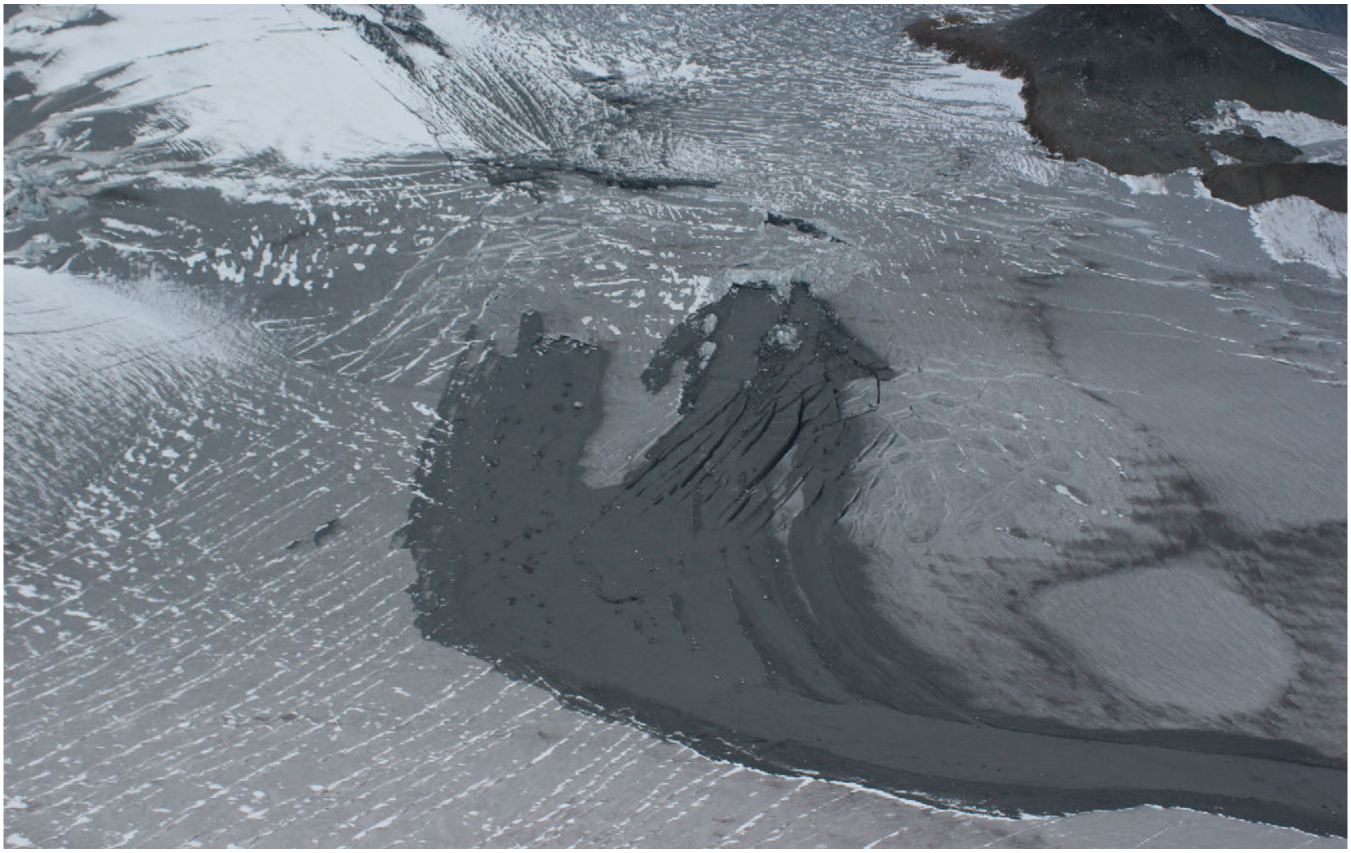


Figure 52. Photograph of debris flow on the north flank of Fourpeaked Mountain. A muddy debris flow emerged from cracks in the Fourpeaked Glacier about 4 km (2.5 mi) north of Fourpeaked Mountain's summit on 17 September 2006. The width of the flow is about 250 m (820 ft) and the white specks are rafted ice chunks up to 5 m (16 ft) across. Fine gray ash coats the glacier surface, except where winds scoured convex surfaces. AVO-UAF Geophysical Institute photograph by Guy Tygat, 20 September 2006.

Figure 53. Photograph of Mount Douglas in the foreground and Fourpeaked Mountain in the background. USGS-AVO photograph by Michael Poland, 30 September 2006.

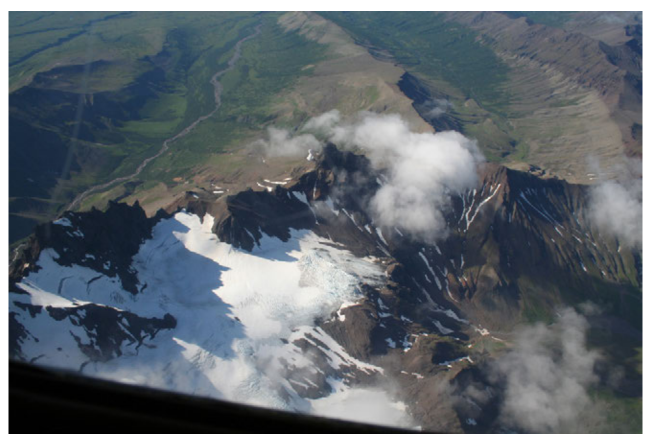


Figure 54. Photograph of the north flank of Kejulik Mountain. NPS photograph by Chuck Lindsay.

Northeast Volcanoes: Mount Douglas

Mount Douglas, the most northeastern volcano forming the main trend of arc-front volcanoes, is ice clad and poorly studied (Figure 53). Much of the volcano has been subjected to glacial erosion, but a ramp of lava flows on the northwest flank is relatively uneroded. Most of the volcano is ice covered, but isolated outcrops of high-silica andesite lava flows are found within the ice. The summit of the volcano has a small crater lake and fumaroles. No historic eruptions have been reported for Mount Douglas; however, unglaciated lava flows are present, and fumaroles are indicative of active thermal processes (Wood and Kienle 1990).

Northeast Volcanoes: Kejulik Mountain

Kejulik Mountain (Figure 54), the southernmost volcano within the park boundary, is a deeply dissected central vent and dike complex (Kienle and Swanson 1983). Its age is unknown.

Geothermal Features

Geothermal features of Katmai include fumaroles, warm springs, warm ground, and crater lakes. A map of these features is provided on Plate 4.

Fumaroles

The numerous fumaroles of the Valley of Ten Thousand Smokes were what made the Katmai area famous and prompted the formation of a national monument to preserve these unique features. Fumaroles (vents from which volcanic gases escape) occur where shallow magma or hot igneous rocks release gases, or where groundwater contacts warm ground to create steam. The fumaroles ("smokes") in the Valley of Ten Thousand Smokes formed along fractures in the ignimbrite, allowing gases trapped in the ash flow and steam from boiling meteoric water to escape into the atmosphere.

In 1917, five years after the eruption, the ignimbrite was still extremely hot. Nearly everywhere on the ignimbrite sheet, 1 m (3 ft) deep pits dug into the surface approached the boiling point and Griggs estimated that plumes of gas more than 150 m (500 ft) tall escaped from more than 1,000 fumaroles. Fumarole temperatures measured during the 1918 and 1919 expeditions showed that 86 vents reached temperatures greater than 190°C (374°F), and 11 ranged from 400°C to 645°C (750°F to 1,190°F). By 1929, only a few hundred fumaroles were visible in the valley, and nearly all were below the boiling point. By the 1940s, less than a dozen fumaroles remained, and by the mid-1960s, gases emitted from only weak fumaroles on the Novarupta dome. The last fumarole on Baked Mountain expired in the 1990s (see summary about fumaroles in chapter 9 of Hildreth and Fierstein 2012). Today, the locations of former fumaroles are recognizable by halos of geothermally altered rock along cracks and funnel-shaped pits (Figure 55).

Although the fumaroles of the Valley of Ten Thousand Smokes slowly extinguished due to cooling of the 1912 ignimbrite sheet, numerous active fumaroles occur on the flanks and in the craters of the active volcanoes. Active fumaroles are mapped on Plate 4. In contrast to the fumaroles of the Valley of Ten Thousand Smokes, which emitted boiling meteoric water and trapped gases from the ignimbrite, the currently active fumaroles are vents for gases formed at high temperatures and pressures within the active volcanic systems (Sheppard et al. 1992).

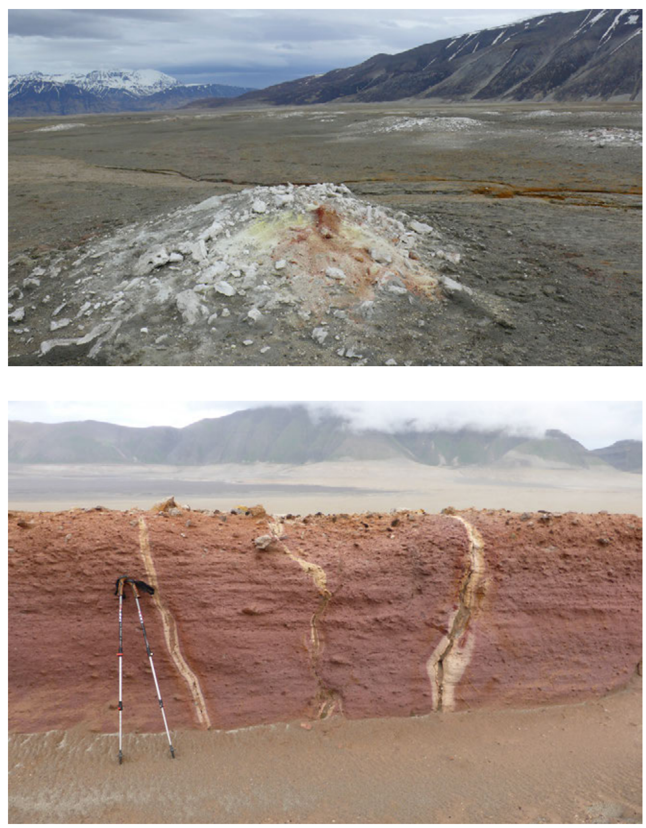


Figure 55. Photographs of an inactive fumarole (top) and alteration halos along fumarole cracks (bottom). Trekking poles (for scale) are approximately 1.3 m (4 ft). NPS photographs by Mike Fitz.

Active fumaroles exist on the following volcanoes: Novarupta, Trident, Martin, Mageik, Griggs, Kukak, Snowy, Fourpeaked, and Douglas, as well as under the crater lakes of Katmai and Kaguyak (Sheppard et al. 1992; Motyka et al. 1994; Hildreth et al. 2003a, 2004; Fierstein and Hildreth 2008; Neal et al. 2009). The fumaroles on the Novarupta dome are weak and only visible on cold days. Prior to the 1953 Trident Volcano eruption, a fumarole was visible in 1951 on the southwest ridge of the central cone, which became the vent site for the new volcanic cone (Southwest Trident). Fumaroles are currently present on the main Trident summit and the Southwest Trident cone (Sheppard et al. 1992; Taryn Lopez, postdoctoral researcher, AVO/UAF-Geophysical Institute, written communication, October 2006). The numerous fumaroles on Mount Martin form a steam column that is commonly visible from Brooks Camp on clear days (Figure 30), which leads to many false eruption reports. Mount Mageik also has a crater lake surrounded by a fumarole field (see Figure 59). The fumaroles on Mount Griggs were noted by Forbes (1965) in a letter to the superintendent warning of a possible eminent eruption because he saw six new fumaroles form along a fissure on the west flank between 1,800 m and 2,100 m (6,000 and 7,000 ft). No eruption has yet occurred, but the fumaroles are still active today (Figure 56; see NPS video at https://youtu.be/qZ3WQ7A6hpI). Little is known about the fumaroles near the summit of Kukak Volcano (Figure 41) or Snowy Mountain (Figure 38). A fumarole field formed on the summit of Fourpeaked Mountain after the 2006 eruption (Figure 49), and Mount Douglas has a fumarole field at its summit (Wood and Kienle 1990). Also, the crater lakes of Mounta Katmai and Kaguyak Crater (shown on Plate 4) are thought to have fumaroles because the relative levels of sulfur and chlorine indicate that these lakes are fed by volcanically derived fluids that originate below the lakes (Sheppard et al. 1992; Fierstein and Hildreth 2008).

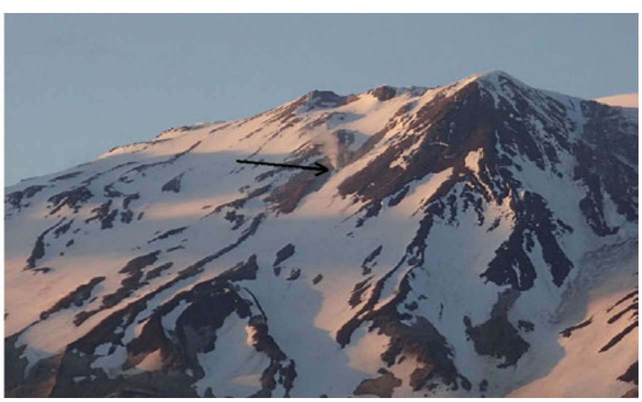


Figure 56. Photograph of the fumarole (denoted by arrow) on the west flank of Mount Griggs. Photograph by Johan Gilchrist (University of British Columbia).

Warm Springs

Warm springs and cold springs are present throughout the volcanic area of Katmai (Plate 4). Warm springs, which have a temperature range of 15–30°C (60–86°F), issue from the ignimbrite sheet and consist of meteoric water heated by an incompletely cooled lens of welded tuff (Lowell and Keith 1991). A particularly dense collection of warm springs originate out of the Trident Volcano 1953–1960 lava flows (Figure 57); these springs are formed by the interaction of surface waters with the cooling Trident Volcano lava flows and the Southwest Trident plug dome (Keith et al. 1992). The temperatures of the springs were measured by Keith et al. (1992) and the northern group had a temperature of 15°C (60°F), and the southern group had a temperature of 40°C (105°F). Concentrations of cesium, rubidium, strontium, arsenic, boron, sodium, and chlorine are higher in the southern group, indicating deeper circulation than the northern springs (Keith et al. 1992). Warm springs potentially exist in the remote areas away from the Valley of Ten Thousand Smokes, but have yet been inventoried and documented.

Warm Ground

Warm ground is any area where geothermal processes have raised the temperature above ambient ground temperature, but no fumaroles are present. Warm ground occurs near Novarupta dome (Hildreth and Fierstein 2012) and on the flanks of Mount Griggs (Plate 4; Forbes 1965). More areas of warm ground undoubtedly exist but have not yet been inventoried and documented.

Crater Lakes

Six crater lakes occur on the following volcanoes: Savonoski, Kaguyak, Martin, Mageik, Douglas, and Katmai (Plate 4; Savonoski not shown). Crater lakes are included in the geothermal features section because most are fed by hydrothermal fluids that keep them warm. The Savonoski crater (Figure 47) was examined to determine its origin as either an impact or volcanic crater (French et al. 1972), but no geochemical or temperature data were published for the lake. The lake in Kaguyak Crater (Figure 48) is 2.7 km (1.7 mi)

Figure 57. Photograph of warm springs originating from the toe of a Trident lava flow. The orange color is formed by iron-concentrating bacteria. NPS photograph by Mike Fitz.

in maximum diameter, has a pH of 5.5, and a normal alpine lake temperature of 4.5°C (40°F) (Fierstein and Hildreth 2008). Fierstein and Hildreth (2008) suggested that the chloride and sulfate values indicated that the lake must have hydrothermal input. The geochemistry of the small shallow lake in Mount Martin summit crater is unknown (Figure 58). The Mageik crater lake is 110 m (360 ft) in diameter, very warm (92°C, 198°F), and very acidic (pH=1–2). Fumaroles under the lake make it appear to boil and sulfide minerals make the water yellow-green (Figure 59; Hildreth et al. 2000). Mount Douglas has a small crater lake with a maximum diameter of 200 m (700 ft); it is a cloudy light blue color and commonly has floating sulfur scum (Figure 60). The lake has very low pH of 1–2 and a warm temperature, 25°C (77°F) (Wood and Kienle 1990).

Figure 58. Photograph of the Mount Martin crater lake and fumaroles. AVO-UAF Geophysical Institute photograph by Taryn Lopez.

Mount Katmai Crater Lake

The crater lake on Mount Katmai is the largest one in the Katmai area with a maximum diameter of 3 km (2 mi) (Figure 28, see Figure 63). Its average normal surface temperature is 5.8°C (42°F) and it has a pH of 2.5–3 (Motyka 1977, 1978). However, Motyka (1977, 1978) measured a temperature anomaly of 21°C (70 °F)

Figure 59. Photograph of Mount Mageik crater and lake. Fumaroles surround the lake, and fumaroles under the lake make it appear to boil. AVO-UAF Geophysical Institute photograph by Taryn Lopez.

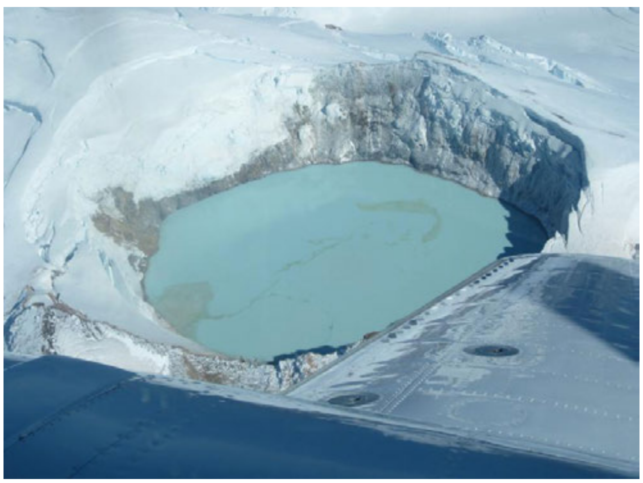


Figure 60. Photograph of Mount Douglas crater lake. The lake is very acidic and has a dark "scum," which likely consists of sulfide minerals, floating on it. (Wood and Kienle 1990). AVO-UAF Geophysical Institute photograph by Taryn Lopez.

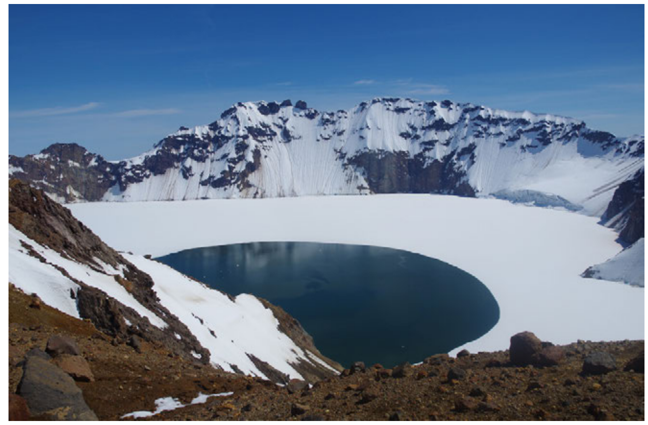


Figure 61. Photograph of the crater lake on Mount Katmai in 2015 showing a hole in the lake ice and a slight discoloration in the middle of the lake that is most likely from ongoing hydrothermal activity. AVO-UAF Geophysical Institute photograph by Pavel Izbekov.

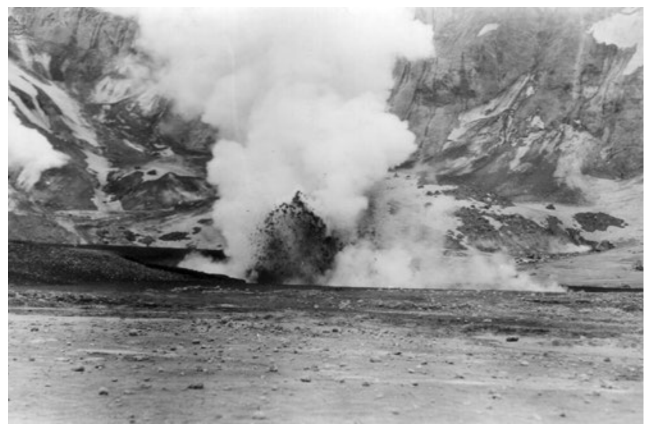


Figure 62. Photograph of a mud geyser on the floor of the Katmai crater in the year 1923. The raised mud ring around the geyser was estimated by Fenner (1930) to be 30 m (100 ft) in diameter. Photograph by Charles Yori; NPS accession number KATM-93.

at the bottom of the lake below a yellow discolored area approximately 500 m (1,600 ft) northeast of the lake's center (Figure 61). This discolored area is over the mud geyser that was observed on the floor of the caldera in 1923 (Figure 62).

The Mount Katmai crater lake began to form after the top of the mountain collapsed during the 1912 eruption. When the Griggs expedition summited Mount Katmai in 1916 and 1917, its members saw a volcanic dome (Horseshoe Island) protruding through a shallow lake on the floor of the crater and estimated the elevation of the lake's surface relative to the rim (Griggs 1922). When Fenner and Yori visited the Katmai crater in July 1923, they found that the lake had drained and the floor had numerous mud pots, thermal springs, fumaroles, and a mud geyser (Figure 62) emanating from a flat lake bed (Fenner 1930, as summarized in Motyka 1977). Filling of Mount Katmai's crater lake was initially rapid at an average rate of 5.7 m/yr (19 ft/yr); it has slowed to an average rate of 1.1 m/yr (4.3 ft/yr).

A detailed history of Mount Katmai's crater lake level changes is provided by Fenner (1930), Muller and Coulter (1957), and Motyka (1977, 1978). With financial support from the NPS, Motyka also spent four years

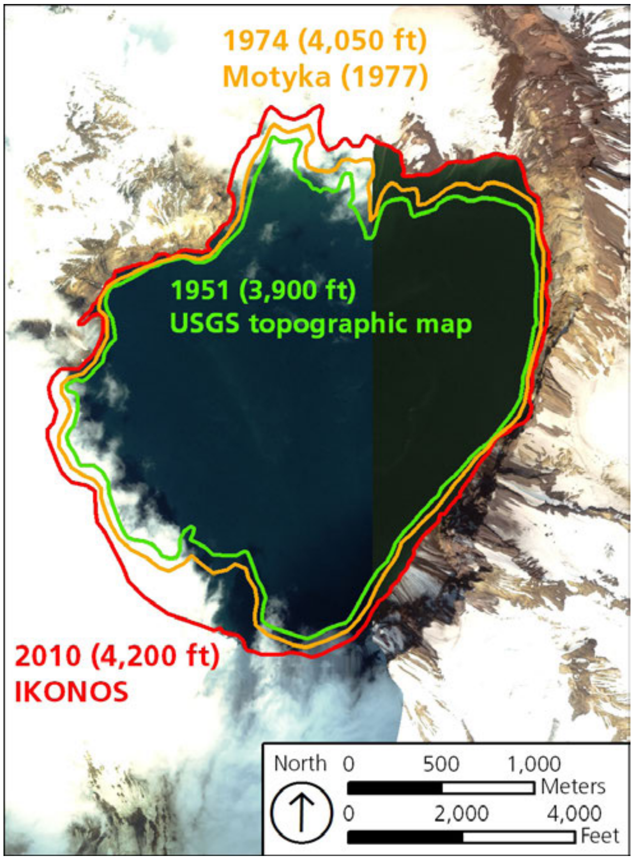


Figure 63. Satellite image of the crater lake in Mount Katmai overlain by shoreline outlines in 1951, 1974, and 2010. The lake is currently rising at a rate of approximately 1.2 m/yr (3.9 ft/yr).

(1974–1977) studying the crater lake level changes and chemistry. In summary, when Griggs viewed the crater from the rim in 1917, he estimated that the lake was 10–20 m (33–66 ft) deep. When Fenner and Yori visited the crater in 1923, the lake was gone (Figure 62) and the elevation of the crater floor was approximately 1,040–1,050 m (3,410-3,440 ft). In 1951, the lake elevation was 1,200 m (3,900 ft), which corresponds to an increase of about 160 m (524 ft) in 28 years, or an average rate of 5.7 m/yr (19 ft/yr). Motyka's measurement in 1977 determined the lake level was at 1,242 m (4,075 ft), which is an increase of 42 m (138 ft) since 1951 and corresponds to a rate of 1.6 m/yr (5.2 ft/yr). Motyka surmised that the significant drop in the rate of lake level rise was due to the increased hydraulic head forcing water through the underlying sandstones of the Naknek Formation.

IKONOS satellite imagery collected in 2010 shows the lake level at approximately 1,280 m (4,200 ft) when the lake outline is placed on the USGS topographic map (Figure 63). Comparing the 2010 lake level to the 1977 elevation, the lake rose 38 m (125 ft) in 33 years, which corresponds to a rate of 1.2 m/yr (3.9 ft/yr). Assuming the rate averages 1 m/yr, the lake level could reach the lowest elevation on the rim of the crater (1,490 m, 4,900 ft) in about 200 years. However, it may reach equilibrium like Crater Lake in Oregon has through loses by evaporation and groundwater leakage (see Crater Lake National Park GRI report by KellerLynn 2013).

Glaciations

Map units: glacier deposits—**Qhg, Qm, Qblu, Qblik, Qbld, Qblo, Qbln, Qblil, Qblk, Qmh, Qmhg, Qmho, Qjhd**; glacial end moraines (**"Glacial Feature Lines"** layer); and associated alluvial and glaciolacustrine deposits—**Qho, Qac, Ql, Qgl, Qglf, Qjho**

The Katmai area is replete with well-preserved glacial landforms that are evidence of a long history of glaciation during the latter part of the Pleistocene Epoch (~100,000–12,000 years ago). The Alaska Peninsula held the western extent of the North American continental ice sheet, and glaciers covered most of map area, except for the highest ridges. Located along the south coast of Alaska, the Alaska Peninsula received (and still receives) abundant precipitation. During the Pleistocene Epoch, precipitation fell predominately as snow and formed glaciers that blanketed the mountain crest, blocked Cook Inlet, and formed an ice field between Kodiak Island and the Alaska Peninsula along Shelikof Strait. Glaciers north and south of the Katmai area had depocenters on the east side of the Alaska Peninsula in Cook Inlet, but the glaciers flowed west across the peninsula through the Iliamna Lake and Becharof Lake valleys. The glaciers that shaped the Naknek Lake area originated on the volcanoes and flowed down the Savonoski River and Rainbow River valleys where it merged, then split into three fingers that flowed down (1) Iliuk Arm and Lake Brooks, (2) North Arm of Naknek Lake, and (3) Grosvenor and Coville Lakes (Figure 64, Plate 1). The terrain between the mountains and Bristol Bay is wide and gently sloping, so it was a deposition zone that preserved the deposits from the various glacial advances. In contrast, the Pacific side of the mountain crest is steep and had greater snowfall, so glaciers persisted for a longer time at low elevations, which left behind only a few small deposits of the latest Pleistocene glaciations (Plate 1).

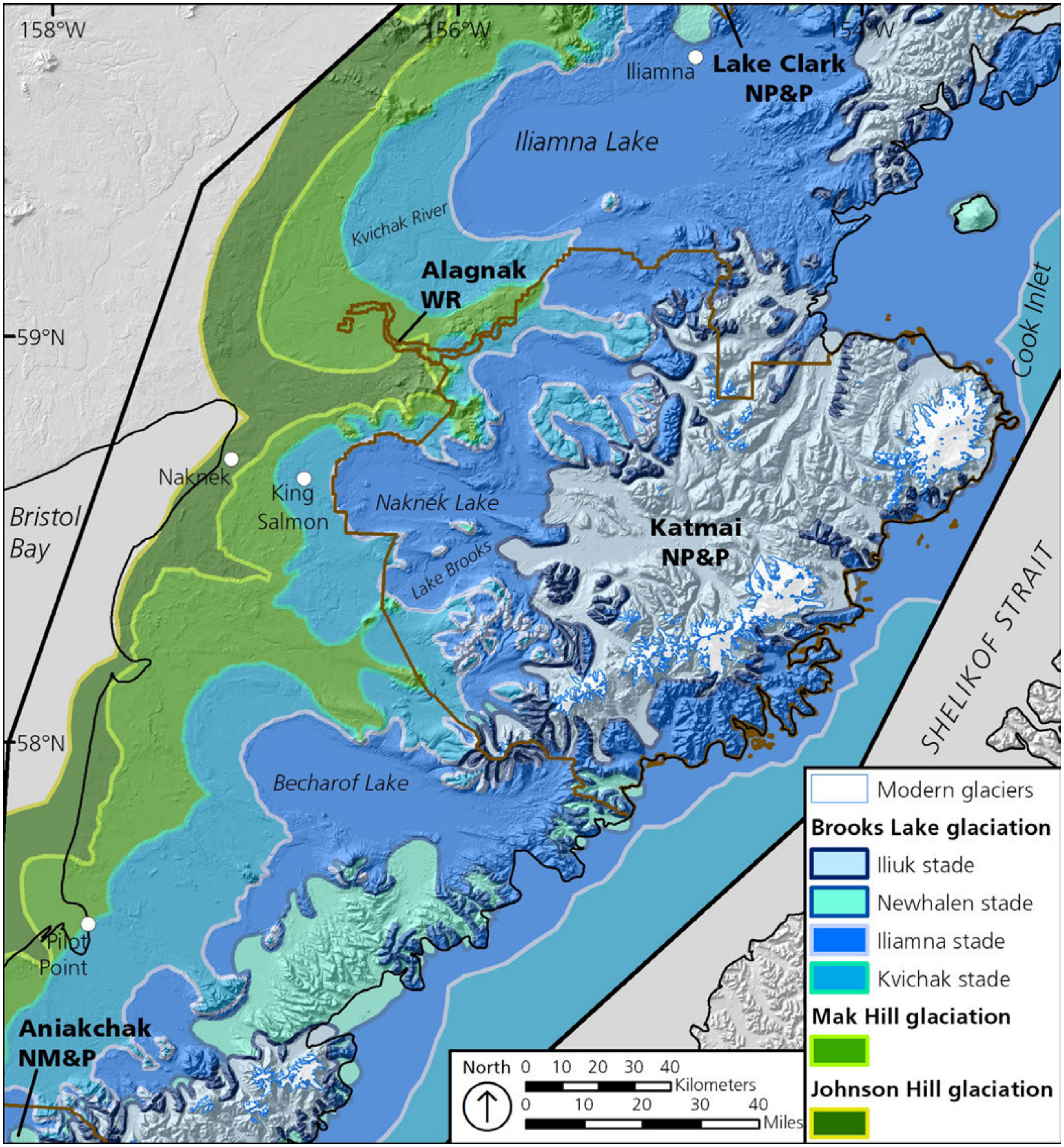


Figure 64. Map showing the glacier extents during glaciations and stades of the Katmai area. NP&P: National Park and Preserve. NM&P: National Monument and Preserve. WR: Wild River. Map created with information from Detterman and Reed (1973), Detterman (1986), Detterman et al. (1987b), and Riehle and Detterman (1993).

All the types of glacial deposits shown in Figure 65 were left behind after the retreat of the Pleistocene glaciers. Terminal (end) moraines mark the furthest extent of the glacial advances and are mapped on Plate 1. The moraine deposits consist of coarse, angular, poorly sorted material forming ridges (Figure 66). The source maps (Detterman and Reed 1973; Detterman et al. 1987b; Riehle and Detterman 1993) include descriptions of knob-and-kettle topography, which refers to the lumpy deposits left behind as a glacier

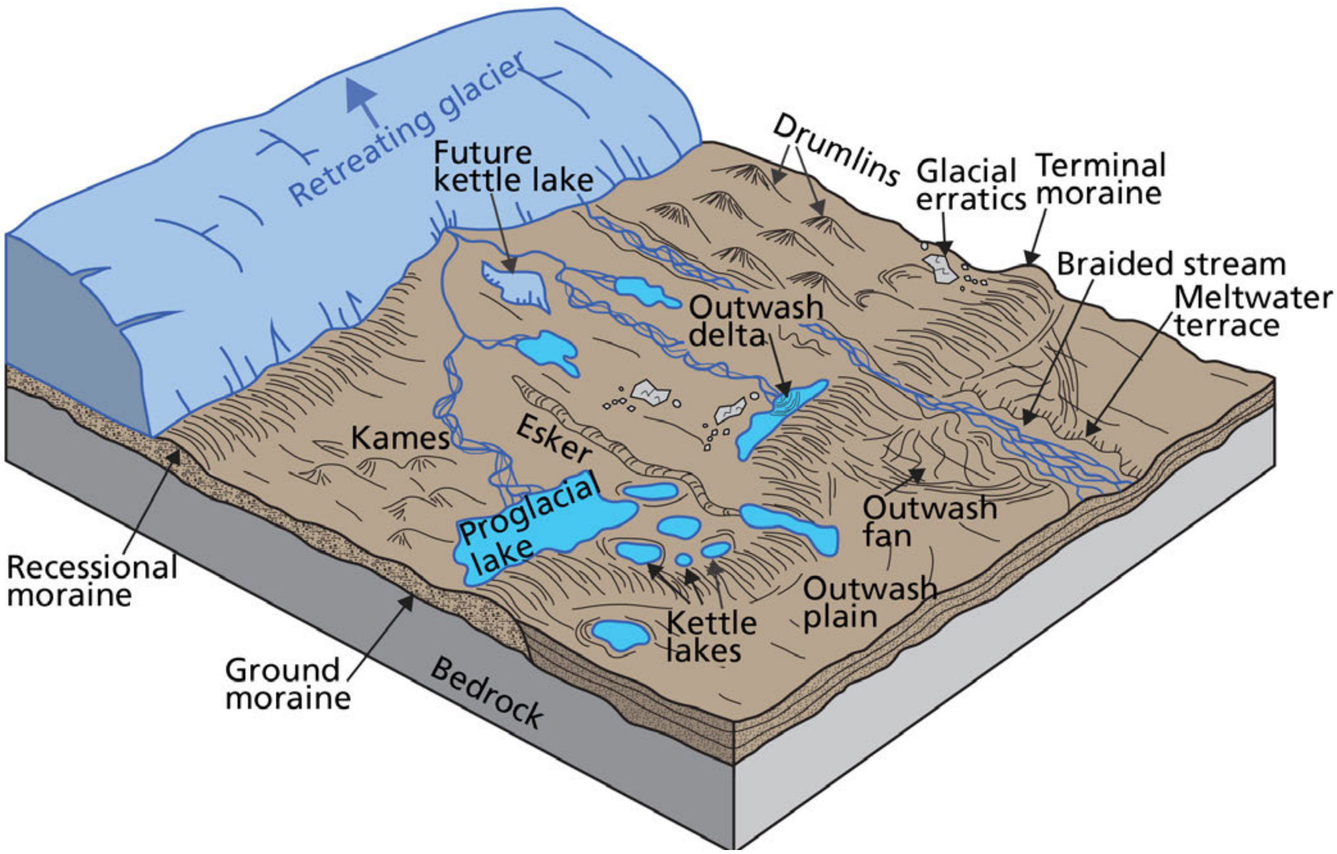


Figure 65. Diagram showing common types of glacial deposits. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 66. Photograph of the Iliuk stade moraine dividing the Iliuk Arm (right) from the greater Naknek Lake (left). The moraine between the water bodies is approximately 3 km (2 mi) long. View is east-northeast, looking towards Mount La Gorce (center top of the photograph). Brooks Camp is located out-of-view to the left. NPS photograph by Kaiti Critz.

recedes (also referred to as kame topography). Kettle lakes formed when stranded ice blocks, which were incorporated in the unconsolidated glacier drift or alluvial deposits, later melted, leaving enclosed depressions. Proglacial lakes formed in front of receding glaciers where glacial deposits, typically moraines, created dams that blocked surface water. Glacial lake deposits (unit **Ql** on Plate 1) were left behind when these lakes drained after the dams eroded. Outwash deposits accumulated where meltwater streams or rivers deposited well-sorted gravel and sand, forming relatively flat areas downstream of terminal moraines (units **Qho**, **Qblo**, **Qmho**, **Qjho** on Plate 1). Where flow was more constrained to valleys, abandoned channels (**Qac**) also formed in areas draining the receding glaciers.

Abrahamson (1950) and Muller (1952, 1953) named and described the glacier deposits in the Naknek Lake area and developed a relative timeline of glacier advances for the Naknek Glacier. Three Pleistocene glaciations are preserved in the map area, from oldest to youngest, they are the (1) Johnson Hill, as indicated by map units **Qjhd** and **Qjho**; (2) Mak Hill (**Qmh**, **Qmhg**, and **Qmho**); and (3) Brooks Lake (**Qblu**, **Qbld**, **Qblo**, **Qblk**, **Qblil**, **Qbln**, and **Qblik**). Deposits from an older glaciation are present on the west side of Kvichak Bay, but the deposits are poorly preserved and little is known about their age. The Brooks Lake glaciation had four stades, from oldest to youngest, are the Kvichak (**Qblk**), Iliamna (**Qblil**), Newhalen (**Qbln**), and Iliuk (**Qblik**) (Detterman and Reed 1973). The absolute age ranges of the glacial advances are shown in Figure 67.

Johnson Hill Glaciation

The Johnson Hill deposits (**Qjhd**, **Qjho**) are the oldest deposits from the Naknek Glacier in the map area. Johnson Hill deposits are present in the map area between the Alagnak and Naknek Rivers (Plate 1). Glacial deposits of this age are severely degraded by erosion, and their kettle lakes have filled with sediment. A clear terminal moraine has not yet been identified. Similar deposits are recognized on the north side of Kvichak Bay. The age of the Johnson Hill deposit is older than can be dated using radiocarbon isotopes, so its age is unknown (Detterman 1986).

Mak Hill Glaciation

The Mak Hill glaciation was originally named after glacier deposits (**Qmh**, **Qmhg**, **Qmho**) on a hill with the vertical angle bench mark (VABM) named "Mak" located approximately 5 km west of King Salmon (Muller 1952). The Mak Hill glacial deposits are severely degraded, and no clear moraine deposits are observable in the area. The Mak Hill glaciation took place at least 43,000 cal. yr BP, as determined from radiocarbon ages of organic matter in syn- or post-glacial deposits (Detterman 1986; Stilwell and Kaufman 1996). However, this age is at the limit of the radiocarbon technique, so the deposits may be much older.

The correlation of the glacial deposits at Mak Hill and Naknek Lake with the terminal moraines at Iliamna Lake and Becharof Lake is in question (see Figure 64). Riehle and Detterman (1993) reassigned the Mak Hill glacial deposits between Iliamna Lake and Becharof Lake to the Kvichak stade of the Brooks Lake glaciation, not the Mak Hill glaciation (as shown in Figure 64 and Plate 1). By doing so, the sequence of moraines in the Naknek area matched the number of moraines in the Iliamna Lake and Becharof Lake areas, north and south respectively. However, Stilwell and Kaufman (1996) correlated the Naknek Lake moraine with both the Kvichak River and Iliamna Lake moraines. They proposed that the northern (Iliamna Lake) and southern (Becharof Lake) areas had different advance histories than the Naknek area because they were sourced from the Cook Inlet and Shelikof Straits area, not from the western side of the Aleutian Range like the glaciers in the Naknek Lake area. These changes were made on limited radiocarbon ages, so further geochronological work of the moraines in the Naknek Lake area may help resolve these differing interpretations.

Brooks Lake Glaciation

The Brooks Lake glaciation (**Qblu**, **Qbld**, **Qblo**, **Qblk**, **Qblil**, **Qbln**, and **Qblik**) was defined by Muller (1952) for the well-preserved glacial moraines around and in Lake Brooks and Naknek Lake. The Brooks Lake deposits are better preserved than those of earlier glaciations in that they have sharper moraine crests and are less eroded. The stades within the Brooks Lake glaciation were named after moraines in the Lake Iliamna area.

The oldest stade of the Brooks Lake glaciation is the Kvichak stade (**Qblk**). It was named after the Kvichak River, which drains Iliamna Lake. Part of the Kvichak River moraine is located in the map area to

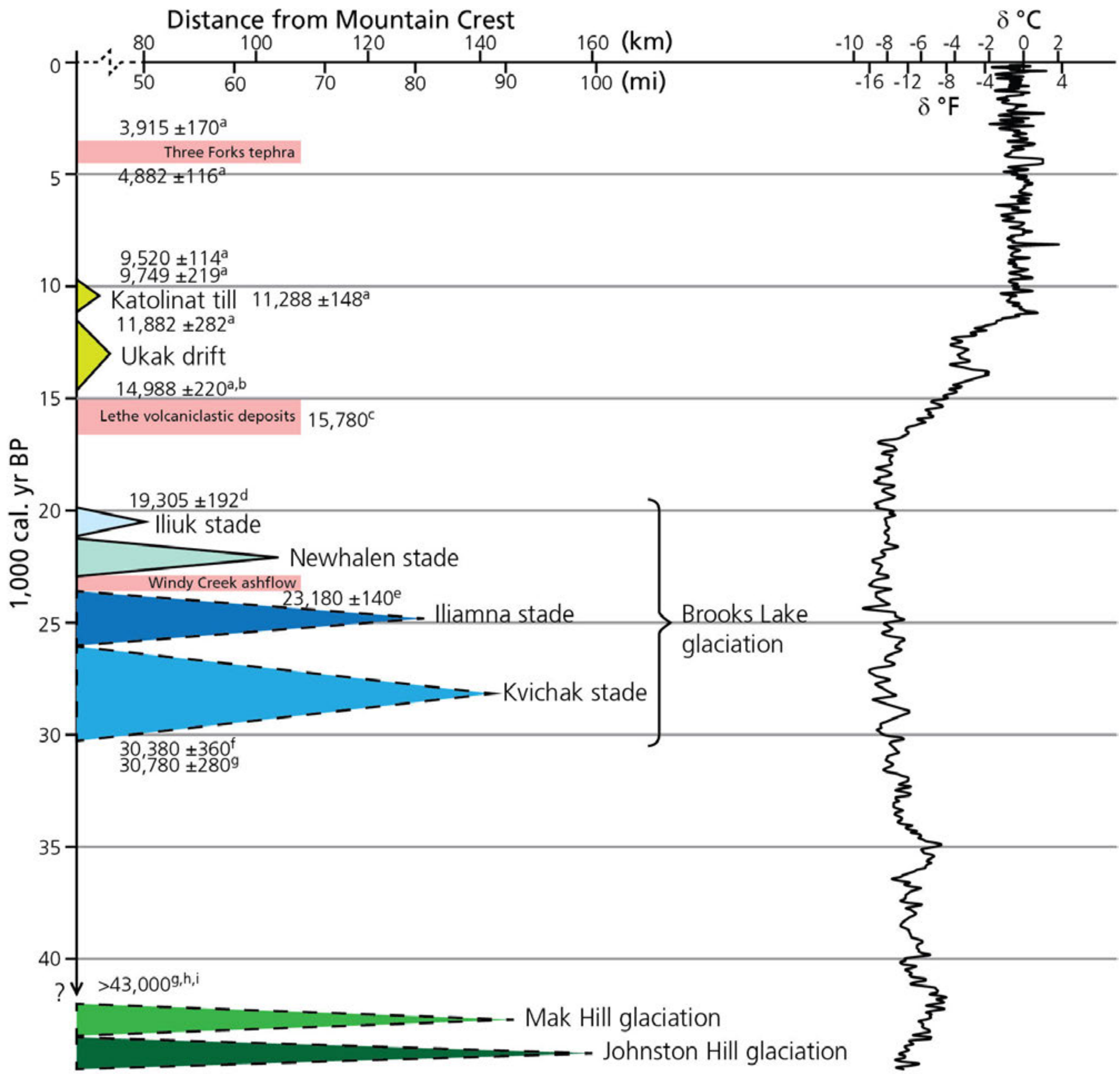


Figure 67. Diagram showing the distance from the mountain crest for the various glacial advances and their absolute age ranges based on radiocarbon ages. The distances from source for the Ukak (25 km, 15 mi) and Katonlinat (30 km, 20 mi) advances were measured at the head of the Valley of Ten Thousand Smokes; whereas, the older glaciations were measured at the head of the Rainbow River valley. Ages of overlying tephra deposits help constrain the age of some of the glacier deposits. Also shown is the global temperature deviation curve from Petit et al. (1999). Warmer temperatures are to-the-right; colder are to-the-left. Radiocarbon ages are reported in calibrated years before present (before 1950) from the following sources: (a) Pinney and Begét (1991b), (b) Pinney and Begét (1991a), (c) Brubaker et al (2001), (d) Reger et al.(1996), (e) Hildreth and Fierstein (2003), (f) Mann and Peteet (1994), (g) Stilwell and Kaufman (1996), (h) Detterman (1986), and (i) Riehle and Detterman (1993).

the north of the Alagnak River. This oldest stade is not well represented by a distinct end moraine in the Lake Brooks and Naknek Lake area, but Riehle and Detterman (1993) mapped glacial deposits that they assigned to the Kvichak stade west of Lake Brooks near the King Salmon River and around the hill with the VABM named "Granite" at about the elevation of 183 m (600 ft). Plant matter underlying outwash associated with the Kvichak moraine to the north of the map area provided a maximum age of 30,400±340 cal. yr BP for the Kvichak stade (Stilwell and Kaufman 1996).

The Iliamna stade (**Qblil**) is named after the prominent end moraine that dams Iliamna Lake. Correlative moraines dam Kukaklek, Nonvianuk, and Naknek Lakes. The outer moraine located about 10 km southwest of Lake Brooks is also correlated with the Iliamna stade. The Iliamna moraine is overlain by the Windy River tephra, which has a maximum age of 23,180±140 cal. yr BP, so the Iliamna stade took place more than 23,000 years ago (Stevens 2012). Mann and Peteet (1994) dated organic material below outwash associated with the Naknek Lake moraine, which provides a maximum age of 30,380±360 cal. yr BP for the Iliamna stade.

The Newhalen stade (**Qbln**) is named after moraine deposits along the Newhalen River, which flows into the north side of Iliamna Lake. In the map area, the moraines that dam Hammersly Lake, the North Arm of Naknek Lake, and Lake Brooks are correlated with the Newhalen stade by Riehle and Detterman (1993).

The Iliuk Arm moraine (**Qblik**) divides the Iliuk Arm from the rest of Naknek Lake and is the type moraine for the Iliuk stade. Additional moraines correlative with the Iliuk stade are the Lake Grosvenor moraine that separates Lake Grosvenor from Lake Coville; the Kulik Lake moraine that separates Kulik Lake from Nonvianuk Lake; and the Battle Lake moraine that separates Battle Lake from Kukaklek Lake. The Newhalen and Iliuk stades are constrained with radiometric ages between 19,880±210 and 23,180±140 cal. yr BP (Pinney and Begét 1991a; Reger et al. 1996; Hildreth and Fierstein 2003).

Other Glacier Deposits

The Ukak drift and Katolinat till are two minor glacial advances that span the Pleistocene-Holocene boundary (11,700 years ago), and are present in the Three Forks area (Pinney and Begét 1991a). Ages of these advances are estimated to be approximately 12,000–8,500 years ago.

The Pacific side of the range contains only a few small areas with glacial deposits mapped as mapped undivided Brook Lake Glaciation (**Qblu**) and Iliuk Stade (**Qbil**) age deposits (Plate 1), but the ages of these deposits is not constrained. Steep mountain slopes and a short distance between the mountain crest and the coast was not an environment conducive for preservation of older glacial deposits. Only the most recent glacial deposits are preserved. One interesting exposure of glacier deposits underlies a lava flow from Mount Katmai in the Katmai River canyon (Griggs 1917).

Glacial Moraine Dammed Lake Levels
Map unit: **Ql**

As the glaciers receded, the freshly deposited end moraines dammed the water melting from the glaciers to form proglacial lakes. Nearly every proglacial lake in the Katmai area contained more water and covered a larger area than present-day lakes. For example, proglacial lake Naknek was up to 53 m (175 ft) above the present lake level (Muller 1952, 1963; Dumond 1981; Kaufman and Stilwell 1997). When the Iliamna stade glacier retreated, a proglacial lake Naknek began to form, and the higher lake level eventually filled the many valleys of the area (Figure 68). The water flowing over the moraines slowly eroded into the moraines and lowered the lake levels. When the water was higher, waves on the lakes formed wave-cut terraces, wave-cut cliffs, and beach ridges on the hillslopes surrounding the lakes (e.g., Figure 69). Proglacial lake sediments (**Ql**) were deposited on the underlying glacier deposits and are exposed around the lakes in the area.

Dropping water levels of the proglacial lake Naknek left behind small lakes that were cut off from the path to the ocean, which stranded salmon that eventually became the Kokanee populations. As the lake level dropped, Lake Brooks and Brooks River formed. Water flowing over the newly exposed bedrock formed Brooks Falls, which now forms a constriction to salmon, which created a prime fishing area for indigenous humans and bears.

Modern Glacier Features and Changes
Map units: **Qsg**, **Qrg**; **Qg**; (**"Glaciers"** on Plate 1)

Glaciers of the Katmai area are clustered in three groups (1) in the Katmai volcanic cluster, (2) in the Fourpeaked to Douglas volcanoes area, and (3) scattered in the Walatka Mountains on the north (see Figure 73). An example of typical glaciers on the ice-covered volcanoes and their features are shown in Figure 70. As of 2009, the Katmai Area had an ice-covered area of around 915 km^2 (350 mi^2) (Loso et al. 2014). There are no glaciers in Alagnak Wild River.

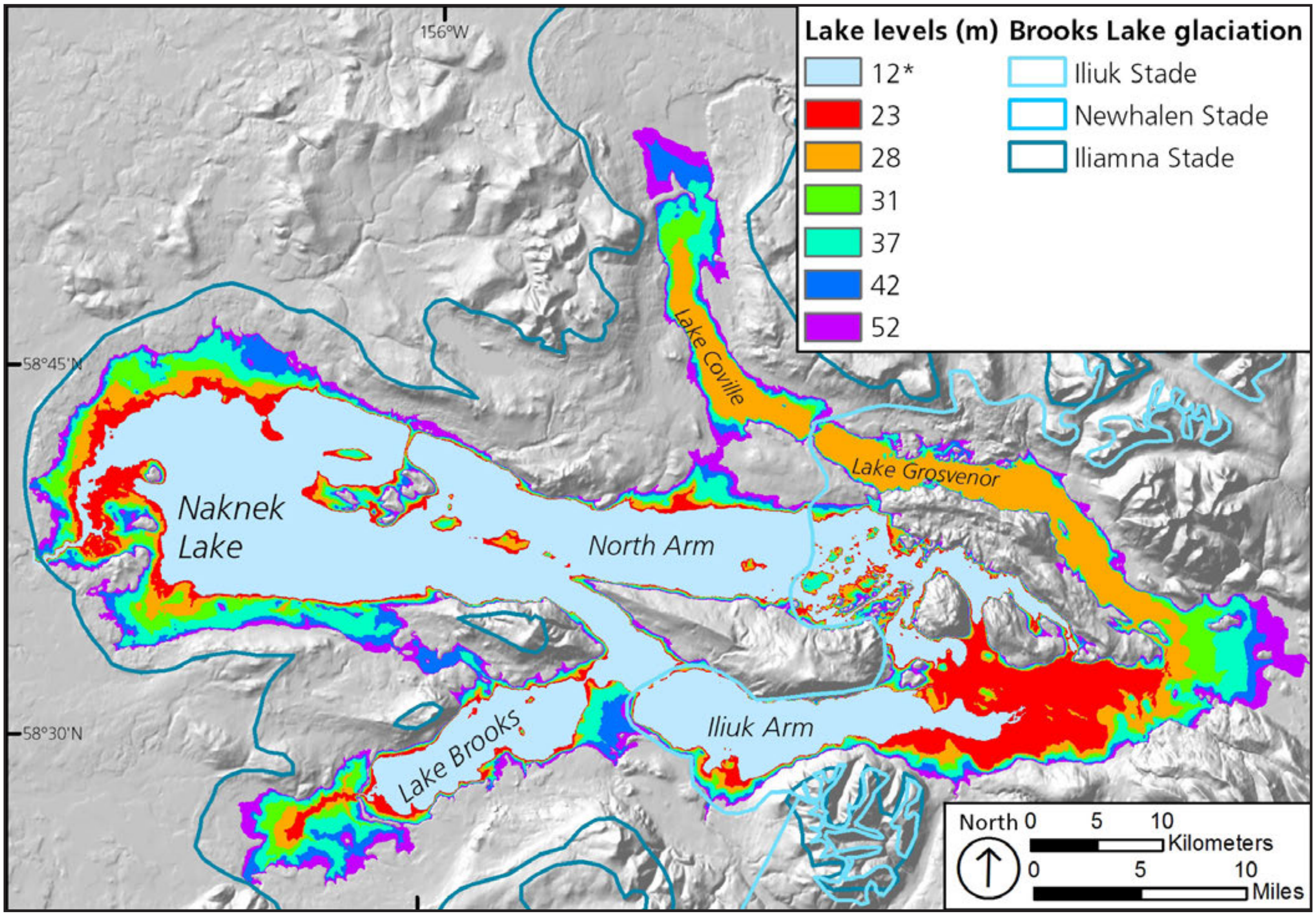


Figure 68. Map showing the extent of the proglacial lake Naknek at varying lake levels defined by major wave-cut terraces. The colored lake terrace levels were created by "filling" the digital elevation model up to the major wave-cut terrace levels listed in Muller (1952, 1963), Dumond (1981), and Kaufman and Stilwell (1997). The asterisk next to 12 m denotes the current lake level. The glacial moraines on the west end of Naknek Lake and southwest of Lake Brooks dammed the glacial melt waters to form the larger proglacial lake. Hillshade derived from National Elevation Dataset.

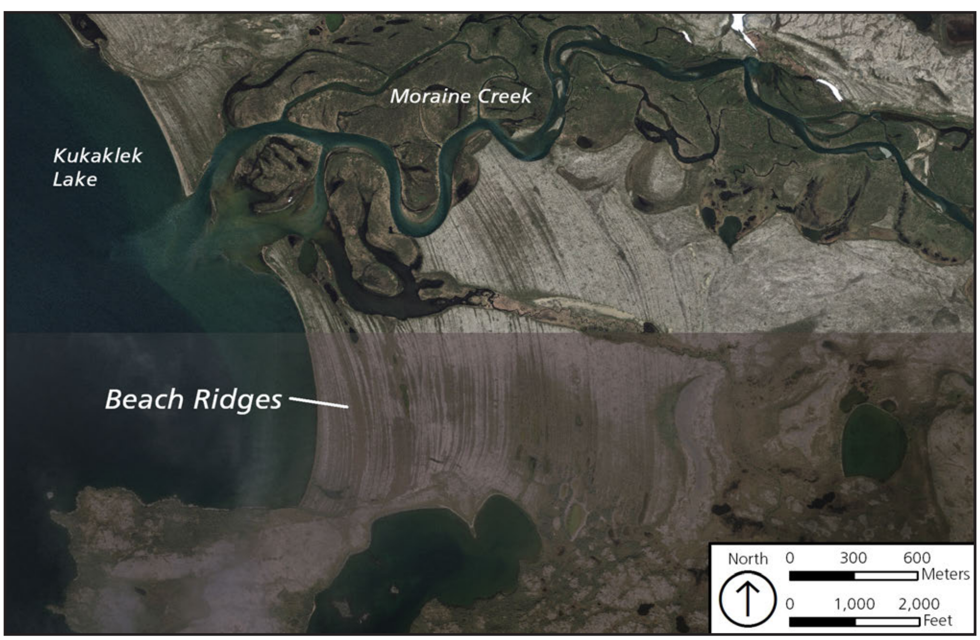


Figure 69. Satellite (IKONOS) image mosaic of beach ridges along the eastern shore of Kukaklek Lake at the outlet of Moraine Creek.

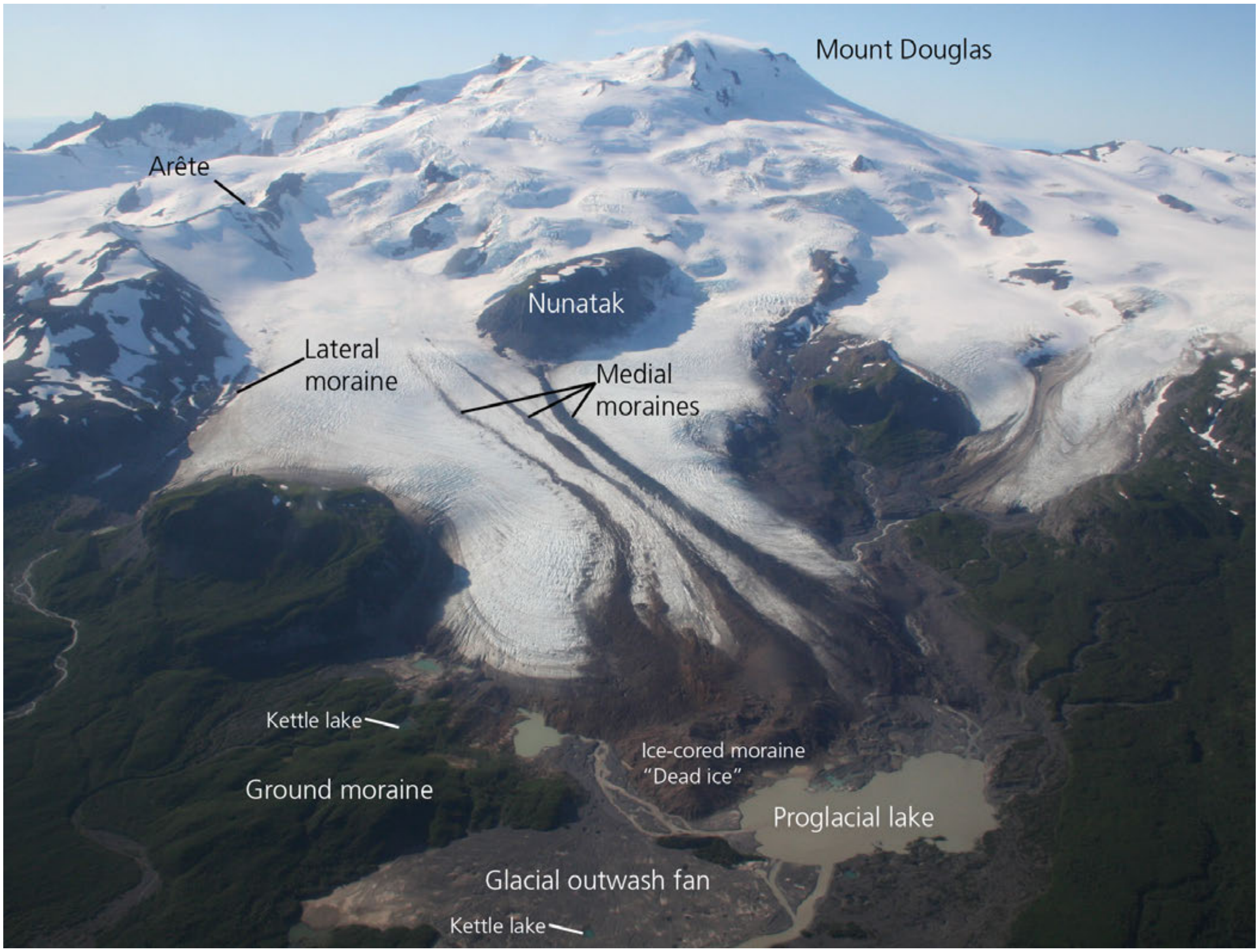


Figure 70. Photograph showing glacial features. The unnamed glaciers are sourced from a broad icefield on the northwest side of Mount Douglas. Where two glaciers meet, a medial moraine forms from the lateral moraines of each glacier. Arêtes are knife-edge ridges that form between two glaciers. Nunataks are isolated knobs of exposed bedrock surrounded by glacial ice. The ice-cored moraine at the toe of the glacier is hummocky debris covered ice that is also referred to as "dead ice," because it is no longer part of the moving glacier. Kettle lakes form where moraine or outwash material buries glacial ice that has melted to leave a depression. NPS photograph by Chuck Lindsey.

Loso et al. (2014) inventoried glacier changes of all the glaciers of Alaska by comparing topographic maps from the 1950s and 1960s to modern satellite imagery. In the Katmai area, these investigators counted 298 glaciers from the satellite imagery. The area covered by glaciers decreased from 1,060 km^2 to 914 km^2 (410 mi^2 to 353 mi^2), or reduced by 14%. Error in the satellite analysis may result in the difficulty of identifying the glacial extent for glaciers with substantial superglacial drift (**Qsg**), like that which overlies the toes of the Serpent Tongue Glacier and the Knife Creek Glaciers (Plate 1). Most glaciers in the Katmai area are retreating, like most glaciers in Alaska, but some of the glaciers still covered by thick deposits of 1912 ash (which provided an insulating "blanket") have advanced (Figure 71, Figure 72, Figure 73). For a detailed overview of the effects of ash on the glaciers see Hildreth and Fierstein (2012, p. 171–173). Terminus retreat was the response seen in most glaciers, including notable retreats of up to 4 km (2.4 mi) for glaciers on Fourpeaked Mountain and Mount Douglas, as well as Hallo Glacier (Figure 71) and others on the Denison to Devils desk volcanic cluster.

Following the 1912 eruption, new glaciers have formed in the Katmai caldera (Figure 74). The collapse of the glacier-clad summit during the eruption "beheaded" the glaciers and left steep ice cliffs on the west and north sides of the caldera (Griggs 1922). Sometime after 1923, a permanent ice field accumulated on the south wall of

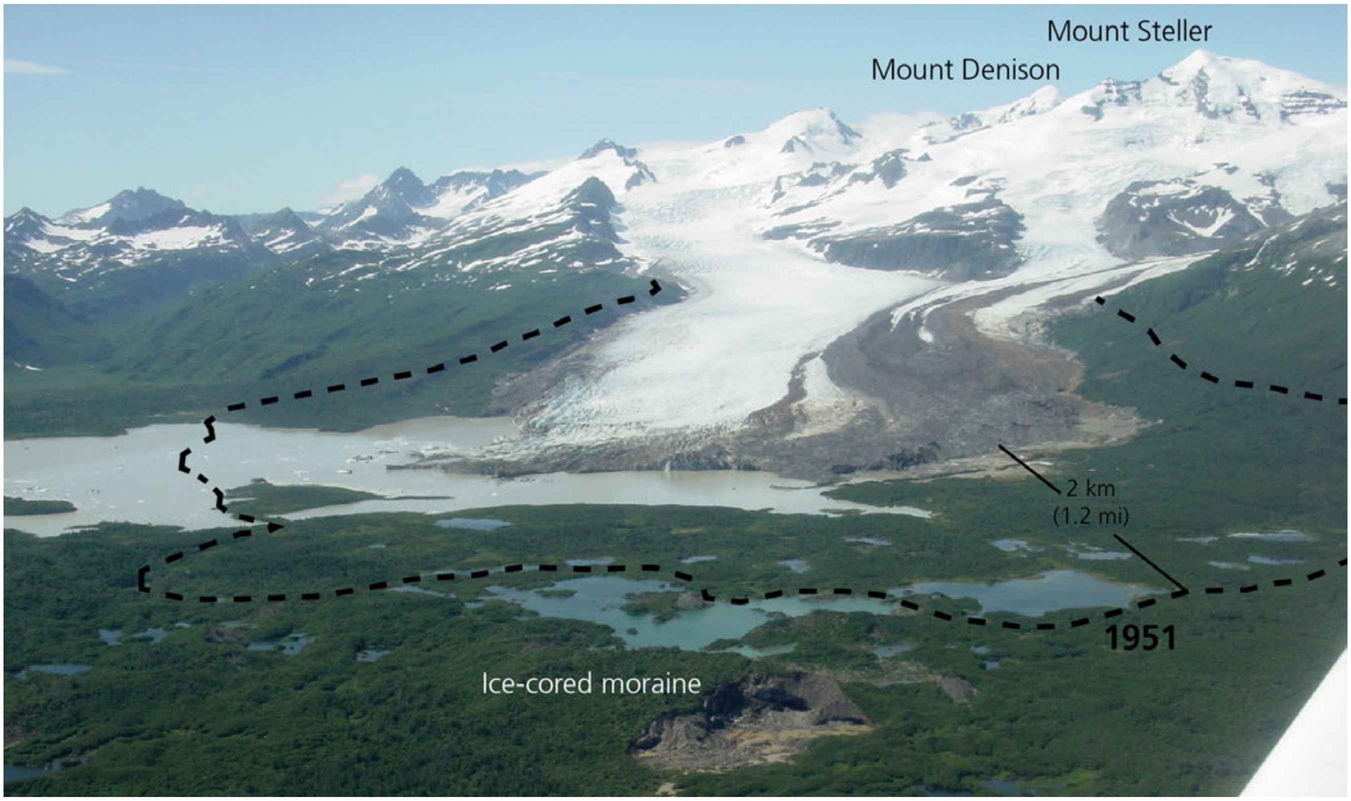


Figure 71. Photograph of Hallo Glacier in 2007. The approximate extent of the glacier in 1951, based on USGS topographic map, is shown as a dashed line. NPS photograph by Chuck Lindsay.

Figure 72. Photograph of one of the Knife Creek Glaciers. Ash from the 1912 eruption still extensively coats the surface of the lower portion of the glacier more than 100 years after the eruption. The ash cover was thick enough to "insulate" the glacier, causing it to advance when the majority of glaciers in the Katmai area and Alaska have retreated. NPS photograph by Chad Hults.

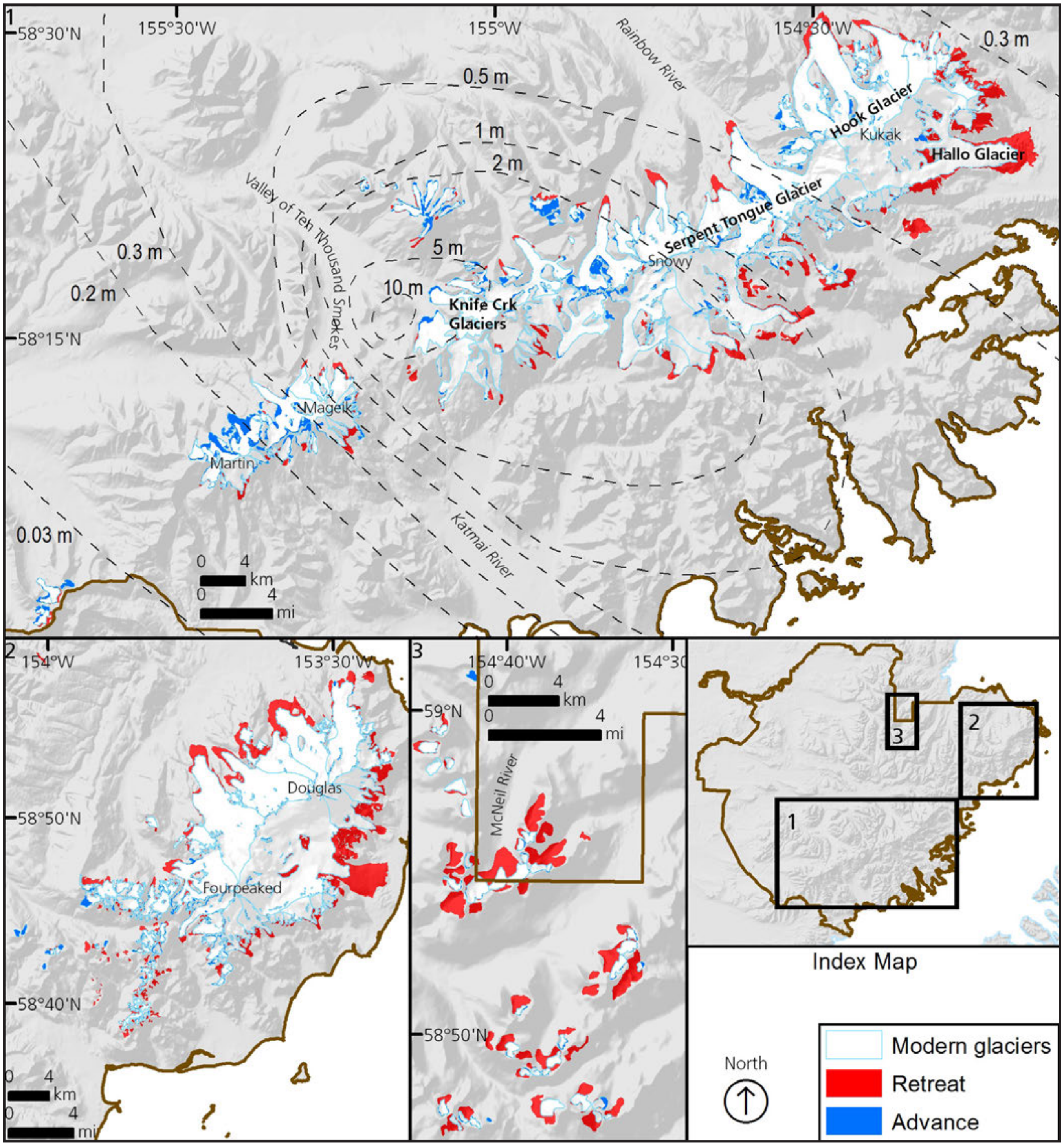


Figure 73. Map showing the extent of the glaciers as mapped on 1950s USGS topographic maps as compared to the modern glacial extent derived from satellite images mostly from 2009. The top frame (1) of the Katmai volcanic cluster area shows the isopachs of the 1912 eruption ash-fall depths from Fierstein and Hildreth (1992) and Hildreth and Fierstein (2003). Many of the glaciers around the Novarupta vent area have advanced, but outside of the main ash fall area most glaciers have retreated. The glacier with the greatest advance, 1 km (0.6 mi), is on the north side of Mount Martin; whereas, the Hallo Glacier has retreated approximately 2 km (1.3 mi). Frame (2) is of the Fourpeaked Mountain and Mount Douglas area. It predominately shows extreme glacier retreat. Fourpeaked Glacier had the greatest retreat of about 4 km (2.4 mi). Frame (3) is of the Walatka Mountains area, where all the small alpine glaciers have retreated. Maps created with data from Arendt and Rich (2013).

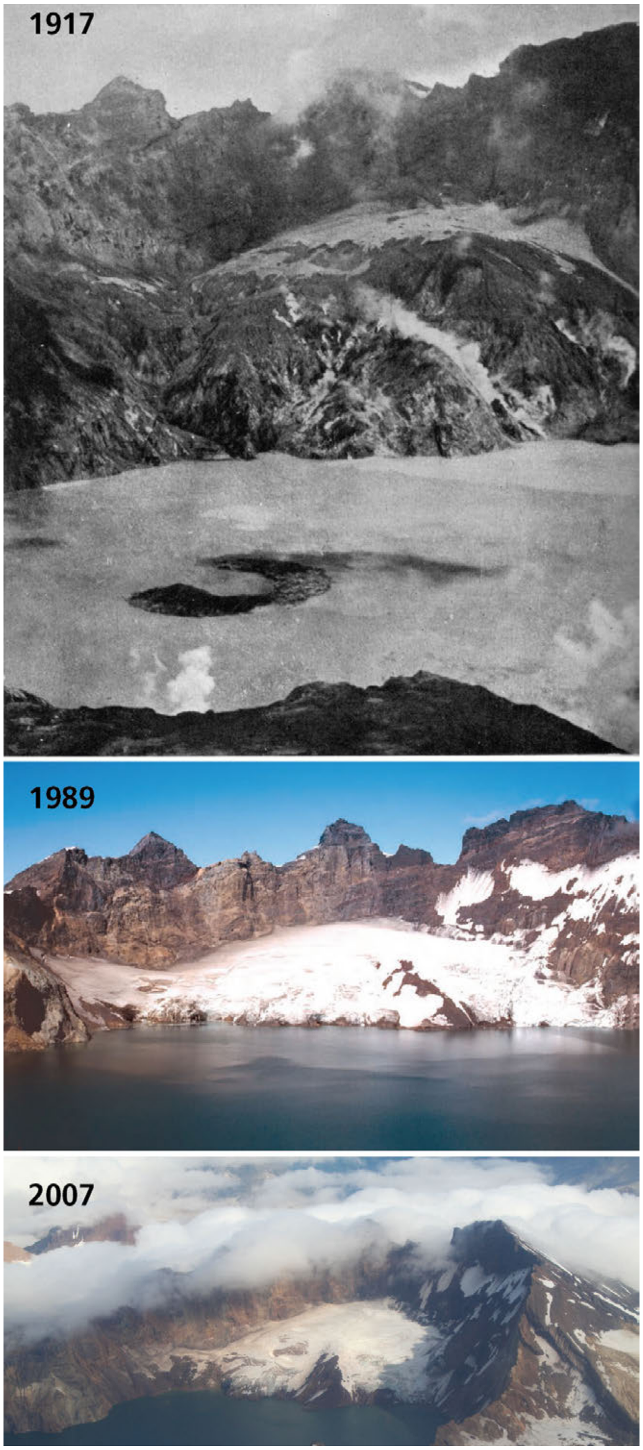


Figure 74. Comparative photographs of the north side of the Katmai caldera showing the growth of the northern glacier. Top: The glacier started as a thin snowfield in 1917. National Geographic Society photograph by John Shipley (Griggs 1922, p. 172). Center: It was a large active glacier in 1989. USGS-CalVO photograph by Judy Fierstein (figure 136B in Hildreth and Fierstein 2012). Bottom: The glacier had shown some retreat by 2007. NPS photograph by Chuck Lindsay.

the caldera, and by 1935, Hubbard observed glaciers forming on the caldera walls (summarized by Muller and Coulter 1957). As reported by Muller and Coulter (1957), two well-formed glaciers were clinging to the north and south sides of the caldera walls, and an icefall was cascading down the southwest side of the caldera in 1953 (Figure 75); these features are still active today.

Thirty rock glaciers (**Qrg**) are mapped in the Katmai area (Plate 1; Figure 76). Rock glaciers are jumbled masses of boulders and smaller rock material that may bury an ice glacier ("ice-cored") or have ice filling much of the spaces between the rocks ("ice-cemented").

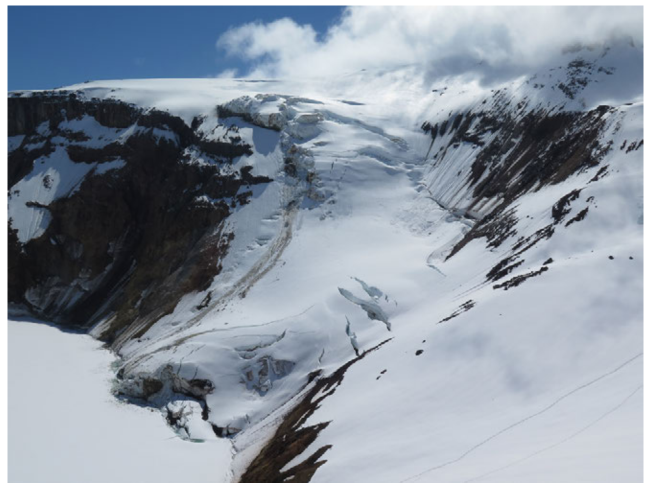


Figure 75. Photograph of the icefall from the glacier on the southwest wall of the Katmai caldera. NPS photograph by Chad Hults.

Permafrost Features

Map unit: **Qsf**

Although the average annual temperature at King Salmon is above freezing (1.8°C, 35.2°F; http://akclimate.org/), isolated permafrost is present in the western portion of the Katmai area in the low hills and on the coastal plain and sporadic permafrost is present at higher elevations(Abrahamson 1950; Thompson 1954; Jorgenson et al. 2008; Figure 77). In low-lying areas, the presence of permafrost is commonly correlated with an insulating cover of peat and thick vegetation mats of sphagnum mosses, sedge, and cottongrass; and found in areas underlain by fine-grained surficial deposits (Detterman and Reed 1973, p. 15). Permafrost is present in the loess-covered areas of the Mak Hill Glaciation, and proglacial lake deposits (**Ql**). Frost wedges have been observed along cut banks

Figure 76. Photograph of a rock glacier (Qrg) in the hills of the headwaters of Ikagluik Creek. This is an example of an ice-cored rock glacier that is glacier ice completely covered with rocky debris. NPS photograph by Bruce Giffen.

of the Naknek River and the coastal plain, and frost-wedge crack nets are present at higher elevations on a pass near Kaguyak Crater (Thompson 1954; Cahalane 1959). Abrahamson (1950) hypothesized that the presence of permafrost in an area with an annual temperature above freezing was due to the thermal and water absorption properties of peat allowing the winter cold to penetrate better than the summer heat; whereas, Muller (1952) suggested that the permafrost of the coastal area was instead a remnant from the Pleistocene glaciations.

Intense frost action has modified the landscape since deglaciation. Older glacial deposits are weathered smooth by prolonged frost action, but younger deposits that have been exposed more recently have sharper features. Frost action heaves large rock fragments to the surface that produces a striped pattern on hillslopes and polygonal structures on flatter surfaces (Muller 1952). Solifluction deposits (**Qsf**) are found on slopes throughout the Katmai area and form where water-saturated lobes of soil creep downhill over underlying, frozen ground.

Coastal Features

Map units: **Qtf, Qes, Qb, Qmt**

The Katmai coast has 737 km (458 miles) of shoreline (Curdts 2011), which is a mix of rugged wave-eroded sea cliffs on the headlands and protected bays (Figure 78). Beach deposits (**Qb**) are chiefly sand derived from local surficial deposits, but beaches along Katmai and Dakavak Bays include abundant pumice from the 1912 eruption. Tidal flat (**Qtf**) and estuarine (**Qes**) deposits are present in many of the protected bays along the coasts and consist of silt and mud below mean high tide. Steep slopes that continue below the water level are common along the shoreline, but broad estuaries and large beaches are present along deltas fed by sediment laden glacially fed rivers. A simple classification of the morphologic features of the coast was developed by Harper and Morris (2005).

Beach Berms

Beach berms (**Qb**, in part), semi-parallel ridges located inland of the modern coastline, are present in many of the protected bays, some places with stranded shorelines far inland from the modern shoreline. For example, Hallo Bay has stranded logs on beach ridges as far as 1.5 km (1 mi) inland of the modern coastline. Beach berms are formed where sediment input from rivers is greater than erosion from waves (Figure 79). Longshore currents transport the sediment along the coast and during large storms, sediment and logs are piled up to form the berms. As the process continues, the berms build seaward.

Raised Marine Terraces and Sea Caves

Raised marine terraces are present along the coast of Shelikof Strait and Kamishak Bay (**Qmt**) (Detterman and Reed 1973; Detterman et al. 1987b; Riehle and Detterman 1993; Crowell and Mann 1996). In Kamishak Bay, well-developed wave-cut platforms (Figure 80) are covered by beach deposits and are 15 and 27 m (50 and 90 ft) above the modern high tide line. The wave-cut platform and associated deposits constitute a marine terrace. On an island in Kamishak Bay, Harper and Morris (2005) documented relict sea caves and sea cliffs, well-above modern sea level, that formed before uplift of the island (Figure 81). Along

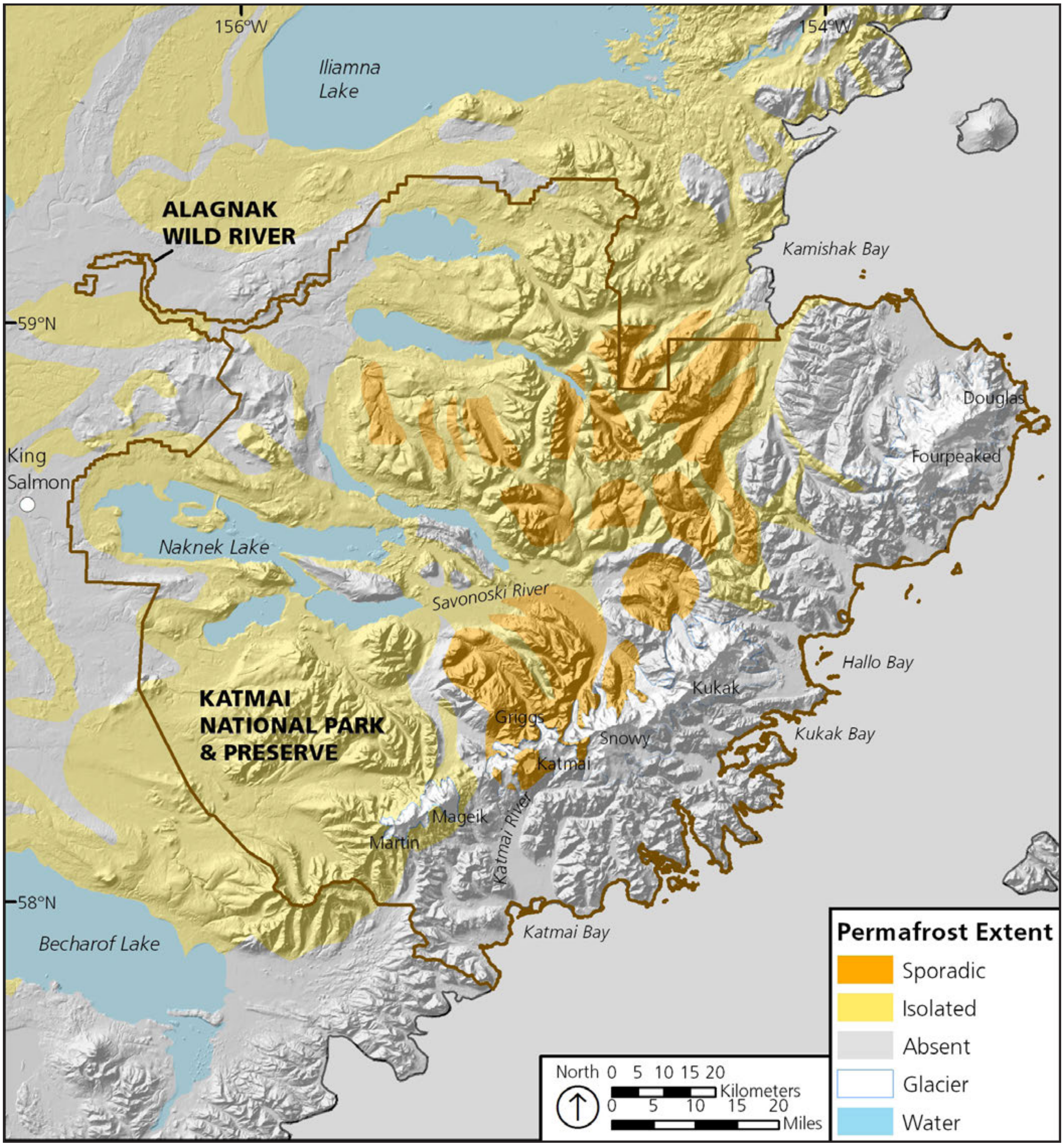


Figure 77. Map showing the permafrost extent in the Katmai area. Sporadic: areas where 10–50% of the ground is underlain by permafrost; Isolated: areas where <10% of the ground is underlain by permafrost. Map created with data from Jorgenson et al. (2008). Hillshade derived from National Elevation Dataset.

the southern coast of the Katmai area, Detterman et al. (1987b) also found marine terraces at the 40–45 m (130–150 ft) level.

The terraces on the Katmai coast are much higher than the terraces on the Bristol Bay coast, which are found only as high as 12–18 m (40–60 ft) (Detterman et al. 1987b; Riehle and Detterman 1993). Organic material on top of 4 m (14 ft) of sand overlying the 15 m (50 ft) terrace in the Douglas River area was deposited

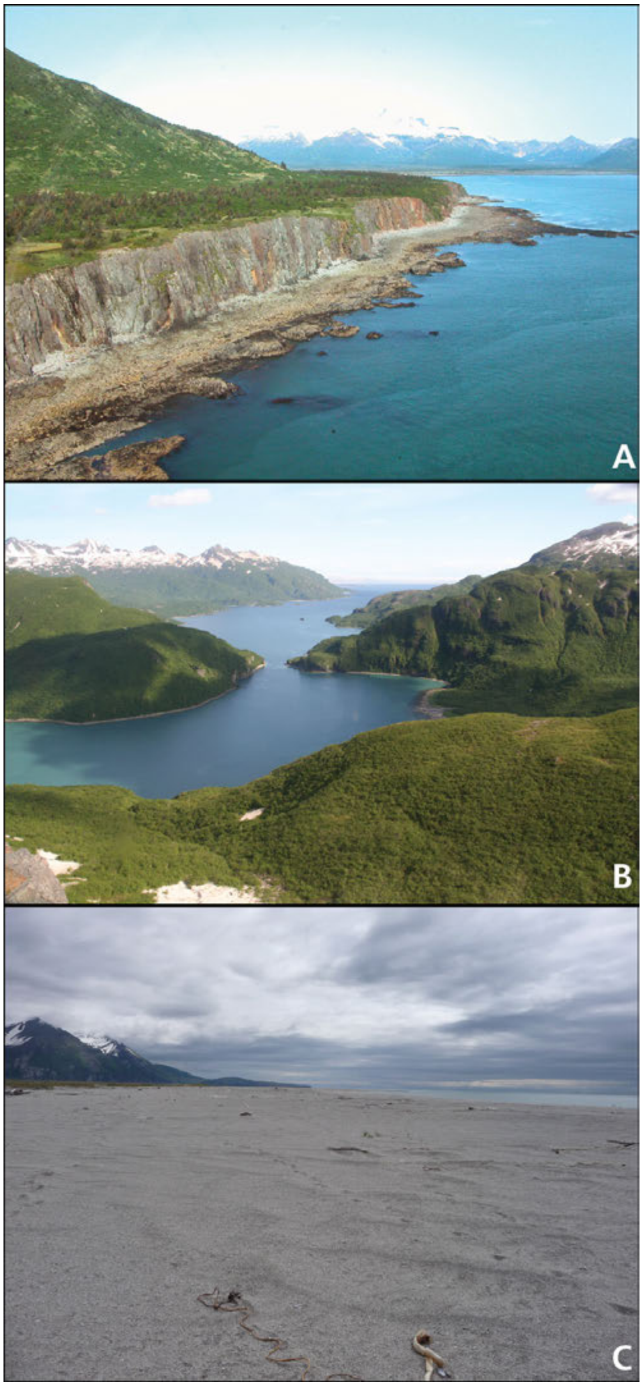


Figure 78. Photographs of three major types of coastline in the Katmai area. (A) Sea cliffs along the exposed Cape Nukshak, south side of Hallo Bay. Photograph katmai_5011 from the NOAA Alaska ShoreZone database: http://alaskafisheries.noaa.gov/mapping/szflex/. (B) Protected but rocky Hidden Harbor. NPS photograph by M. Torre Jorgenson. (C) Large beach in Katmai Bay near the mouth of the sediment laden Katmai River. NPS photograph by Carissa Turner.

2,720±310 years BP, which corresponds to an uplift rate of approximately 3–6 mm/yr (0.1–0.2 in/yr) (Detterman and Reed 1973). This rate is close to the 8 mm/yr (0.3 in/yr) uplift rate measured using GPS at Dakovak Lake (Freymueller et al. 2008). For comparison, a GPS survey marker located 80 km (50 mi) inland, on an island in the North Arm of Naknek Lake, is rising at half the rate of the coast, 4 mm/yr (0.15 in/yr) (Freymueller et al. 2008).

The Katmai coast is rising in part from tectonic uplift and in part from isostatic adjustments following deglaciation. The weight of glacial ice can depress Earth's crust and when it melts, the crust gradually rebounds. Detterman (1986) provided a brief overview of the tectonic and isostatic evidence for the Alaska Peninsula, suggesting that these marine terraces may be primarily the result of differential glacial isostatic rebound. Because the peninsula is located over the Aleutian megathrust, the relative effects of ongoing deformation, movement along faults that create earthquakes, and isostatic rebound are hard to decipher. Long-term uplift rates are sometimes disrupted by distinct events; for example, based on tide station level changes in Kukak Bay, the 1964 earthquake caused the area to subside 20 cm (0.5 ft) (Plafker 1969).

Modern Surficial Deposits and Processes

Map units: **Qs, Qsw, Qa, Qaf, Qt, Qls, Qc, Qd**

Modern surficial deposits have been formed in the last few thousand years, and many are still forming today by geomorphic processes. Some surficial deposits have not been differentiated and are mapped as **Qs** in Plate 1. Swamp deposits (**Qsw**), organic peat and silt accumulations, formed in closed basins in low-lying areas.

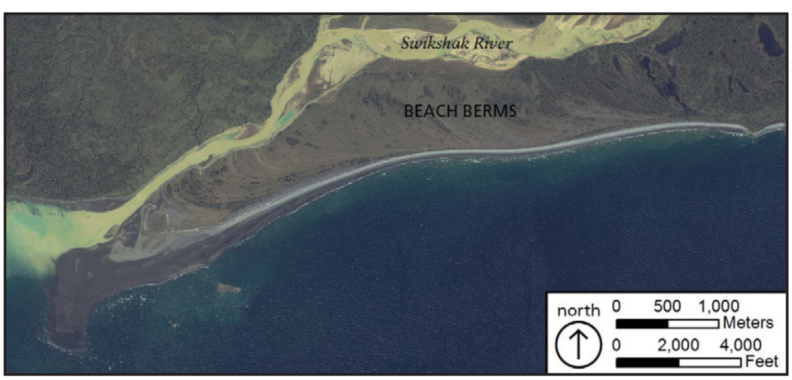


Figure 79. Satellite (IKONOS) image of beach berms forming at the outlet of the Swikshak River. Sediment output from the sediment-laden river is greater than the rate of erosion by waves.

Figure 80. Photograph of a raised marine terrace (Qmt). The island, located near the mouth of the Douglas River, was cut flat by waves. Subsequently, it has risen approximately 15 m (50 ft). The foreground is a modern wave-cut platform that cuts across dipping beds of the Naknek Formation, Snug Harbor Siltstone Member. Photograph ci09hm_08129b from the NOAA Alaska ShoreZone database: http://alaskafisheries.noaa.gov/mapping/szflex/.

Figure 81. Photograph of marine terraces, sea cliffs, and sea caves raised above the modern high tide level. This island near the mouth of the Douglas River in Kachemak Bay is a raised marine terrace about 15 m (50 ft) above the modern high tide level. The cliffs and sea caves have vegetation below them indicating that they are also raised above the high tide level. NPS photograph by Sara Venator.

Alluvial deposits (**Qa**) are found along all the modern river floodplains and consist primarily of sand and gravel deposits, but locally include boulders eroded from bedrock or glacial deposits. Alluvial fan deposits (**Qaf**) are fan-shaped alluvial deposits that form along moderately to steeply sloping areas. Alluvial terrace deposits (**Qt**) are sorted, stratified gravel and sand deposits that are higher than modern floodplains. They were formed by the complex interplay among uplift of the land by tectonic or glacial isostatic rebound, lowering of the outlet caused by sea level or lake level changes, or changes in sediment influx. Landslide deposits (**Qls**) are made up of unsorted deposits of chaotic debris forming lobate masses at the bases of steep slopes throughout the map area (Plate 1). Colluvial deposits (**Qc**) made up of loose, coarse angular blocks of rocks that form small cones and talus slopes are found throughout the map area on or at the base of steep slopes (Plate 1). Colluvium is indicative of rockfall and rockslides (see "Geohazards" section). Small dune fields (**Qd**) are found primarily along beaches and stream terraces and near the Valley of Ten Thousand Smokes (Plate 1). With the exception of **Qls** and **Qc**, all the units listed above are mapped within Alagnak Wild River (Plate 1).

Mesozoic Bedrock

The bedrock of the Katmai area includes a nearly complete sequence spanning the Mesozoic Era (252–66 MYA; Plate 2; Plate 3). Triassic (252–201 MYA) greenstone (altered basaltic rocks) that made up an ocean floor was intruded and overlain by Lower Jurassic (201–174 MYA) plutonic (intrusive magma bodies) and volcanic rocks of the Talkeetna arc. The Bruin Bay fault uplifted the arc and sediment eroded from the arc was deposited along a narrow shelf (Figure 82) during the Upper Jurassic to Lower Cretaceous (164–100 MYA) (Burk 1965; Trop et al. 2005; Wartes et al. 2013). Evidence from paleomagnetism, fossil assemblages, and depositional environments suggests that the rocks formed originally in tropical waters in the Late Triassic (237–201 MYA), were transported to boreal (high latitude) environments in the Late Jurassic (164–145 MYA), moved back down to low latitudes

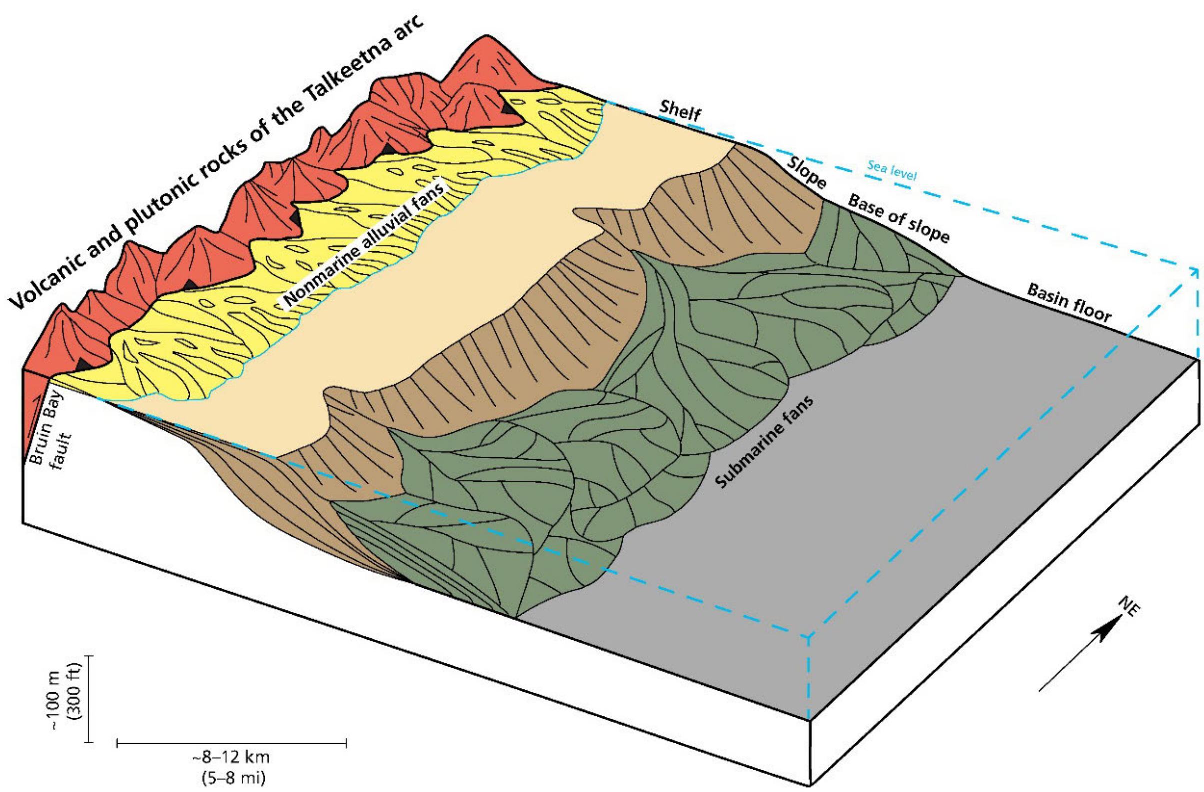


Figure 82. Diagram showing the depositional environments of Mesozoic nonmarine and marine rocks of the Katmai area. The Bruin Bay fault (left side of graphic) is a major reverse fault that pushed up the volcanic and plutonic rocks of the Talkeetna arc (see "Faults and Folds" section). Redrafted from Herriott et al. (2015) after Reading and Richards (1994).

in the mid-Cretaceous (110–90 MYA), then rapidly moved northward along the coast of North America to their present location (see "Terrane Translation and Accretion" section). Plate tectonics has played a major role in the formation of the rocks of Katmai, transporting them to the North American continent from out in the proto-Pacific Ocean, and causing the deformation and uplift that is still ongoing today.

Cottonwood Bay Greenstone
Map unit: **TRc**

The oldest rock in the Katmai area is the Upper Triassic (237–201 MYA) Cottonwood Bay Greenstone (**TRc**) that crops out in a small exposure near Takayofo Creek (Plate 1). It consists of slightly altered submarine basalt flows and diabase sills (Riehle et al. 1993). The rocks possibly represent a volcanic seamount.

Kamishak Formation
Map units: **TRk, TRku, TRkm**

The Upper Triassic (237–201 MYA) Kamishak Formation (**Trk**) consists of up to 800 m (2,600 ft) of limestone and interbedded basalt flows and breccia exposed along the King Salmon River in the southwest part of the map area and the McNeil River area on the most northern portion of the map area (Plate 1; Detterman and Reed 1980; Riehle et al. 1993). North of the map area, the unit consists of reef deposits formed on a shallow marine shelf (Riehle et al. 1993; Detterman et al. 1996). Interbedded volcanic rocks indicates that volcanism was coeval during deposition of the limestone. Fragments of unidentifiable fossil fragments, and coral fragments are found in the map area (Miller et al. 1995). North and south of Katmai the unit is fossiliferous, so the unit in the map area most likely contains fossils. The following fossils were identified in the Kamishak Formation north of Katmai in the Iliamna quadrangle (Detterman and Reed 1980), and south of the Katmai area at Puale Bay (Detterman et al. 1996): **Ammonites**: *Alloclionites*, Holoritinid; **Bivalves**: *Monotis*, *Plicatula*, *Halobia*; **Corals**: *Koilocoenia*, *Oppelismilia*, *Thamnasteria*; **Others**: *Heterastridium*, bryozoans, crinoids, echinoderm spines, gastropods.

Talkeetna Arc
Map units: **Jtk, Jgr, Jgd, Jqd, Jgb**

The Talkeetna arc is made up of Lower Jurassic (201–174 MYA) volcanic rocks and plutons of the Peninsular terrane and crop out northwest of the Bruin Bay fault (Plate 1). The Talkeetna Formation (**Jtk**) was defined in the Talkeetna Mountains (hence the name), but the unit extends far down the Alaska Peninsula. It consists of up to 1,200 m (4,000 ft) of lava flows, tuff, volcaniclastic sandstone and conglomerate, volcanic breccia, and lahar deposits of basaltic andesite or andesite composition (Riehle et al. 1993). The Talkeetna Formation represents the volcanic carapace and interbedded marine sedimentary rocks of an island volcanic arc. No fossils have been reported from the Talkeetna Formation in the Katmai area. However, in the Talkeetna Mountains, the unit contains marine invertebrates. Fossil ammonites, gastropods, and the bivalves *Corbicellopsis* and *Oxytoma* are present in the Talkeetna Formation south of Katmai at Puale Bay (Detterman et al. 1996).

The volcanic rocks of the Talkeetna arc were fed by plutons that now crop out in the map area as the Jurassic (radiometric ages range from 190 to 160 MYA) plutonic rocks of the Alaska-Aleutian Range batholith (units **Jgr**, **Jgd**, **Jqd**, **Jgb** in Plate 1). These plutons consist of granite, granodiorite, tonalite, diorite, quartz diorite, and gabbro. The plutons locally intrude older rocks and metamorphosed them into quartzite, schist, amphibolite, gneiss, and migmatite. These rocks are metamorphosed older country rock that are mapped as the Kakhonak Complex (**JPk**). The Kahhonak Complex is mapped within Alagnak Wild River (Plate 1).

Shelikof Formation
Map unit: **Js**

The Middle Jurassic (Bathonian(?) to Callovian, 168–164 MYA) Shelikof Formation (**Js**) crops out in the southern portion of the Katmai area (Plate 1; Detterman et al. 1987a, 1996). The unit is thick-bedded to massive graywacke and conglomerate that represents deep- to shallow-water deposition. The conglomerate contains abundant volcanic grains, so it represents erosion of the volcanic carapace of the Talkeetna arc. No fossils have been reported in the Katmai area, but at the type section (area where the unit is defined) in Puale Bay and in the Chignik and Sutwik quadrangles, south of Katmai, the unit contains **Ammonites**: *Cadoceras*, *Pseudocadoceras*, *Stenocadoceras*, *Iniskinites*; and the **Bivalve**: *Meleagrinella* (Detterman et al. 1981, 1996). There is potential for the outcrops in the Katmai area to yield fossils.

Naknek Formation

Map units: **Jn, Jnk, Jnc, Jni, Jns, Jnn**

The most extensive Mesozoic rock unit within the map area is the Upper Jurassic (164–145 MYA) Naknek Formation, which crops out east of the Bruin Bay fault (Plate 1). The type section is in the Mount Katolinat area. Maximum thickness of the Naknek Formation is 3,200 m (10,500 ft), with an average thickness of 1,700–2,000 m (5,600–6,600 ft) (Detterman et al. 1996).

The formation is divided into six members; five of which crop out in the Katmai area (from bottom to top): Chisik Conglomerate (**Jnc**); Northeast Creek Sandstone (**Jnn**); Snug Harbor Siltstone (**Jns**); Indecision Creek Sandstone (**Jni**); and Katolinat Conglomerate (**Jnk**). Where these members cannot be distinguished, the formation was mapped as undivided (**Jn**). The following unit descriptions and interpretations of depositional environments were derived from Riehle et al. (1993), Miller et al. (1995), and Detterman et al. (1996).

The stratigraphically lowest member (oldest) is the nonmarine Chisik Conglomerate (**Jnc**), which is 600 m (2,000 ft) of massive thick-bedded conglomerate with lenses of cross-bedded sandstone, which was deposited in a fluvial environment (Figure 82). The unit contains clasts made up of granitic rocks, quartzite, schist, chert, and quartz. The second from lowest member is the nonmarine and shallow marine Northeast Creek Sandstone (**Jnn**), which is 200–600 m (660–2,000 ft) of fine to medium grained sandstone that is laminated and contains both eolian (windblown) and fluvial

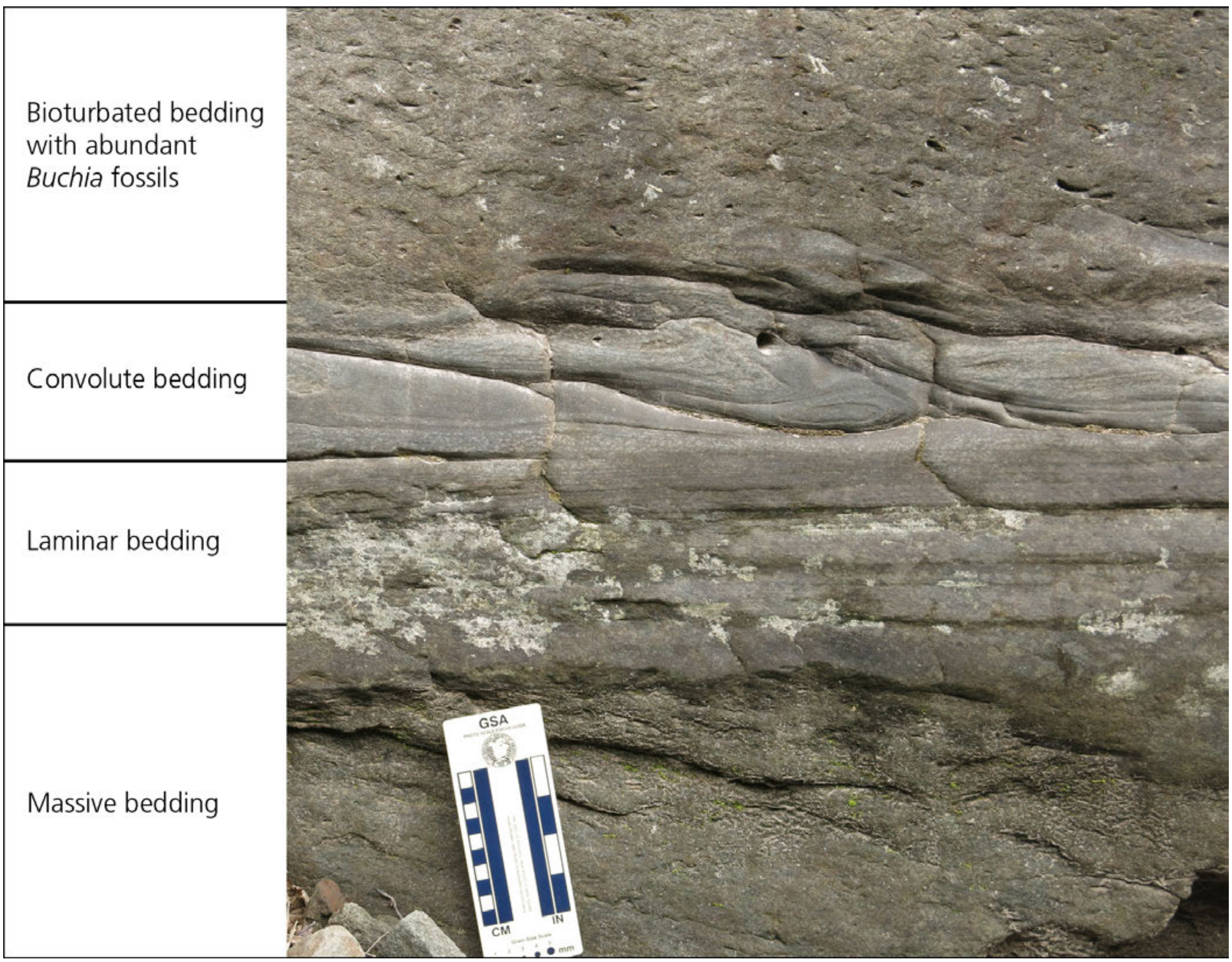


Figure 83. Photograph of bedding forms in the Naknek Formation, Snug Harbor Siltstone Member near Ukak Falls. These sedimentary structures are typical of submarine debris flows common in outer shelf and slope environments. NPS photograph by Chad Hults.

(river) cross-bedding that developed in fluvial and nearshore environments (Figure 82). Conglomerate beds in the Northeast Creek Sandstone contain predominately plutonic clasts, but also clasts of chert and white quartz. The next lower member in the map area is the marine Snug Harbor Siltstone (**Jns**) (Figure 83) that consists of dark-gray sandy siltstone and shale with a few sandstone interbeds and moderately abundant calcareous concretions. The unit is 200–600 m (660–2,000 ft) thick and was deposited in outer shelf and slope environments (Figure 82). The Indecision Creek Sandstone Member (**Jni**) is a marine arkosic sandstone and siltstone 400–800 m (1,300–2,600 ft) thick deposited in shallow-shelf to nearshore marine environments (Figure 82). The highest member is the nonmarine Katolinat Conglomerate (**Jnk**) that is 450 m (1,500 ft) thick and consists of massive pebble-cobble conglomerate and interbedded sandstone deposited in fluvial and beach environments (Figure 82). The conglomerate contains abundant clasts of plutonic rocks, quartz and minor chert, and metamorphic rocks.

The arkosic nature of the sandstones and the abundant plutonic clasts in the conglomerates suggest that the Naknek Formation was derived predominantly from plutonic rocks of the Talkeetna arc (Burk 1965; Detterman et al. 1996). In general, the lower members are marine and minor nonmarine sedimentary rocks that were deposited in braided river and deltaic environments. As marine waters transgressed (got deeper), the middle members were deposited along a marine shelf, slope, and submarine fan. Waters regressed (got shallower), so the upper Katolinat Conglomerate member was deposited in beach and

Figure 84. Map showing the extent of the Naknek Formation (green area) along the Alaska Peninsula and Talkeetna Mountains; a distance greater than 1,100 km (700 mi). Major faults are shown as black lines. Drafted with map compilations from Wilson et al. (1998, 2006, 2012, 2013, 2015). Hillshade derived from National Elevation Dataset.

shoreface environments (Figure 82; Miller et al. 1995). These rocks represent a marine transgressive-regressive cycle (relative sea level rise then fall). Also, depositional environments change laterally in the Naknek Formation with coarser-grained nonmarine sedimentary rocks located on the northwestern margins of the Naknek Formation, and deeper marine facies occurring on the southeast (Detterman et al. 1996).

The Naknek Formation is an extensive unit found on the Alaska Peninsula and the southern Talkeetna Mountains (Figure 84). The Naknek Formation is present only on the southeastern side of the Bruin Bay fault, which was an active reverse fault during the time of deposition (Burk 1965; Trop et al. 2005; Wartes et al. 2013). The rocks of the Peninsular terrane were uplifted on the northwest side of the fault and high-energy streams eroded older rocks and deposited the sediment on the southeastern flanks of the terrane (Figure 82). The rapid deposition of the Naknek Formation records a major uplift and unroofing (extensive erosion) event that affected the Peninsular terrane (Trop et al. 2005).

Diverse fossils, listed below, are found in the Naknek Formation of the Katmai area.

The undivided Naknek Formation (**Jn**) is known for its abundant *Buchia* bivalve fossils (Figure 85) but also contains the following: **Ammonites**: *Phylloceras*; *Cardioceras*; **Bivalves**: include abundant *Buchia*, as well as *Astarte*, *Eumicrotis*, *Lima*, *Meleagrinella*, *Pholadomya*, and *Pleuromya*; **Brachiopod**: rhynchonellid; **Belemnite**: *Cylindroteuthis*; **Fish** (turbot): *Scophthalmus*; **Other**: bone fragments (Keller and Reiser 1958; Detterman and Reed 1980; Miller et al. 1995).

The Northeast Creek Sandstone Member (**Jnn**) contains **Bivalves**: *Buchia*, *Pleuromya*, *Tancredia* (Elder and Miller 1993; Miller et al. 1995).

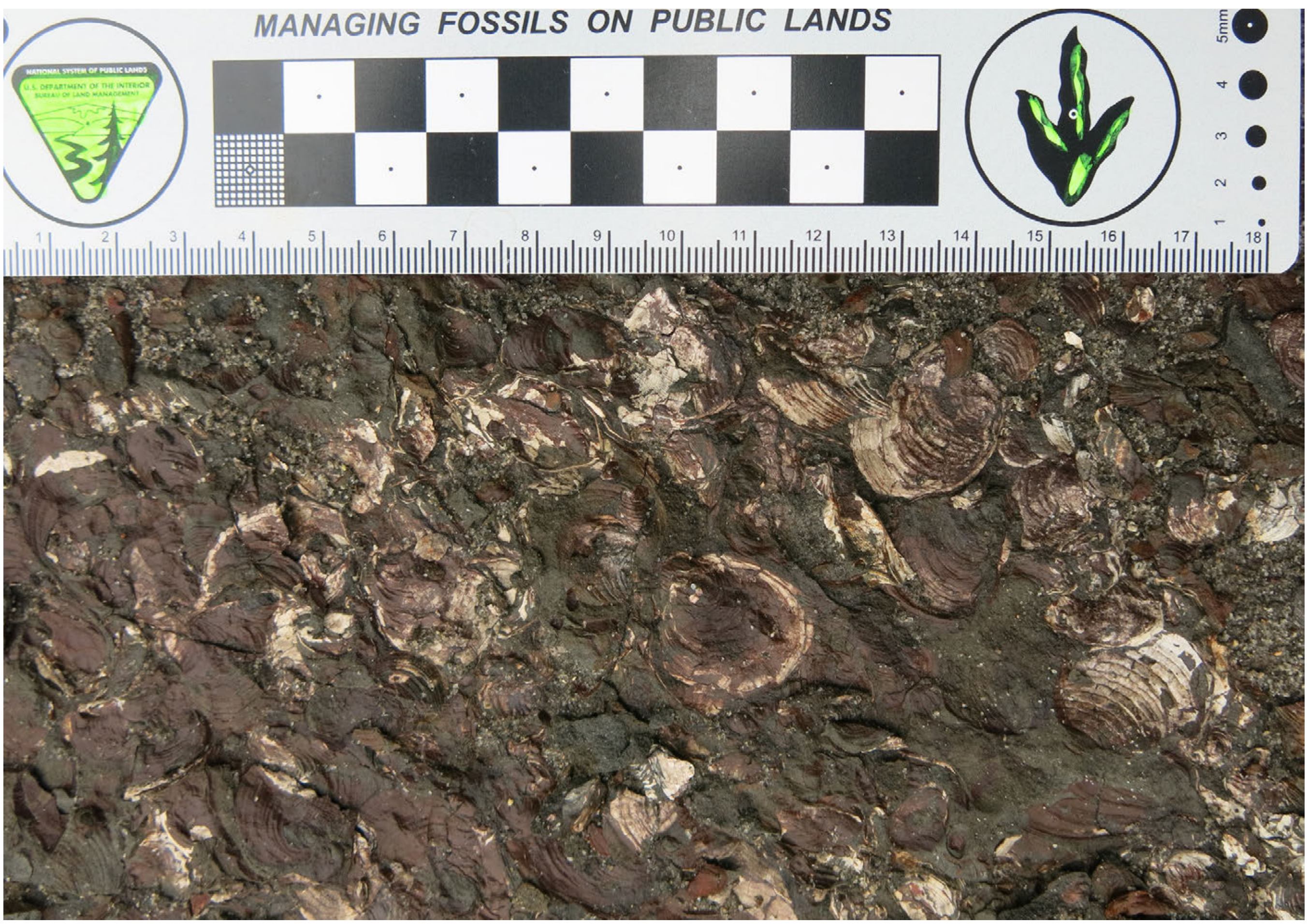


Figure 85. Photograph of *Buchia mosquensis* bivalve fossils in the Naknek Formation Snug Harbor Siltstone member near the Ukak River. NPS photograph by Chad Hults.

The Snug Harbor Siltstone Member (**Jns**) contains the following fossils: **Ammonites**: *Cardioceras*, *Lytoceras*, *Phylloceras*, *Partschiceras*, *Perisphinctes*, *Aulocosphinctoides*, *Partschiceras*; **Belemnite**: *Cylindroteuthis*; **Bivalves**: *Arctica*(?), *Buchia*, *Camptonectes*, Cardiid, Corbiculid, *Entolium*, *Meleagrinella*, *Nuculana*, *Ostrea*, Pectinid, *Pholadomya*, *Pseudolimea*, *Thracia*, Venerid, *Astarte*, *Goniomya*, *Grammatodon*, *Isocyprina*, *Oxytoma*, *Pleuromya*, *Quenstedtia*, *Tancredia*; **Echinoderm**: Cidarid; **Polychaete** (worm): *Ditrupa*; **Gastropod**: *Turbo*; **Scaphopod**: *Dentalium*; **Other**: bone fragments (Detterman and Hartsock 1966; Detterman and Reed 1980; Miller et al. 1995; Fiorillo et al. 2004).

The Indecision Creek Sandstone Member (**Jni**) contains the following fossils: **Ammonites**: *Amoeboceras*, *Lytoceras*, *Ochetoceras*, *Partschiceras*, *Phylloceras*; **Bivalves**: *Astarte*, *Buchia*, *Camptonectes*, Corbiculid, *Entolium*, *Lima*, Limidae, *Meleagrinella*, *Opis*, *Oxytoma*, Ostreid, Pectinid, *Pholadomya*, *Pleuromya*, *Pseudolimea*, *Tancredia*; **Belemnite**: *Cylindroteuthis*; **Scaphopod**: *Dentalium*; **Polychaete** (worm): *Ditrupa*; **Gastropod**: *Turbo*; **Other**: barnacle (Miller et al. 1995).

The Katolinat Conglomerate Member (**Jnk**) contains the bivalve genera *Buchia* and *Corbicula* (Riehle et al. 1993; Miller et al. 1995).

Fossil plant debris is common in the Naknek Formation. South of the map area near the Kejulik River, petrified wood was found in the unit (Albanese and Goff 1987), so the outcrops in the park could also contain petrified wood.

Significant vertebrate paleontological resources found in the Naknek Formation include bone fragments in the Snug Harbor Siltstone that were found in the park and just south of the park along the shores of Becharof Lake (Weems and Blodgett 1996; Fiorillo et al. 2004). Farther south along the Alaska Peninsula, dinosaur tracks were discovered in the 1970s and revisited in 2011 (Druckenmiller et al. 2011). The park contains extensive outcrops of the Naknek Formation, so the potential exists of finding more bone material and dinosaur tracks in the formation.

Staniukovich Formation
Map unit: **Kst**

The Lower Cretaceous (Berriasian to Valanginian, 145–133 MYA) Staniukovich Formation (**Kst**) crops out in the hills east of Mount Griggs and consists of 100 m (330 ft) of marine cross-bedded sandstone. It was deposited in shallow marine waters on a marine shelf (Figure 82), probably along offshore barrier bars (Riehle et al. 1993). It contains abundant *Buchia* bivalves (Riehle et al. 1993; Miller et al. 1995).

Herendeen Formation
Map unit: **Khe**

The Lower Cretaceous (Hauterivian and Barremian, 133–125 MYA) Herendeen Formation (**Khe**) crops out in the Douglas River, American Creek, and Katmai River areas and consists of calcareous (consisting of calcium carbonate) sandstone that is commonly cross-bedded, and interbedded siltstone and shale (Riehle et al. 1993). The unit is mostly made up of Inoceramus fragments (Figure 86) that are so abundant that it was originally called a limestone (Atwood 1911). In general, it is relatively thin, 25 m (80 ft), but is as much as 250 m (800 ft) thick in places (Riehle et al. 1993). The unit was deposited along a marine shelf (Figure 82; Miller et al. 1995). It unconformably underlies the Kaguyak Formation and is conformable with the underlying Staniukovich Formation (Miller et al. 1995). Fossils include **Ammonites**: *Acrioceras*, *Hoplocrioceras*?, Phylloceratid; **Bivalves**: *Anomia*, *Entolium*, *Homomya*, *Inoceramus* prisms, *Pseudolimea*; **Belemnites**: *Acroteuthis*, *Cylindroteuthis*; **Brachiopods**: indeterminate (Miller et al. 1995; Detterman et al. 1996).

Figure 86. Photograph of the bivalve *Inoceramus ovatoides* in the Herendeen Formation. Photograph by Robert Blodgett.

Pedmar Formation
Map unit: **Kp**

The Upper Cretaceous (Albian, 113–100 MYA) Pedmar Formation (**Kp**) crops out at two locations, one along the coast at Katmai Bay (type section) and another in the mountains between Mount Griggs and Snowy Mountain (Plate 1). The thin unit consists of 80 m (260 ft) of marine sandstone and minor amounts of siltstone and shale. No deposits are present to fill in the gaps in time between the underlying Herendeen Formation (**Kh**) and overlying Kaguyak Formation (**Kk**), so disconformities exist between the units. The Pedmar is unusual, because Albian age rocks are not common along the Alaska Peninsula (Detterman et al. 1996). Miller et al. (1995) suggested that the unit was deposited in a shallow marine shelf environment, indicated by the abundant plant detritus (Figure 82). Although the unit is thin, it contains the following diverse fossils: **Ammonites**: *Anagaudryceras*, Anisoceratid, *Cleoniceras*, *Marshallites*, *Parajaubertella*, *Puzosia*, *Tetragonites*, *Zelandites*, *Mesopuzosia*, *Desmoceras*; **Bivalves**: *Anomia*, *Aucellina*, *Entolium*, *Panopea*?, Trigoniid; **Belemnites**: *Acroteuthis*; **Nautiloid**; **Gastropod**: *Polinices* (Miller et al. 1995; Detterman et al. 1996).

Kaguyak Formation
Map unit: **Kk**

The Upper Cretaceous (upper Campanian to lower Maastrichtian, 80–68 MYA) Kaguyak Formation (**Kk**) crops out along the eastern portion of the map area (Plate , Figure 87) from Kamishak Bay to the Katmai River. The type locality is along the north shore of Kaguyak Bay. The unit is as much as 1,050 m (3,400 ft) thick with lower beds consisting of thin-bedded siltstone and thin limestone that contain abundant ammonites and *Inoceramus* bivalve fossils (Riehle et al. 1993). The upper beds consist of graded graywacke sandstone and siltstone beds that have flame structures, rip-up clasts, load casts, and flute casts (Riehle et al. 1993). These structures of the upper part are characteristic of turbidite (underwater debris flow) deposition in submarine fan environments (Figure 82; Miller et al. 1995; Detterman et al. 1996). The Kaguyak Formation contains abundant and diverse fossils including **Cephalopod**: Nautiloid; **Ammonites**: *Baculites*, *Canadoceras*, *Didymoceras*, *Diplomoceras*, *Exiteloceras*, *Gaudryceras*, *Glyptoxoceras*,

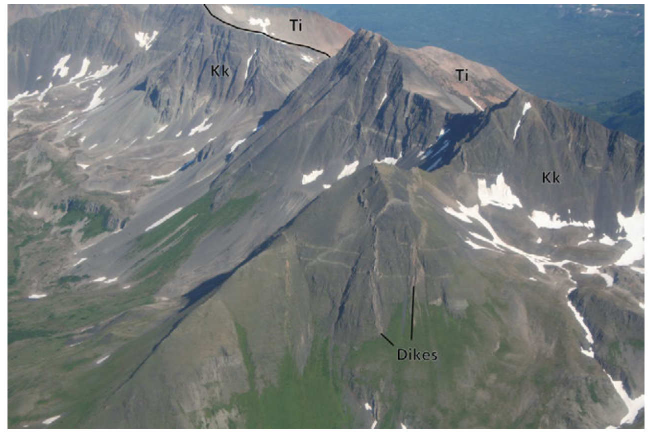


Figure 87. Photograph of dark gray, fine-grained sedimentary rocks of the Kaguyak Formation (unit Kk in Plate 1) in the hills above Big River. The hills include lighter gray dikes that intruded the formation and were probably offshoots from the nearby, larger Tertiary intrusive bodies (Ti). NPS photograph by Chuck Lindsay.

Hypophylloceras, *Lytoceras*, *Neophylloceras*, *Nostoceras*, *Pachydiscus*, and *Patagoisites*; **Belemnites:** *Acroteuthis* and *Cylindroteuthis*; **Bivalves:** *Anomia*, *Acila*, Arcid, *Calva*, *Clisocolus*, *Glycymeris*, *Goniomya*, *Indogrammatodon*?, *Inoceramus*, *Lima*, *Nemodon*, *Nucula*, *Nuculana*, Ostreid, Pectinid, *Pholadomya*, *Pleuromya*, *Protocardia*, *Sphenoceramus*, *Teredo*, Trigoniid, Venerid, *Yaadia*, and *Yoldia*; **Brachiopod**: Rhynchonellid; **Echnioderm**: *Isocrinus*; **Gastropods:** *Acteonid*, *Anisomyon*, *Biplica*, Cerithiid, *Forsia*, Fusid, *Gyrodes*, *Polinices*, *Remnita*, *Tessarolax*, *Trochus*, and *Zinsitys*; **Scaphopod**: *Dentalium* (Keller and Reiser

Figure 88. Photograph of the ammonite *Pachydiscus kamishakensis* from the Kaguyak Formation. This specimen is approximately 24 cm wide (scale in centimeters), but they can be 1 m (3 ft) or more in diameter. NPS photograph of accession number KATM-00165 9080.

1958; Detterman and Reed 1980; Miller et al. 1995; Detterman et al. 1996). A notable fossil is the large ammonite *Pachydiscus kamishakensis* (Figure 88), which can be 1 m (3 ft) or more across.

Tertiary Sedimentary and Igneous and Bedrock

The sedimentary record of the Katmai area continues into the Tertiary, but unlike during the Mesozoic, the Tertiary rocks are nonmarine (Plate 2; Plate 3). The Paleocene (66–56 MYA) rocks consist of fluvial sandstone and conglomerate of the Ketavik Formation, and Copper Lake Formation. The units contain coal beds and plant fossils. Uplift must have been great to form coarse-grained nonmarine rocks. Clast types in conglomerate suggest the sediment was sourced from erosion of the Talkeetna Arc. The Paleocene sedimentary units do not contain volcanic rocks, so there was no active volcanism in the area at that time.

Igneous activity had been occurring on mainland Alaska during the early Tertiary. The center of the activity shifted to what is now the Alaska Peninsula and the Aleutian Island chain in the early Tertiary. The initiation of volcanism around 55 million years ago (early Eocene) suggests that a major change took place in the plate configuration along the western Alaskan margin (e.g., Scholl et al. 1986, 2015; Scholl 2007). The nature of the tectonic shift is still in question (see summary in Scholl 2007). One explanation may be that before 55 MYA, an oceanic plate was subducting under the Beringian margin, but broke around 55 MYA. A piece of the oceanic plate currently floors the southern portion of the Bering Sea and a new subduction zone was initiated along what is now the Aleutian Island chain and Alaska Peninsula. Another possibility is that extension behind the arc front moved the arc southward from the Beringian margin to its present position. Research on this topic is ongoing.

Tertiary Sedimentary Rocks

Ketavik Formation
Map unit: not mapped

The upper Paleocene to lower Eocene (59–48 MYA) Ketavik Formation (Ketavik is the native name for the lagoon at the mouth of the Brooks River) is a fluvial sandstone and conglomerate that crops out in small, obscure exposures along Naknek Lake west of Brooks Camp (Parrish et al. 2010) and at Brooks Falls (Figure 89). Although plant fossils have been recognized along

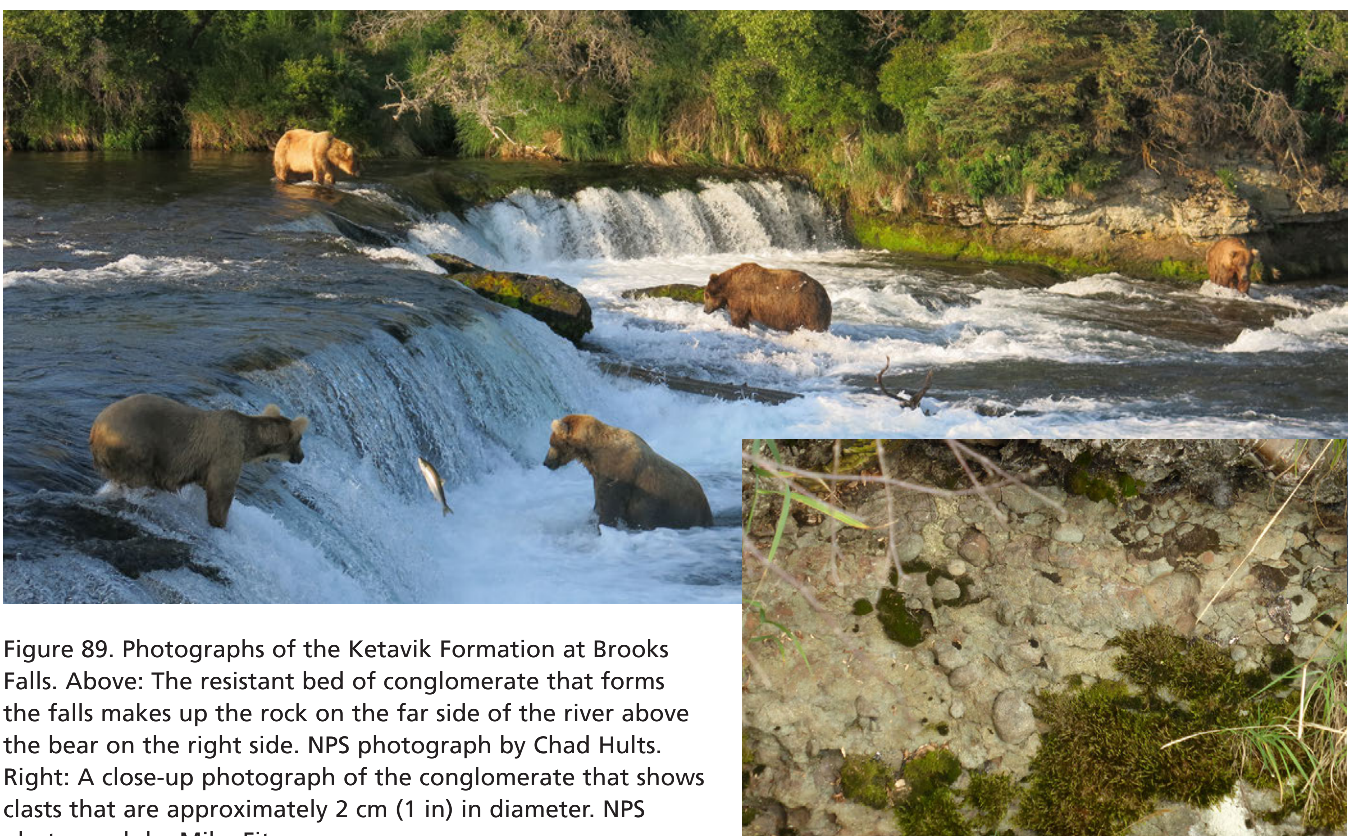


Figure 89. Photographs of the Ketavik Formation at Brooks Falls. Above: The resistant bed of conglomerate that forms the falls makes up the rock on the far side of the river above the bear on the right side. NPS photograph by Chad Hults. Right: A close-up photograph of the conglomerate that shows clasts that are approximately 2 cm (1 in) in diameter. NPS photograph by Mike Fitz.

the shoreline near Brooks Camp for many years, this formation had not been mapped by previous authors, so does not show up on Plate 1. Conglomerate beds are more common near the lower portions of the unit and contain predominately volcanic and volcaniclastic rocks that are similar to the adjacent Talkeetna Formation. Fossil leaves and wood are common and include *Platimeliphyllum*, a genus known from the Kamchatka Peninsula and Sakhalin Island, but previously undocumented from North America. Coniferous wood fossils include genera *Cedrus*, *Cupressinoxylon*, *Metasequoia*, and *Pinus*; and a dicot wood of the genus *Platanoxylon*. Needles were identified as the genus *Glyptostrobus*. The following genera of leaf fossils were identified: Betulaceae (birch family), *Cercidiphyllum* (saxifrage), *Chaetoptelea* (elm), *Cocculus* (vine), *Corylites*, *Juglans* or *Carya* (Juglandaceae) (walnut or hickory), *Parashorea*, *Platanus* (plane trees or sycamore), *Platimeliphyllum*, and *Zizyphoides*.

Copper Lake Formation
Map unit: **Tc**

The lower Eocene (56–48 MYA) and possibly upper Paleocene (59–56 MYA) Copper Lake Formation (**Tc**) crops out near Kukaklek Lake on the north and around Fourpeaked Mountain and Mount Douglas (Plate 1; Figure 90). The formation is made up of a sequence of massive fluvial conglomerate and interbedded sandstone and siltstone about 1,000 m (3,300 ft) thick that represents braided river deposits (Houston 1994; Detterman et al. 1996). Deposits are missing between the underlying Upper Cretaceous (100–66 MYA) Kaguyak Formation and the overlying late Oligocene (34–23 MYA) Hemlock Conglomerate, so the contacts are considered disconformable (Detterman et al. 1996). The clasts in the conglomerate are volcanic, plutonic, metamorphic, and limestone. Paleocurrent structures suggest transport of material was directed to the southeast, indicating that the provenance was the Alaska-Aleutian Range batholith and Mesozoic sedimentary and metamorphic rocks (Houston 1994; Detterman et al. 1996). Carbonaceous debris and minor coal are present in finer-grained sediments (Detterman et al. 1996). The unit contains pollen and fossil leaves of the following genera: *Acer* (maple), *Crataegus* (hawthorn), *Dennstaedtia* (fern), *Equisetum* (horsetail), *Myrica* (bayberry), *Osmunda* (fern), *Sequoia* (redwood), and *Ulmus* (hazel) (Hollick 1936; Detterman and Reed 1980; Houston 1994).

Hemlock Conglomerate
Map unit: **Th**

The Oligocene or earliest Miocene(?) (34–20 MYA) Hemlock Conglomerate (**Th**) crops out on the Katmai coast and is a fluvial sandstone and conglomerate and minor siltstone, shale, and coal (Detterman et al. 1996). Locally, the unit contains minor volcanic clasts, including pumice, and tuff beds (Detterman et al. 1996). The unit is poorly consolidated and is as much as 550 m (1,800 ft) thick (Riehle et al. 1993). It was

Figure 90. Photograph showing moderately dipping, bedded rocks of the Copper Lake Formation along sea cliffs north of Cape Douglas. The lighter beds are sandstone and the darker beds are carbonaceous siltstones or coal. Photograph katmai_0886 from the NOAA Alaska ShoreZone database: http://alaskafisheries.noaa.gov/mapping/szflex/.

deposited in a braided fluvial system with highly sinuous channels (Houston 1994). This unit disconformably overlies Copper Lake Formation at Cape Douglas and unconformably overlies the Kaguyak Formation (**Kk**) (Riehle et al. 1993; Detterman et al. 1996). The unit is locally altered to hornfels (heated and recrystallized) near the intrusions of Tertiary granitic intrusive rocks (**Ti**) (Riehle et al. 1993). The unit contains rare tree stumps in growth position, abundant plant fossils of broadleaf deciduous plants, evergreen needles, and pollen (Riehle et al. 1993; Houston 1994; Detterman et al. 1996). Genera identified include *Acer* (maple), *Aesculus* (soapberry), *Alnus*, *Andromeda*, *Betula* (birch), *Corylus*, *Cupania* (soapberry), *Equisetum* (horsetail), *Hicoria*, *Ilex* (holly), *Juglans* (walnut), *Phyllites*, *Picea* (spruce), *Populus* (poplar), *Pterospermites*, *Sequoia* (redwood), *Taxodium* (cypress), *Ulmus* (hazel), *Vaccinium* (heather), and *Vetrix* (*Salix*) (willow) (Knowlton 1904; Miller et al. 1995).

Tertiary Igneous Rocks

Map units: **Tglv, Tab, Tiu, Togq, Tm, TKgd, Td**

Tertiary plutonic, volcanic, and volcaniclastic rocks in the map area range in age from late Eocene to Pliocene (40–2.6 MYA; Plate 2). Four groups of Tertiary igneous rocks are recognized in the Katmai area:
(1) the Meshik Volcanics north of Naknek Lake (including Alagnak Wild River), (2) the Gibraltar Lake Tuff on the most northern edge of the map area, (3) the volcanic rocks of the Barrier Range near Katmai and Snowy Mountain, (4) the undivided intrusive rocks underlying Fourpeaked Mountain and Mount Douglas. The Tertiary igneous rocks are part of a larger belt of similar age igneous rocks that span the length of the Alaska Peninsula and continue up to the Alaska Range (Figure 91). The Tertiary igneous rocks represent initiation of volcanic activity that started in the early Tertiary (about 50 MYA) and continues today. Tertiary igneous rocks intrude and unconformably overlie (break in deposition) the Mesozoic rocks of the Katmai area (see "Mesozoic Bedrock" section).

Meshik Arc

Map units: **Tm**, **Togq**

The oldest Tertiary igneous activity resulted in the formation of the late Eocene to early Oligocene (40–28 MYA) Meshik Volcanics (**Tm**). Detterman and Reed (1980) identified numerous volcanic necks and domes that were the eruptive centers of the volcanic

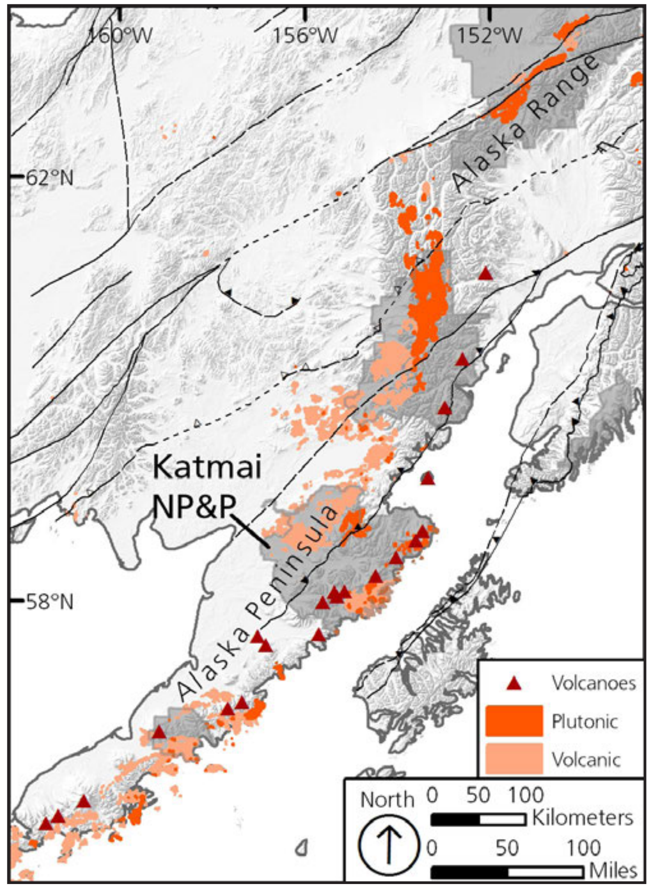


Figure 91. Map showing the extent of Tertiary igneous rocks (Eocene to Miocene, 56–5 MYA) along the Alaska Peninsula and into the Alaska Range. The Tertiary igneous rocks represent a belt of volcanic rocks that closely parallel the modern volcanic arc (shown as red triangles). Drafted with map compilations from Wilson et al. (1998, 2006, 2012, 2013, 2015). Hillshade derived from National Elevation Dataset.

rocks (Plate 1). The Meshik Volcanics consist of basaltic to dacitic flows, agglomerate, ash, and minor volcaniclastic rocks (Wilson 1985; Detterman et al. 1996). In the central portion of the map area, Riehle et al. (1993) measured 600 m (2,000 ft) of compact, highly porphyritic andesitic and dacitic lava flows and breccia. In the northern portion of the map area, Detterman and Reed (1980) estimated the volcanic rocks could be as much as 1,000 m (3,300 ft) thick. These rocks are highly varied in composition; most are intermediate andesite and basaltic andesite, but felsic rhyolite to mafic olivine basalt also occur. Most of the volcanic rocks have a distinctive texture where phenocrysts (mineral crystals) form clusters among finer-grained matrix that has tiny, elongated, typically parallel minerals (called glomeroporphyritic pilotaxitic). Other rocks are highly vesicular (containing cavities formed by gas bubbles) and/or aphanitic (mineral crystals too small to see without a microscope). Ages of these volcanic rocks in the map area range from 45 to 25 MYA (Thrupp and Coe 1986; Shew and Lanphere 1992). The rocks contain minor interbedded mudflows, sandstone, coaly shale, and siltstone. Some of these sedimentary rocks locally contain petrified wood and leaf fossils that provide evidence for an early Tertiary age (Keller and Reiser 1958). Early Eocene(?) (56–49 MYA) sedimentary rocks lie below the volcanic rocks and are rich in volcanic clasts, which suggests that volcanism may have started at that time.

Late Tertiary (Oligocene, 34–23 MYA) granodiorite and quartz diorite (**Togq**) plutons are mapped near the Meshik Volcanics (Plate 1) and have similar ages that range from 38 to 27 MYA (Detterman and Reed 1980; Shew and Lanphere 1992). These are most likely the plutonic roots of the Meshik Volcanics.

Volcanic Rocks of Barrier Range
Map units: **Tab**, **Ti**

The late Tertiary (Miocene to Pliocene 23–2.6 MYA) volcanic rocks of Barrier Range (**Tab**) crop out on the western portion of the map area along the coast, from Kukak Bay to the Katmai River (Plate 1; Figure 92). The rocks consist of up to 800 m (2,620 ft) of andesitic and dacitic porphyritic lava flows, tuffs, and breccias. The unit overlies the Hemlock Conglomerate (**Th**) and the contact between the two is gradational.

Gibraltar Lake Tuff
Map units: **Tglv**

The Gibraltar Lake Tuff (**Tglv**) consists of rhyolitic crystal and lithic tuff that unconformably overlies the Meshik Volcanics (**Tm**) in the northern part of the map area (Plate 1). The unit is made up of Pliocene(?) (5.3–2.6 MYA) white tuff that is as much as 180 m (600 ft) thick that overlies Oligocene(?) to Pliocene(?) (34–2.6 MYA) slightly to intensely welded light- to medium-gray and tan rhyolitic crystal and lithic tuff that is at least 300 m (1,000 ft) thick and possibly as much as 730 m (2,400 ft) thick (Detterman and Reed 1980). The Gibraltar Lake Tuff represents an isolated younger eruption event not directly related to the underlying Meshik Volcanics (Detterman and Reed 1980).

Figure 92. Photograph of columnar jointed lava flow of the volcanic rocks of the Barrier Range on Takli Island in Amalik Bay. Photograph katmai_0089 from the NOAA Alaska ShoreZone database: http://alaskafisheries.noaa.gov/mapping/szflex/.

Other Tertiary Igneous Rocks
Map units: **Tiu**

Numerous undifferentiated and undated intrusive rocks (**Tiu**) are present throughout the map area. These rocks are mainly hypabyssal (shallow intrusive) rocks that are commonly porphyritic and consist chiefly of quartz diorite, granodiorite, or tonalite (Riehle et al. 1993; Hildreth and Fierstein 2003). These rocks intruded early Tertiary and older sedimentary rocks along the west coast from Cape Douglas to the Katmai River. The intrusive bodies probably were the sources of the volcanic rocks of the Barrier Range (**Tab**) and the small dacitic and andesitic lava flows (**Tvu**).

Faults and Folds

The major geologic structure of the Katmai area is the Bruin Bay fault, which runs through the middle of the park from the southwest to the northeast (Plate 1) and extends most of the length of the Alaska Peninsula, from near Aniakchak National Monument and Preserve through Lake Clark National Park and Preserve (Detterman and Hartsock 1966; Riehle et al. 1993; Stevens and Craw 2003; Gillis et al. 2013; Figure 84). It is a major reverse (high-angle thrust) fault, meaning that rocks above the fault plane were pushed "up" the fault relative to rocks below (Figure 82). The fault plane dips to the northwest with the "upthrown" side on the northwest. Uplift is as much as 3,000 m (10,000 ft), and the fault generally dips 60°–70°W. It produced a crushed zone hundreds of meters wide and caused drag folds in adjacent sedimentary rocks (Figure 93). During the Late Jurassic Period (164–145 MYA) it uplifted the plutonic roots of the Talkeetna volcanic arc on the west side of the fault, which led to marine deposition of the thick sequence of sedimentary rocks on the east side of the fault (Plate 3). The rocks on the northwest side of the fault are lightly to highly metamorphosed; whereas, sedimentary rocks on the southeast side of the fault are

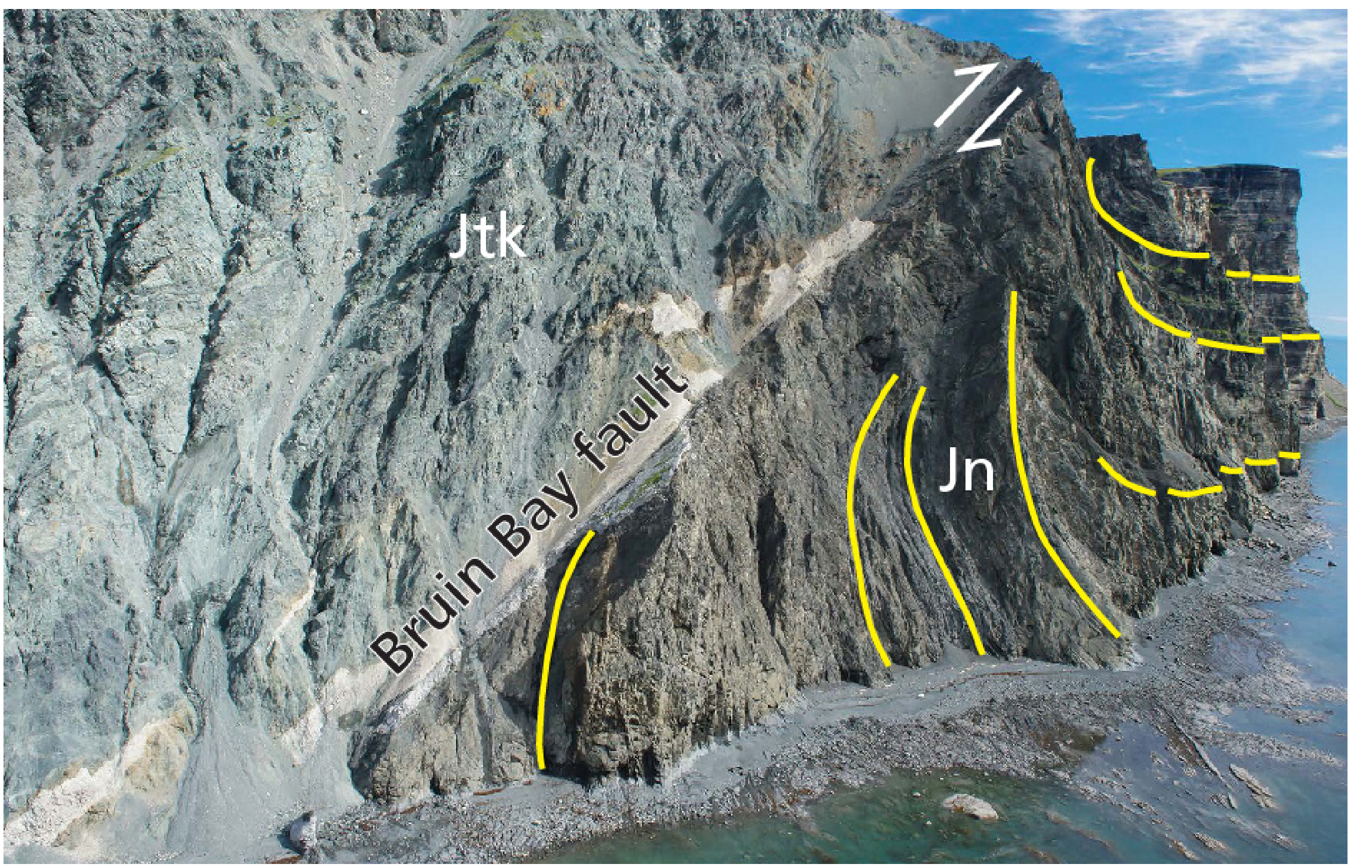


Figure 93. Photograph showing drag folds in the Naknek Formation along the Bruin Bay Fault. The southwest dipping fault has brought the Lower Jurassic Talkeetna Formation (Jtk) over the Upper Jurassic Naknek Formation (Jn). Bedding planes in the Naknek Formation (highlighted in yellow) are folded near the fault towards the direction of motion along the fault. Alaska Division of Geological and Geophysical Surveys photograph (modified from figure 32 in Gillis et al. 2013) taken at Contact Point in Bruin Bay, just north of the park boundary.

nearly flat lying with only mild, broad regional folds (Riehle et al. 1993). Evidence suggests that the fault may have been active (or reactivated) for about 118 million years, until the late Oligocene Epoch (28 MYA) (Detterman and Reed 1980). Other minor faults are also present throughout the map area (Plate 1).

Anticlines (“A” shaped folds) and synclines (“U” shaped folds) are included in the geologic map in Plate 1. The folding involved the Miocene (23–5 MYA) volcanic rocks of the Barrier Range, so folding occurred sometime in the last 10 million years (Riehle et al. 1993).

Terrane Translation and Accretion

Alaska is a collage of imported rocks called terranes (Figure 94). Terranes are packages of rocks that were transported on different plates and accreted together along suture zones (faults). Only a small area of Alaska along the Canadian border on the north end of Yukon-Charley National Preserve is an in-place, undisturbed part of the North American craton. The rest of Alaska consists of pieces of crust that arrived from elsewhere or are offset portions of the North American craton.

The Mesozoic rocks of Katmai belong to a group of rocks called the Peninsular terrane (Figure 94), which is thought to have originated far to the south in the proto-Pacific Ocean and was added to southern Alaska in the late Mesozoic (Stone and Packer 1977, 1979; Plafker et al. 1994; Kent and Irving 2010; Hults et al. 2013). The Mesozoic strata of the Alaska Peninsula are altogether as thick as 8,500 m (30,000 ft) and range in age from Late Triassic to Cretaceous (237–66 MYA); their base is nowhere exposed, although an islet of Permian

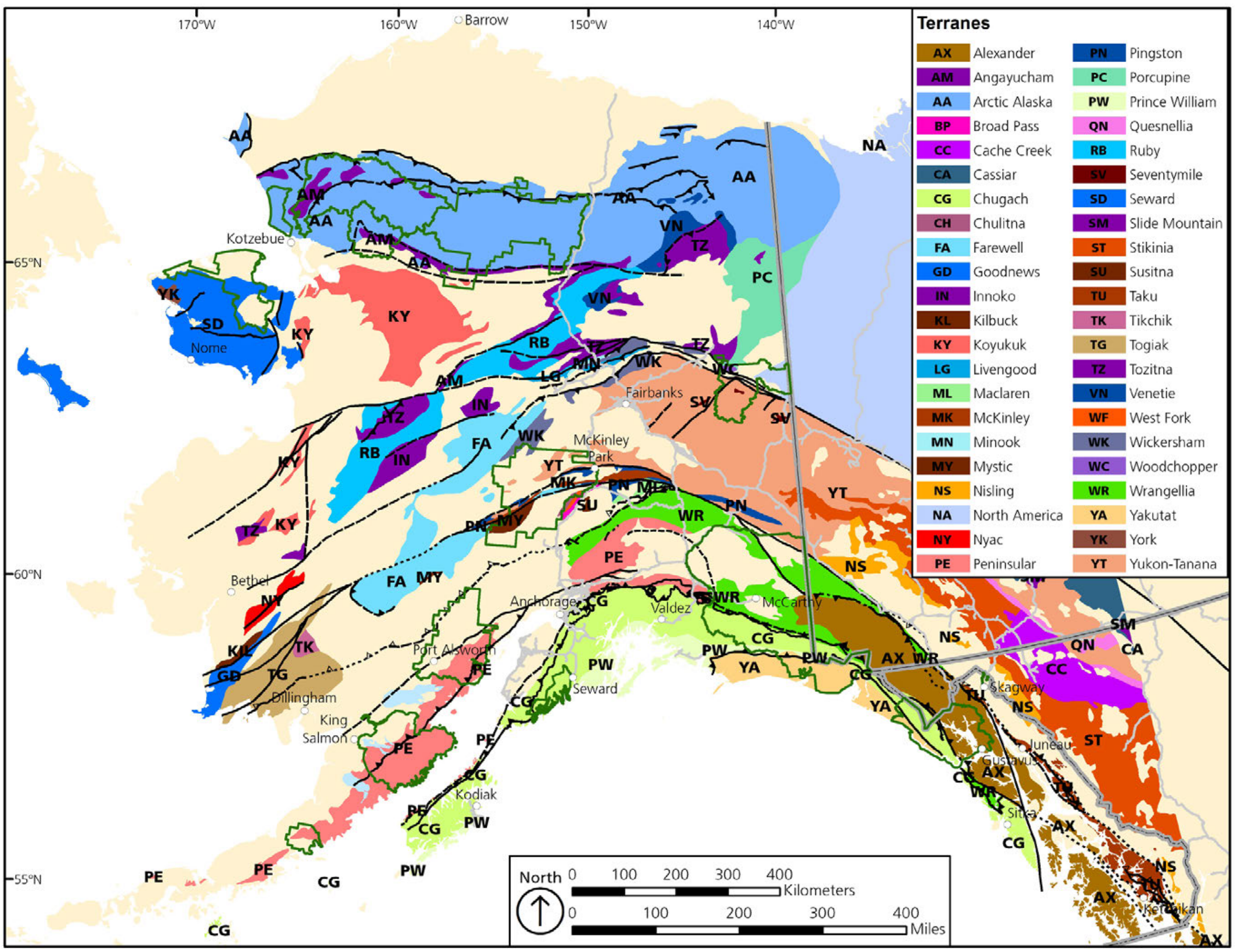


Figure 94. Map showing the terranes of Alaska. The Alaska Peninsula is underlain by the Peninsular terrane (PE). The pre-Tertiary rocks of Katmai are a nearly complete section of the Peninsular terrane stratigraphy. Modified from Silberling et al. (1992).

(299–252 MYA) limestone crops out near Puale Bay south of Katmai (Detterman et al. 1987b, 1996). The key identifiers of the Peninsular terrane are the Lower Jurassic (201–174 MYA) volcanic rocks of the Talkeetna Formation, which represent an island arc that formed some distance off the North American margin in the proto-Pacific Ocean.

The Peninsular terrane is part of the larger Wrangellia composite terrane, which, in Alaska, spans from the Alaska Peninsula to southeast Alaska (Peninsular [PE], Wrangellia [Wr], and Alexander [AX] terranes in Figure 94). Paleomagnetic evidence from rocks of the Wrangellia composite terrane in other places in Alaska, including Wrangell-St. Elias National Park and Preserve, indicate that the terrane was in the equatorial region in the Triassic Period (252–201 MYA) (Hillhouse 1977; Hillhouse and Gromme 1984). Paleomagnetic evidence and fossil assemblages from these terranes suggest that the Lower Jurassic (201–174 MYA) Talkeetna arc most likely formed offshore and south of its current position relative to the North American continent (Figure 95). By the mid-Cretaceous Period (110–90 MYA), the Peninsular terrane was somewhere off of Baja California. Stone and Packer (1977) coined the term "Baja Alaska" to represent the south to north translation history of these rocks. These original results have wide margins of error, but are similar to paleomagnetic measurements in other related Upper Cretaceous rocks of southern Alaska and British Columbia (Hillhouse and Coe 1994; Stamatakos et al. 2001; Kent and Irving 2010). Because of the abundant Canadian studies, the idea is now referred to as the "Baja-BC hypothesis" (see summary in Cowan et al. 1997). These data initiated an ongoing debate over the amount of translation these rocks have undergone since the Cretaceous Period.

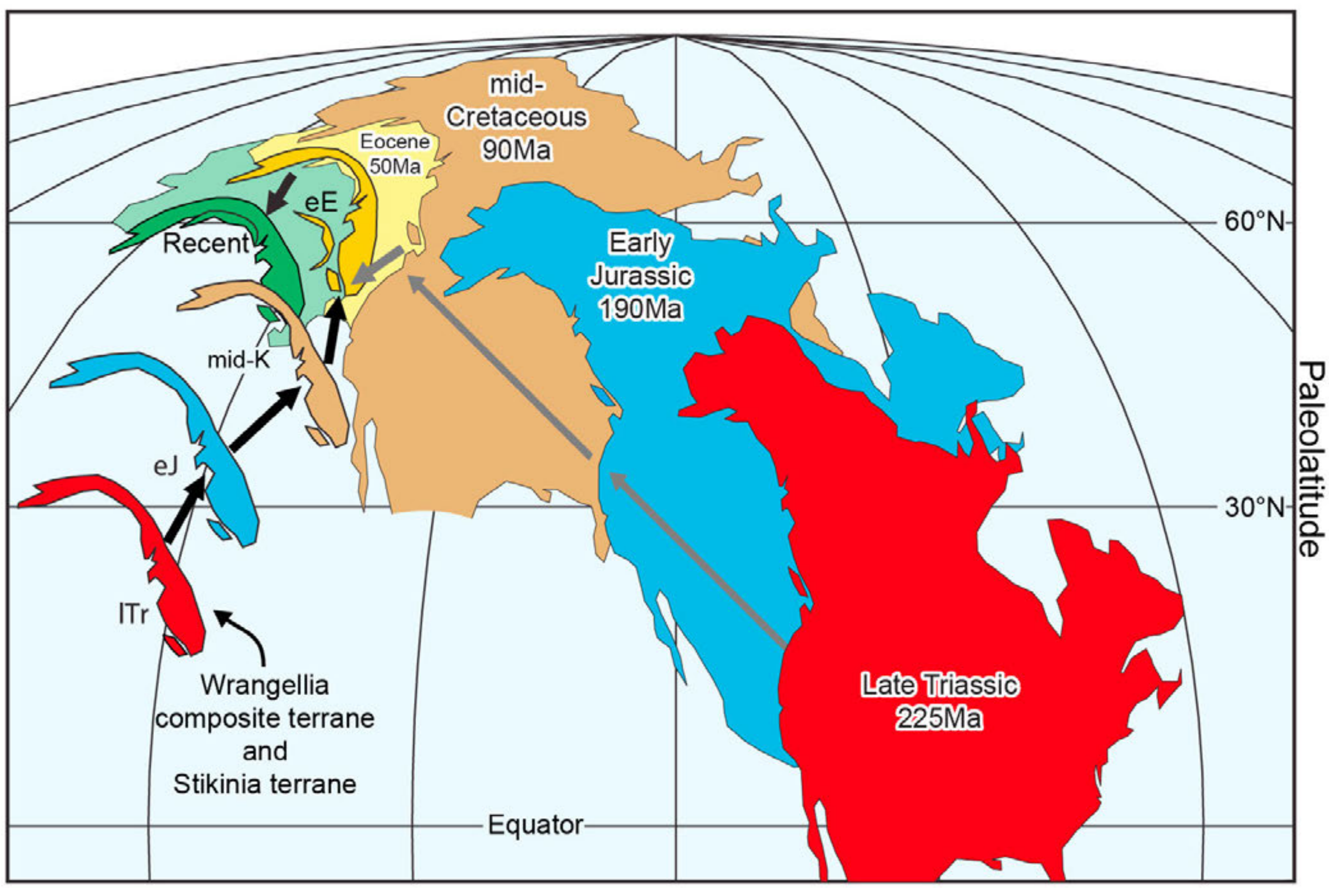


Figure 95. Paleogeographic map showing the Wrangellia composite terrane translation history from the Late Triassic to the present. Rocks of the Katmai area are located on the Peninsular terrane, which is the far western end of the Wrangellia composite terrane (Plafker et al. 1989; Nokleberg et al. 1994; Rioux et al. 2010). Evidence from fossils suggests that the terrane was far offshore of North America during the Late Triassic and Jurassic Periods, but how far offshore is not known. Modified from Kent and Irving (2010) to include the Peninsular terrane.

The geographic position of the Peninsular terrane through time (paleogeography) is important for understanding the past environments and habitats of extinct species found in the rock record of the Katmai area. For example, most dinosaurs lived on land, so dinosaur tracks in the Naknek Formation indicate that the Peninsular terrane was near a continent during the Late Jurassic (164–145 MYA). The Lower Jurassic (202–174 MYA) rocks of the Peninsular terrane were formed as an island arc separate from a continent, so an understanding of the terrane translations would shed light on the possible pathways dinosaurs followed to roam onto the terrane. A recent discovery of marine glacial deposits in the Upper Jurassic (164–145 MYA) Naknek Formation (Wartes and Decker 2015) suggests that the Peninsular terrane experienced a very cold climate during a global period of greenhouse conditions. Translation of the Peninsular terrane, north–south and east–west, affected the paleoenvironment of deposition and the biodiversity of fossils in the rocks of the Katmai area. However, investigators have studied the translation history of the terrane, and related terranes, but there is little consensus over the amount of translation experienced by the terranes of the northern Cordillera.

Geologic History

This section provides a condensed chronology of geologic events in the order that they formed the geologic features discussed in the Geologic Features and Processes section.

Late Triassic (237–201 MYA)

Cottonwood Bay Greenstone (**TRc**) and Kamishak Formation (**Trk**) represent oceanic crust (or a seamount) topped by coral reefs that formed near the equator.

Early Jurassic (201–174 MYA)

Subduction related to the Talkeetna arc formed plutons of the Alaska-Aleutian Range batholith (**Jgr**, **Jgd**, **Jqd**, **Jgb**) and volcanic rocks of the Talkeetna Formation (**Jtk**). These igneous rocks intruded and overlie the older rocks. Older rocks were altered by the heat from the intrusions, which formed the metamorphic rocks of the Kakhonak Complex (**JPk**).

Middle Jurassic (Bathonian(?) to Callovian, 168–164 MYA)

The shallow to deep marine rocks of the Shelikof Formation (**Js**) formed offshore from sediment eroded off of the volcanic Talkeetna arc.

Late Jurassic (164–145 MYA)

The widespread Naknek Formation (**Jn**, **Jnc**, **Jnn**, **Jns**, **Jni**, **Jnk**) formed from the eroded sediment of the uplifted volcanic and plutonic rocks of the Talkeetna arc. The Bruin Bay fault was active during this time, uplifting the rocks on the northwest, which were eroded and shed into the adjacent basin, forming the Naknek Formation. The lack of limestone and abundance of boreal *Buchia* fossils indicate northerly transport of the Peninsular terrane through this time.

Early Cretaceous (145–135 MYA)

Continued uplift and erosion of the Peninsular terrane formed the sandstone of the Staniukovich Formation (**Kst**). However, by the time the overlying calcareous rocks of the Herendeen Formation (**Khe**) were deposited, the erosion (and possibly uplift) had begun to subside.

Early to Mid-Cretaceous (135–90 MYA)

Lack of significant deposition and the presence of disconformities and unconformities suggest that the mid-Cretaceous was a time of uplift. The Albian (112–100 MYA) Pedmar Formation (**Kp**) is a thin unit 80 m (260 ft) thick that was deposited during the mid-Cretaceous Period. During that time, the Peninsular terrane was far south of where it is today, somewhere between the latitude of Washington State and Baja California.

Latest Cretaceous (80–68 MYA)

Marine deposition picked up again with the deep-water turbidites of the Kaguyak Formation (**Kk**).

Late Paleocene to Early Eocene (59–49 MYA)

The Peninsular terrane was uplifted above sea level by the start of Tertiary time because the Ketavik (not mapped) and Copper Lake Formations (**Tc**) are nonmarine coarse sandstones and conglomerates deposited by rivers. During the Late Cretaceous Period to early Eocene Epoch, the Peninsular terrane was transported northward along the margin of North America.

Late Eocene to Pliocene (40–2.6 MYA)

After a short hiatus in deposition represented by an unconformity in the rock record, volcanism returned to the Peninsular terrane with the eruption of the Meshik Volcanics (**Tm**), volcanic rocks of the Barrier Range (**Tab**), and the Gibraltar Lake Tuff (**Tglv**). These volcanic rocks were fed by the various magmatic bodies (**Tiu**). The Oligocene, or possibly earliest Miocene (34–20 MYA), Hemlock Conglomerate (**Th**) represents river deposits formed during the eruption of the Meshik Volcanics as indicated by its abundant volcanic clasts. Volcanism suggests that subduction picked up again along the margin, which is continuing today as the Aleutian arc.

Quaternary (2.6 MYA–Present)

Volcanism was nearly continuous through the late Eocene Epoch to the present day, and today's volcanoes form the Aleutian arc. This volcanism, along with tectonic forces from the subduction of the Pacific Plate, formed the high mountains of the Katmai area. The mountains were sculpted by glaciers during the Pleistocene Epoch, which left wide U-shaped valleys in the mountains and deposited thick piles of glacial sediments on the lowlands. Glacial moraines left by these glaciers dam many of the lakes of Katmai. As the glaciers retreated, volcanic and fluvial processes began to dominate the landscape. For example, the 1912 eruption filled the U-shaped valley of the River Lethe with a thick ignimbrite sheet and deposited ash fall over much of the surrounding region. This loose material is still shedding from the mountain sides and choking the rivers with sediment. Winds move the loose material, making it hard for life to take hold in the constantly shifting landscape.

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety and preservation of natural and cultural resources in Katmai National Park and Preserve and Alagnak Wild River.

Three meetings were held to discuss GRI products, geology of the park units, and resource management issues. These meetings were held with NPS natural resource managers, NPS Southwest Alaska Network staff, NPS Alaska Region specialists, and geologists with experience in the Katmai area. A scoping meeting was held in 2005 (Graham 2005); a preliminary report kick-off meeting was held with Troy Hamon on 6 November 2014, and a report kick-off call was held on 27 January 2015. Attendees of the scoping meeting and report kick-off call are listed in Appendix D.

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

- Volcanic Hazards
- Coastal Issues
- Seismic and Tsunami Hazards
- Glacier Changes
- Paleontological Resource Inventory, Monitoring, and Protection

Previously published NPS reports that address geologic resource management issues include:

- *Katmai National Park and Preserve and Alagnak Wild River: Natural Resource Condition Assessment* (Zanon et al. 2015)
- *Katmai National Park and Preserve foundation statement* (NPS 2009a)
- *Katmai National Park and Preserve, Aniakchak National Monument and Preserve, Alagnak Wild River long-range interpretive plan* (NPS 2009b)

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

Preservation of Katmai's Natural Features for Inspiration and Study

The Katmai area has been an ideal laboratory for understanding volcanic processes and monitoring the regeneration of ecosystems after a catastrophic eruption. Since its inception, geologic research has been a primary mission for Katmai National Park and Preserve, and managers have supported or facilitated research that does not impinge on its wilderness character. The balance between preserving the wilderness character of the park and providing reasonable access for geologic research was tested with the proposal to drill into the Novarupta vent, termed the "The Katmai Drilling Project" (Sattler 1990). The scope of the proposal was large enough for the initiation of an extensive inter-agency evaluation of conducting important scientific research in an area designated as wilderness (National Research Council 1989). During the evaluation stage of the project, numerous research projects were permitted for collecting geologic information for supporting the Katmai Drilling Project (Eichelberger et al. 1991) and an environmental impact statement was prepared. In the end, the final project was not permitted. Even though this project was not permitted, many geologic research projects of various scopes have been permitted since the unit's conception and, in some cases, led and supported by the National Park Service. For example, the 1953 Katmai Project was a multi-agency, multi-year, integrated research project that was supported and led by the National Park Service. Other government agencies have had teams of researchers study the geology of Katmai over many years. Since the 1980s, the Alaska Volcano Observatory (USGS, UAF, and State of Alaska Division of Geologic and Geophysical Surveys) has had ongoing research projects, held field classes, and installed and maintained a seismic network for real-time monitoring of the volcanoes. A concise chronology of the extensive geologic exploration over the last 100 years is presented in Appendix A and further detailed by Hildreth and Fierstein (2012, chapter 4). The results from these research projects provide material for Katmai staff to prepare interpretive programs, hikes, and products, which are used to educate visitors about the geologic processes that created Katmai's spectacular landscape. The results are used to inform management decisions, protect visitors, and integrate with other natural resource sciences.

Geohazards

The Katmai area has a very high potential for geologic hazards ("geohazards"). This section contains a list of potential geohazards in the Katmai area along with a brief description of each hazard and areas susceptible to them. When available, resources related to each type of hazard are provided. Katmai contains, and is adjacent to, active volcanoes. Strong wind events frequently resuspend ash from the 1912 eruption. Hydrothermal processes produce acidic waters, which can fill crater lakes and cause harm to sensitive riverine and lacustrine ecosystems. The area overlies the tectonically active Aleutian megathrust, and movement on this thrust causes frequent and large earthquakes. Steep slopes in the mountainous areas are susceptible to landslides and rockfall. Coastal areas are vulnerable to tsunamis originating from earthquakes or volcanic mass flows.

Volcanic Hazards

Map units: **Qv, Qpd, Qafd, Qvd, QTv**

Volcanic eruption potential is high in the Katmai area, because Katmai contains 24 Quaternary volcanoes, ten of which are considered active, and five have erupted in historic time (Table 3). According to the USGS volcanic threat assessment (Ewert et al. 2005), six volcanoes are listed as a high threat: Katmai, Novarupta, Trident, Griggs, Mageik, and Martin. Four are listed as a moderate threat: Denison, Douglas, Kukak, and Snowy. Fourpeaked was listed as a low threat volcano, but after the 2006 eruption it is a higher threat. Although 14 of the Quaternary volcanoes are not considered active, the eruption of Fourpeaked highlights the uncertainty of volcanic hazard assessments in the Katmai area.

The volcano hazard assessment for the Katmai cluster of volcanoes by Fierstein and Hildreth (2001) noted that all types of volcanic hazards depicted in Figure 96 can be expected at Katmai. Areas farther away from the volcanoes are susceptible to tephra fall, and rivers flowing from the volcanoes are susceptible to lahar flows (Figure 97). Although volcanic deposits from past eruptions have been mapped (Plate 1), these deposits only provide evidence of past activity, so should not be considered a park-wide geohazards map or assessment.

The active volcanoes are monitored in near real-time by the USGS Alaska Volcano Observatory (for more information visit http://avo.alaska.edu). Generally, volcanic eruptions are preceded by earthquakes that can be detected by the AVO seismic network (Figure 98). Each seismic station consists of a buried seismometer, a power system (deep-cycle batteries and solar panel array), electronic processor, digitizer, and a radio and antenna. Data are examined daily by AVO analysts; some of the data are shared with the public via the AVO website: https://avo.alaska.edu/webicorders/. In addition to the seismic network, the following methods are used to detect volcanic unrest at Alaska volcanoes:

- Daily satellite analysis of images from space to look for signs of elevated surface temperatures or airborne volcanic ash.

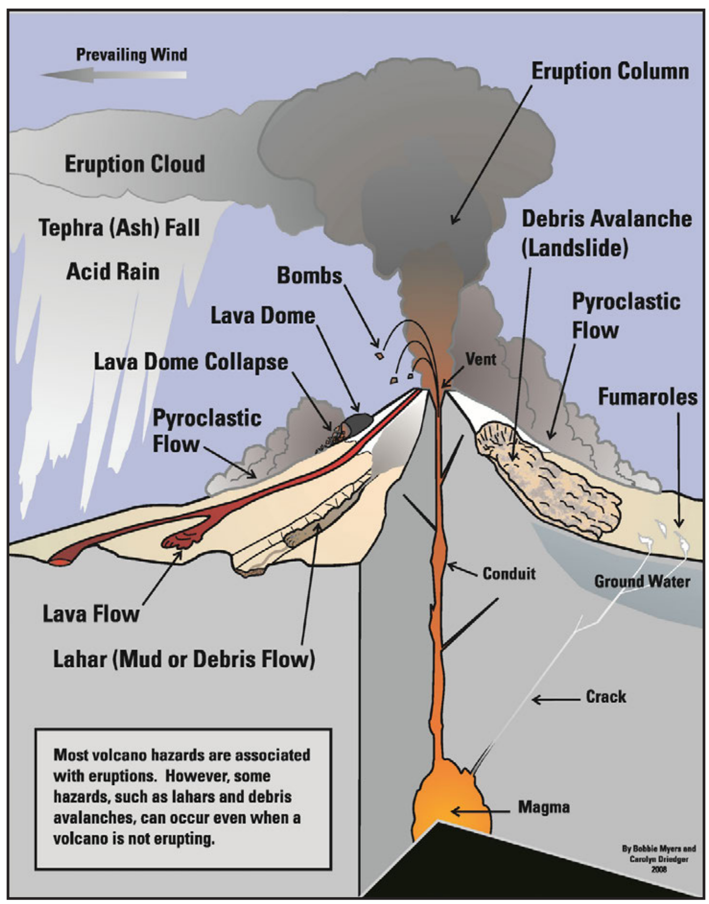


Figure 96. Diagram showing the types of volcanic hazards that have and could occur at Katmai. USGS graphic by Myers and Driedger (2008).

- Regional infrasound capability that may be able to detect explosions, with potentially hours of delay.
- Space-based radar interferometry (InSAR) is used to detect uplift or subsidence that may occur prior to eruptions, though this is not a real-time technique.
- Pilot reports and other direct observations of changes at a volcano.

Much has already been written about the volcanic hazards of Katmai and plans for response to eruptions, so this report provides only a cursory review. For more detailed information of volcanic hazards, resource managers should consult the following resources:

- The Alaska Volcano Observatory website (http://avo.alaska.edu) contains near real-time information

Figure 97. Map showing active volcanoes and drainages at risk for lahar flows. Lahars are mud or debris flows from a volcano (see Figure 96). Red triangles are active volcanoes and orange shaded areas show river valleys that are at risk for lahar flows. Modified from Fierstein and Hildreth (2001).

regarding the status of volcanoes and hazards across the state.

- *Preliminary Volcano-Hazard Assessment for the Katmai Volcanic Cluster, Alaska* (Fierstein and Hildreth 2001) is an assessment of the volcanic hazards for the Katmai volcanic cluster and is available at http://pubs.er.usgs.gov/publication/ofr00489.
- *The Alaska Interagency Operating Plan for Volcanic Ash Episodes* (Madden et al. 2014), available at http://avo.alaska.edu/downloads/reference.php?citid=3996 provides federal and state agencies with guidance for responding to volcanic eruptions.
- *Volcanism in National Parks: Summary of the Workshop Convened by the US Geological Survey and National Park Service, 26–29 September 2000,*

Figure 98. Map showing the locations of seismic stations maintained and monitored by AVO. A meteorological station and webcam are also at station KABU in the Valley of Ten Thousand Smokes.

Redding, California (Guffanti et al. 2001) is a summary of resource management issues related to volcanoes in national parks and is available at http://pubs.usgs.gov/of/2001/0435/.

Understanding the effects of volcanic eruptions to the physical morphology of the landscape and ecology was listed as a highly desirable objective for the inventory and monitoring plan for the Southwest Alaska Network parks (Bennett et al. 2006). In the *Geological Monitoring* chapter about volcanoes, Smith et al. (2009) described six vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability.

Dynamic Volcanic Landscape

Volcanic eruptions frequently change the landscape of the Katmai area. Geomorphic processes are affected by the intermittent addition of material into the active hydrologic and atmospheric systems. Volcanic eruptions and associated earthquakes potentially cause landslides that can flow for kilometers down valleys or cross valleys. Volcanic eruptions can disturb ecosystems and in very large eruptions, like the 1912 eruption, can obliterate all life and create a sterile landscape. The landscape and ecologic effects of the 1912 eruption are discussed in the "Geologic Features and Processes" section. Table 4 lists the geomorphic and ecologic effects of a major explosive volcanic eruption.

Crater Lake Explosions and Acidic-Water Flooding

Lakes in the active volcanic craters of Mounts Douglas, Martin, Mageik, and Katmai (Plate 4; see "Crater Lakes" section) create the potential hazard of lake water and magma violently mixing to generate an explosive phreatomagmatic eruption where water and magma interact, intensifying the eruption. The violence of the interaction is controlled by a number of factors, including magma type, volume, rate of extrusion, degree to which the magma is fragmented by expanding internal gas bubbles, and water depth. Typically, the most explosive water-magma mixing occurs if the water is shallow (a few meters to tens of meters deep), if the magma extrudes rapidly, and if the magma breaks into coarse particles before it is quenched. These conditions allow rapid transfer of heat from the magma to the water, generating steam and explosive eruptions. Eruptions beneath deep water, where the pressure is high enough to inhibit the expansion of steam, tend to be much less violent than those through shallow water. Slow rates of lava extrusion typical of lava flows and silicic domes also inhibit violent mixing with water. Faster extrusion rates and large volumes of gas-rich silicic magma could overcome even deeper water, with explosive results. The depth of water in the crater lakes of Mounts Martin and Mageik is very shallow, but the water in Katmai caldera is known to be more than 250 m (820 ft) deep (Motyka 1977, 1978). With a surface area of 4.3 km^2 (1.6 mi^2), the lake volume is more than 1 km^3 (0.4 mi^3). In contrast, the areas covered by the Martin and Mageik lakes are each less than 0.03 km^2

Table 4. Geomorphic and ecological processes following a large volcanic eruption.

Timeframe	Geomorphic Processes	Ecologic Processes
Hours–Days	Deposition of meters thick pyroclastic debris and ash fall, debris flows, caldera collapse, damming of rivers, and lahars. Pyroclastic flows may form tsunamis.	Charring, burial, and suffocation of vegetation and wildlife. Acid rain falls and sulfur rich deposits increase acid levels in water bodies.
Days–Years	Rapid erosion and deposition: gullying, sloughing of steep slopes, and heavy sediment load in streams causes aggregation of river floodplains and rapid progradation of deltas.	High acid levels in lakes and streams kill fish, aquatic life, and vegetation. Land animals must migrate or risk dying of starvation from lack of food or grinding down teeth from coarse tephra. Where deposits are thinner, native plants may grow through the deposits. Trees may temporarily benefit from the lack of competition from buried vegetation.
Years–Decades	Slowing erosion and deposition: gullies widen and slope angles decrease, wind deflation of loose surfaces in areas of thick deposits, and slower river aggregation and progradation of deltas.	Recolonization of stable surfaces by pioneer vegetation. Return of wildlife attracted to the new vegetation. Return of salmon runs and aquatic life.
Decades–Centuries	Stabilization of surface morphology	Maturation of ecosystems.
Centuries–Millennia	Major eruption disrupts the landscape and starts the cycle over.	Major eruption disrupts the landscape and starts the cycle over

Modified from Waythomas (2015)

($0.01 mi^2$), and they are probably only a few meters deep. Because of the large volume of water in Mount Katmai's crater lake, and because of repeated silicic and fragmental eruptions from that volcano, an eruption through the Katmai crater lake is considered both likely and quite dangerous. Although the volume of water in the Martin and Mageik crater lakes is small, it would likely add intensity to any crater-derived eruption.

The disruption of such acidic lakes also increases the possibility of local acid rainfall and of sending acid water-rich lahars and debris flows downhill from those summits. Floods of acidic volcanic lake water can have catastrophic effects on riverine and lake ecosystems. For example, during winter 2004–2005, a small acidic crater lake on Chiginagak volcano, near Aniakchak National Monument and Preserve, broke through a glacial dam and flooded the streams that run into Mother Goose Lake (Figure 1) and the King Salmon River. The event killed all aquatic life in a stream below the mountain, Mother Goose Lake, and the King Salmon River, preventing the annual salmon run. Severe vegetation damage and die-offs occurred around the streams as high as 150 m (500 ft) above the stream level (Schaefer et al. 2008). The crater lakes on Mounts Mageik, Martin, Katmai, and Douglas are extremely acidic, with pH levels between 1 and 3. Such acidic water, released during an eruption or breach, would cause severe damage to stream and lake ecosystems.

Windstorms and Resuspension of 1912 Ash

Air quality is affected periodically by resuspension of 1912 ash during strong northwesterly wind events (e.g. Hanlon 2015). The strong wind events usually occur in spring and fall during times of low snow. A handful of events occur nearly every year and commonly cause

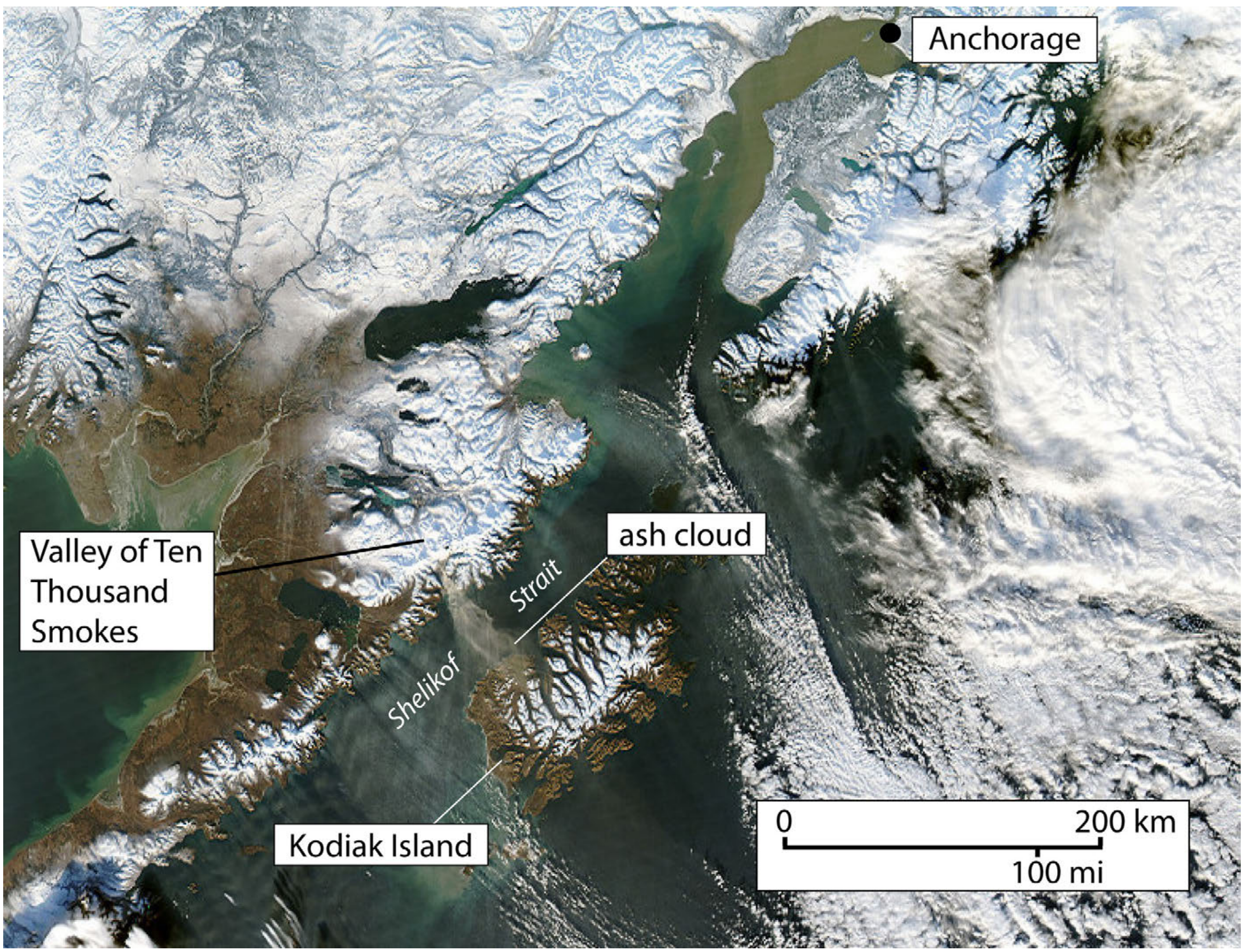


Figure 99. Satellite (MODIS) image of ash being resuspended from the Valley of Ten Thousand Smokes and creating an ash cloud over Shelikof Strait. NASA image (taken 29 November 2010) courtesy of USGS-AVO.

flight cancellations. Climate change may increase the frequency of these events due to warmer temperatures leading to lower snow cover during the spring and fall. Cloud heights have been estimated between 1,000–3,500 m (4,000–11,000 ft) above sea level, and distances up to 250 km (150 mi) to Kodiak Island and beyond (Figure 99). These resuspension events are not caused by an active volcanic eruption but have led to many spurious reports of eruptions (Hadley et al. 2004; McGimsey et al. 2005; Hanlon 2015)

Air quality during these events is often a concern of residents of Kodiak Island, so in 2015 the Alaska Volcano Observatory initiated a monitoring campaign to test the frequency and severity of airborne ash from these events (see https://www.avo.alaska.edu/news.php?id=991 for information about resuspended ash). Particulate monitoring stations were installed on Kodiak Island at Kodiak and Larsen Bays during summer 2015 (Kristi L. Wallace, USGS-AVO, research geologist, telephone communication, 30 October 2015). When a strong wind event is forecast, cooperators put out measuring buckets to capture airborne particulates. A meteorological station was installed and co-located with a seismic station in the Valley of Ten Thousand Smokes. The project is run in cooperation with the Alaska Department of Environmental Conservation, Division of Air Quality. Official warnings about these ash resuspension events (volcanic ash advisories and forecasts of ash fall) are issued by the National Weather Service (http://www.weather.gov/afc/, http://aawu.arh.noaa.gov). Air quality hazards and guidance are provided by the Alaska Department of Environmental Conservation, Division of Air Quality (http://dec.alaska.gov/Applications/Air/airtoolsweb/Advisories/Index).

Landslides and Rockfall

Map Units: **Qls**, **Qc** (in part)

Landslides (**Qls**) and rockfall (**Qc** in part) occur on steep slopes, particularly those greater than 40°. Landslide events are generally triggered by high-rainfall, seismic, or volcanic events. Plate 1 shows where large landslides (**Qls**) have occurred in the past, some of which slid for many kilometers down valleys below high mountains during the 1912 eruption (Riehle and Detterman 1993; Hildreth and Fierstein 2003). Landslides can dam river drainages and impound water. Subsequent breaches of the dam and floods have occurred, including on the Katmai River a few years after the 1912 eruption (Griggs 1922). Rockfall occurs below steep slopes and their deposits are mapped as part of the colluvium map unit (**Qc** on Plate 1). A summary map of landslide and rockfall deposits is presented in Figure 100. No comprehensive hazard map for the park unit or areas of interest have yet been compiled. In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Seismic Activity

Earthquakes are common in the Katmai area because it lies over the Aleutian megathrust (Figure 4) and contains numerous volcanoes. Tectonic earthquakes are associated with movements of plates of Earth's crust. Volcanic earthquakes are associated with movement of magma beneath the surface or eruptions onto the surface. Volcanic earthquakes are generally moderate strength whereas subduction megathrusts generate the largest earthquakes of any type of plate boundary. The 1964 Great Alaskan, or Good Friday, earthquake was a subduction earthquake and registered a magnitude 9.2, the most powerful earthquake in recorded North American history. According to the USGS 2009 probabilistic seismic hazard analysis model (Figure 101), the probability for a moderate earthquake, greater than magnitude 5.5, in the next 20 years is between 0.20 and 0.50 or a 20% to 50% "chance."

The direct effect of shaking from an earthquake may make a person fall down, but it is the indirect effects of an earthquake, such as rockfall and landslides, that pose the highest risk to park resources and visitors. However, the lack of major infrastructure within the area limits the risk to human development. The Brooks Camp area and the park headquarters at King Salmon have a low probability of having a larger earthquake directly underneath in the next 20 years (0.10–0.25), but being built on unconsolidated lacustrine and glacial deposits makes the areas vulnerable to shaking from adjacent high probability earthquake areas.

The AVO seismic stations provide seismic monitoring capability for the Katmai area. Earthquake hazards are actively monitored by the US Geological Survey in conjunction with the Alaska Earthquake Information

Center (http://www.aeic.alaska.edu/). Zanon et al. (2015) identifies seismic activity as a "key resource" and provides a summary of seismic activity, measures, and causes in the Katmai area. Additional information is available in the *Geological Monitoring* chapter where Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

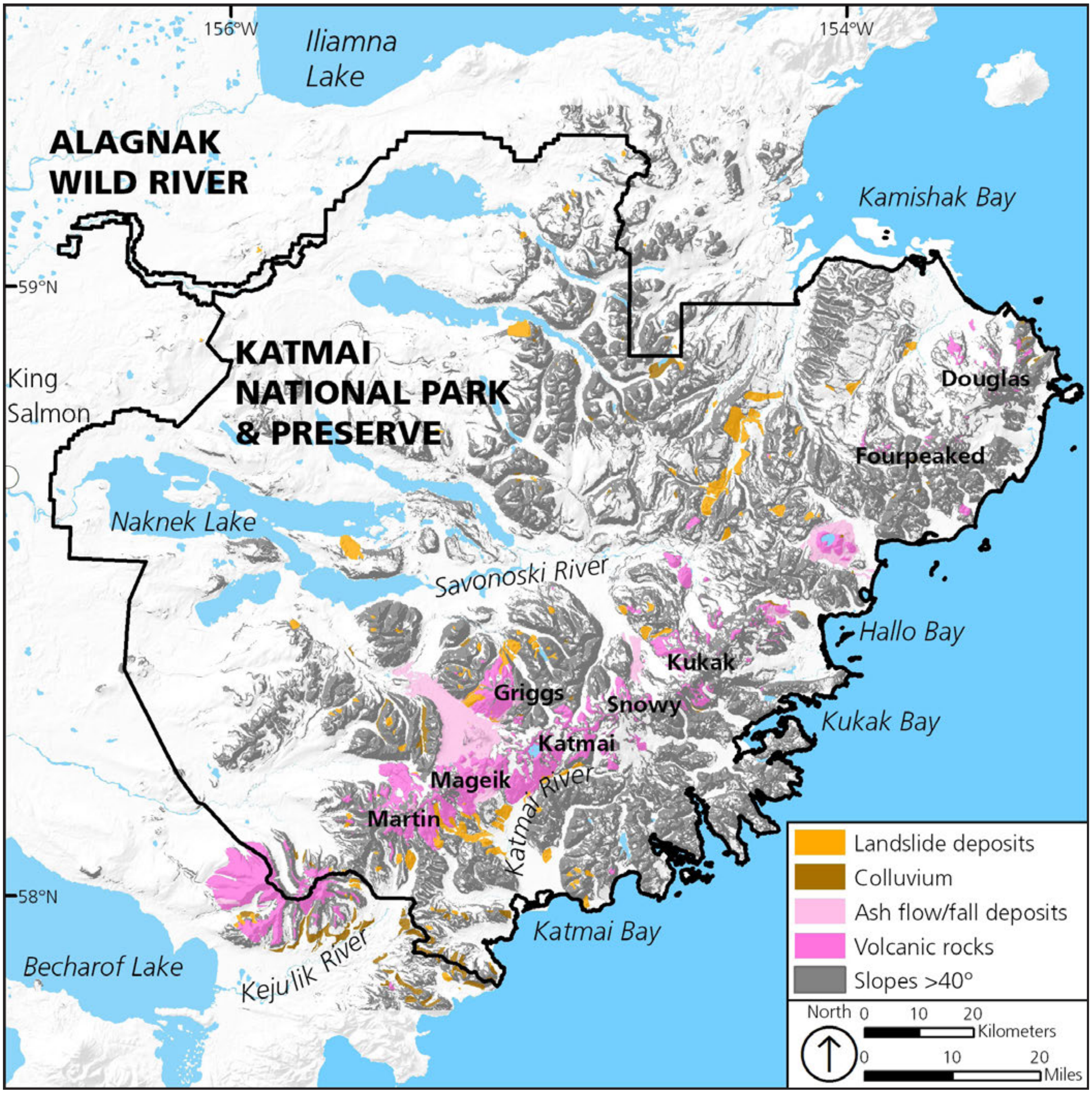


Figure 100. Cursory hazard map showing volcanic rocks, volcanic ash, pyroclastic flow deposits, landslide deposits, colluvial deposits, and slopes susceptible to rockfall or landslides (compilation of map units from Plate 1). Slopes greater than 40° have a high potential for producing rockfall. Slope map was derived from the National Elevation Dataset 30 m grid digital elevation model.

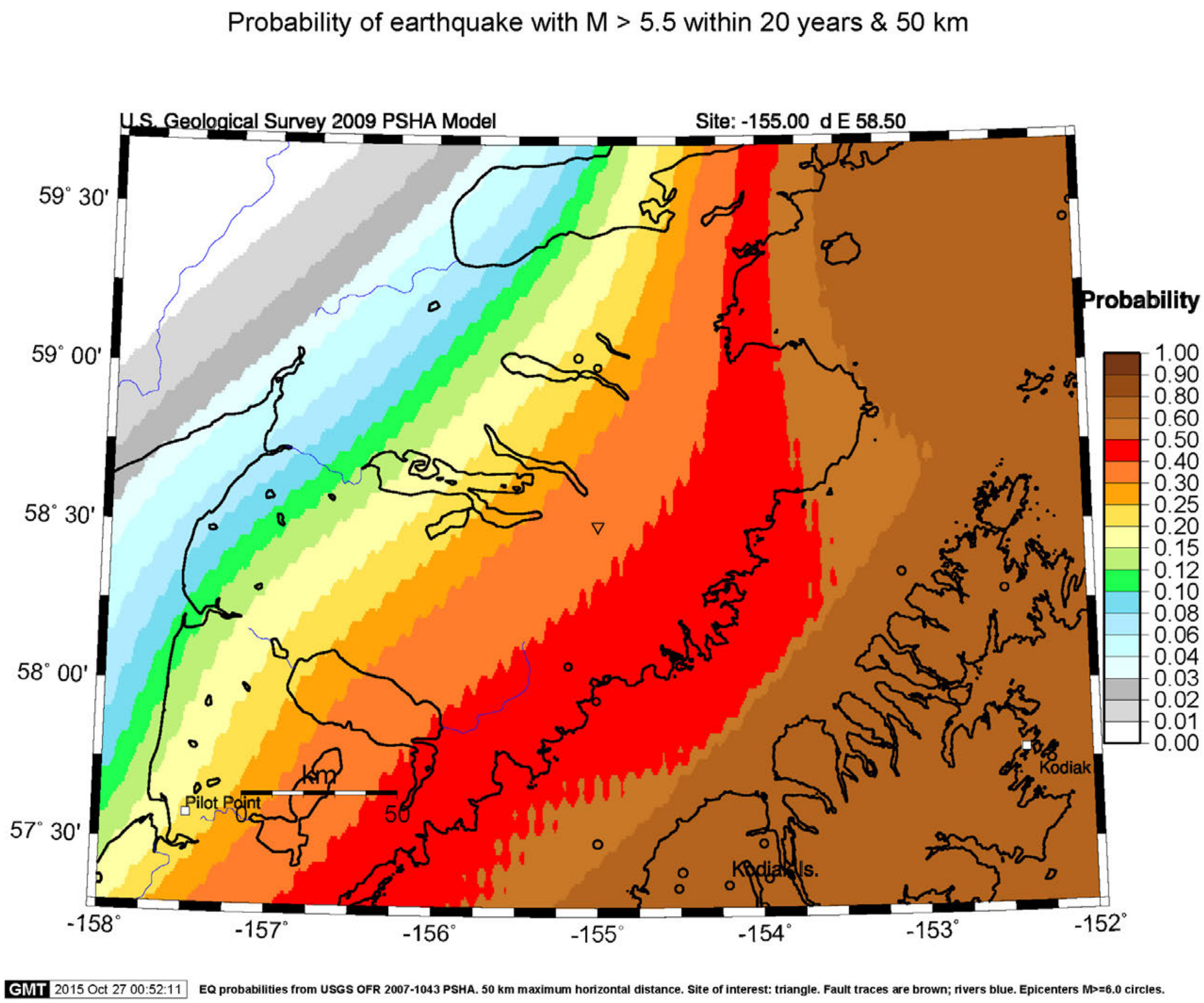


Figure 101. Map showing the probability of earthquake of magnitude 5.5 or greater over the next 20 years in the Katmai area. Map generated using the USGS earthquake probability mapping program (http://geohazards.usgs.gov/eqprob/2009/index.php).

Tsunami Hazards

No known historic tsunami studies have been conducted for the Katmai area, but studies around Cook Inlet, on Kodiak Island, on the Alaska Peninsula, and islands across Shelikof Strait indicate that the region is susceptible to potentially large tsunamis. Tsunamis affecting Katmai could be caused by landslides associated with tectonic or volcanic earthquakes.

Movement along the Aleutian megathrust can cause the sea floor to rise or fall significantly, so the area has a high potential for earthquake generated tsunamis, as illustrated by the 1964 Alaska "Good Friday" earthquake and tsunamis (more information about this earthquake is available at http://earthquake.usgs.gov/earthquakes/events/alaska1964/), the 2004 Indian Ocean earthquake and tsunami, and the 2011 Tōhoku earthquake and tsunami in Japan. Large earthquakes anywhere along the circum-north Pacific can generate tsunamis that may hit the Katmai coast. The Katmai coast may be partially protected from distant circum-Pacific earthquake generated tsunamis by Kodiak Island, but the wrap-around effect (increase in height behind an island) could be significant. Preliminary models indicate that a very large earthquake (magnitude 9.0) on the Aleutian megathrust near Kodiak Island has the potential to produce a run-up height of 20 m (66 ft) along the coast of Katmai (Dmtry Nicolsky, UAF-Alaska Earthquake Center, Tsunami Modeler, written communication, 29 October 2015).

Ash flows from volcanoes can also be a major tsunami generator. In particular, the northern Katmai coast lies only 30 km (20 mi) from Augustine Volcano, which is the most historically active volcano in Cook Inlet. The island contains evidence of numerous ash flows that reached the shoreline, as many as 14 in the last 2,000 years (Waythomas et al. 2006). Evidence of tsunamis generated from these mass flows is preserved in oral and written history, and by tsunami deposits around Cook Inlet (Beget and Kowalik 2006; Beget et al. 2008). Models show that a tsunami generated from an ash flow on Augustine Volcano will reach the northern shores of Katmai within 30–40 minutes, leaving little warning and response time for people on the shores of Kamishak Bay (Beget and Kowalik 2006; Waythomas et al. 2006).

The NOAA Pacific Tsunami Warning Center (based in Palmer, Alaska) monitors global earthquakes and tsunami potential for the coast of North America and publishes real-time watches, warnings, and advisories on its website (http://ptwc.weather.gov/).

Geothermal Features Inventory and Monitoring

Katmai National Park and Preserve is one of 16 units in the National Park System, nine of which are in Alaska, with significant thermal features as designated by the Geothermal Steam Act of 1970 (amended in 1988). As documented on 3 August 1987 in the Federal Register (v. 52, no. 148, p. 28790–28800), Novarupta and vicinity is a significant thermal feature within the park. The actual extent of the feature covers more than 1,500 km^2 (600 mi^2) and includes the following volcanoes: Novarupta, Mount Martin, Mount Mageik, Trident, Griggs, Kukak, and Katmai. Smaller scale geothermal features within and near these volcanoes, and elsewhere in the park, include fumaroles, warm springs, warm ground, and crater lakes. Geothermal features are described in the "Geothermal Features" section and mapped on Plate 4. Geothermal features are subject to monitoring as required by the Geothermal Steam Act. The act prohibits geothermal leasing in parks, and authorizes the Secretary of the Interior to mitigate or not issue geothermal leases outside parks that would have a significant adverse impact on notable thermal features within the park. The act also requires inventorying and monitoring significant geothermal features of the park. In the *Geological Monitoring* chapter about geothermal systems and hydrothermal features, Heasler et al. (2009) described the following methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry.

Coastal Issues

Map units: **Qmt**, **Qb**, **Qa** (in part), **Qaf** (in part), **Qd** (in part)

The rugged Katmai coast, encompassing 737 km (458 mi) of shoreline, is constantly changing (see "Coastal Features" section). Dynamic geological processes have shaped and continue to shape the coast. Raised marine terraces (**Qmt**) and stranded sea caves provide evidence of uplift in the last few thousand years (Riehle and Detterman 1993; Harper and Morris 2005). The 1964 earthquake caused the area to subside 20 cm (0.5 ft) (Plafker 1969). Sediment input after the 1912 eruption increased in many of the rivers flowing to the coast (Griggs 1922). This increase of sediment dramatically reshaped the coastline by forming large alluvial fans (**Qaf**) and filling in previously large bays (e.g., Katmai Bay). Large glaciers near the coast produce sediment laden rivers that form alluvial fans (**Qaf**) and wide beaches (**Qb**). Wind transportation and deposition of the glacial silt forms extensive dune fields (**Qd**). Extensive beach ridge complexes are present in most protected bays with large river systems. The Katmai coast is a geomorphically dynamic place, but little work has been done to understand the processes that shape the coast.

Relative and eustatic sea level along the Katmai coast is changing in response to a number of factors, including isostatic rebound (land level rise) and climate change. Climate change may lead to sea level rise, increased storm strength, and ocean acidification, which could alter the current coastal geomorphic processes and coastal ecosystem (Winfree et al. 2014). Raised marine terraces indicate that the relative sea level has decreased over the last several thousand years due to isostatic rebound and plate tectonic movement. Sea level fluctuated as the Pleistocene glaciers melted, which increased global water levels (Crowell and Mann 1996). This interplay between land levels and water levels explains why tide gauge records from the nearest tide station in Seldovia, Alaska, show relative sea level has decreased by around 0.04 mm/yr since 1964 (NOAA: http://tidesandcurrents.noaa.gov/sltrends/sltrends.html). For the Katmai area, the Intergovernmental Panel on Climate Change (IPCC) models predict that absolute sea level in the region will increase about 37 cm (1.2 ft) by the end of the century (Intergovernmental Panel on Climate Change 2013), which is a rate of about 4 mm/yr (0.16 in/yr). However, given the faster rate of land level uplift along the Katmai coast (8 mm/yr; 0.3 in/yr; Freymueller et al. 2008), the rate of absolute sea level will not keep pace with the rate of land level changes, and relative sea level is likely to decrease over the next few decades. Uplift has preserved archeological sites from inundation and erosion along the coastline (Crowell and Mann 1996). However, increased erosion from increasing storm frequency should also be expected in the future. Storms are predicted to become stronger as waters become warmer. Warmer waters will likely alter storm tracks and provide more water vapor to fuel and intensify the storms. Conditions are becoming more conducive for storms to travel farther north in the Northern Hemisphere.

A simple classification of shore zone morphology was published by Harper and Morris (2005); the study provided a line dataset depicting coasts that are made of rock, sediment, wetland, or channel. This classification does not fully describe the complex, and in some places, very wide shore zone of the Katmai coast. A more detailed shore zone geomorphic map could help with modeling potential effects of climate change or sudden tectonic subsidence on the Katmai coast. Such a map could be used for understanding dynamic coastal geomorphic systems, and integrating these systems with shore zone biological and archeological inventories. Understanding the physical morphology of the coast was listed as highly desirable objectives for the inventory and monitoring plan for all parks in the Southwest Alaska Network (Bennett et al. 2006).

The NPS Coastal Adaptation Handbook (RM 39-3; in review, expected 2016) will provide climate change adaptation guidance to coastal park managers in the 118 parks, including Katmai, that have been identified by their regional offices as potentially vulnerable to sea level change. Focus topics will include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, and infrastructure. The handbook will also provide guidance on developing communication and education materials about climate change impacts. Case studies of the many ways that park managers are implementing adaptation strategies for threatened resources, including Alaska parks, are available in Schupp et al. (2015). Additional reference manuals that guide coastal resource management include NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction, which can provide insight for managers in parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: Beach Nourishment Guidance (Dallas et al. 2012) for planning and managing nourishment projects. The National Park Service is also developing a climate change response strategy that connects climate science with historic preservation planning. The summary report from the Preserving Coastal Heritage workshop in 2014 identified and described six climate change adaptation options for cultural resources and cultural landscapes: (1) no active intervention, (2) offset stressors, (3) improve resilience, (4) manage change, (5) relocate or facilitate movement, and (6) document and release. Additional information about the workshop, and associated presentations and reports, are available at https://sites.google.com/site/democlimcult/. In the *Geological Monitoring* chapter on coastal resources, Bush and Young (2009) listed the following vital signs for inventorying and monitoring coasts: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. The NPS Water Resources Division, Ocean and Coastal Resources Branch website (http://www.nature.nps.gov/water/oceancoastal/) has additional information about servicewide programs and the resources and management programs at the coastal parks.

Fluvial Erosion

Fluvial erosion along steep river banks is a threat to archeological sites, especially along the Brooks and Alagnak Rivers. Extreme erosion along the Brooks River has exposed artifacts at the aptly named "Cutbank" site. This site was recognized in the 1950s as potentially threatened by river erosion. In 2002, NPS personnel found that the river had removed approximately 6 m (20 ft) of a terrace. Bundy et al. (2005) conducted an emergency site investigation and concluded that erosion at the site is a chronic problem and developed an annual monitoring plan.

The Alagnak Wild River corridor protects the river's scenic landscape, natural characteristics, cultural heritage, and recreational and subsistence activities. Cultural sites along the river are generally within 50 m (160 ft) of the river banks, so river bank erosion threatens the cultural resources (Curran 2003). The river is both meandering and braided and changes course over time. By comparing air photos and satellite imagery over the last 50 years, Curran (2003) found that the river's upper and lower reaches have been relatively stable, with only minor meander migrations; whereas, the middle, braided portion has had substantial changes. That investigation monitored bank erosion at numerous sites over two years and found that motorized boat traffic increased bank erosion rates, but that the traffic did not appear to have altered the natural mechanisms of channel change.

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Glacier Changes

The area covered by glaciers has decreased from 1,060 km^2 to 915 km^2 (410 mi^2 to 350 mi^2) since 1950. This equates to a loss of 14% (Loso et al. 2014). Most glaciers in the Katmai area are receding, like most glaciers in Alaska, but glaciers that were covered by thick deposits of 1912 ash are not receding and some have advanced (Figure 73). Terminus retreat was the response seen in most individual glaciers, including notable retreats by glaciers on Fourpeaked Mountain and Mount Douglas in the northeast section of the park, and Hallo Glacier and others on the Kukak Volcano edifice.

Alaska-wide, Loso et al. (2014) noted that the trend of warmer summers and wetter winters will continue for at least the next 50 years, and warming will accelerate. Recent glacier trends of negative mass balance, diminished ice cover, and reduced ice volume are predicted to intensify as climate changes (Loso et al. 2014). Glacial extent is considered a key natural resource condition for the Katmai area and information on glaciers, measures, stressors, and reference condition is summarized by Zanon et al. (2015). Four parameters were identified by Karpilo (2009) to monitor glacial changes: (1) mass balance, (2) terminus, (3) area, and (4) surface velocity. Understanding the changes due to retreat of Pleistocene and modern glaciers was listed as an essential objective of the Southwest Alaska Network inventory and monitoring plan (Bennett et al. 2006).

Paleontological Resource Inventory, Monitoring, and Protection

Map units: **Tc, Th, Khe, Kk, Jni, Jns**

The Katmai area contains approximately 550 fossil localities. The Alaska Regional Office maintains a database of all known fossil localities for Katmai National Park and Preserve. No known fossil localities or resources occur in Alagnak Wild River. Blodgett et al. (2016) provided a review of paleontological resources from Katmai National Park and Preserve. Their inventory was based primarily on literature review, review of unpublished internal USGS E&R "Evaluate and Report" documents, and brief site visits. The Mesozoic sedimentary units contain abundant invertebrate and a few vertebrate marine fossils, and the Tertiary units contain well-preserved plant fossils, including petrified wood (see "Mesozoic Bedrock" and "Tertiary Sedimentary Rocks" sections). The units with the most abundant fossils are the Ketavik Formation (not mapped), Copper Lake Formation (**Tc**), Hemlock Conglomerate (**Th**), Herendeen Formation (**Khe**), Kaguyak Formation (**Kk**), and the Naknek Formation, namely the Indecision Creek (**Jni**) and Snug Harbor Siltstone (**Jns**) Members.

Most places in the park are relatively inaccessible, but plant fossils are easily accessed from Brooks Camp, and invertebrate fossils are present near the popular bear viewing area at Hallo Bay. Furthermore, unusual fossils like the large ammonites (Figure 88) found in the Kaguyak Formation (**Kk**) may attract non-permitted collecting and are a priority for protection.

Although a park-specific survey has not yet been completed for the park and preserve, a cursory paleontological summary was completed for the Southwest Alaska Network by Kenworthy and Santucci (2003), and a more in-depth review was provided by Blodgett et al. (2016). A detailed inventory and field-based paleontological resource survey of interesting or sensitive fossil sites can provide detailed, site-specific descriptions and resource management recommendations. Katmai National Park and

Preserve has diverse and abundant fossil resources and would benefit from a baseline field inventory of paleontological resources in order to develop monitoring and interpretive programs.

Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as archeological sites. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix C). All fossils are protected from collection by the 2009 Paleontological Resources Preservation Act. Fossils collected under research permits are accessioned by the NPS curatorial staff and held in NPS curation centers or at research institutions for ongoing research projects. As of August 2016, Department of the Interior regulations associated with the act were being developed. In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described the following methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (4) human access/public use. All of these are potential vital signs at Katmai. Fossils along NPS coastlines present additional management challenges and considerations as outlined by Brunner et al. (2009). The NPS Fossils and Paleontology website, http://go.nps.gov/fossils_and_paleo, provides more information.

Abandoned Mineral Lands (AML)

The USGS Alaska Resource Data File (ARDF; http://ardf.wr.usgs.gov/) lists 18 metaliferous mineral occurrences or deposits in Katmai National Park and Preserve. None are listed for Alagnak Wild River. Small-scale mining and prospecting historically occurred in the Katmai area at 11 sites between the early 1900s and the 1980s. Mineral occurrences and prospected mineral resources included pumicite from the Novarupta eruption (Moxham 1952), placer gold, coal, and copper. Most of the sites have not been relocated in the field by NPS staff, but are unlikely to pose any resource or safety-related issues based on knowledge of the historic operations. No known safety issues exist at any AML sites within Katmai. One mine site, Pfaff copper prospect, is considered "medium" priority for mitigation (Burghardt et al. 2014). Diesel-contaminated soil at the Pfaff copper prospect is the only documented resource issue that has been associated with AML in Katmai. After several years of soil treatment, the Alaska Department of Environmental Conservation declared the site to be adequately cleaned up in 2011. The abandoned mine structures are unsightly but pose no known safety or environmental threat.

Potential Petroleum Development

The Katmai area is surrounded by oil and gas reservoirs. The Cook Inlet area contains reserves that supply natural gas to much of south-central Alaska and crude oil to a refinery on the Kenai Peninsula. The Iniskin Peninsula area of the Alaska Peninsula, 60 km (40 mi) north of Katmai, has been explored for oil since the 1800s. Offshore exploration wells have been drilled less than 25 km from the northeastern coast (Figure 102). State tax credits for Cook Inlet exploration over the last few years has increased exploration, although most of it has been in the northern portions of the inlet. The Bureau of Ocean Energy Management (BOEM) is preparing an environmental impact statement for a potential lower Cook Inlet lease sale (Bureau of Ocean Energy Management 2014). The notice of intent states that the proposed area "reduces potential effects to parks, preserves, and wildlife refuges by placing a buffer between the area considered for leasing and the Katmai National Park and Preserve, the Kodiak National Wildlife Refuge, and the Alaska Maritime National Wildlife Refuge" (Bureau of Ocean Energy Management 2014, p. 63437).

Oil spills from exploration or production activity in Cook Inlet have the potential to severely harm the coastal ecosystems of Katmai. The Katmai coast supports a complex ecosystem that was impacted by the Exxon Valdez oil spill in 1989. Crude oil was stranded along the entire length of the coastline. Future petroleum exploration and development is possible, if economic conditions warrant, on state oil lease tracts west of Katmai National Park and Preserve (Figure 102). Native corporation and state lands within the authorized boundary can be developed; however, NPS regulations limit the impact that development would have on the park resources. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of view sheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. The NPS

Figure 102. Map showing location of oil and gas wells near the Katmai area shown as black points (Wilson et al. 2012), proposed BOEM Cook Inlet Lease Sale 244 boundary shown in red (Orr and Brown 2013; Bureau of Ocean Energy Management 2014), and Alaska State oil lease tracts on the west side of Katmai shown as gray squares. Relief derived from National Elevation Dataset.

Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information about external exploration and development.

Soils and Permafrost

Map unit: **Qsf**

The soils changed dramatically after the 1912 eruption (see the "Landscape Changes Caused By the 1912 Eruption" section). The eruption deposited a layer of ash over the entire Katmai area, and areas near the eruption were buried so deeply that it formed a sterile landscape. A primary purpose of preserving the Katmai area was to study the regeneration of vegetation after the 1912 eruption, but such an investigation is limited without a soils map, which has not yet been completed. A park specific soils map is planned to be completed by the Inventory and Monitoring Program in 2018.

Soil temperature and permafrost were listed as important physical elements of the Southwest Alaska Network Vital Signs Monitoring Plan (Bennett et al. 2006). Climate scenarios indicate a rise in average annual temperature of 2.6°C (4.7°F) by 2040 in the Katmai area, and permafrost melting was identified as a potential major change to the park in the Southwest Parks Climate Change Scenarios Report (Winfree et al. 2014) and the Natural Resource Condition Assessment (Zanon et al. 2015). Other than the general permafrost map of the King Salmon area by Abrahamson (1950) and the Jorgenson et al. (2008) permafrost map of Alaska (Figure 77), no detailed permafrost map has been produced for the Katmai area. Furthermore, no permafrost or soil temperature monitoring plan has been established. In the *Geological Monitoring* chapter about permafrost conditions and processes, Osterkamp and Jorgenson (2009) described two vital signs for monitoring permafrost conditions and processes: thermal state and physical conditions. Park managers may find this information useful in developing a monitoring plan for the Katmai area.

Geologic Map Data

This section summarizes the geologic map data available for Katmai National Park and Preserve and Alagnak Wild River. A poster (Plate 1, in pocket) displays the map data draped over a hillshade of the National Elevation Dataset of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The source of digital geologic map data for National Park System units in Alaska is the Alaska digital geologic map database, which is compiled and maintained under the direction of Fredric H. Wilson of the USGS Alaska Science Center. Wilson has been compiling geologic data for the state of Alaska for more than two decades and has produced numerous regional geologic maps as part of this project with support from the NPS Geologic Resources Inventory (see http://mrdata.usgs.gov/geology/state/state.php?state=AK).

The source of the digital geologic map data for Katmai National Park and Preserve and Alagnak Wild River is an updated version of the statewide database. The most recent digital data sets for the Katmai area were published as regional geologic maps of the area:

Wilson, F. H., R. B. Blodgett, C. D. Blomé, S. Mohadjer, C. C. Preller, E. P. Klimasauskas, B. M. Gamble, and W. L. Coonrad. 2006. Preliminary reconnaissance bedrock geologic map for the northern Alaska Peninsula area, southwest Alaska. Open-File Report 2006-1303 (1:250,000). US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2006/1303/.

Wilson, F. H., R. L. Detterman, and G. D. Dubois. 1999. Preliminary geologic framework of the Alaska Peninsula, southwest Alaska, and the Alaska Peninsula terrane. Open-File Report 99-317 (1:500,000). US Geological Survey, Reston, Virginia. http://geopubs.wr.usgs.gov/open-file/of99-317/.

Wilson, F. H., C. P. Hults, H. R. Schmoll, P. J. Haeussler, J. M. Schmidt, L. A. Yehle, and K. A. Labay. 2009. Preliminary geologic map of the Cook Inlet region, Alaska; including parts of the Talkeetna, Talkeetna Mountains, Tyonek, Anchorage, Lake Clark, Kenai, Seward, Iliamna, Seldovia, Mount Katmai, and Afognak 1:250,000-scale quadrangles. Open-File Report 1108 (1:250,000). US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2009/1108/.

For the Katmai area, the Wilson et al. (1999) compilation was based on the following geologic maps:

Detterman, R. L., J. E. Case, F. H. Wilson, and M. E. Yount. 1987a. Geologic map of the Ugashik, Bristol Bay, and western part of Karluk quadrangles, Alaska. Miscellaneous Investigations Series Map 1685 (1:250,000). US Geological Survey, Reston, Virginia.

Detterman, R. L., and B. L. Reed. 1973. Surficial deposits of the Iliamna quadrangle, Alaska. Bulletin 1368-A (1:250,000). US Geological Survey, Reston, Virginia.

Detterman, R. L., and B. L. Reed. 1980. Stratigraphy, structure, and economic geology of the Iliamna quadrangle, Alaska. Bulletin 1368-B (1:250,000). US Geological Survey, Reston, Virginia.

Detterman, R. L., F. H. Wilson, M. E. Yount, and T. P. Miller. 1987b. Quaternary geologic map of the Ugashik, Bristol Bay, and western part of Karluk quadrangles, Alaska. Miscellaneous Investigations Series Map 1801 (1:250,000). US Geological Survey, Reston, Virginia.

Riehle, J. R., and R. L. Detterman. 1993. Quaternary geologic map of the Mount Katmai quadrangle and adjacent parts of the Naknek and Afognak quadrangles, Alaska. Miscellaneous Investigations Series Map 2032 (1:250,000). US Geological Survey, Reston, Virginia.

Riehle, J. R., R. L. Detterman, M. E. Yount, and J. W. Miller. 1993. Geologic map of the Mount Katmai quadrangle and adjacent parts of the Naknek and Afognak quadrangles, Alaska. Miscellaneous Investigations Series Map I-2204 (1:250,000). US Geological Survey, Reston, Virginia.

Wilson, F. H., R. B. Blodgett, C. D. Blomé, S. Mohadjer, C. C. Preller, E. P. Klimasauskas, B. M. Gamble, and W. L. Coonrad. 2006. Preliminary reconnaissance bedrock geologic map for the northern Alaska Peninsula area, southwest Alaska. Open-File Report 2006-1303 (1:250,000). US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2006/1303/.

Wilson, F. H., R. L. Detterman, and G. D. Dubois. 1999. Preliminary geologic framework of the Alaska Peninsula, southwest Alaska, and the Alaska Peninsula terrane. Open-File Report 99-317 (1:500,000). US Geological Survey, Reston, Virginia. http://geopubs.wr.usgs.gov/open-file/of99-317/.

Wilson, F. H., C. P. Hults, H. R. Schmoll, P. J. Haeussler, J. M. Schmidt, L. A. Yehle, and K. A. Labay. 2009. Preliminary geologic map of the Cook Inlet region, Alaska; including parts of the Talkeetna, Talkeetna Mountains, Tyonek, Anchorage, Lake Clark, Kenai, Seward, Iliamna, Seldovia, Mount Katmai, and Afognak 1:250,000-scale quadrangles. Open-File Report 1108 (1:250,000). US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2009/1108/.

Surficial Geologic Mapping of Alagnak Wild River in Dillingham Quadrangle

At the start of this project, the area around the Alagnak River was mapped as unconsolidated deposits, undifferentiated. The surficial geology was clear in the detailed imagery available through Google Earth, so Chad Hults, lead author, digitized the geology in Google Earth. This dataset was merged into the GRI GIS dataset as the "Geologic Units (Dillingham Quadrangle)" and "Geologic Contacts (Dillingham Quadrangle)" layers. These data are visible on Plate 1.

Geologic Map of the Katmai Volcanic Cluster

The following map is a more detailed map of the Katmai volcanic cluster. It is not part of the GRI GIS data but is available to NPS employees via the GIS Theme Manager (downloadable at https://irma.nps.gov/DataStore/Reference/Profile/2188597).

Hildreth, W., and J. Fierstein. 2003. Geologic map of the Katmai volcanic cluster, Katmai National Park, Alaska. Geologic Investigations Series I-2778 (1:63,360 scale). US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/imap/i2778/.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.2. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

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

The following components are part of the GRI GIS data:

- A GIS readme file (katm_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format.
- Layer files with feature symbology (Table 5).
- Federal Geographic Data Committee (FGDC)–compliant metadata.
- An ancillary map information document (katm_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures.
- An ESRI map document (katm_geology.mxd) that displays the GRI GIS data; and
- A version of the map data viewable in Google Earth (katm_geology.kmz).

Use Constraints

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

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

Table 5. GRI GIS data layers for the Katmai area.

Data Layer	On Poster?	Google Earth Layer?
Age-Date Sample Localities	No	No
Volcanic Point Features	Yes	No
Caldera Boundary Line Features	Yes	Yes
Glacial Feature Lines (moraine, ice limit, and kame-terrace scarp)	Yes	No
Geologic Line Features (lineaments and escarpments)	Yes	No
Folds	Yes	Yes
Faults	Yes	Yes
Linear Dikes	Yes	Yes
Alteration and Metamorphic Area Boundaries	Yes	No
Alteration and Metamorphic Areas (areas of contact metamorphism or hydrothermal alteration)	Yes	Yes
Geologic Contacts (Dillingham Quadrangle)	Yes	Yes
Geologic Units (Dillingham Quadrangle)	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of September 2016. Refer to Appendix C for laws, regulations, and policies that apply to NPS geologic resources.

Geology of Alaska

- Geologic Map of Alaska: http://dx.doi.org/10.3133/sim3340
- Alaska Digital Geologic Map and Geologic Data Online Viewer: http://mrdata.usgs.gov/geology/state/alaska.html
- Alaska (Minerals) Resource Data File: http://ardf.wr.usgs.gov/
- Alaska Paleontology Database: http://www.alaskafossil.org/
- Alaska Division of Geological and Geophysical Surveys (and Alaska USGS) publications: http://dggs.alaska.gov/pubs/pubs.jsp

Geology of National Park Service Areas

- NPS Geologic Resources Division—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/geology/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

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

US Geological Survey Reference Tools

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- Geologic names lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: History of Exploration

A thorough history of geologic exploration of the Katmai area was compiled by Hildreth and Fierstein (2012, Chapter 4). This appendix provides a concise chronology of historic geologic exploration and provides references to published reports.

1898—Josiah E. Spurr led a USGS party through southwest Alaska and passed through Naknek Lake and Katmai Pass (Spurr 1900).

1912—George C. Martin (USGS geologist) conducted a survey of the surrounding communities gathering information about the 1912 eruption (Martin 1913).

1913—George B. Rigg (US Bureau of Soils) conducted a coastal survey examining the eruption's impact on kelp and intertidal algae with the assistance of Robert F. Griggs (Griggs 1918a, 1919).

1915–1930—Robert F. Griggs led numerous National Geographic expeditions to the site of the eruption and discovered the Valley of Ten Thousand Smokes (Griggs 1917, 1918b, 1918c, 1918d, 1918e, 1933). Griggs' seminal book (Griggs 1922) was published, which covered the 1912 eruption and its effects on the surrounding area, and is a synthesis of all of the expeditions prior to 1922.

1923—Clarence N. Fenner and Charles Yori explored the Katmai area, and Walter R. Smith led a USGS party that explored and mapped the area from Katmai to Savonoski (Smith 1925).

Figure A1. Griggs expedition, Baked Mountain Camp in 1919. Mount Martin in the background. National Geographic Society photograph by Emery C. Kolb (Griggs 1922, p. 264).

Figure A2. Bernard Hubbard inspecting a bread-crust bomb adjacent to the steaming Novarupta dome in 1935. Image provided by Archives and Special Collections, Santa Clara University Library; The Bernard R. Hubbard, S. J. Alaskan Photographs, 1927–1961, VTS-35-330.

1929–1934—Bernard R. Hubbard explored the Katmai area (Hubbard 1932, 1935).

1953—Katmai Project. A comprehensive, multi-agency geologic and biologic investigation of the monument sponsored by the National Park Service in cooperation with the US Geological Survey, US Navy, Public Health Service, and various universities.

1954—Garniss H. Curtis and Jack Sheehan examined the deposits and postulated that the ignimbrite was sourced from the Novarupta vent and not from Mount Katmai (Curtis 1968).

1963—Robert W. Decker and Peter L. Ward, supported by the University of Alaska Fairbanks (UAF)-Geophysical Institute, began a geophysical study of the Valley of Ten Thousand Smokes, which included installing seismic monitoring stations and measuring gravity.

1965—The Baked Mountain Huts (see cover photograph) were built by the UAF-Geophysical Institute with assistance of the US Air Force.
Ed Berg and Jürgen Kienle continued the seismic and geophysical studies of the Valley of Ten Thousand Smokes and Katmai Pass.
NASA and USGS Apollo moon landing field training mission to Katmai to study rocks and landscapes similar to those that may be encountered on the moon. Astronauts included Buzz Aldrin, William Anders, Charles Bassett, Eugene Cernan, Roger Chaffee, Walt Cunningham, Rusty Schweikart, Dave Scott, and C. C. Williams (Schaber 2005).

1969—Robert Forbes initiated a multi-year geophysical study of the Katmai area, the results of which were never published. Draft manuscripts are available in the Alaska NPS curation center, and the UAF-Geophysical Institute.

1975—Roman J. Motyka accessed the Mount Katmai crater lake using an inflatable raft to make water quality measurements (Motyka 1977).

1976—Wes Hildreth begins studying the Katmai area and spends much of next 40 years studying the Katmai volcanoes.

1980—Judy Fierstein first steps foot in the Katmai area as an assistant to Wes Hildreth, which was the start of a fruitful research collaboration that resulted in numerous publications and culminated in the capstone centennial report of the eruption and volcanoes of Katmai (Hildreth and Fierstein 2012).

1983–1987—James R. Riehle and Robert L. Detterman of the US Geological Survey conducted an Alaska Mineral Resources Assessment Project, which produced the primary geologic maps used for the GRI compilation in Plate 1 (Riehle and Detterman 1993; Riehle et al. 1993).

1985—John Eichelberger proposes a scientific project to drill into the Novarupta vent and adjacent areas to understand the inner workings of the volcano. Although the project was eventually not permitted by the National Park Service, many research projects were conducted during the preparations for the project.

1987–1988—Judy Fierstein initiated a tephra study along both shores of Shelikof Strait to measure thicknesses of the 1912 ash fall layers (Fierstein and Hildreth 1992; Fierstein and Nathenson 1992).

1989–1990—Geophysical expeditions were carried out by numerous researchers in support of the proposed drilling project (Eichelberger et al. 1991).

1992—Fierstein and Hildreth (1992) publish a detailed analysis and stratigraphy of the eruption sequence.

1996—Hildreth and Fierstein begin work on a detailed geologic map of the Katmai cluster volcanoes (Hildreth and Fierstein 2003).

1994–2010—Fierstein, Wilson, Houghton, and Hildreth characterized 1912 near-vent deposits in unprecedented detail, elucidating eruption processes for large explosive events.

Appendix B: Potential Geologic Research, Inventory, and Monitoring Projects

This section provides some suggestions for future geologic studies of the Katmai area. This list was compiled by the authors after meetings with park staff, review of the foundation statements and founding documents, the GRI scoping report, and reviewing available geologic literature for the area. This list is not an exhaustive list of research, nor is it a list of the highest priority research to support park management. Some of the studies suggested have clear ties to park management issues; other studies have broader interests and applications. In addition to USGS, Alaska Geological Survey, and NPS Alaska Region Office, the Geoscientists-in-the-Parks (GIP; http://go.nps.gov/gip) and Mosaics In Science (http://go.nps.gov/mosaics) internship programs are potential sources to recruit assistance for these projects.

In general, the volcanic features formed during the 1912 eruption have been the focus of most geologic research in the park. The other volcanoes of the park have only been studied at the reconnaissance level. The surficial geology and glacial geology of the Brooks Camp area have been a focus for understanding the archeological resources of the area, but outside of that area, little research has been conducted. The bedrock geology has been mapped at the 1:250,000 scale, which is considered a reconnaissance level of detail. The bedrock units contain a great abundance of paleontological resources, so more detailed study of these rocks is warranted. The coastal morphology has not been studied in detail. Volcanic hazards have been addressed by the Alaska Volcano Observatory (AVO), but many other hazards exist that could cause harm. No detailed systematic study or monitoring of the volume changes of the numerous glaciers has been conducted.

- **Conduct detailed study of the eruptive history of the 24 Quaternary (up to 2.6 MYA) volcanoes.** Most of the Quaternary volcanoes have only been studied at a reconnaissance level. A more detailed study of these volcanoes will form a better understanding of their eruptive histories and lead to better assessment of their eruption potential. For example, the eruption of Trident Volcano was out of heavily eroded peaks that would have been considered an old and dead volcano. Fourpeaked Volcano was listed as a low concern according to the USGS volcanic threat assessment (Ewert et al. 2005), but the 2006 eruption surprised AVO staff, and now rates as a higher threat. Very little is known about the eruptive histories of most of the Quaternary volcanoes, so a complete understanding of their eruptive potential is not known. The volcanoes north of Kaguyak are remote and ice covered, so have not been studied in detail. However, the eruption of Fourpeaked and the active fumaroles on many of the volcanoes suggest that they are active.
- **Study the Pliocene (5.3–2.6 MYA) volcanic centers.** Pliocene volcanic centers have been little studied. For example, the dissected Pleistocene (2.6–0.01 MYA) or Pliocene (5.36–2.6 MYA) volcanic rocks make up the Kejulik Mountains, but little effort has been made to study these volcanic rocks, which lie on strike with the main Aleutian volcanic arc front, are well-exposed, and close to King Salmon.
- **Understand the landscape geomorphic changes in response to the 1912 eruption.** Detailed geomorphic mapping and analysis of the 1912 eruption features and its effects have only been side notes to the volcanic research. An understanding of the geomorphic changes caused by the eruption would provide a framework for better understanding the response of ecosystems to volcanic disturbances. Methods could include review of old photos and repeat photographs, aerial photography, and satellite imagery such as Landsat to measure stream erosion, aggregation, delta growth, and revegetation of thick volcanic deposits. Of particular interest would be the study of the aggradation and stream avulsion of the Ukak, Savonoski, and Katmai Rivers. Examples of geomorphic effects of volcanic eruptions, including connections to ecology, were outlined in Waythomas (2015).

- **Map fissures using IKONOS imagery.** The fissure and fracture geometry may be useful for interpreting the cooling history of the ignimbrite; modeling water flow within the ignimbrite; modeling differential erosion of the ignimbrite; and modeling differential contraction/compaction/welding of the ignimbrite.
- **Monitor the crater lakes**. The crater lakes have evidence of active volcanic inputs in the form of high sulfur, acid, and temperature levels, so the monitoring of these lakes' hydrochemistry may lead to a better understanding of these geothermal features. Also monitor the rising lake level in Katmai Crater.
- **Search for dinosaur tracks and bone in the Naknek Formation.** Dinosaur tracks were found in the Naknek Formation farther south on the Alaska Peninsula (Druckenmiller et al. 2011), and bone fragments have been found (Fiorillo et al. 2004). The type section of Naknek Formation is in the park, and the unit is extensive through the park, so there is a high potential for finding dinosaur tracks or bones.
- **Conduct detailed geomorphic mapping.** The available geomorphic maps of the Katmai area were compiled at the 1:250,000 scale from air photos. New InSAR derived digital elevation models provided through the Alaska Statewide Mapping Initiative (http://www.alaskamapped.org/sdmi) could be used to make more detailed surficial maps and landform maps. Geomorphic mapping would provide a better understanding of surficial processes such as landslides, floods, and glaciation, which impact human use and management of rugged landscapes. The materials and landforms produced by these geomorphic processes influence soils and vegetation patterns, and provide indications of geohazards, prehistoric use, and ecological disturbances.
- **Conduct detailed coastal geomorphology mapping**. The coast is a dynamic place that is constantly changed by the addition of sediment from glacially fed rivers and eroded by storm waves. The coast is tectonically uplifting and sea levels and storm frequency are forecast to rise, so understanding the coastal geomorphic processes would provide park managers with a better framework for predicting ecological changes and protecting or preserving infrastructure and cultural resources. Methods could include interpretation using remote sensing, photogrammetry, or LiDAR.
- **Conduct detailed bedrock geology and surficial geology map of Brooks River area**. Brooks Camp and the Brooks River National Historic Landmark is the most visited area of the Katmai area, so a detailed bedrock and surficial geology map would be useful for interpretation and integration with cultural studies.
- **Create a comprehensive geohazards map**. AVO staff members have produced a volcanic hazard assessment for the Katmai cluster, but as described in the "Geologic Resource Management Issues" section of this report, many other geohazards can occur in areas away from the volcanoes. A cursory hazard map showing potential rockfall and landslide areas map is provided in Figure 100. A comprehensive geohazards map and analysis could help managers identify areas of high potential. Particular areas of interest could be mapped or modeled in more detail where infrastructure may be damaged and where staff or visitors spend extended periods of time.
- **Date glacial moraines**. Surface dating of glacial moraines would help better constrain their ages and test correlation hypotheses. Plate 1 shows the deposits from the various glaciations, and Figure 64 shows a glacial extent map for the region surrounding Katmai. The Katmai area holds a well-exposed record of past glaciations, but the dating of the glacier deposits is still reconnaissance level at best. An understanding of past climate could be improved with better control on the ages of the glaciations, which could lead to significant revisions to the glacial history of the Alaska Peninsula. The results of such as study could initiate a new generation of moraine and outwash investigations in the Katmai area.
- **Cosmogenic and radiometric dating of the lake terraces**. Dating of the lake terraces will better constrain the timing of draining Naknek Lake in relation to the timing of glacial retreat. These lake terraces formed the foundations for the ancient dwellings and the draining of the lake allowed the Brooks River to form, creating a good fishing site.
- **Date raised marine terraces.** The uplift rates of the coast are provided from only two sources: a single modern GPS survey marker (Freymueller et al. 2008) and limited radiocarbon ages on organic material on a few raised marine terraces (Detterman and Reed 1973; Crowell and Mann 1996). A study focused on surveying and inventorying marine terraces and relict sea caves,

inventorying marine terraces and relict sea caves, and better dating these features, would improve the constraints for the uplift rate of the coast and understanding of earthquake effects on the coastal ecology and landforms.

- **Conduct a reconnaissance study of tsunami deposits along the coast**. No tsunami deposits have yet been identified along the coast, but preliminary modeling of an earthquake generated tsunami indicates that the run-up heights of a tsunami may be on the order of tens of meters. The probability is good that a tsunami has hit the coast in prehistoric times, so deposits may be hidden in the uplands of the many bays.
- **Model the possible effects of volcanic activity on the glaciers and downstream hydrologic effects**. Many volcanoes in the Katmai area have substantially sized glaciers. The effects of volcanic activity on the overlying glaciers could cause catastrophic changes to downstream ecosystems and geomorphology. Types of effects could be described, areas of potentially affected areas could be mapped, and baseline data could be collected prior to eruptions.
- **Map "interesting geologic features."** The GRI scoping report (Graham 2005) identified the need for a map showing "interesting geologic features" such as those indicative of the 1912 eruption, volcanoes, geothermal activity, crater lakes, beach berms, beach ridges, terminal moraines, ancient glacial lakes, the 1964 earthquake, and raised terraces.
- **Prepare geologic fact sheets, website content, and other interpretive products**:
    - **Brooks Camp area geology**. The Brooks Camp area is the most visited area in the park, so geologic information about the immediate area would be useful for visitors.
    - **Ukak Falls geology**. The Ukak Falls area is the most visited area outside of Brooks Camp, so geology information about the Naknek Formation, its fossils, and the ignimbrite would be useful.
    - **1912 Novarupta eruption and Valley of Ten Thousand Smokes**. Many park information newsletters and interpretive products contain information about the 1912 eruption and its deposits, but a simplified fact sheet describing the features is not available.
    - **Glacial history of Naknek Lake area**. Most visitors to Katmai fly over the spectacularly exposed glacial moraines and other glacial features of the area. A fact sheet describing these features with a map pointing out the main features seen from the air along common flight paths would provide visitors with an aerial guide to the geomorphic features of the park.

Appendix C: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2016).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by Congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include… erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089 (coral reefs) (1998)** calls for reduction of impacts to coral reefs. **Executive Order 13158 (marine protected areas) (2000)** requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 16 USC § 1901 et seq**. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC § 1 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to -demonstrate bona fide title to mineral rights; -submit a plan of operations to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.
Geothermal	**Geothermal Steam Act of 1970, 30 USC § 1001 et seq. as amended in 1988**, states that -no geothermal leasing is allowed in parks; -"significant" thermal features exist in 16 park units (features listed by the NPS at **52 Fed. Reg. 28793-28800** [August 3, 1987], and thermal features in Crater Lake, Big Bend, and Lake Mead); -NPS is required to monitor those features; and -based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable	**Section 4.8.2.3** requires NPS to -preserve/maintain integrity of all thermal resources in parks. -work closely with outside agencies, and -monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil and Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq**. do not authorize the BLM to lease federally owned minerals in NPS units. Exceptions: Native American Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, (25 USC § 396)**, and the **Indian Leasing Act of 1938 (25 USC §§ 396a, 398 and 399)** and **Indian Mineral Development Act of 1982 (25 USC §§ 2101-2108)**, all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. BLM regulations at 4**3 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. Regulations re: Native American Lands within NPS Units: **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC §§ 2101-2108)**. **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Appendix D: Scoping Participants

The following people attended the GRI scoping meeting for the Southwest Alaska Network, held on 14–18 February 2005 or a follow-up report writing kick-off meeting held on 27 January 2015. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2005 Scoping Meeting Participants

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

2015 Report Kick-off Participants

Name	Affiliation	Position
Michelle Coombs	USGS Alaska Volcano Observatory	Research Geologist
Judy Fierstein	USGS California Volcano Observatory	Research Geologist
Mike Fitz	NPS Katmai/Aniakchak	Visual Information Specialist
Troy Hamon	NPS Katmai/Aniakchak	Natural Resources Manager
Chad Hults	NPS Alaska Region/Geologic Resources Inventory	Geologist
Peter Kirchner	NPS Southwest Alaska Network	Physical Scientist
Katie Myers	NPS Lake Clark/Katmai/Aniakchak	Museum Curator
Dale Vinson	NPS Katmai/Aniakchak	Cultural Resources Specialist
Roy Wood	NPS Katmai/Aniakchak	Chief of Interpretation

NPS 127/134578, September 2016

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U.S. Department of the Interior

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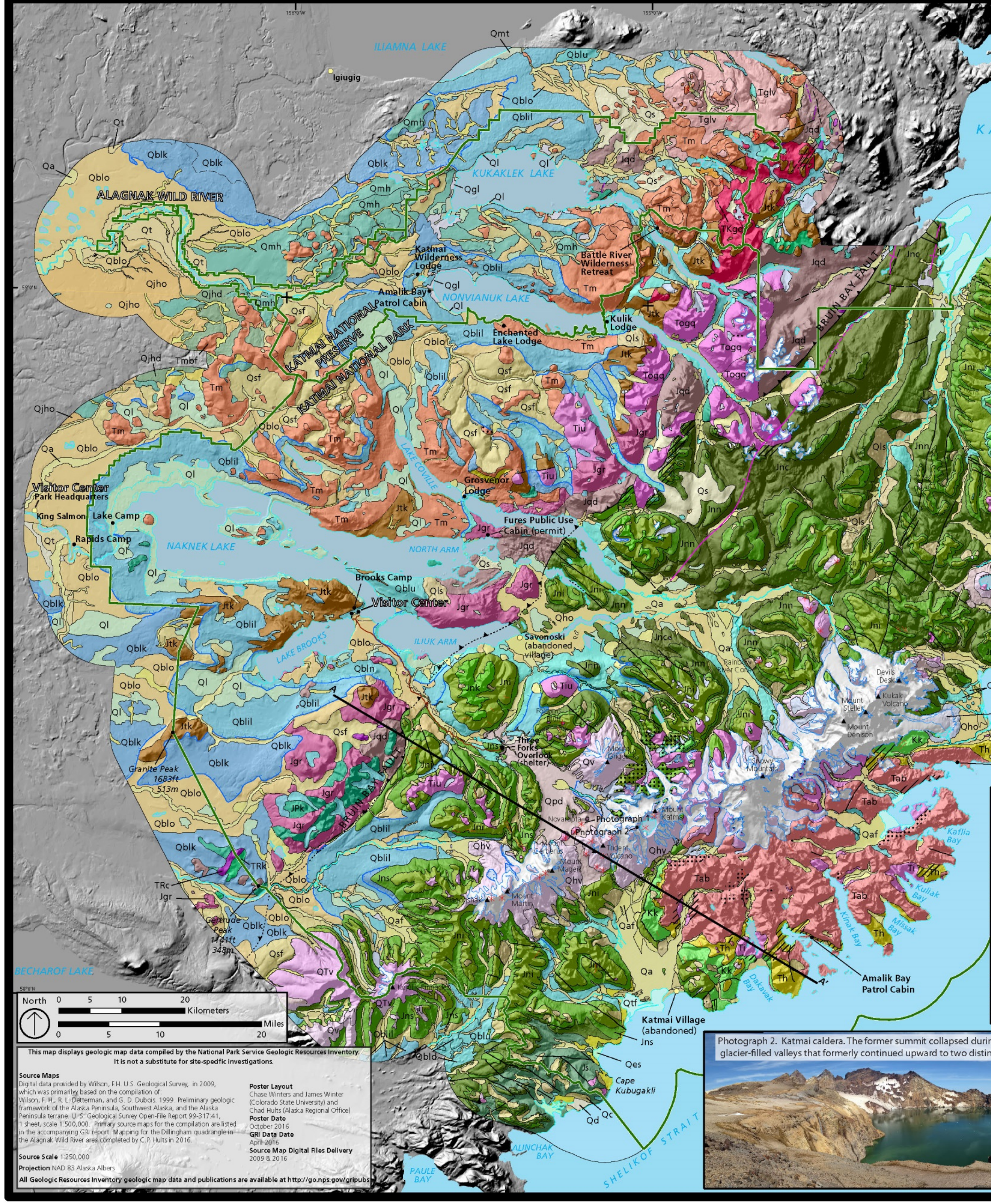
Geologic Map of Katmai National Park and Preserve and Alagnak Wild River

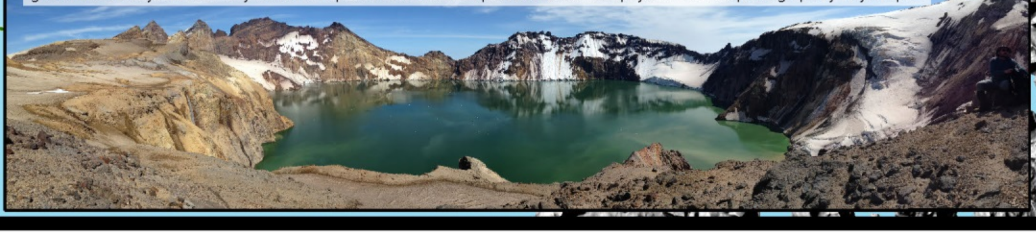
Alaska

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



Photograph 1. Novarupta Dome. The dome was extruded out of the source vent of the 1912 eruption. NPS photograph by Mike Fitz.



Photograph 2. Katmai caldera. The former summit collapsed during the 1912 eruption. The steep walls of the caldera truncate glacier-filled valleys that formerly continued upward to two distinct peaks. AVO/UAF-Geophysical Institute photograph by Taryn Lopez.

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

Source Maps
Digital data provided by Wilson, F.H. U.S. Geological Survey, in 2009, which was primarilyy based on the compilation of:
Wilson, F. H., R. L. Detterman, and G. D. Dubois. 1999. Preliminary geologic framework of the Alaska Peninsula, Southwest Alaska, and the Alaska Peninsula terrane. U. S. Geological Survey Open-File Report 99-317:41, 1 sheet, scale 1:500,000. Primary source maps for the compilation are listed in the accompanying GRI report. Mapping for the Dillingham quadrangle in the Alagnak Wild River area completed by C.P. Hults in 2016.

Source Scale 1:250,000

Projection NAD 83 Alaska Albers

Poster Layout
Chase Winters and James Winter (Colorado State University) and Chad Hults (Alaska Regional Office)

Poster Date
October 2016

GRI Data Date
April 2016

Source Map Digital Files Delivery
2009 & 2016

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

NPS Boundary

Infrastructure
City/village; Point of interest
Valley of Ten Thousand Smokes Road

Volcanic Point Features
Cone, plug, dome
Vent
Volcano

Geologic Cross Section Line
A-A'; see Plate 3

Geologic Contacts
Known or certain, dashed where approximate, short dashed where inferred, dotted where concealed '?' where queried
Water or shoreline
Ice or glacial

Caldera Boundary Line Features
Caldera boundary, known or certain

Glacial Feature Lines
End moraine, known or certain

Geologic Line Feature
Wave-cut scarps, known or certain

Geologic Lineament Line Features
Lineament, known or certain

Folds
Anticline, known or certain, dotted where concealed, '?' where queried
Syncline, solid where known or certain, dashed where inferred, dotted where concealed, '?' where queried

Faults
Thrust fault, known or certain, dotted where concealed
Normal, oblique, strike-slip or unknown offset fault, solid where known or certain, dashed where appoximate, short dashed where inferred, dotted where concealed, '?' where queried

Linear Dikes
Td - Dikes (Tertiary), known or certain

Alteration and Metamorphic Areas
Area of hydrothermal alteration
Area of contact metamorphism

Geologic Units

Water

Glaciers

Qs — Surficial deposits (Quaternary)
Undifferentiated unconsolidated deposits

Qtf — Tidal flat deposits (Holocene)
Well-sorted and stratified, subtidal silt, and gravel

Qa — Alluvial deposits (Quaternary)
Poorly to well sorted and stratified, rounded sand, gravel, and boulders

Qb — Beach deposits (Quaternary)
Moderately well sorted, locally stratified sand, gravel, and lag boulders

Qes — Estruarine deposits (Quaternary)
Silt and fine sand, typically containing organic content

Qaf — Alluvial fan deposits (Quaternary)
Poorly to moderately sorted angular alluvial deposits forming fans

Qc — Colluvium (Quaternary)
Coarse angular blocks forming cones below steep slopes

Qsf — Solifluction deposits (Quaternary)
Silt and organic deposts mixed with angular blocks

Qls — Landslide deposits (Quaternary)
Chaotic angular debris forming lobes below steep slopes

Qt — Alluvial terrace deposits (Quaternary)
Alluvial deposits forming terraces above modern floodplains

Qac — Abandoned channel deposits (Quaternary)
Alluvial deposits in abandoned channels, commonly located in front of moraines

Ql — Lacustrine deposits (Quaternary)
Silt and fine sand, and local wave-cut terraces of beach deposits

Qsw — Swamp deposits (Quaternary)
Organic silt and clay

Qmt — Marine terrace deposits (Quaternary)
Wave-cut terraces topped by beach deposits raised above modern sea level

Qd — Eolian deposits (Quaternary)
Fine-to medium-grained sand, or ash and lapilli-sized pumice forming dunes

Qm — Moraines and other glacial deposits (Quaternary)
Unsorted, unstratified boulders, gravel, sand, and clay, locally stratified

Qsrg — Superglacial drift and rock glacier deposits (Quaternary)
Angular unsorted debris with interstitial ice or overlying ice

Qhg — Glacial deposits of Holocene glaciations (Holocene)
Glacier deposits that are witin 3 km (1.5 mi) from modern glaciers

Qho — Outwash deposits of Holocene glaciations (Holocene)
Poorly to moderately-well sorted sand and gravel forming plains in front of moraines

Qv — Volcanic rocks, undivided (Quaternary)
Undifferenciated volcanic rocks, mainly andesite and dacite flows, tuff, and breccia

Qvd — Volcanic domes (Quaternary)
Andesite, dacite, and rhyolite domes

Qpd — Pyroclastic and debris-flow deposits (Holocene and late Pleistocene?)
Nonsorted and variably indurated ash and blocks in VTTS and at Kaguyak volcano

Qafd — Ash-flow and ash-fall deposits (Quaternary)
Unconsolidated ash on Katmai and Kaguyak volcanoes

QTv — Older volcanic rocks (Quaternary and Pliocene?)
Andesite and dacite lava flows, breccias, and tuffs

Qblu — Brooks Lake Glaciation, drift, undivided (Pleistocene)
Glacier deposits that are only slightly weathered

Qblik — Brooks Lake Glaciation, drift of Iliuk Advance, drift deposits (Pleistocene)
Glacier deposits forming end moraines 50-70 km from source

Qbld — Brooks Lake Glaciation, drumlin field deposits (Pleistocene)
Glacier deposits forming lobate hills with long axis in direction of glacier flow

Qblo — Brooks Lake Glaciation, drift and outwash deposits, undivided (Pleistocene)
Outwash deposits in front of Brooks Lake glaciation moraines

Qbln — Brooks Lake Glaciation, drift of Newhalen Advance, drift deposits (Pleistocene)
Glacier deposits forming end moraines 70-90 km from source

Qblil — Brooks Lake Glaciation, drift of Iliamna Stade, drift deposits (Pleistocene)
Glacier deposits forming end moraines 70-120 km from source

Qblk — Brooks Lake Glaciation, drift of Kvichak Advance, drift deposits (Pleistocene)
Glacier deposits forming end moraines 90-140 km from source

Qgl — Glaciolacustrine deposits (Pleistocene)
Lacustrine deposits associated with Brooks Lake or older glacial deposits

Qmh — Mak Hill Glaciation, drift deposits (Pleistocene)
Moderately weathered glacier deposits forming discontinuous ridges 100-140 km from source

Qmho — Mak Hill Glaciation, outwash deposits (Pleistocene)
Outwash deposits in front of Mak Hill glaciation moraines

Qjhd — Johnson Hill drift, drift deposits (Pleistocene)
Highly weathered glacier deposits forming subdued ridges 140-160 km from source

Qjho — Older outwash deposits (Pleistocene)
Outwash deposits in front of Hohnson Hill glaciation moraines

Tglv — Gibraltar Lake Tuff (Tertiary, Pliocene? to Oligocene?)
Rhyolitic crystal and lithic tuff

Tab — Volcanic rocks of Barrier Range (Late Tertiary, early Pliocene to late Oligocene)
Andesitic and dacitic porphyritic lava flows, and tuffs and breccias

Tiu — Intrusive rocks, undivided (Pliocene and late Miocene, Granitic plutonic rocks?)
Quartz diorite, granodiorite, and tonalite hypabyssal stocks and dikes

Th — Hemlock Conglomerate (late Oligocene)
Fluvial sandstone and conglomerate and minor siltstone, shale, and coal

Togq — Granodiorite and quartz diorite (Oligocene)

Tm — Meshik Volcanics (Tertiary, Oligocene and Eocene)
Basalt, andesite, dacite lava flows, pyroclastic flows, and tuff

Tc — Copper Lake Formation (early Eocene and Paleocene?)
Fluvial conglomerate and interbedded sandstone and siltstone

TKgd — Granodiorite (Tertiary and (or) Cretaceous)

Ksr — Sedimentary rocks (Cretaceous)
Fluvial, crossbedded sandstone with lag gravels in channels

Kk — Kaguyak Formation (Late Cretaceous; Maestrichtian and Campanian)
Lower marine siltstone and thin limestone; upper graywacke and siltstone

Kp — Pedmar Formation (Early Cretaceous; Albian)
Marine sandstone and minor amounts of siltstone and shale

Khe — Herendeen Formation (Early Cretaceous; Barremian and Hauterivian)
Marine calcareous sandstone and interbedded siltstone and shale

Kst — Staniukovich Formation (Early Cretaceous; Valanginian and Berriasian)
Marine cross-bedded sandstone

Kqm — Quartz monzonite (Late Cretaceous)

JPk — Kakhonak(?) Complex (Late Jurassic? to Permian?)
Quartzite, schist, amphibolite, gneiss, and migmatite

Jn — Naknek Formation (Late Jurassic; Tithonian to Oxfordian)
Arkosic conglomerate, sandstone, and shale

Jnk — Naknek Formation, Katolinat Conglomerate Member (Late Jurassic; Tithonian)
Fluvial and near-shore pebble-cobble conglomerate and interbedded sandstone

Jnc — Naknek Formation, Chisik Conglomerate Member (Late Jurassic; Oxfordian)
Fluvial, thick-bedded conglomerate with cross-bedded sandstone

Jni — Naknek Formation, Indecision Creek Sandstone Member (Late Jurassic; Tithonian and Kimmeridgian)
Nearshore marine to shallow shelf arkosic sandstone and siltstone

Jns — Naknek Formation, Snug Harbor Siltstone Member (Late Jurassic; Kimmeridgian and Oxfordian)
Shelf and slope sandy siltstone and shale, contains calcareous concretions

Jnn — Naknek Formation, Northeast Creek Sandstone Member (Late Jurassic; Oxfordian)
Aeolian and fluvial, laminated, fine to medium-grained, cross-bedded sandstone

Jgr — Granite and granodiorite (Late? and Middle Jurassic)

Jqd — Tonalite and quartz diorite (Middle and Early Jurassic)

Jgb — Diorite and gabbro (Middle and Early Jurassic)

Js — Shelikof Formation (Middle Jurassic; Callovian)
Shallow marine thick-bedded to massive graywacke and conglomerate

Jtk — Talkeetna Formation (Early Jurassic)
Basalt and andesite flows, tuff, volcaniclastic sandstone and conglomerate

TRk — Kamishak Formation (Late Triassic; Norian)
Limestone and interbedded basalt flows and breccia

TRc — Cottonwood Bay Greenstone (Late Triassic; Norian?)
Altered submarine basalt flows and diabase sills

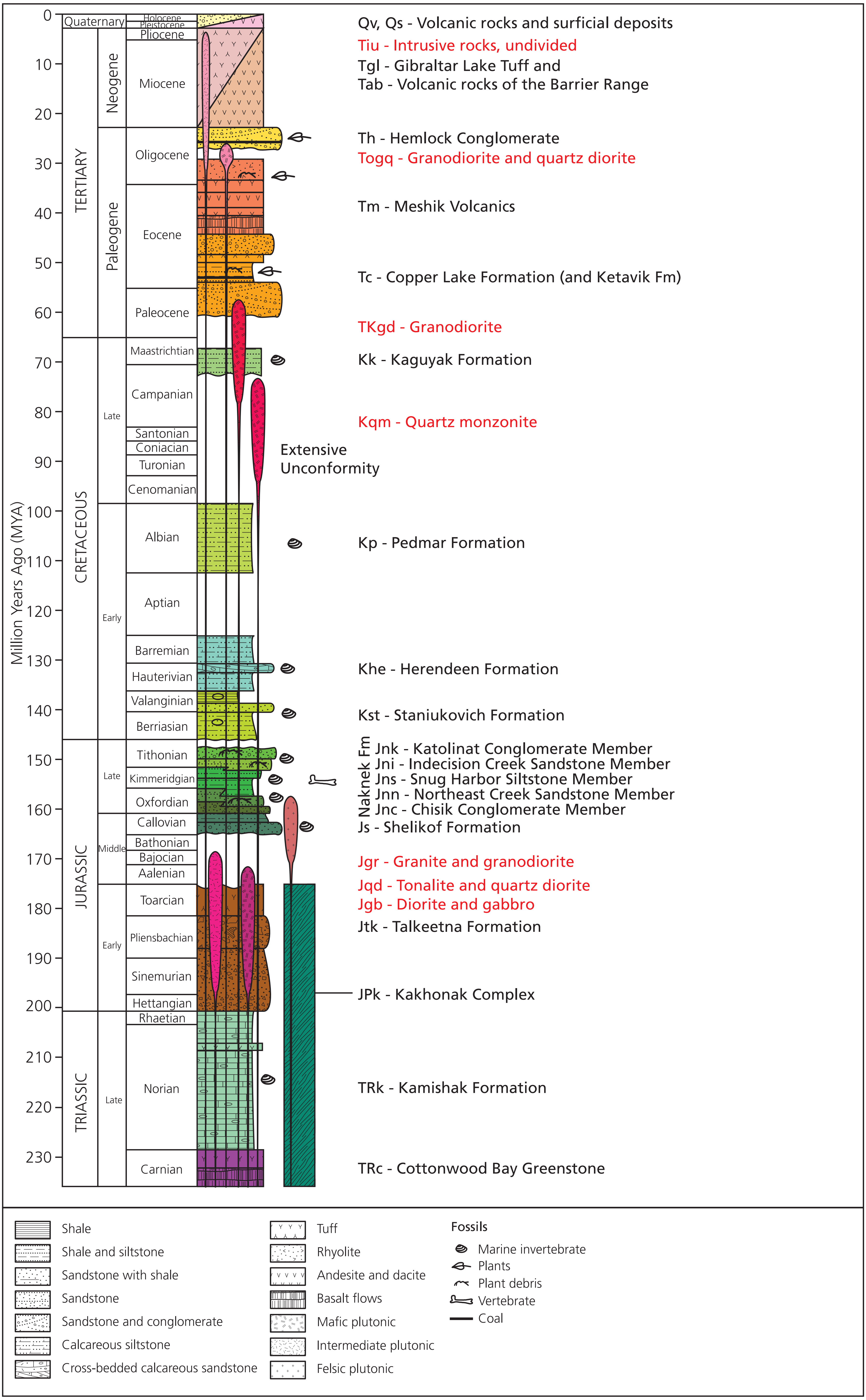


Plate 2. Stratigraphic chart of the bedrock units of the Katmai area. Colors of geologic units correspond to those used in Plate 1. Red unit labels and names signify plutonic (intrusive) rocks. Blank areas without sedimentary units are generally time periods of uplift or quiescence, which create unconformities in the stratigraphic record.

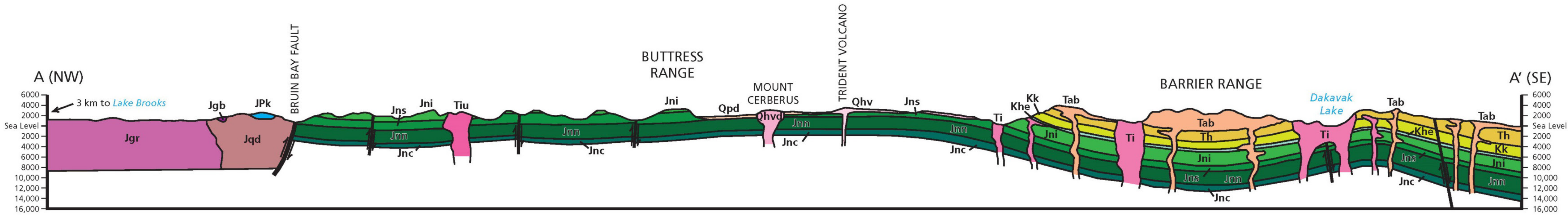


Plate 3. Cross-section from near Brooks Lake to Amalik Bay showing the bedrock and volcanic units (see Plate 1 for location and unit names). Modified from Riehle et al. (1993).

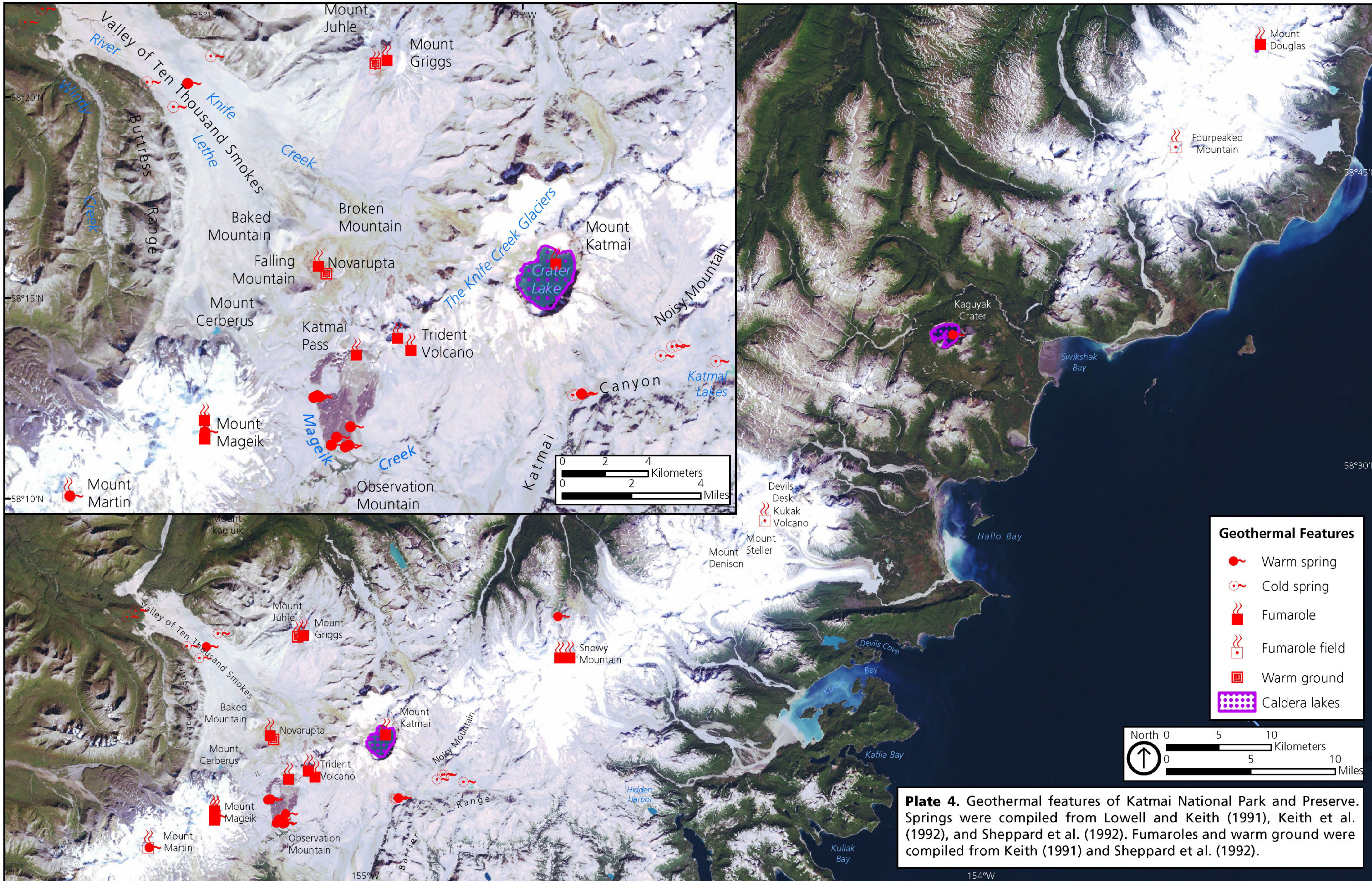


Plate 4. Geothermal features of Katmai National Park and Preserve. Springs were compiled from Lowell and Keith (1991), Keith et al. (1992), and Sheppard et al. (1992). Fumaroles and warm ground were compiled from Keith (1991) and Sheppard et al. (1992).