National Park Service
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Natural Resource Stewardship and Science

Bering Land Bridge National Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2024

ON THE COVER
Photograph of a volcanic feature, "tumulus," that formed in the Lost Jim lava flow (map unit Qlj). This flow is composed of pahoehoe lava, a type of lava characterized by smooth, ropy surfaces. Tumuli are common pahoehoe feature and form by injection of lava beneath an overlying solidified crust, creating a domed structure. The Lost Jim lava flow erupted about 1,605 years ago, making it the youngest of five distinct volcanic formations that together form a plateau around Imuruk Lake. NPS photograph courtesy of David Swanson (NPS Arctic Inventory and Monitoring Network).

THIS PAGE
Photograph of the granite tors near Serpentine Hot Springs. Tors are exposed mases of rock (usually jointed granite) that rise abruptly from the surrounding landscape. The tors near Serpentine Hot Springs are composed of rock belonging to the Oonatut Granite Complex (map unit Ktg), one of the tin-bearing granitic intrusions that formed on the Seward Peninsula between 80 million and 70 million years ago. National Park service photograph courtesy of Bering Land Bridge National Preserve.

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

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Contents

Executive Summary ..... **ix**
Products and Acknowledgments ..... **xv**
GRI Products xv
Acknowledgments xv
Geologic Setting and Significance **1**
Park Establishment and History 1
Geologic Setting 2
Geologic Significance and Connections 4
Geologic Features and Processes **9**
Bedrock 9
Volcanism 16
Cave Resources 27
Serpentine Hot Springs 30
Quaternary Surficial Deposits 32
Permafrost and Thermokarst 34
Coastal Features 36
Paleontological Resources 40
Geologic History **43**
Terrane Translation and Accretion 43
Late Proterozoic Eon to Devonian Period 43
Late Jurassic to Earliest Cretaceous Periods 44
Cretaceous Period 45
Eocene to Early Oligocene Epochs 46
Late Oligocene to Holocene Epochs 46
Geologic Resource Management Issues **47**
Geologic Resource Management 47
Geohazards 47
Abandoned Mineral Lands Mitigation 52
Oil and Gas Development Potential 53
Geothermal Features Inventory and Monitoring 55
Caves and Associated Landscape Management 56
Permafrost Monitoring 56
Coastal Issues 59
Paleontological Resources Inventory, Monitoring, and Protection 60
Geologic Map Data **63**
Geologic Maps 63
Source Maps 63
GRI GIS Data 63
GRI Map Poster 64
Use Constraints 64
Literature Cited **65**
Additional References **81**
Geology of National Park Service Areas 81
NPS Resource Management Guidance and Documents 81
Climate Change Resources 81
Geological Surveys and Societies 81
Appendix A: History of Geologic Exploration **83**
Appendix B: Scoping Participants **91**
Appendix C: Geologic Resource Laws, Regulations, and Policies **93**

Figures

Figure 1. Map of Bering Land Bridge National Preserve and surrounding area. xvi
Figure 2. Photographs of Nome in 1900 and 1901 during the beginning of the Nome Gold Rush. 2
Figure 3. Map of Beringia. 3
Figure 4. Map contrasting the glacier extent in North America during the last glacial period and the present. 4
Figure 5. Geologic time scale. 5
Figure 6. Pressure-temperature diagram showing metamorphic facies. 10
Figure 7. Photograph of unit DOx. 11
Figure 8. Photographs of bedded metaturbidites belonging to unit DCks at Sullivan Bluffs. 12
Figure 9. Map of the igneous plutonic rocks on the Seward Peninsula. 13
Figure 10. Diagram showing the classification of felsic intrusive igneous rocks. 14
Figure 11. Photograph of porphyritic biotite granite belonging to the outer zone of the Oonatut Granite Complex. 15
Figure 12. Photograph of the granite tors around Serpentine Hot Springs. 17
Figure 13. Diagrams showing different models of tor formation. 17
Figure 14. Map of the geologic units around Imuruk Lake. 19
Figure 15. Photograph of the Twin Calderas. 20
Figure 16. Photograph showing the contrasting Lost Jim and Camille lava flows. 21
Figure 17. Photograph of the Lost Jim cone. 21
Figure 18. Photograph of the Lost Jim lava delta. 22
Figure 19. Photographs showing some of the features of the Lost Jim lava flow. 23
Figure 20. Map of the Espenberg volcanic field. 24
Figure 21. Photograph of scoria from the cinder cones on Devil Mountain. 25
Figure 22. Photograph of maar-derived deposits found along the rim of the Devil Mountain maar. 25
Figure 23. Map of the Bering Sea volcanic province distribution. 26
Figure 24. Photograph of one of the Trail Creek Caves. 27
Figure 25. Photographs showing the different rock types found at Trail Creek caves. 27
Figure 26. Series of diagrams showing how a lava tube forms. 28
Figure 27. Map and photos of Lost Jim lava tubes. 29
Figure 28. Photograph of a sea cave or alcove. 30
Figure 29. Map of hot springs and granitic plutons on the Seward Peninsula. 31
Figure 30. Map showing the location of geothermal sites in Alaska. 32
Figure 31. Photograph of yedoma. 33
Figure 32. Photograph of the Kuzitrin River. 33
Figure 33. Map of mean annual temperature and permafrost in the preserve. 34
Figure 34. Photographs showing permafrost-related geomorphic features. 35
Figure 35. Map showing a satellite view of the thaw-lake plain. 36
Figure 36. Photographs of coastal geomorphology found in the preserve. 38
Figure 37. Map and graph showing the decline of September sea ice during the 1979–2017 period. 39
Figure 38. Map of erosion and accretion rates through the period of 1950–2003. 40
Figure 39. Photograph of a mammoth tooth. 41
Figure 40. Photograph of petrified wood. 42
Figure 41. Map of the terranes of Alaska. 44
Figure 42. Map showing the paleogeography of the Middle Ordovician (approximately 458 million years ago). 45
Figure 43. Map of the Arctic Alaska-Chukotka microplate and the Canada and Amerasian basins. 45
Figure 44. Map showing the two volcanic areas in the preserve. 48
Figure 45. Geohazard map. 50
Figure 46. Photograph of a large piece of ice-rich ground detaching from the coast. 50
Figure 47. Photograph showing solifluction lobes in the Bendeleben Mountains. 51
Figure 48. Earthquake probability map of Alaska. 52
Figure 49. Diagram showing different types of faults. 53
Figure 50. Photograph of the miners cabin and partially full barrel at Humbolt Creek mine. 53
Figure 51. Map showing estimated undiscovered oil and gas. 54
Figure 52. Photograph of Serpentine Hot Springs. 55

Figure 53. Photographs showing erosional features related to thawing permafrost. 57
Figure 54. Map showing susceptibility of terrain to active-layer detachments. 57
Figure 55. Maps showing projected ground temperature for the 1950s, 2000s, 2050s, and 2090s. 58
Figure 56. Maps showing projected active layer thickness for the 1950s, 2000s, 2050s, and 2090s. 59
Figure 57. Painting of the ice cliffs of Eschscholtz Bay. 85
Figure 58. Fossil illustration by Richardson (1854). 86

Tables

Table 1. Ages of volcanic eruptions in the preserve. 18
Table 2. Sizes of the Espenberg maars. 23
Table 3. Impacts of tephra fallout. 49
Table 4. GRI GIS data layers for Bering Land Bridge National Preserve. 64
2007 Scoping Meeting Participants 91
2017 Conference Call Participants 91

Executive Summary

The Geologic Resources Inventory (GRI) program provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resources Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2008 and a follow-up report writing meeting in 2017 (see Appendix B). This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. Chapters of this report discuss the geologic setting, highlight distinctive geologic features and processes, describe the geologic history leading to the present-day landscape, address geologic issues facing resource managers, and provide information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

Bering Land Bridge National Preserve (referred to as the "preserve" throughout this report) protects a landscape that once lay in the heart of a landmass known as "Beringia." Beringia stretched from the Mackenzie River in Canada to the Lena River in Russia and was up to 1,000-km (620-mi) wide. The Bering Land Bridge formed the center of Beringia, uniting eastern (North America) and western (Russia) Beringia during the glacial periods of the Pleistocene Epoch (2.58 million–11,700 years ago). Animals such as mammoths, bison, muskoxen, and even early humans used the Bering Land Bridge to travel from Asia to North America. As climate warmed at the end of the Pleistocene Epoch, the Bering Land Bridge was flooded, severing the terrestrial connection between North America and Asia. The geologic and paleontological resources in Bering Land Bridge National Preserve contain a record of Beringia. The protection, study, and interpretation of this record is one of the main reasons the preserve was established.

In addition to containing a geologic record of Beringia, the preserve encompasses a much longer history in its bedrock, which dates back to the late Proterozoic Eon (1.0 billion–541 million years ago). Geologic features tell the story of the preserve's evolution since that time. This story includes long-distance tectonic translation, the building and collapse of the Brooks Range, and relatively recent volcanism. Ongoing geologic processes such as erosion, deposition, volcanism, and slope movements continue to shape the preserve's landscape today. The preserve's geologic features and processes are important natural resources, significant interpretive opportunities, and factors vital in addressing visitor safety and resource management.

Geologic features and processes covered in this report include the following:

- Bedrock. The bedrock of Bering Land Bridge National Preserve has been split into four groups based on rock type, age, tectonic affinity, and metamorphic history: (1) Nome Complex, (2) York terrane, (3) high-grade metamorphic and associated igneous rocks, and (4) Mesozoic and Cenozoic igneous rocks. The Cenozoic volcanic rocks that are included in this last group are discussed in the "Volcanism" section. The Nome Complex contains rocks of various lithologies that exhibit structural and metamorphic features formed during a shared high-pressure metamorphic event. Before the metamorphic event that altered the rocks, the Nome Complex consisted of sedimentary rocks deposited on a carbonate platform. During the Jurassic to Cretaceous Periods, subduction of the Nome Complex produced blueschist-facies metamorphic mineral assemblages in many of the rocks. The Nome Complex reached peak pressures of around 1.2 GPa (nearly 12,000 times the pressure at Earth's surface) at about 40 km (25 mi) deep. Subsequent extension brought the Nome Complex back up to the surface of the earth. The Nome Complex reached peak temperatures during exhumation. During this time greenschist- to amphibolite-facies minerals locally overprinted the blueschist-facies mineral assemblages. The York terrane crops out near Ear Mountain in the western portion of the preserve. The York terrane has been split into two parts: (1) the York Mountains succession, a well-studied sequence of strata that is found in the central York Mountains, and (2) older rocks that are not as well understood. The York Mountains succession is generally not

metamorphosed and retains primary sedimentary features, while the units with uncertain affinities have undergone metamorphism up to low greenschist facies conditions. York terrane rocks that occur within preserve boundaries belong to this second more enigmatic group. High-grade metamorphic rocks, which have reached amphibolite-granulite facies, occur in the Kigluaik, Bendeleben, and Darby Mountains, as well as to the north of the Oonatut Granite Complex. The three metamorphic complexes (Kigluaik, Bendeleben, and Darby Mountains) consisting of high-grade metamorphic rocks surrounding plutons. Both the Bendeleben and Kigluaik metamorphic complexes form dome-shaped structures called gneiss domes, whereas the structure in the Darby Mountains is more complex. Gneiss domes are found all over the world and are associated with areas where the roots of mountains are exposed. Three suites of igneous plutons intruded the rocks on the Seward Peninsula during the Cretaceous Period: (1) plutons with an alkalic composition formed 110 million–96 million years ago, (2) calc-alkaline plutons formed 95 million–80 million years ago, and (3) tin-bearing granite plutons formed 80 million–69 million years ago. In the preserve, these Cretaceous intrusive rocks include the Oonatut Granite Complex (**Ktg**) exposed around Serpentine Hot Springs; the Crossfox Butte, Asses Ears, Virginia Butte, and Nimrod Hill stocks (**Ks**), which are exposed to the north and east of Imuruk Lake; and the Kuzitrin and Bendeleben plutons (**Kbk**), which occur in the Bendeleben Mountains in the southernmost part of the preserve.

- Volcanism. Volcanism has occurred intermittently in the preserve starting around 28 million years ago, with the majority of the activity occurring within the last 6 million years. Two volcanic fields exist in the preserve: (1) Imuruk volcanic field and (2) Espenberg volcanic field. The Imuruk volcanic field consists of 75 known volcanic vents and widespread lava flows. Hopkins (1963) divided the lava flows into five distinct volcanic formations that differ in terms of age: (1) Kugruk volcanics (28–26 million years old), (2) Imuruk volcanics (6.1 million–5.2 million years old), (3) Gosling volcanics (900,000–800,000 years old), (4) Camille lava flow (25,000–11,000 years old), and (5) Lost Jim lava flow (1,605 years old). The Lost Jim lava flow displays volcanic features typical of pahoehoe lava flows, including lava channels and tubes, skylights, shatter rings, tumuli, and lava-rise plateaus. Additionally, the Lost Jim lava flow contains atypical depressions around the outer periphery of the flow interpreted to be formed by lava-induced permafrost melt. The Espenberg volcanic field consists of five small shield volcanoes (Devil Mountain and four other unnamed topographic highs) and four volcanic craters called "maars." The shield volcanoes probably formed in the absence of permafrost, while the maars formed by the explosive interaction of magma and permafrost. The Espenberg maars are the four largest maars known on Earth (Begét et al. 1996), and include White Fish maar (160,000 years old), North and South Killeak maars (62,000 years old), and Devil Mountain maar (17,500 years old). Their exceptional size is the result of them forming via the interaction of magma with ice, as opposed to other maars that typically form through the interaction of magma and liquid water.
- Paleontological Resources. Paleontological resources, or fossils, occur within the preserve's bedrock and surficial deposits. The fossils in the preserve can broadly be divided into two groups: (1) Paleozoic fossils found in bedrock and (2) Cenozoic fossils found mainly in surficial deposits. Paleozoic (541 million–251.9 million years ago) fossils occur in the Nome Complex and York terrane. Metamorphism of the Nome Complex destroyed many of the fossils that may have originally been present and for the most part only sparse, poorly preserved fossils remain. The remaining fossils include corals, stromatoporoids, bryozoan, brachiopods, graptolites, conodonts, radiolarians, lapworthellids, and ichthyoliths. The York terrane is split into the Ordovician–Devonian (485 million–359 million years ago) York Mountains succession, located to the south of the preserve, and older rocks that are not as well understood. These older rocks range in age from the latest Proterozoic Eon to the Ordovician Period, and have yielded poorly preserved conodonts, chitinozoans, and brachiopods. The preserve also contains younger Cenozoic fossils that record the history of Beringia. Fossils in the preserve that correspond to the time of Beringia include mammals (e.g., mammoths, horses, and bison), palynomorphs, plant macrofossils, insects, arachnids, ostracods, mollusks, charophytes, rhizopods, and diatoms. One notable Pleistocene deposit that contains fossils is the Kitluk Paleosol. The Kitluk Paleosol is an ancient soil horizon that dates to the height of the last glacial period (21,500 years ago) and preserves a snapshot of the Beringia environment on the Seward Peninsula during that time.
- Quaternary Surficial Deposits. General types of Quaternary sediments in the preserve include eolian (windblown) silt deposits called "loess," colluvial (slope) deposits, alluvium (stream deposits), lacustrine (lake) sediments, and coastal marine deposits. Eolian silt deposits almost completely cover the northern half of the preserve and can also be found overlying the older lava flows around Imuruk

Lake. Of note, the eolian deposits on the "upper" coastal plain of the preserve (mapped by Jorgenson [2001]) contain large amounts of ground ice that formed at the same time as the loess. The syngenetic accumulation of loess, ground ice, and permafrost formation resulted in tens of meters of ice-rich sediment known as "yedoma." Slopes of the preserve contain a variety of colluvial deposits including talus and scree on the steepest slopes; solufluction deposits; active-layer detachments; and mixtures of loess, peat, and frost-churned bedrock. Alluvium is present along all the major streams in the preserve, with modern river floodplains containing most of the alluvium. Alluvial deposits consist of sand, gravel, and silt, commonly mantled by a layer of peat in low-energy areas. Lacustrine deposits and Holocene peat cover most of the preserve's "lower" coastal plains. The lacustrine deposits are mainly formed in thermokarst lakes, and the peat deposits generally form in poorly drained former thermokarst lake basins.

- Permafrost and Thermokarst. Most of the preserve is within the zone of continuous permafrost, which means that permafrost underlies more than 90% of the landscape (Jorgenson et al. 2008). Permafrost is ground (soil, sediment, or rock, plus any ice or organic material) that remains frozen for at least two consecutive years. Permafrost thickness in the preserve is mostly unknown, but boreholes scattered throughout the Seward Peninsula revealed thicknesses between 5 and 107 m (16 and 350 ft). Based on the mean annual temperature distribution in the preserve and permafrost thickness distribution elsewhere in Alaska, the permafrost is probably thickest on the northern coastal plain of the preserve. Geomorphic features related to permafrost or thawing permafrost are found throughout the preserve. These features include solifluction lobes, pingos, ice-wedge polygons, and thremokarst lakes. By the 2050 decade, Panda et al. (2016) predict a 2°C (4°F) rise in average permafrost temperature and a 5 to 20 cm (2 to 8 in) increase in active layer thickness in the preserve. This would result in only a small amount of permafrost lost but would trigger widespread thermokarst and landscape change because of a thickening of the active layer. Landscape changes are expected to be particularly dramatic in the ice-rich coastal plains of the northern part of the preserve.
- Coastal Features. Bathymetry offshore from the preserve slopes gently, reaching depths of only 10 m (33 ft) between 3 and 15 km (2 and 9 mi) offshore. This is because the preserve is bordered by a shallowly submerged region of continental crust called the Bering-Chukchi shelf that connects North America and Asia. During glacial periods, lowered sea level exposed the Bering-Chukchi shelf and created the Bering Land Bridge. During interglacial periods (such as today), higher sea level causes the Bering-Chukchi shelf to become flooded, severing the terrestrial link between North America and Asia. The northwest coast of the preserve is dominated by several large coastal lagoons protected by barrier islands and spits and backed by ice-rich tundra bluffs. The east-facing coast is composed of narrow sandy beaches backed by ice-rich tundra bluffs, the Nugnugaluktuk and Goodhope estuaries, and bedrock cliffs. Cape Espenberg, a series of beach ridges that comprise a 1–2-km- (0.6–1.2-mi-) wide and 29-km- (18-mi-) long spit separates the northwest- and east-facing coasts. During the winter and parts of the spring and fall landfast sea ice, which envelopes the coast of the preserve, protecting it from storms and lessening coastal erosion. Sea ice in the Arctic has been declining since it was first monitored in 1979, and between 1982 and 2014 the amount of time sea ice persisted just offshore the preserve decreased by about 5 weeks per year. Continued reduction in landfast sea ice is predicted to increase coastal erosion.
- Cave Resources. Caves exist in the preserve in three contexts: (1) Trail Creek caves in marble outcrops of the Nome Complex, (2) lava tubes in the Lost Jim lava flow, and (3) sea caves or alcoves near the eastern end of the preserve's coast. Trail Creek caves are a set of 13 caves known to contain archeological and paleontological resources. The caves range in length from 2.5 to 31 m (8.2 to 102 ft). Preferential development of caves in schist pockets could indicate that weathering and transport of the more friable schist contributed to the formation of the caves. Thirty-four lava tubes have been mapped in a small portion of the Lost Jim lava flow, and many more likely occur in other areas of the flow. Mapped lava tubes range in size from 10 m (33 ft) to more than 100 m (328 ft) long. During mapping, not all caves were explored to their full length, and many contiguous caves probably have been separated by subsequent roof collapse. Sea caves or alcoves exist near the eastern end of the preserve's coast and are visible in imagery from the NOAA Alaska ShoreZone database. The sea caves have not yet been investigated, but numerous caves are visible along the 4.5-km (2.8-mi) stretch of coast where bedrock units belonging to the Nome Complex crop out.
- Serpentine Hot Springs. Serpentine Hot Springs is the only geothermal site within the preserve. It consists of two distinct thermal areas (Serpentine Hot Springs proper and Arctic Hot Springs) that are located about 600 m (1,970 ft) apart on Hot Springs

Creek. The waters of Serpentine and Arctic Hot Springs are likely fed by the same source as evidenced by their virtually identical chemical compositions and similar maximum subsurface temperatures of 127 ±3°C (260 ± 5°F). Groundwater chemistry indicates the waters are meteoric in origin with a saline component that arises from bedrock leaching or seawater. Many of the hot springs in northern Alaska, including Serpentine Hot Springs, are closely associated with granitic plutons. The rocks beneath and around Serpentine Hot Springs belong to a Late Cretaceous biotite granite stock called the Oonatut Granite Complex (associated with map unit **Ktg**; see poster, in pocket). Fractures in the granite allow meteoric water to circulate particularly deep. Deeply circulating water heats up because of the geothermal gradient and then returns to the surface along fractures in the rock. Subsurface-temperature estimates for Serpentine Hot Springs indicate that the thermal waters circulate to depths of 3.3–5.3 km (2.1–3.3 mi).

Two meetings—one in 2008 and one in 2017—were held to discuss GRI products, geology of the park units, and resources management issues. Participants at these meetings included NPS natural resource managers, NPS Arctic Network staff, NPS Alaska Region specialists, and geologists with expertise in the Bering Land Bridge National Preserve area. At these meetings, participants identified the following geologic resource management issues:

- Geohazards. Geologic hazards, commonly referred to as "geohazards," include volcanic eruptions, earthquakes, landslides, and permafrost–thaw related land collapses. Neither of the two volcanic fields within the preserve have been active within historical time (since about 1760), and the US Geological Survey (USGS) Alaska Volcano Observatory does not monitor them. Volcanic hazards that could be associated with an eruption in the preserve today include active lava flows, tephra fallout, and base surges. Of these hazards, tephra fallout has the potential to cause the most widespread impact to park resources. Although active lava flows and base surges could result in significant impacts in localized areas, these hazards would occur in remote areas of the preserve and the chance of loss of property or life is not a great. Most of the preserve has gentle relief, so the majority of areas have a low potential for landslides. Most slope movements in the preserve are related to permafrost thaw. These include detachment of large blocks along the coast, solifluction, and active-layer detachments (discussed more in "Permafrost Monitoring"). According to the USGS 2007 seismic hazard map of Alaska, the preserve has a 10% probability for an earthquake to cause peak ground acceleration of between 6% and 17% of the acceleration of gravity (9.8 m/s2 [32 ft/s2]) in the next 50 years. This amount of peak horizontal acceleration would be perceived as moderate to strong shaking and could potentially cause very light to light damage. The direct impacts of an earthquake in the preserve would be limited because there is little infrastructure, but an earthquake near Nome, where park headquarters and the visitor's center is located, could pose a more substantial threat.
- Abandoned Mineral Lands Mitigation. Several small-scale placer gold mines (Humbolt Creek, Esperanza Creek, and Goose Creek) operated in what is now the preserve. The Humbolt Creek mining claim was valid as recently as the late 2000s. The abandoned placer gold mines and mining features that still exist are considered cultural resources, and 14 sites in the preserve are related to historic placer gold mining. This includes the Fairhaven Ditch historic canal, which is a 38-mi- (61-km-) long ditch used to transport water from Imuruk Lake to placer mining sites. An environmental site assessment at the Humbolt Creek mine noted a small amount of petroleum released into the ground from one of the barrels left on site. Mercury in a quantity near the clean-up limit of the Alaska Department of Environmental Conservation was also present at the Humbolt Creek mine in the soils beneath the blacksmith shop. The preserve's state of the park report (NPS 2016) recommended that the barrel be removed to prevent further release of petroleum into the environment.
- Oil and Gas Development Potential. The Kotzebue and Hope basins (known together as the Hope Basin Planning Area) are located to the north of the Seward Peninsula. Deposits assigned to these basins occur in the subsurface in the northern part of the preserve as well as offshore beneath the Kotzebue Sound and Chuckchi Sea. These basins contain an estimated 0.2 billion barrels of undiscovered oil and an estimated 3.8 trillion cubic feet barrels of undiscovered gas. There is potential for oil and gas development in the preserve in areas where the surface and subsurface rights are non-federally owned near Cape Espenberg. There is also the potential for offshore development adjacent to the preserve if the final Bureau of Ocean Energy Management (BOEM) 2019–2024 National Outer Continental Shelf Oil and Gas Leasing Program contains lease sales in the Hope Basin Planning Area. However, failure of the Cape Espenberg and Nimiuk Point wells to recover oil or gas makes the probability for renewed efforts to drill within the preserve relatively low. Additionally, the disinterest in past lease sales in the Hope Basin

Planning Area combined with the low resource estimates compared to other assessment areas of northern Alaska reduces the probability of offshore oil and gas development.

- Caves and Associated Landscape Management. The preserve currently contains 48 documented caves. Cave features are nonrenewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request (also see Appendix B). Trail Creek caves have received the most study of the caves within the preserve. Two of the Trail Creek caves were excavated by an archeologist in 1949 and 1950. All 13 caves were investigated by NPS archeologist in 1985, and NPS scientists mapped five of the 13 known caves in 2017. The Lost Jim lava flow contains 34 known lava tubes and likely many more that have yet to be documented. Given the size of the Lost Jim lava flow, multiple surveys will likely be needed to fully inventory the lava tubes. Imagery from the NOAA Alaska ShoreZone database shows sea caves or alcoves developed in bedrock near the eastern end of the preserve's coast. These caves have not yet been investigated or mapped by NPS staff.
- Coastal Issues. The coastal regions of the preserve contain important paleontological, archeological, and biological resources, so understanding changes in the coast is critical. The Arctic Network Inventory and Monitoring Program monitors coastal erosion in the preserve. Mean erosional rates were 0.68 m/yr (2.2 ft/yr) between 1950 and 1980, 0.26 m/yr (0.85 ft/yr) between 1980 and 2003, and 0.68 m/yr (2.2 ft/yr) between 2003 and 2014. Overall, coastal processes have become increasingly dynamic over time, which is likely related to climate–change related factors such as sea ice decline. Climate change–induced increases in storm strength in the Arctic are expected to contribute to future erosion. Sea level along the coast of the preserve is projected to rise in the future, with projections of 0.18–0.21 m (0.59–0.70 ft) by 2050 and 0.37–0.6 m (1.2–2.0 ft) by 2100. No NPS infrastructure exists along the coast of the preserve that would be threatened by sea level rise, but coastal sediments that contain non-renewable archeological and paleontological resources are at risk.
- Geothermal Features Inventory and Monitoring. The preserve is one of the 16 units in the National Park System with significant thermal features as designated by the Geothermal Steam Act of 1970 (amended in 1988). Serpentine Hot Springs is the most visited location in the preserve and is a culturally significant site to Alaska Natives. Infrastructure at Serpentine Hot Springs includes a bunkhouse, bathhouse, privy, and airstrip. Water sampling in 2010 found that total coliform bacteria were elevated at sites closest to the structures; fecal coliform levels, however, were within the range of Alaska's drinking water and water recreation standards. In 2009, NPS managers and park planners began developing a management plan for Serpentine Hot Springs, but the process was stymied by a lack of baseline data. To address the data gaps, a study was undertaken to describe the hydrology, geochemistry, water chemistry, and microbiology of Serpentine Hot Springs, the results of which are summarized by Nordstrom et al. (2015).
- Permafrost Monitoring. Permafrost underlies nearly all of the preserve and has been selected as one of the "vital signs" subjected to long-term monitoring by the Arctic Network Inventory and Monitoring Program. Climate change is likely to cause future permafrost thaw in the preserve. The consequences of significant thaw could include creation and drainage of thermokarst lakes; mass wasting; release of methane and carbon dioxide; and changes in hydrology, soil temperature, and sedimentation that will affect nutrient cycling and vegetation communities. Active-layer detachments and retrogressive thaw slumps (erosional features produced by permafrost thaw) in the preserve have been mapped on satellite images from 2006–2009. Twenty-two active-layer detachments were identified by this mapping, exposing a total area of 2.9 ha (7.2 ac); all the active-layer detachments occurred in the southeastern portion of the preserve, in the Bendeleben Mountains or Bendeleben Foothills. Retrogressive thaw slumps were also mapped on satellite images from 2006–2009, but none were found in the preserve. With continued climate warming, thermokarst, particularly ice wedging, is likely to become widespread in the preserve. If the permafrost warming predicted by Panda et al. (2016) occurs, wedge ice will thaw and the ground over the wedges will subside across vast expanses of the preserve's lowland terrain. This will result in the formation of many new small ponds, some of which will expand to form larger water bodies as thawing progresses. Meanwhile, linear thaw features along ice wedges will breach the shores of existing lakes, causing them to drain suddenly.
- Paleontological Resources Inventory, Monitoring, and Protection. Paleontological resources, or fossils, are non-renewable resources that are subject to science-informed inventory, monitoring,

protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. The predicted future widespread thawing of permafrost poses the most significant threat to paleontological resources in the preserve. Fossil material frozen in permafrost commonly displays exceptional preservation, but these fossils also degrade quickly once thawed. In addition, the frozen nature of these deposits means that natural erosion rates will accelerate as temperatures rise. The environmental circumstances that preserve these fossils are predicted to disappear, therefore, these valuable resources will be lost if they are not documented, collected, or stabilized. Pleistocene mammal fossils are also vulnerable to loss as a result of unauthorized collection. Pleistocene bones, especially mammoth tusks and teeth, can be sold for up to thousands of dollars. The sale of fossils collected from Native and privately owned land is legal, but unpermitted fossil collection is prohibited on NPS lands. Evidence of apparent fossil collection–related behavior in the preserve includes the presence of human footprints systematically arrayed along the bluffs in the vicinity of the Nugnugaluktuk River (Chad Hults, NPS Alaska Regional Office, regional geologist, personal communication, 15 November 2017). Other unauthorized fossil collecting incidents may be taking place but have gone unrecognized as a result of the infrequent presence of NPS personnel in the preserve.

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 (USGS) and NPS 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), which includes a poster presenting the GIS data (see poster, in pocket). These products are designed and written for non-geoscientists.

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 B 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.

Acknowledgments

This report could not have been completed without the research produced by many scientists working in the Bering Land Bridge National Preserve area for more than a century. The authors would like to thank our reviewers, Julie Dumoulin (USGS Alaska Science Center, research geologist), and Andrew Tremayne (NPS Alaska Regional Office, archeologist), for sharing their expertise and providing valuable feedback. An additional thank you goes to Chad Hults (NPS Alaska Regional Office, geologist) for providing invaluable guidance, encouragement, and feedback during the writing process. We would like to thank all the people who participated in the pre-report meeting, for providing ideas about topics to address and pointing the authors to sources of information that may have otherwise been overlooked. Thank you to Jeff Rasic (Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve, chief of resources) for reviewing the introduction of this report; Paul Burger (NPS Alaska Regional Office, hydrologist) for providing data, discussion, and review of sections relating to Serpentine Hot Springs and caves; and Tahzay Jones (NPS Alaska Regional Office, coastal oceans coordinator) for providing data, discussion, and review of the coastal sections of this report. Additional thanks goes to Katie KellerLynn for editing this report and to Trista L. Thornberry-Ehrlich (Colorado State University, research associate) for producing some of the graphics used in this report.

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Source maps published by the US Geological Survey listed in "Geologic Map Data" section

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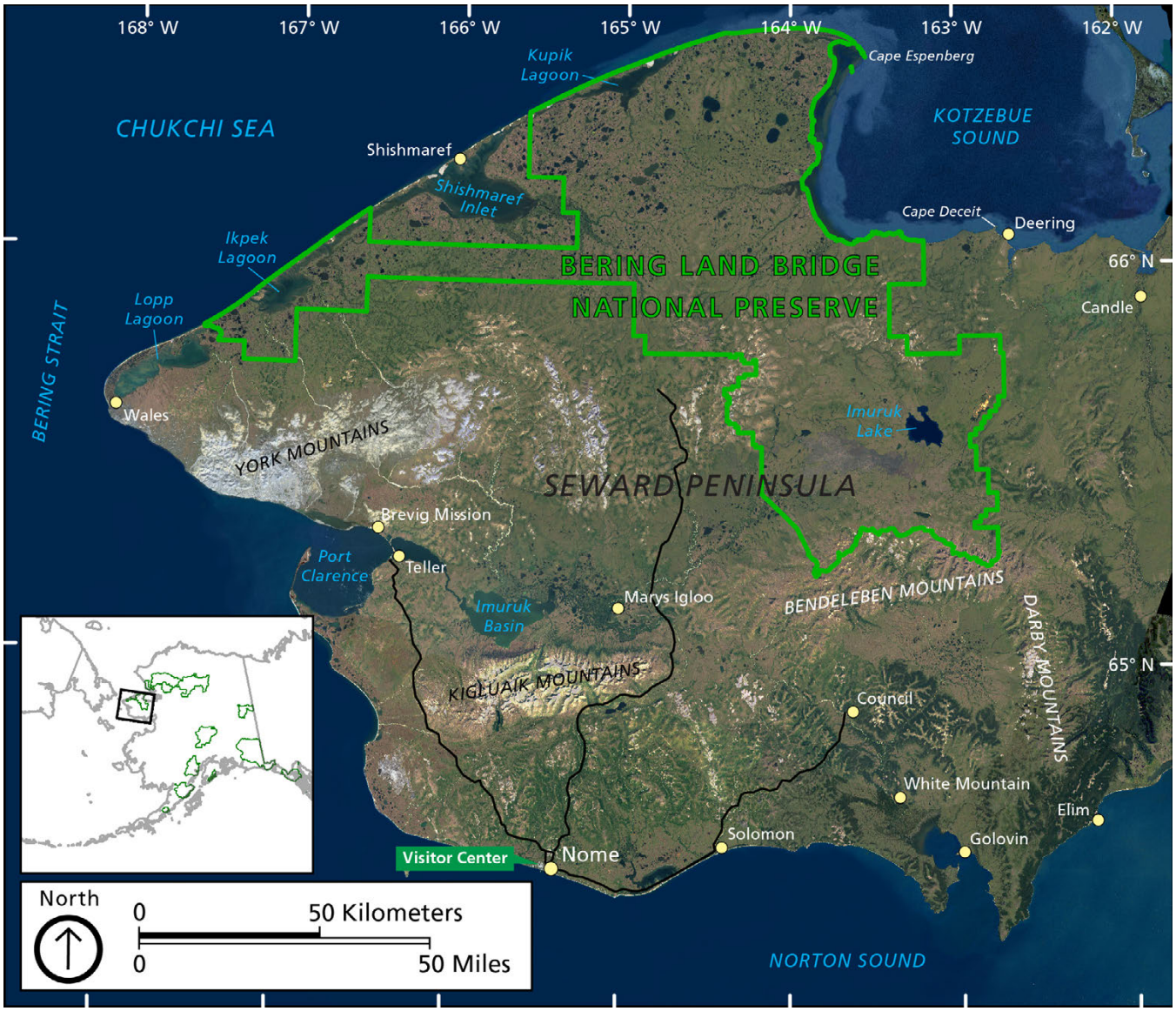


Figure 1. Map of Bering Land Bridge National Preserve and surrounding area.
Map shows the location of the preserve (green line) and the geographic features of the preserve and surrounding area mentioned in the text. Satellite image map created by the National Park Service (2011).

Geologic Setting and Significance

This chapter describes the regional geologic setting of Bering Land Bridge National Preserve and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment and History

Bering Land Bridge National Preserve (Figure 1), referred to as "the preserve" throughout this report, was established by the passage of the Alaska National Interest Lands Conservation Act (ANILCA) on 2 December 1980. The preserve contains archeological, paleontological, and biological resources that record the history of the Bering Land Bridge—a region that connected Asia and North America during the last glacial period. Many of the reasons set out in the enabling legislation for establishing the preserve are either geologic in nature or closely tied to the preserve's geology. These include the protection and interpretation of the preserve's volcanic lava flows and ash explosions, coastal formations, and other geologic processes; to allow for the archeological and paleontological study of plant and animal migration across the Bering Land Bridge; and to provide for recreation and education activities in the Serpentine Hot Spring area (ANILCA 1980).

Located in northwest Alaska, the preserve protects nearly 1.1 million ha (2.7 million ac) of land encompassing much of the northern half of the Seward Peninsula (Figure 1). The northern part of the preserve is characterized by flat to rolling coastal plains, with topographic highs formed by Devil Mountain and three other Quaternary shield volcanoes (Hopkins 1988; Jorgenson 2001). The northern coastal plains are also dotted with many small lakes formed by thawing permafrost. Five large lakes in the vicinity of Devil Mountain stand out in terms of size; these lakes are the Espenberg maars (craters formed by explosive volcanic eruptions) (Hopkins 1988). Of note, the Espenberg maars are the largest maars known on Earth because of their unique formation through permafrost (Begét et al 1996). The southern part of the preserve is characterized by greater topographic relief: the York Mountains foothills can be found in the southwest of the preserve, and the Bendeleben Mountains and foothills occur in the farthest southeastern part of the preserve. Around Imuruk Lake, recent volcanism has formed a plateau composed of basaltic lava flows, dotted with pyroclastic cones and shield volcanoes (Hopkins 1963). Continuous permafrost underlies nearly all of the preserve, resulting in distinctive geomorphic features such as solifluction lobes, pingos, ice-wedge polygons, and thermokarst lakes.

The preserve contains 919 km (571 mi) of shoreline and 35,534 ha (87,808 ac) of water, primarily in the form of large coastal lagoons (Curdts 2011). The preserve's coast is characterized by barrier islands, spits, and narrow beaches that are backed by ice-rich tundra bluffs, as well as stretches of estuaries and bedrock sea cliffs. Most of the coast faces northwest towards the Chukchi Sea, but a small portion faces east to Kotzebue Sound. The Bering Strait, which conducts water between the Arctic and Pacific Oceans, lies just to the south and west of the preserve. This sliver of water separates Russia from Alaska and is only 82 km (51 mi) wide at its narrowest point.

The preserve's headquarters and visitor center are located about 160 km (100 mi) to the south, in the city of Nome. Nome is the largest city on the Seward Peninsula, with a population of 3,793 (US Census Bureau 2017). The preserve is one of the most remote units in the National Park System; no roads extend into the preserve, and the city of Nome is not connected to a road system that extends beyond the Seward Peninsula. Access to the preserve can be achieved by plane, boat, or hiking in the summer, with the added option of snowmobile access in the winter. In 2017, the preserve received 2,642 visitors; this number was estimated based on the 2010 visitation because park facilities currently lack accurate counters (NPS 2019).

The first people to lay eyes on the land that would one day become Bering Land Bridge National Preserve were likely some of the first people to arrive in North America. During the height of the last glacial period (known as the last glacial maximum; approximately 24,000–14,000 years ago) (Dyke et al. 2002), the preserve lay in the center of a vast ice-free region known as "Beringia.". Humans occupied parts of Beringia during the last glacial maximum (Hoffecker et al. 2016; Potter et al. 2018; Tremayne 2018). Towards the end of the Pleistocene Epoch, early humans may have traveled to the rest of North America by utilizing coastal routes that circumvented the large ice sheets or via an ice free corridor that developed between the retreating Cordilleran and Laurentide ice sheets (Braje et al. 2017).

People continued to inhabit the Bering Strait region following the first arrival of humans to North America. The cultures that developed in this area are characterized by the use of marine-based technologies, elaborate art, and extensive trade networks (Schaaf and Smith 1996). Traditional subsistence hunting-and-gathering activities formed the primary means of survival on the Seward Peninsula. These activities included hunting marine mammals and caribou,

fishing, and collecting eggs and berries. By the 1800s, ten or eleven Iñupiaq and Yupik societies thrived on the Seward Peninsula (Schaaf and Smith 1996). The societies had distinct group names, territories, dialects or subdialects, and material cultures (Schaaf and Smith 1996; Burch 2006). Many places now located within the preserve possess cultural significance to the native inhabitants of the Seward Peninsula, including Cape Espenberg, Ear Mountain, Kuzitrin Lake, Imuruk Lake, and Sullivan Bluffs (see https://www.nps.gov/bela/learn/historyculture/alaska-natives-and-early-people.htm for more details).

Starting in the late 1700s, Europeans began to explore the Bering Strait area (see Appendix A for more details about the history of geologic exploration). Contact with Europeans induced change in the cultures native to the Seward Peninsula, including the incorporation of foreign objects into their material culture, increased fur trading, and the onset of reindeer herding (Ray 1975). British explorer Captain James Cook was the first European to chart the coast of the Seward Peninsula in 1778. Both Russian and English explorers continued to survey the region into the 1800s. Early explorers noted the presence of an ice-rich bluff along Kotzebue Sound that contained mammoth and other mammal fossils (Kotzebue 1821; Beechey 1831). The discovery of the bluff named "Elephant Point" (located about 85 km [53 mi] east of the preserve on the coast of Escholtz Bay) prompted some of the earliest paleontological research in northwest Alaska (Beechey 1831; Richardson 1854; Quackenbush 1909).

The Nome Gold Rush of the early 1900s gained the Seward Peninsula national attention and a dramatic influx of people. Gold was first discovered on the Seward Peninsula by Baron Otto von Bendeleben during an 1865–1866 expedition to survey a route for a proposed trans-continental telegraph line from Europe to America (Collier et al. 1908). Despite this early discovery, a mining boom did not occur here for another 32 years. During 1898, the "Three Lucky Swedes"—Jafet Lindeberg, Erik Lindblom, and John Brynteson—discovered the first placer gold deposits of commercial importance on Anvil Creek. This discovery sparked a 10-year mining frenzy in the region known as the Nome Gold Rush. An influx of miners caused the population of Nome to expand from an estimated 250 in 1898 to more than 20,000 during the height of the gold rush then down to 2,600 by 1910 as gold production declined (Figure 2). Between 1899 and 1909 mining on the Seward Peninsula yielded more than $46 million. For more information, see https://www.nps.gov/articles/alaska-goldrush-national-historic-landmarks.htm.

Figure 2. Photographs of Nome in 1900 and 1901 during the beginning of the Nome Gold Rush. The top photograph shows the Nome wharf in 1900, and the bottom photograph is of the city of Nome in 1901. Following the discovery of gold in 1898, about $3,000,000 worth of gold was mined in the Nome area during the summer of 1899 and exported in the fall (Collier et al. 1908). This alerted the outside world to the magnitude of the gold discovery, and during the 1899-1900 winter interest in "the golden sands of Nome" grew to levels comparable to that of the Klondike Gold Rush two years earlier. By July 1, 1900, over 50 vessels had transported over 20,000 people to Nome, many of whom took up residence in rows of tents along the water front (Collier et al. 1908). Photographs from the USGS Denver Library Photographic Collection (see https://library.usgs.gov/photo/#/).

Geologic Setting

The "Bering Land Bridge," from which Bering Land Bridge National Preserve derives its name, refers to a 1,000-km (620-mi) swath of land between Alaska and Siberia that, while shallowly submerged by the Bering and Chukchi Seas today, was subaerially exposed during the glacial periods of the Pleistocene Epoch (2.58 million–11,700 years ago) (Colinvaux 1964; Hopkins 1967). The Bering Land Bridge formed the center

Figure 3. Map of Beringia.
Beringia was a largely unglaciated landmass that stretched from the Mackenzie River in Yukon Territory to the Lena River in Russia. The modern coastline is shown in dark green. The coastline during the Last Glacial Maximum (LGM) is shown in light green. Glacier extent during the LGM is shown in white. Map by Amanda Lanik using information from Becker et al. (2009) and Ehlers et al. (2011).

of a larger landmass referred to as "Beringia" (Figure 3; Hulten 1937). Beringia was an unglaciated region stretching from the Lena River in Russia to the Mackenzie River in Yukon Territory that supported a diverse assortment of Pleistocene megafauna (Hopkins et al. 1982). Many of these animals, such as mammoths, bison, muskoxen, caribou, lions, brown bears, wolves, and even early humans, used the Bering Land Bridge to travel from Asia to North America.

The waters between Alaska and Siberia are underlain by the Bering-Chukchi shelf, which is a shallowly submerged region of continental crust that forms the Bering Land Bridge when sea level is lower (light green areas on Figure 3). The Bering Land Bridge has undergone periodic exposure and submergence in accordance with climate-induced fluctuations in global sea level (Hopkins 1959). These sea level fluctuations are driven by the advance and retreat of continental glaciers corresponding to glacial and interglacial periods of the Pleistocene Epoch. During Pleistocene glacial periods, colder global temperatures caused glaciers to advance, trapping water on land in the form of ice and decreasing sea level worldwide (Figure 4). An opposite affect occurs during interglacial periods when global temperatures increase, continental glaciers retreat, and sea level rises. Because the Earth is currently in an interglacial period, the Bering Land Bridge is submerged by water and a terrestrial link between Asia and North America no longer exists.

The most recent exposure of the Bering Land Bridge was during the last glacial period, which ended around 12,000 years ago. During this period, growth of the Laurentide and Cordilleran ice sheets covered most of northern North America under ice, isolating northwest Alaska from the rest of North America. Alaska was instead part of Beringia, which had a much colder and more continental climate than northern Alaska today (Guthrie 2001). The cold, dry climate caused loess (windblown silt) and permafrost to form simultaneously, leaving thick accumulations of ice-rich sediment known as "yedoma" throughout much of the coastal plain of the preserve (see the "Quaternary Surficial Deposits" section for more details; Kanevskiy et al. 2011; Shur et al. 2009, 2012). These sediments

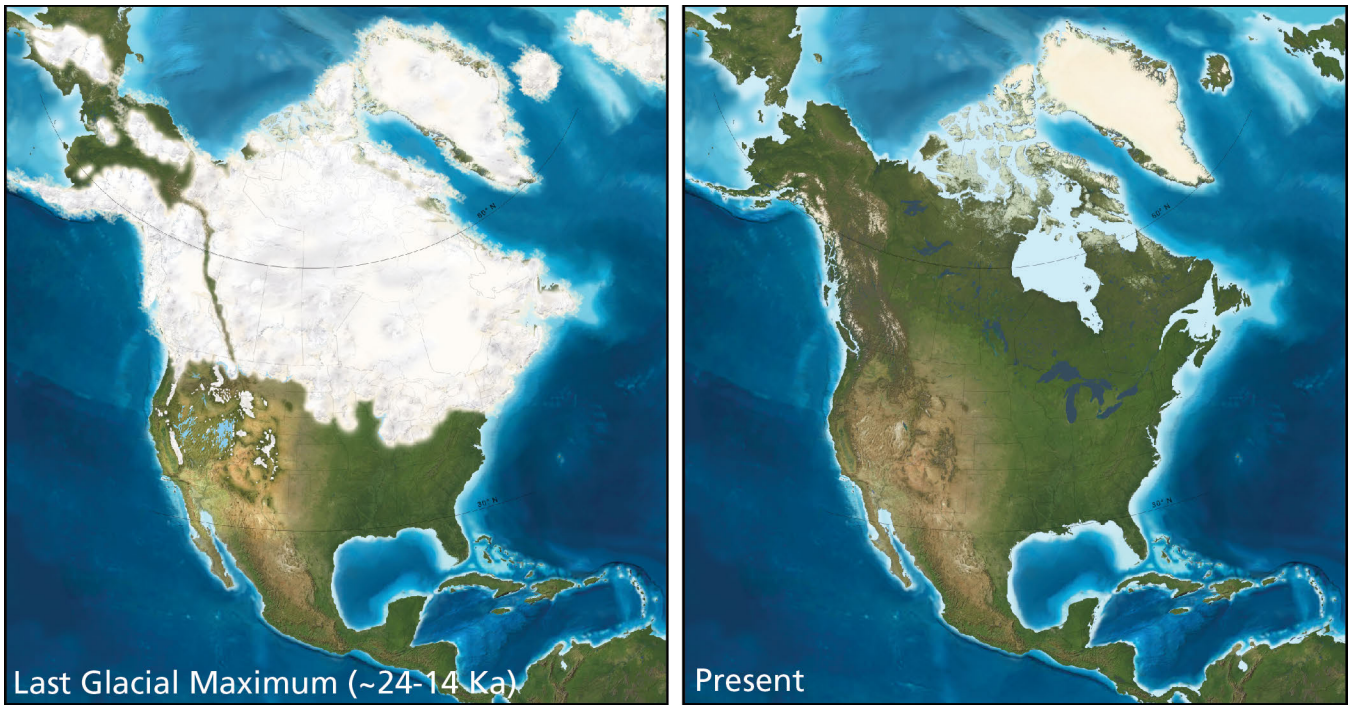


Figure 4. Map contrasting the glacier extent in North America during the last glacial period and the present.
Basemaps are "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information.

preserve fossils and soil (i.e., Kitluk Paleosol) that record the natural history of Beringia on the Seward Peninsula.

Tectonically, the preserve is part of a larger crustal block that stretches from northern Alaska to northeastern Russia called the Arctic Alaska-Chukotka microplate. During the Mesozoic Era, the Arctic Alaska-Chukotka microplate rotated away from the Canadian Arctic Archipelago to its present day position (Figure 5; see the "Geologic History Section" for more information). Most of the Arctic Alaska-Chukotka microplate is well above sea level today; for example, the Brooks Range in northern Alaska forms a significant part of the microplate. In the Bering Strait Region, however, extension that started about 120 million years ago and continues to the present day (Dumitru et al 1995) has caused crustal thinning to the extent that this area is currently below sea level (Klemperer 2002).

Geologic Significance and Connections

The geologic history and ongoing geologic processes in the preserve represent important park resources and interpretive opportunities, as well as factors that impact resource management and visitor safety. Many geologic features influenced the history of the preserve, its reason for establishment, other resources, and visitor safety. These include mineral deposits, granite tors, volcanoes and lava flows, paleontological resources, permafrost, coastal features, caves, and Serpentine Hot Springs, but perhaps most significant of these resources, opportunities, and factors is the Bering Land Bridge itself and the geologic deposits that preserve its history.

The Bering Land Bridge formed as a result of the preserve's geologic and tectonic setting. During the Jurassic Period (201 million–145 million years ago) and Cretaceous Period (145 million–66 million years ago), the mountain building event that created the Brooks Range caused significant crustal thickening in parts of northern Alaska, including the Seward Peninsula. However, subsequent extension led to crustal thinning in the Bering Strait region, exhuming deeply buried rocks and producing a broad continental shelf between Alaska and Siberia. Because the Bering-Chukchi continental shelf is only slightly lower than mainland Alaska and Siberia, it is susceptible to periodic exposure and submergence as sea level fluctuates. Additionally, the history of the Bering Land Bridge, including its physical geography, environmental conditions, flora, and fauna are recorded in the rock, sediments, and fossils now found within the preserve (ANILCA 1980).

Cenozoic volcanism created volcanic features in the preserve including lava flows, lava cones, and the

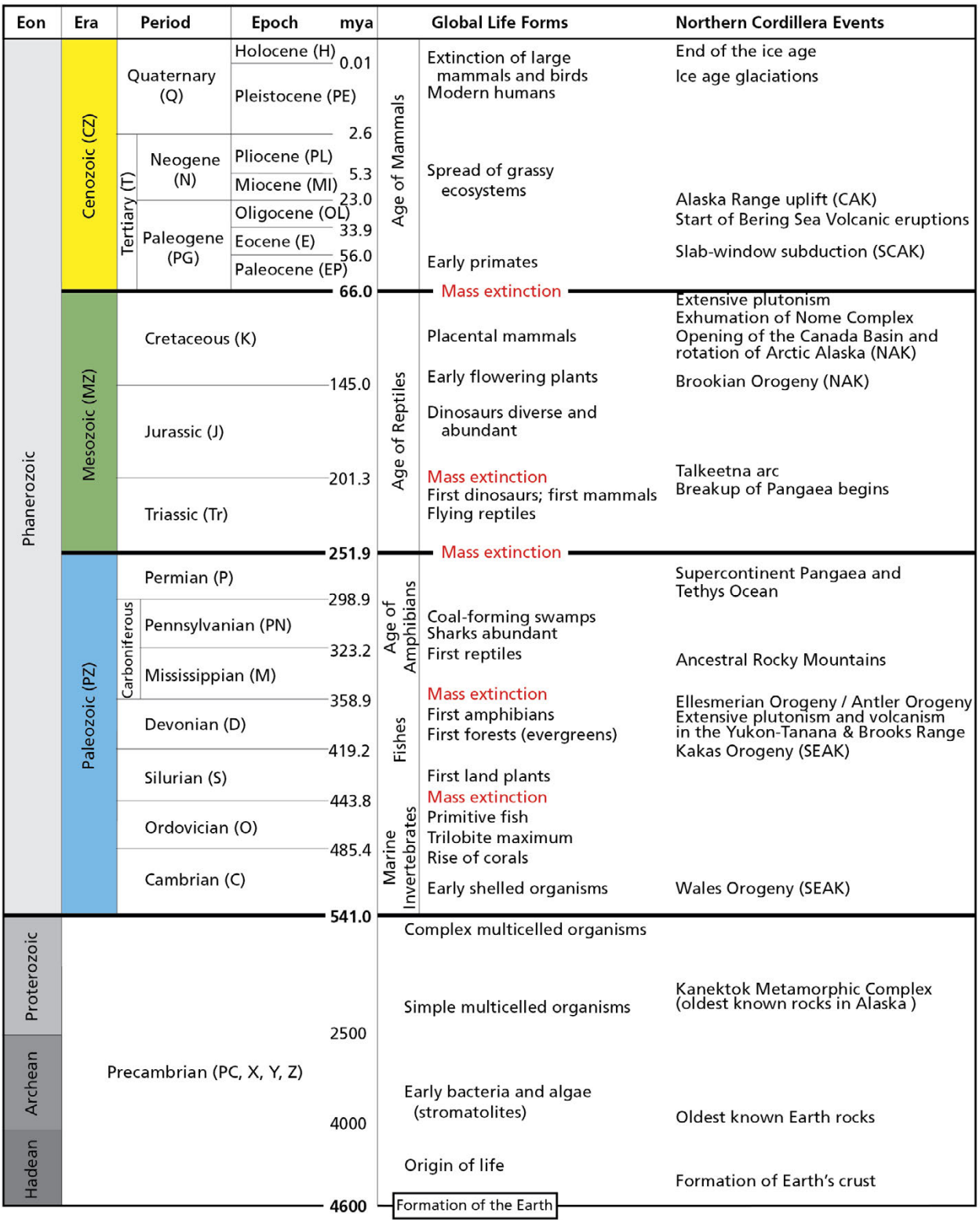


Figure 5. Geologic time scale.
The figure shows the onset of major global evolutionary and tectonic events of the North American continent and the Northern Cordillera. SCAK = south-central Alaska; SEAK = southeast Alaska; NAK = northern Alaska; and CAK = central Alaska. The divisions of geologic time are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Ages of the timescale are millions of years ago (MYA). Refer to this graphic for ages when time periods are mentioned in the text. Ages are from the International Commission on Stratigraphy (http://stratigraphy.org/index.php/ics-chart-timescale, version v2019/05).

largest maars (volcanic craters caused by the interaction of magma and water) on Earth (Begét et al 1996). Volcanism is the product of the preserve's tectonic setting, specifically extension in the Bering Strait region. Volcanic features are a prominent part of the preserve's landscape, and the protection and interpretation of them is outlined in the preserve's enabling legislation (ANILCA 1980). Near Cape Espenberg, maars form unusually large lakes and shield volcanoes, such as Devil Mountain, form topographic highs. Around Imuruk Lake, effusive lava eruptions over the past 28 million years have formed a vast plateau covered with volcanic rock and dotted with lava cones (Hopkins 1963; Swanson et al. 1981). Hopkins (1988) dated the youngest eruption in the preserve–the Lost Jim lava flow—to 1,605 ± 238 calendar years before present (cal yr BP) (Table 1; see "Volcansim" section for more information); while there is some uncertainty as to the accuracy of this date, for simplicity the age of 1,605 years ago will be used throughout this report. In addition to forming distinctive features on the landscape, recent volcanism has left its mark on the cultural history of the Seward Peninsula. Notably, the eruption of the Lost Jim lava flow is described in the oral history of the Inupiat-speaking Kaweruk people native to central Seward Peninsula (Oquilluk and Bland 1981; Hopkins 1988). The following is a passage from chapter two of the book "People of Kauwerak: Legends of the Northern Eskimo," by Oquilluk and Bland (1981). This passage recounts a story about Ekeuhnick, a legendary leader of the Inupiat people, that seems to be describing the eruption of the Lost Jim lava flow.

On the third day after the people moved, Ekeuhnick went to the spring again before the sun went down. He rested and watched the animals drinking at the springs. He enjoyed seeing them. Later, he started back towards the place his people lived.

Suddenly, he could feel the ground shaking under him. Three times the shaking of the ground passed under his feet. Then he heard a roaring and a loud rumble. He looked back and saw that the great mountain was blowing up. The noise got worse and worse and he began to get scared. A big black smoke came out from the top of the mountain. A terrible red tongue of fire came out of the top of the smoke. At the same time, red hot coals came out from the top and rolled down the side of the mountain towards the old place of his people. Ekeuhnick began to hear all kinds of confusion. He looked around and saw many kinds of birds and animals running and flying toward him.

The animals were all running away together, big and small, and the birds in the air. As the animals passed by, Ekeuhnick jumped up and rode on the back of a scared stampeding bear. He held it tight by the neck so they could keep up with the other animals. There was so much noise from the birds in the air and the animals he could not hear the noise of the mountain or anything else.

Together Ekeuhnick, the birds, and the animals fled fast away from the mountain. The birds and animals, every living thing was running and flying at the same time, all in the same direction.

Ekeuhnick's people, far away and safe from the mountain, heard an awful noise like a terrible bellow coming from behind them. Everyone turned and looked. A great spear of fire was coming from the mountain from the top. Everything was blazing all around it. There was a red-orange color rolling all the way down from the top of the mountain to the bottom. The people were amazed and very frightened. Now those people began to see the things Ekeuhnick had told them about. It was happening, and his words were true.

All the birds and animals around began running and flying across the plain. They made so much noise that the people got more scared. It seemed everything on the mountainside was burning and the fire was coming down to the plain below the mountain. The people could see birds and animals running away before the fire and coming towards them.

The animals were traveling so fast that soon they came near to where the people were standing. Then Ekeuhnick jumped off the big bear. He joined his people. He was relieved when he looked back at the mountain so far away from them. His people were glad to see Ekeuhnick. They thought he was burned up by the mountain fire. Now that his words were coming true, they would talk together more about the things Aungayoukuksuk had foretold.

Two days after the eruption, Ekeuhnick woke up early and went to where he used to meet with Aungayoukuksuk. It was cold and the wind was blowing. The weather turned good when he came round to the place of the old man. He saw Aungayoukuksuk still sitting there in the same place. He was glad to meet Ekeuhnick again.

"Now," said the old prophet, "you are to become my servant so you may serve and lead your people. You must go beyond this mountain on a long journey."

Ekeuhnick sat down face to face with Aungayoukuksuk. He looked around the place. He saw a great change. There was only black rock, like water frozen, everywhere. There was no kind of green living things around and not even a bird or animal anywhere. He saw that the water was still running from the springs same as ever. The place seemed deserted, it was so quiet.

Igneous plutonic rocks intruded the Seward Peninsula during the Cretaceous Period. Today, these resistant rocks rise abruptly from low-relief tundra to form freestanding outcrops called tors. One of the most prominent areas where tors dot the landscape is around Serpentine Hot Springs. Serpentine Hot Springs is the most visited site in the preserve and is used for religious, medicinal, spiritual, and recreational purposes. The presence of thermal waters at Serpentine Hot Springs is tied to the plutonic rocks in the area. Fractures allow water to circulate particularly deeply, where it is heated up and then conveyed back to the surface, producing the hot springs.

During the time when igneous plutons were forming, gold-bearing veins also formed in the rocks on the Seward Peninsula. The discovery of this gold sparked the Nome Gold Rush between 1899 and 1909. Thousands of people flocked to the Seward Peninsula, resulting in the establishment of Nome, the largest city on the Seward Peninsula and the location of the preserve's headquarters and visitor center. Remnants of the gold rush mining are still found within the preserve, which contains three inactive mine sites and the Fairhaven Ditch historic canal, a 38-mi- (61-km-) long ditch dug without the assistance of power tools that transported water from Imuruk Lake to placer mining sites.

Geologic Features and Processes

This section describes the distinctive geologic features of Bering Land Bridge National Preserve, the past geologic processes that formed those features, and the ongoing geologic processes that shape the landscape today. The preserve's bedrock is presented first, which is divided into four groups based on rock type, age, tectonic affinity, and metamorphic history. This section is followed by a detailed discussion of the recent volcanic rocks in the preserve. Caves developed in the preserve's bedrock are discussed next, followed by a description of the only geothermal feature in the preserve, Serpentine Hot Springs. Surficial features and deposits, as well as ongoing geologic processes are discussed next, including a discussion of the preserve's Quaternary surficial deposits, permafrost, and coastal features. Lastly, paleontological resources, or fossils, are discussed, which occur in both the preserve's bedrock and surficial deposits.

Bedrock

The preserve's bedrock records a long geologic history that stretches back to the late Proterozoic Eon (see poster, in pocket, for a geologic map of the preserve and surrounding area; for an explanation of the geologic time periods discussed in this and other sections, see Figure 5). The majority of the bedrock underlying the Seward Peninsula, along with other rocks in the Brooks Range and on the Chukotsk Peninsula, represent the remains of a continental margin that developed during the late Proterozoic Eon and Paleozoic Era (Dumoulin et al. 2002). In the Mesozoic Era, a volcanic arc collided with the rocks of northern Alaska, resulting in the formation of the Brooks Range (Moore et al. 1994). During the earliest stages (latest Jurassic Period) of this mountain building event, the southern margin (including the Nome Complex found within the preserve) was partially subducted beneath the colliding arc (Till 2016). The Brooks Range orogeny (mountain building event) was followed by extension, magmatism, and collapse of the Brooks Range during the Cretaceous Period. Some of the rocks that formed the core of the mountain range were brought to the surface (e.g., Nome Complex; Till et al. 2011). During the Cenozoic Era (Cenozoic volcanic rocks are discussed in detail in the "Volcanism" section of this report), extension-related normal faulting formed small mountain ranges (e.g., Bendeleben Mountains; McDannell et al. 2014) and sedimentary basins (e.g., Hope basin), and caused volcanism on the Seward Peninsula (Dumitru et al. 1995).

Based on rock type, age, tectonic affinity, and metamorphic history, the bedrock on the Seward Peninsula has been split into groups by Till et al. (2011). As mapped by Till et al. (2011; see poster, in pocket), the bedrock within the preserve belongs to four different groups: (1) Nome Complex (map units **PZm, Oim, Od, DOx, Ds, Ddm, DObm, DCks**), (2) York terrane (**OPRI**), (3) high-grade metamorphic and associated igneous rocks (**PZPRg, PZPRh, PZPRm**), and (4) Mesozoic and Cenozoic igneous rocks (**Ktg, Ks, Kgu, Kbk, QTv, Qlj**). The US Geologic Names Lexicon ("Geolex"), which is a national compilation of names and descriptions of geologic units, refers to the Nome Complex as the Nome Group (see https://ngmdb.usgs.gov/Geolex/search). The term "complex" is used in this report instead of "group" because a complex refers to a series of rocks that have more complicated structural relationships, and many newer studies refer to the unit as the Nome Complex (see Till et al. 2011, 2014, Till 2016, and Hoiland et al. 2018).

Nome Complex

The Nome Complex makes up most of the Seward Peninsula and consists of rocks of various lithologies (physical characteristics) that exhibit structural and metamorphic features formed during a shared high-pressure metamorphic event (Till et al. 2011). Metamorphism, which is an alteration of a rock's mineralogy or texture by heat or pressure, led to the development of blueschist and greenschist metamorphic minerals in many of the rocks assigned to the Nome Complex (see Figure 6 for an explanation of metamorphic facies). Till et al. (2011) subdivided the Nome Complex into three parts based on rock type and structural relationships: (1) "Layered Sequence," which contains units that are structurally layered over much of the central Seward Peninsula; (2) "Scattered Metacarbonate Rocks," which contains widely distributed dolostones and marbles; and (3) "Metaturbidites," which contains schist and marble exposed on the north and southeast coast of the Seward Peninsula. The geologic units found within the preserve that belong to the Nome Complex are **DOx**, **Ds**, **Oim**, **PZm**, **Ddm**, **Od**, **DObm**, and **DCks** (see poster, in pocket).

Before the metamorphic event that altered the rocks, the Nome Complex consisted of sedimentary rocks deposited on a carbonate platform (see "Geologic

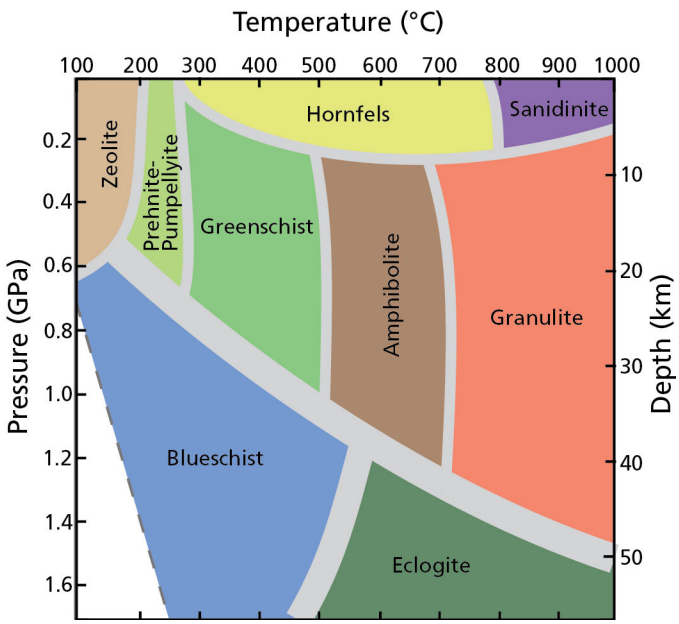


Figure 6. Pressure-temperature diagram showing metamorphic facies.
During metamorphism, various metamorphic minerals will develop depending on original rock chemistry, pressure, and temperature. Metamorphic facies are characterized by mineral assemblages that form under similar pressure-temperature conditions. The processes that led to metamorphism can sometimes be inferred by metamorphic facies. For example, hornfels- and sanidinite-facies minerals form under high temperature and low pressure conditions, which is typically the result of contact metamorphism (metamorphism of rocks that come into contact with magma). Conversely, blueschist-facies minerals, like those belonging to the Nome Complex form under high pressure and low temperature regimes typical of a subduction zone. Rocks in the preserve have undergone blueschist- and greenschist-facies metamorphism (Nome Complex) and amphibolite- to granulite-facies metamorphism (high-grade metamorphic rocks). Figure modeled after Winter (2001).

History" for a discussion of the paleogeography; Dumoulin 2002; Till et al. 2011, 2014; Dumoulin et al. 2014). Sparse fossil assemblages combined with radiometric ages indicate that the protolith (original rock prior to metamorphism) of the Nome Complex formed during the late Proterozoic Eon–Devonian Period (1.0 billion–359 million years ago) (Till et al. 1986; Till et al. 2014). Although penetrative deformation (changes throughout the rock) has destroyed many of the primary sedimentary structures and fossils, some of the units still contain lithologic characteristics indicative of deposition on a continental shelf, slope, and basin (Patrick 1988; Hannula et al. 1995; Till et al. 2011, 2014). Fossils and sedimentary features typical of shallow water deposition can be found in units **Cd, Sd, Od, and Ddm**, whereas units **DObm** and **DCbm** contain features typical of rocks formed in continental slope to marine basin environments (Till et al. 2011).

During the Jurassic–Cretaceous Periods, metamorphism of the Nome Complex produced blueschist-facies mineral assemblages in many of the rocks (Sainsbury et al. 1970; Thurston 1985), which are locally overprinted by greenschist-facies assemblages (Figure 6; Till et al. 2011). Glaucophane, one of the blue minerals from which blueschist-facies draws its name, has been recognized on the Seward Peninsula since the early 1900s (Smith 1910; Moffit 1913). Blueschist-facies minerals form under high-pressure and low-temperature conditions typical of subduction zones (Figure 6). Blueschist metamorphism is associated with subduction zones because the subducting plate is relatively cool, causing a depression of the normal geothermal gradient. As such, rocks in subduction zones can reach great depths and experience high pressures without being exposed to temperatures as high as would normally be associated with those depths. During the Jurassic Period (201 million–145 million years ago), the Nome Complex reached peak pressures of around 1.2 GPa at about 40 km (25 mi) depth (Patrick and Evans 1989).

Following this compression, the Bering Strait region transitioned to an extensional regime during the Cretaceous Period (120 million–70 million years ago; Dumitru et al. 1995; Hannula et al. 1995). The extension caused crustal thinning in the region and brought the Nome Complex to the surface. The Nome Complex reached peak temperatures during this exhumation, causing greenschist- to amphibolite-facies minerals to locally overprint the blueschist-facies mineral assemblages (Figure 6; Hannula et al. 1995; Till et al. 2011). Rocks in the southern Brooks Range went through an identical Jurassic–Cretaceous metamorphic history as those in the Nome Complex (Till et al. 2011). Together, these rocks record the subduction of the southern margin of the Arctic Alaska terrane that was the first stage of building the Brooks Range (see "Geologic History" for more details on the Arctic Alaska terrane and its geologic history; Moore et al. 1994; Till 2016).

Units that belong to the "Layered Sequence" subgroup are the most extensive and widely distributed bedrock of the Nome Complex within the preserve (see poster, in pocket). The "Layered Sequence" is made up of units that occur throughout much of the central Seward Peninsula and have a consistent layer-cake structural

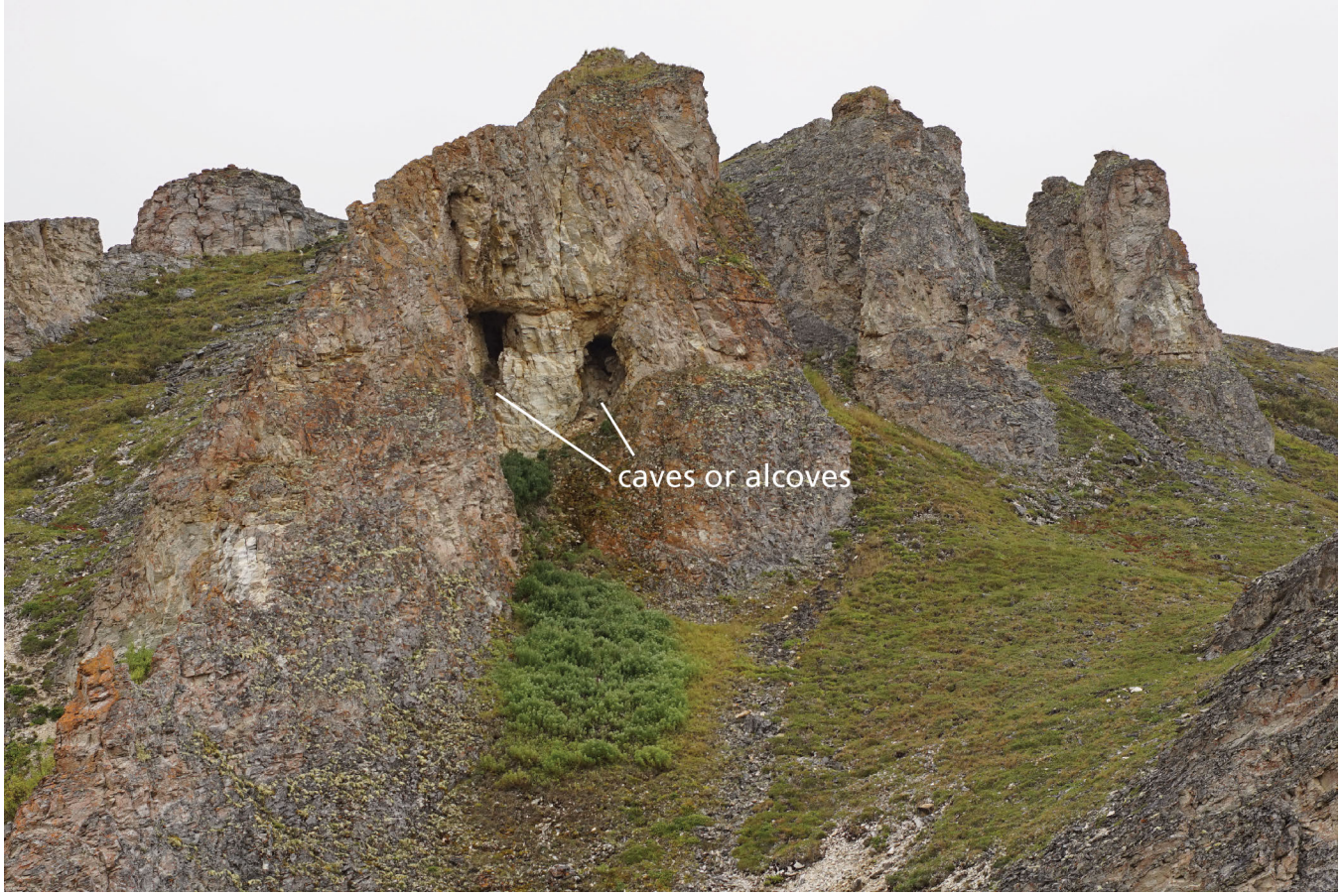


Figure 7. Photograph of unit DOx.
Unit Dox (mixed marble, graphitic metasiliceous rock, and schist) crops out at Trail Creek. Two small caves or alcoves are labeled in white. NPS photograph by Chad Hults (NPS Alaska Regional Office).

relation to one another (Till et al. 2011). Three units belonging to the "Layered Sequence" crop out within the preserve: (1) **DOx**, mixed marble, graphitic metasiliceous rock, and schist; (2) **Oim**, impure chlorite marble; and (3) **Ds**, pelitic schist. These units crop out in the central part of the preserve, to the north and west of the Imuruk Lake volcanic rocks. Unit **Dox**, which is exposed in the preserve along Trail Creek, contains locally developed caves (Figure 7; see "Cave Resources" for more information). The Trail Creek outcrop is dominantly marble but also contains areas of schist.

Rocks that belong to the "Metaturbidite" subgroup of the Nome Complex (**DObm, DCks**) crop out along the coast, in the northeastern-most portion of the preserve (see poster, in pocket). The two units that are found within the preserve are **DCks**, calcareous schist of Kwiniuk Mountain, and **DObm**, black metalimestone and marble (Till et al. 2011). These two units are interlayered on a meter to kilometer scale, so the age of **DCks** is partially derived from the fossil-bearing **DObm** (Till et al. 2011). Fossils from **DObm** include Middle and Late Ordovician graptolites; Ordovician and Silurian–Devonian conodonts, though the Silurian–Devonian age is uncertain; and potentially redeposited Middle–Late Devonian corals (Ryherd and Paris 1987; Harris et al. 1995; Ryherd et al. 1995; Dumoulin et al. 2002; Till et al. 2011). The term "Metaturbitdite" denotes a metamorphic rock that has a turbidite protolith. A turbidite is a type of sedimentary rock formed by submarine density flows composed of turbid water (water with suspended clay, silt, and sand), which cause distinctive sedimentary structures (Bouma 1962). Some of these sedimentary structures are still visible despite subsequent metamorphism (Figure 8). Sedimentary structures, lithology, and fossils indicate that **DObm** represents carbonate platform-derived sediments that were deposited in continental slope and marine basin settings by turbidity and debris flows (Dumoulin and Till 1985; Ryherd and Paris 1987; Harris et al. 1995; Dumoulin et al. 2002).

Geologic units in the preserve that belong to the "Scattered Metacarbonate Rocks" subgroup of the Nome Complex include **PZm**, **Ddm**, and **Od** (see poster, in pocket). All of these units crop out east of Serpentine

Figure 8. Photographs of bedded metaturbidites belonging to unit DCks at Sullivan Bluffs. Relict sedimentary structures at Sullivan Bluffs include graded bedding (coarse grained sediments at the bottom of a bed grading up into finer grained sediments near the top; seen in the alternating light/dark rock color) and cross bedding (angled bedding caused by unidirectional water movement; Till et al. 2011). At other locations, DObm (black metalimestone and marble) displays relict sedimentary structures such as flame structures, loaded bed bottoms, channelized beds, and imbricated rip-up clasts (Till et al. 2011). NPS photographs by Andrew Tremayne (NPS Alaska Regional Office).

Hot Springs, and units **Od** and **Ddm** also crop out near the eastern border of the preserve along the Burnt River (see poster, in pocket). Unit **PZm** consists of coarsely crystalline marble, whereas **Od** consists of dolostone and **Ddm** consists of a combination of dolostone, marble, metalimestone, and minor amounts of chert (Till et al. 2011). All of these units form rubbly outcrops where they are exposed. Whereas **PZm** is too recrystallized to preserve sedimentary structures, both **Ddm** and **Od** possess relict sedimentary structures and fossils indicative of deposition in shallow water environments (Till et al. 2011). Units **Ddm** and **Od** correlate in terms of age and lithologic characteristics with other rocks in the western and central Brooks Range, and **Od** correlates to some of the Ordovician rocks in the York terrane on the southwest part of the Seward Peninsula (Till et al. 2011). This relationship has led researchers to suggest that the Nome Complex, York terrane, and carbonate rocks in the western Brooks Range formed along a shared early Paleozoic continental margin (see the "Geologic History" section for more details; Dumoulin et al. 2002).

York Terrane

The York terrane is not as widespread in the preserve as the Nome Complex, but unit **OPRl** (limestone and dolomitic limestone) does crop out near Ear Mountain in the western portion of the preserve (see poster, in pocket). The York terrane has been split into two parts: (1) York Mountains succession, a well-studied sequence of strata that is found in the central York Mountains, and (2) older rocks that are not as well understood (denoted as "units with uncertain affinities" on the poster, in pocket; Till et al., 2011). The York Mountains succession is generally not metamorphosed and retains primary sedimentary features, whereas the units with uncertain affinities have undergone metamorphism up to low greenschist facies conditions (Till et al. 2011). York terrane rocks that occur within preserve boundaries belong to this second more enigmatic group, specifically unit **OPRl**.

Unit **OPRl** consists of limestone and dolomitic limestone (in part metamorphosed) that range in age from latest Proterozoic to Ordovician (1.0 billion–444 million years old). These rocks contain poorly preserved conodonts, chitinozoans, and brachiopods (Till et al., 2011). Metamorphism of unit **OPRl** varies, with some areas appearing unmetamorphosed while others are recrystallized and have well developed metamorphic fabric (Till et al. 2011).

High-Grade Metamorphic and Associated Igneous Rocks

"High-Grade Metamorphic Rocks," which have reached amphibolite-granulite facies (Figure 6), occur in the Kigluaik, Bendeleben, and Darby Mountains, as well as to the north of the Oonatut Granite Complex in the vicinity of Serpentine Hot Springs (Till et al. 2011). Some of these rocks have the same lithologies as units of the Nome Complex but underwent higher grade

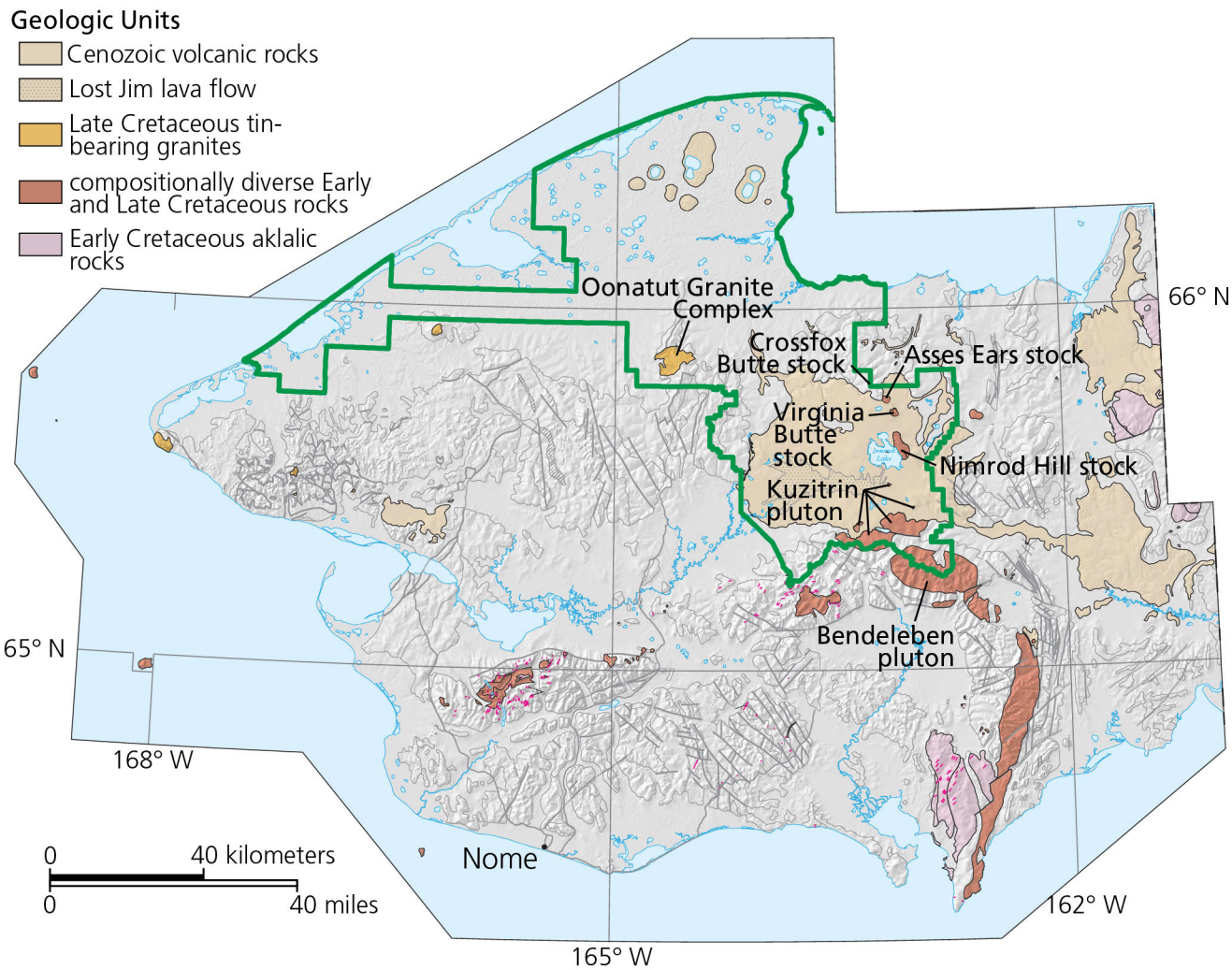


Figure 9. Map of the igneous plutonic rocks on the Seward Peninsula. The plutons that fall within the preserve are labeled. Cenozoic volcanic rocks are also shown on the map, labeled in light brown. Park outline is in dark green. Map modified from Till et al. 2011.

amphibolite-granulite facies metamorphism. However others, including the oldest rocks on the Seward Peninsula dating to 870 million years ago (exposed in the Bendeleben Mountains), have no counterpart in the Nome Complex (Gottlieb and Amato 2007; Till et al. 2011). Within the preserve, rocks categorized as "High-Grade Metamorphic and Associated Igneous Rocks" are found north of Serpentine Hot Springs (**PZPRg**), as well as to the south of the Imuruk Volcanic Field (**PZPRh** and **PZPRm**; see poster, in pocket).

The amphibolite-granulite facies rocks in the southern part of the preserve are part of the Bendeleben Mountains, which contains the Bendeleben pluton at its core (**Kbk**; see "Cretaceous Igneous Rocks" for more information). These rocks represent one of three metamorphic complexes (Kigluaik, Bendeleben, and Darby Mountains) on the Seward Peninsula that consist of high-grade metamorphic rocks (**PZPRh**, **PZPRm**, **PRo**, **PRv**) surrounding plutons (**Kbk**, **Kp**, **Kwc**, **Kd**, and **Kg**; Amato et al. 1994; Gottlieb and Amato 2008; Till et al. 2011; McDannell et al. 2014). Both the Bendeleben and Kigluaik metamorphic complexes form dome-shaped structures called gneiss domes; the structure in the Darby Mountains is more complex (Amato et al. 1994; Till et al. 2011; McDannell et al. 2014). Gneiss domes are found all over the world and are associated with areas where the "roots" of mountains (rocks that form the base of mountains and are therefor deeply buried) have been brought to the surface by uplift and erosion (Whitney et al. 2004).

These metamorphic and plutonic complexes formed during a Cretaceous magmatism and extension event in the Bering Strait region (Amato et al. 1994; Dumitru et al 1995; Gottlieb et al 2008; McDannell et al. 2014). No similar high-grade metamorphic rocks occur in the

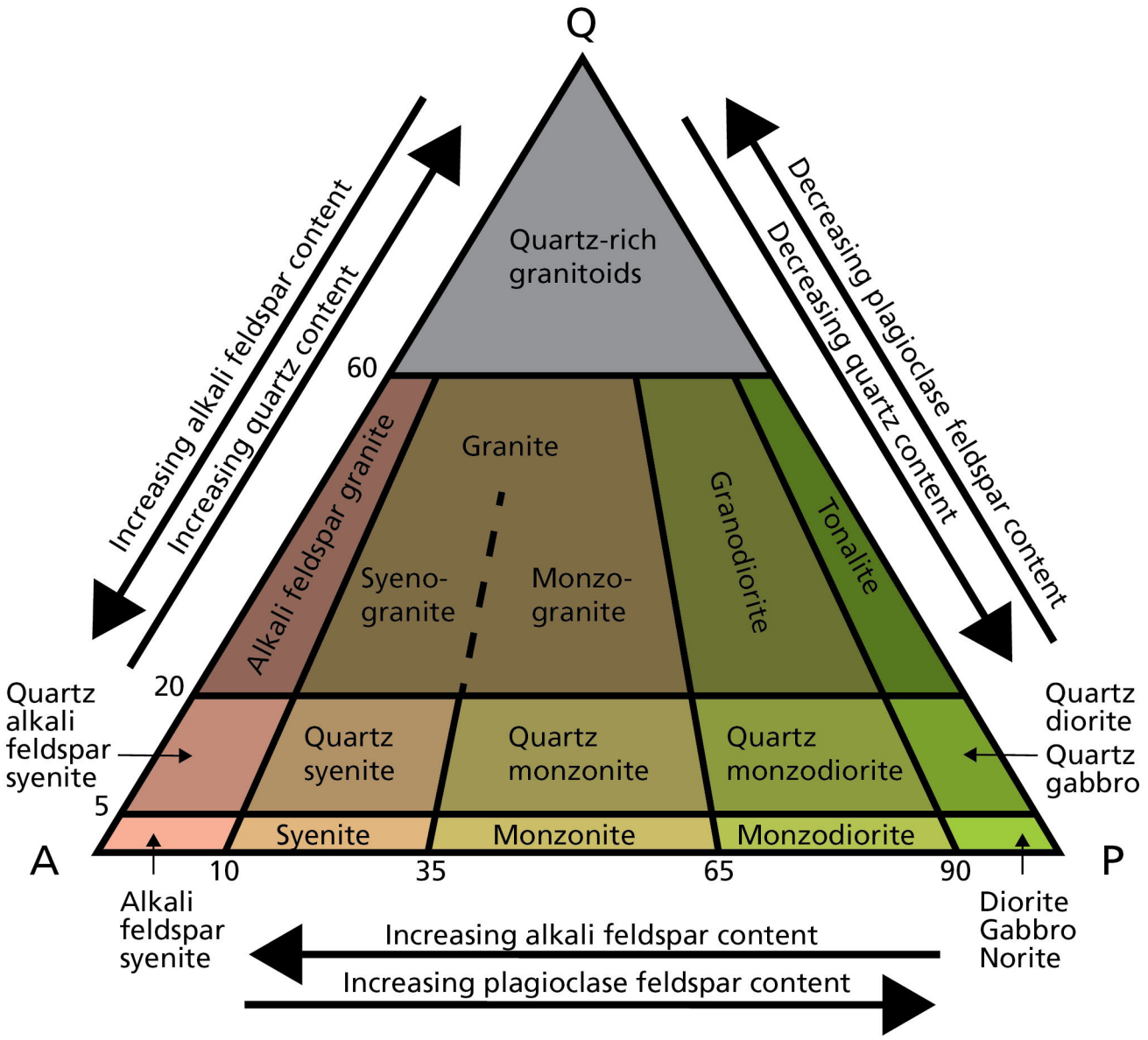


Figure 10. Diagram showing the classification of felsic intrusive igneous rocks. Classification is based on the relative percentages of quartz (Q), alkali feldspar (A), and plagioclase feldspar (P). Stocks identified on the map are composed of various types of intrusive rock including monzogranite, quartz monzonite, syenogranite, and rare syenite and biotite-rich diorite. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Brooks Range, but the Ruby terrane to the east contains high-grade metamorphic rocks that may have been formed by the same metamorphic event as those on the Seward Peninsula (see Figure 41 for a terrane map of Alaska; Roeske et al. 1995; Till et al. 2011). Based on evidence from the Kigluaik gneiss dome, Amato and Wright (1997) suggested that the tectonic setting that generated the magmatism and rise of high-grade gneiss domes during the Late Cretaceous Period was likely a continental arc that was being pulled apart by extension related to slab rollback (retreat and steepening of the subducting plate).

Cretaceous Igneous Rocks

Three suites of igneous plutons intruded rocks on the Seward Peninsula during the Cretaceous Period: plutons with an alkalic composition formed 110 million–96 million years ago, calc-alkaline plutons formed 95 million–80 million years ago, and tin-bearing granite plutons formed 80 million–69 million years ago (Till et al. 1986; Till et al. 2011). On the poster (in pocket), these rocks are grouped with “Mesozoic

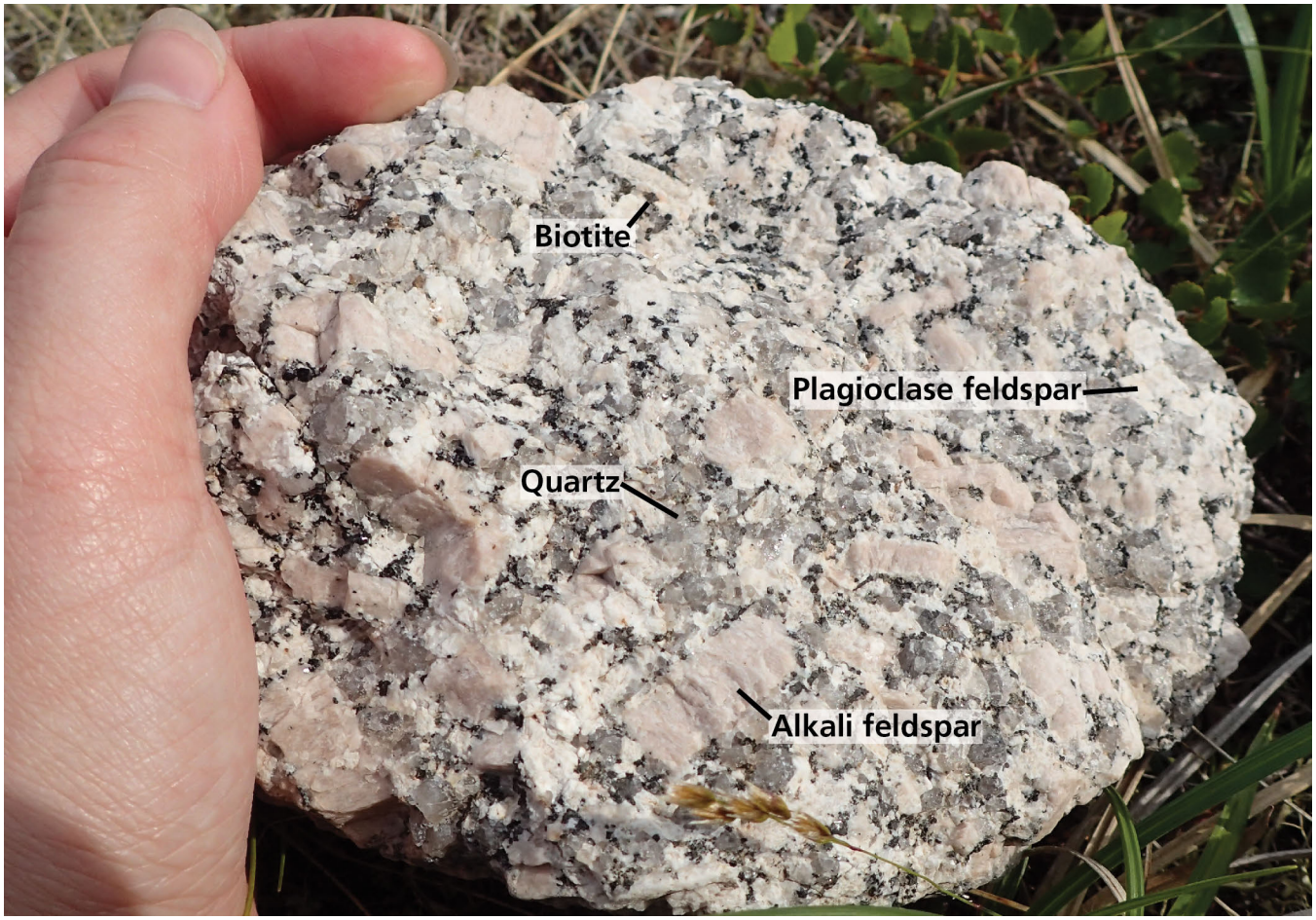


Figure 11. Photograph of porphyritic biotite granite belonging to the outer zone of the Oonatut Granite Complex.
Porphyritic granite contains a set of crystals that are distinctly larger than the rest of the crystals in the granite. The large crystals are referred to as phenocrysts and the rest of the smaller crystals are referred as the groundmass. Porphyritic textures are produced when granite cools at two different rates: (1) an initial slower cooling rate that allowed the larger phenocrysts to form, and (2) a subsequent faster cooling rate that resulted in the formation of the rest of the smaller crystals. In this case, the phenocrysts are light-pink-grey alkali feldspar crystals that are as long as 3 or 4 cm (1 or 2 in) (Hudson 1979). The groundmass is composed of medium-light-grey to medium-grey quartz crystals, white to very light grey plagioclase feldspar crystals, and biotite (Hudson 1979). Other minerals that occur in include sphene, allanite, zircon, and magnetite (Hudson 1979). Labels indicate examples of some of the different minerals in the granite. NPS photograph by Amanda Lanik.

and Cenozoic Igneous Rocks." In the preserve, these Cretaceous intrusive rocks include the Oonatut Granite Complex (**Ktg**) exposed around Serpentine Hot Springs; the Crossfox Butte, Asses Ears, Virginia Butte, and Nimrod Hill stocks (**Ks**), which are exposed to the north and east of Imuruk Lake; and the Bendeleben and Kuzitrin plutons (**Kbk**), which occur in the Bendeleben Mountains in the southernmost part of the preserve (Figure 9).

Felsic intrusive rocks occur as frost-shattered outcrops, rubble fields, and float at four localities to the east and north of Imuruk Lake (Till et al. 2011). These localities are aligned along a northwest-southeast trend, starting with Crossfox Butte stock in the north, followed by Asses Ears and Virginia Butte stocks, and ending to the southeast with Nimrod Hill stock (Figure 9). The stocks are composed of various types of intrusive rock including monzogranite, quartz monzonite, syenogranite, and rare syenite and biotite-rich diorite (Figure 10; Till et al. 1986; Till et al. 2011). The Asses Ears stock contains striking alkali feldspar phenocrysts (larger crystals) that are 2–4 cm (1–2 in) in length (Till et al. 2011). K-Ar radiometric dating indicates these stocks

cooled during the Late Cretaceous Period, yielding ages of 96.3 million ± 2 million years for the Nimrod Hill stock, 94.8 million ± 1.9 million years for the Virginia Butte, and 91.5 million ± 2.8 million years for the Crossfox Butte stock, though this last date is considered suspect because the biotite was altered (Till et al. 1986; Till et al. 2011).

Parts of both the Kuzitrin and Bendeleben plutons extend into the southernmost portion of the preserve. These plutons have been shown using aeromagnetic data to connect at depth (Till et al. 2011). Combined with their similar mineralogy, chemistry, and cooling history, Till et al. (2011) proposed that they are two lobes of the same large intrusive body. The Bendeleben lobe is composed of monzogranite to quartz monzodiorite, and the Kuzitrin lobe is predominately monzogranite (Figure 10; Till et al. 2011). Large inclusions of schist, incorporated into the pluton during its formation, can be seen in the Bendeleben lobe (Till et al. 2011). Radiometric dating has yielded cooling ages of 83 million–81 million years ago (Miller and Bunker 1976; Till et al. 2011; McDannell et al. 2014).

The Oonatut Granite Complex (associated with unit **Ktg**), located in the vicinity of Serpentine Hot Springs, is the largest of seven tin-bearing granite intrusions that form a 170-km- (105-mi-) long belt across northwestern Seward Peninsula (Hudson and Arth 1983). Tin-bearing granites on the Seward Peninsula have either tin lode or placer deposits associated with them, and in the Lost River area these deposits were mined commercially (Sainsbury 1969). K-Ar radiometric dates of the tin-bearing granites range from 80.2 million ± 3 million to 69.2 million ± 2 million years ago, with the Oonatut Granite Complex being the youngest of the seven intrusions (Hudson and Arth 1983). The Oonatut Granite Complex is composed of biotite granite and has distinct zones defined by changes in the texture of the granite (Hudson and Arth 1983). The outermost portion grades from granite that is fine-grained and equigranular (crystals are all the same size) to coarse-grained porphyritic (crystals are two distinct sizes) granite (Figure 11). This zone differs in terms of petrology and geochemistry from the rest of the tin-granite belt and is instead much more similar to the Darby pluton (Hudson and Arth 1983). The rest of the Oonatut Granite Complex is split into three textural facies that can be found in all the other tin-bearing granite plutons on the Seward Peninsula: medium- to very coarse-grained seriate (crystals are different sizes) biotite granite, porphyritic biotite granite, and fine- to medium-grained equigranular to subequigranular biotite granite (Hudson 1979; Hudson and Arth 1983).

Around Serpentine Hot Springs, the Oonatut Granite Complex forms freestanding spires of rock called "tors." The term "tor" is derived from the Celtic word for hill and refers to an exposed mass of rock (usually jointed granite) that rises abruptly from the surrounding landscape (Figure 12 and inside cover). Several models that explain tor development exist (Figure 13), but all models involve the rock making up the tors weathering more slowly than the surrounding rock. For example, tors in Scotland have been found to preferentially develop in coarser-grained granite with wider-spaced jointing (Goodfellow et al. 2014). The Oonatut Granite Complex contains rocks with a variety of grain sizes and these rocks are jointed, so changes in grain size and joint spacing could be a driving force in tor development.

Volcanism

The preserve contains large areas covered by Cenozoic volcanic rocks (see poster, in pocket). These rocks are part of a larger volcanic province that stretches from the Seward Peninsula to the Pribilof Islands, known as the Bering Sea volcanic province (Moll-Stalcup 1994). Cenozoic volcanic deposits occur in the vicinity of Imuruk Lake and Cape Espenberg (see poster, in pocket). The area surrounding Imuruk Lake is covered by lava flows (associated with units **QTv** and **Qlj**) emitted from volcanic vents that erupted during the late Tertiary "Period" (now considered an informal geologic time period, but the term still has widespread use, including in geologic mapping) and Quaternary Period (Hopkins 1963). To the north, volcanism near Cape Espenberg produced five shield volcanoes and four maars (**QTv**; Hopkins 1988; Begét et al. 1996). The Espenberg maars are the largest known on Earth (Begét et al. 1996). The youngest volcanic deposit in the preserve is the Lost Jim lava flow (mapped as Lost Jim Basalt, **Qlj**), which formed only about 1,605 years ago and is described in the oral history of the Inupiat-speaking Kaweruk people native to central Seward Peninsula (see the "Geologic Significance and Connections" section for an excerpt of the oral history; Oquilluk and Bland 1981; Hopkins 1988).

Imuruk Volcanic Field

In the area surrounding Imuruk Lake, widespread lava flows (units **QTv** and **Qlj**; see poster, in pocket) exist that formed within the last 30 million years (Hopkins 1963). The volcanic field consists of 75 known vents surrounded by lava flows with a total estimated volume of 110.0 km^3 (26.39 mi^3) of erupted magma (Mukasa et al. 2007). Based on stratigraphic relationships, degree of weathering, and the thickness of overlying sediments, Hopkins (1963) mapped five distinct volcanic formations around Imuruk Lake: (1) Kugruk volcanics, (2) Imuruk volcanics, (3) Gosling volcanics, (4) Camille

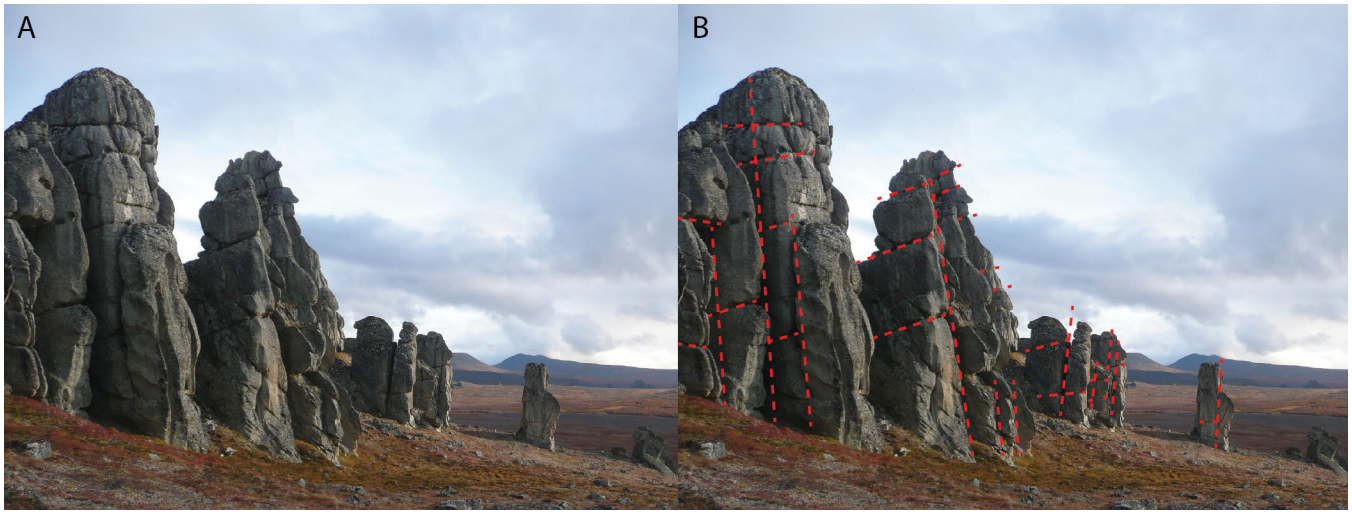


Figure 12. Photograph of the granite tors around Serpentine Hot Springs.
(A) Unannotated photograph. (B) Same photograph, with red dotted lines drawn to highlight the jointing in the granite. Joints are fractures in rock with no discernible offset (as opposed to faults, which have offset). Annotating the joints in this photograph shows that they are a controlling factor on the morphology of the tors; the roughly perpendicular orientation of the joints and weathering along these planes has resulted in the blocky shape of the tors. NPS photograph.

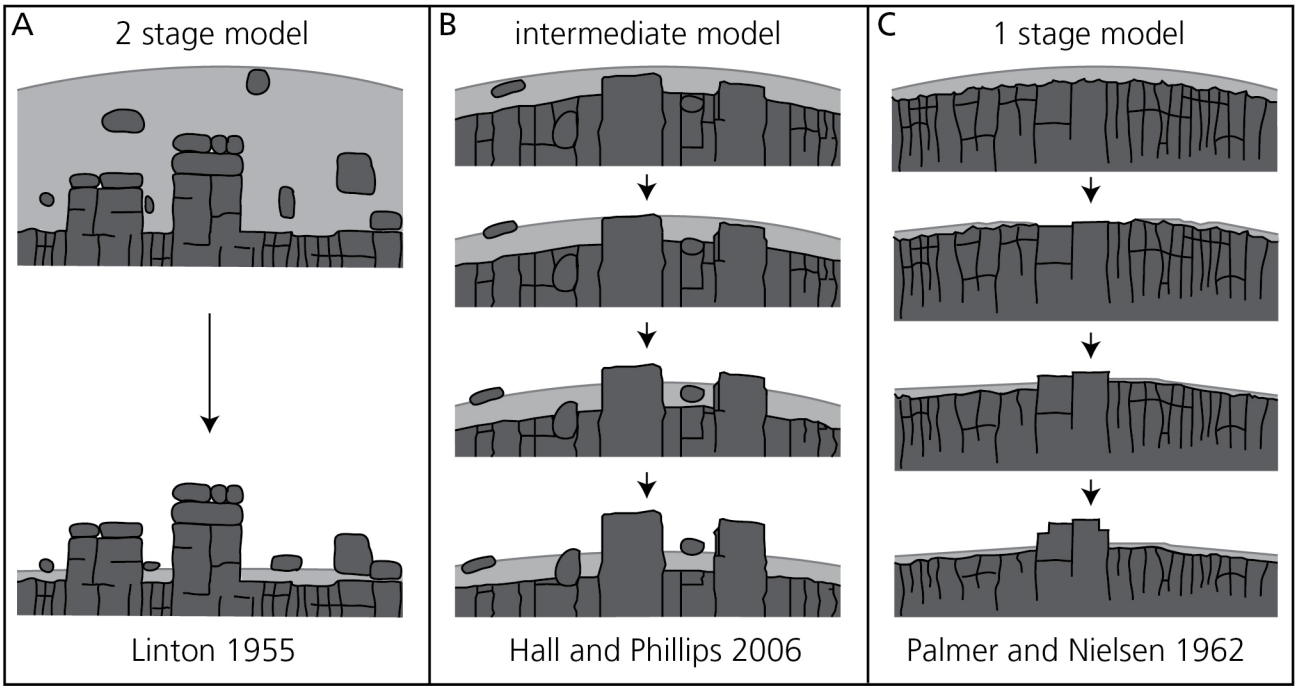


Figure 13. Diagrams showing different models of tor formation.
(A) Linton (1955) proposed a two-stage model in which bedrock is molded into tors by chemical weathering deep (tens of meters) underground and subsequently exposed by the removal of the overlying sediment and soil. (B) An intermediate model was proposed by Hall and Phillips (2006), which involves a combination of chemical weathering under shallow (a few meters) ground cover and preferential weathering after the removal of the overlying sediment and soil. (C) Palmer and Nielsen (1962) proposed a single-stage model where tors form as rock is subaerially exposed, without prior shaping by chemical weathering underground. Some researchers have suggested that the 2 stage and 1 stage models are end members of a continuum, and tors may develop according to either model (or intermediate model) depending on environmental factors (Gunnell et al. 2013). Diagrams modified from Goodfellow et al. (2014).

Table 1. Ages of volcanic eruptions in the preserve.

Eruption event	Map Unit (see poster, in pocket)	Age (years ago)	Dating Method	Age Uncertainty	Reference(s)
Lost Jim lava flow, Imuruk volcanic field	Qlj	1,605	Radiocarbon date from organic material interbedded within the flow	± 238 calibrated years; the organic material may have been contaminated by younger roots, so this age represents the youngest estimate for the Lost Jim lava flow	Hopkins (1988)
Devil Mountain maar, Espenberg volcanic field	QTv	17,500	Radiocarbon date from organic material in tephra	Individual ages have uncertainties between 800 and 100 years	Begét et al. (1996)
Camille lava flow Imuruk volcanic field	QTv	25,000–11,000	Degree of weathering	High	Hopkins (1988); Mukasa et al. (2007)
Devil Mountain, Espenberg volcanic field	QTv	900,000–11,000	Degree of weathering	Very high; age based on comparisons of vent weathering to those in the Imuruk Lake area	Hopkins (1988)
North and South Killeak maar, Espenberg volcanic field	QTv	62,000	$^{40}Ar/^{39}Ar$	± 10,000 years	Begét et al. (2003); Begét et al. (2005)
White Fish maar, Espenberg volcanic field	QTv	160,000	$^{40}Ar/^{39}Ar$	± 8,000 years	Begét et al. (2003); Begét et al. (2005)
Gosling volcanics, Imuruk volcanic field	QTv	900,000–800,000	Whole-rock K-Ar	Not stated	Swanson et al. (1981)
Imuruk volcanics, Imuruk volcanic field	QTv	6.1 million–5.2 million	$^{40}Ar/^{39}Ar$	Individual ages have uncertainties between 50,000 and 120,000 years	Mukasa et al. (2007)
Kugruk volcanics, Imuruk volcanic field	QTv	28 million–26 million	Whole-rock K-Ar	Not stated	Swanson et al. (1981)

lava flow, and (5) Lost Jim lava flow (Figure 14;Table 1). The first four volcanic formations are associated with **QTv** (weathered volcanic rocks); the Lost Jim lava flow is associated with unit **Qlj** (Lost Jim Basalt) (see poster, in pocket).

The oldest of the volcanic formations is the Kugruk volcanics, which have been dated using whole-rock K-Ar isotopes to 28 million–26 million years ago (Table 1; Swanson et al. 1981). The rocks belonging to the Kugruk volcanics are poorly exposed and largely buried by subsequent volcanism in the area. The type section is along the eastern wall of the Kugruk River canyon, 5 km (3 mi) south of Imuruk Lake (Hopkins 1963). At the type section, the Kugruk volcanics are divided into two portions: (1) an upper portion composed of olivine-basalt that is 12 m (40 ft) thick, and (2) a lower portion composed of basaltic-andesite that is more than 6 m (20 ft) thick (Hopkins 1963). The majority of the Kugruk volcanics are weathered in a manner that is different and more penetrating than the overlying lava flows in the area, which Hopkins (1963) interpreted as evidence that the Kugruk volcanics formed when the climate was much warmer than today.

The emplacement of the Kugruk volcanics was followed by a hiatus in volcanic activity of about 20 million years until the eruption of the Imuruk volcanics 6.1 million–5.2 million years ago ($^{40}Ar/^{39}Ar$ dates, Table 1; Mukasa et al. 2007). The Imuruk volcanics are the most widely distributed volcanic unit in the north-central Seward Peninsula; most of the volcanic plateau surrounding Imuruk Lake is probably underlain by several hundred feet of Imuruk volcanics (Hopkins 1963). The Imuruk volcanics consists mainly of basaltic lava flows of the pahoehoe type (lava characterized by smooth, ropy textures) (Hopkins 1963; Mukasa et al. 2007). The lava flows have been subsequently

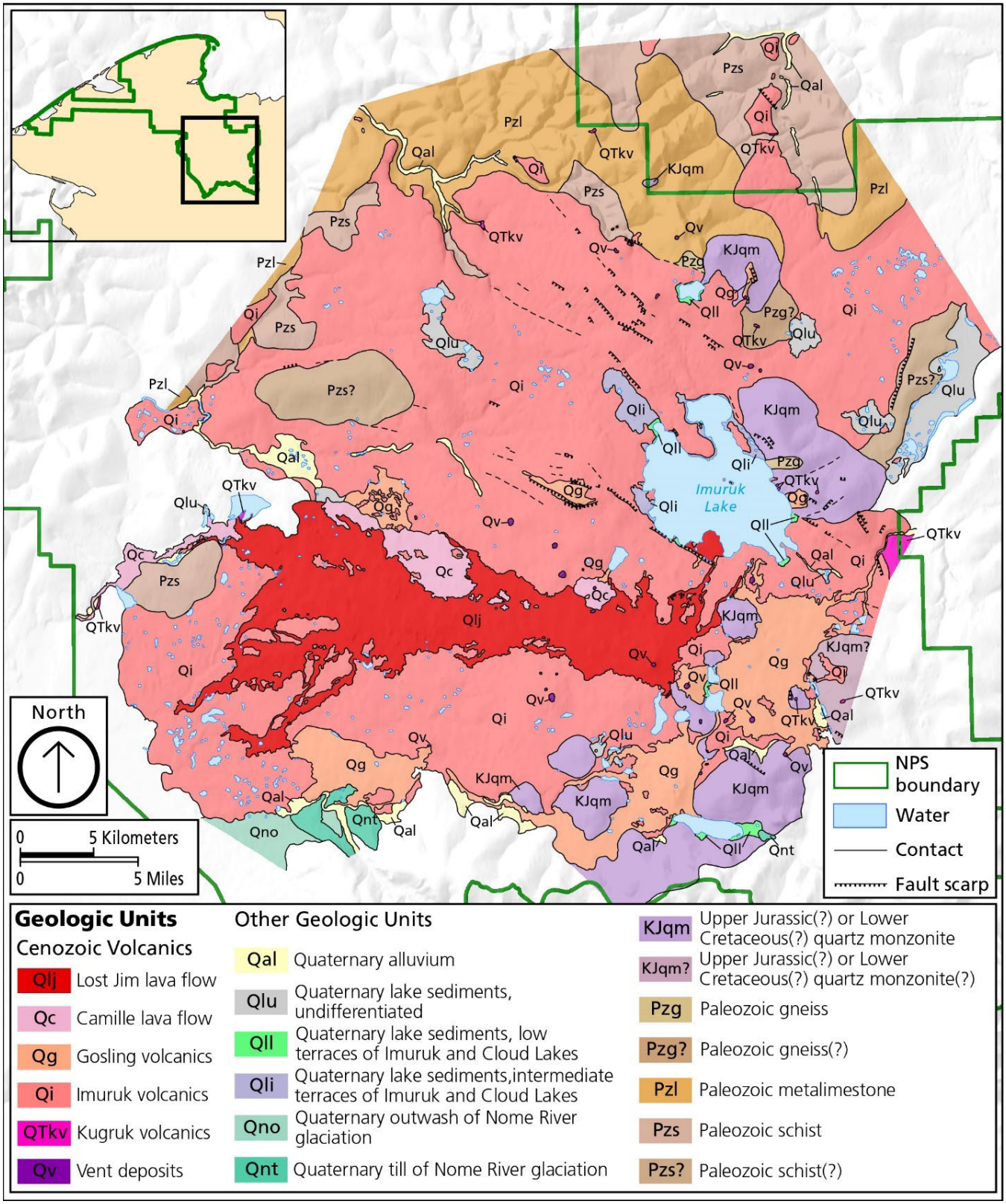


Figure 14. Map of the geologic units around Imuruk Lake.
This includes the five Cenozoic volcanic units, as well as other geologic units in the area. The Cenozoic volcanic units are, from oldest to youngest, the Kugruk volcanics (labeled QTkv; colored bright pink), the Imuruk volcanics (labeled Qi; colored salmon), the Gosling volcanics (labeled Qg; colored light orange), the Camille lava flow (labeled Qc; colored light pink), and the Lost Jim lava flow (labeled Qlj; colored red). Map created after Hopkins (1963).

Figure 15. Photograph of the Twin Calderas.
The Twin Calderas, which formed during the eruption of the Gosling volcanic, are situated at the summit of a 120-m- (400- ft-) high lava dome that accumulated atop a long-lived vent. These craters, called "calderas," formed when magma supporting the dome erupted, causing the top of the dome to destabilize and collapse. The calderas are 520 and 760 m (1,700 and 2,500 ft) in diameter, and 15 and 36 m (50 and 120 ft) deep. NPS photograph.

fractured by frost action and covered by 1–6 m (3–20 ft) of windblown silt (Hopkins 1963). For the most part, these flows erupted from numerous widespread, short-lived vents, but a few longer-lived vents, such as Hoodoo Hill and Largo Ridge, produced small shield volcanoes composed of multiple flows (Hopkins 1963). Additionally, pyroclastic deposits formed cones over some of the vents, including Rhododendron Cone, Andromeda Cone, and Cassiope Cone (Hopkins 1963).

The next eruptive period 900,000–800,000 years ago (whole-rock K-Ar dates, Table 1) produced a group of basaltic and andesitic lava flows assigned to the Gosling volcanics (Swanson et al. 1981). The Gosling volcanics are widely distributed to the south of Imuruk Lake; they overlie the silt-covered Imuruk volcanics, and in turn are overlain by the younger Camille and Lost Jim lava flows (Hopkins 1963). The Gosling volcanics erupted from many vents, including some longer-lived vents such as Twin Calderas, Hoodoo Hill, Virginia Butte, and Skeleton Butte (Figure 15; Hopkins 1963). The Gosling volcanics are 3–15 m (10–50 ft) thick in most areas, but can thicken to up to 45–90 m (150–300 ft) near source vents (Hopkins 1963). While most of the flows are pahoehoe, the Gosling volcanics also include several aa flows (characterized by rough irregular rubbly surfaces) and steep-fronted block lava flows (also characterized by rough rubbly surfaces, but with more regular, smooth-sided rubble) (Hopkins 1963).

The two most recently formed lava flows, the Camille lava flow and the Lost Jim lava flow, are both too young to be dated using the $^{40}Ar/^{39}Ar$ method (Table 1; Mukasa et al. 2007). Instead, frost brecciation (fracturing of the rock by ice freeze and thaw) and the amount of windblown silt atop the flows provide evidence that the Camille lava flow formed during the last glacial maximum (approximately 24,000–14,000 years ago) (Hopkins 1963; Swanson et al. 1981; Moll-Stalcup 1994). In the case of the Lost Jim lava flow, radiocarbon dating of organic material interbedded with basaltic tephra on the northeast shore of Imuruk Lake yielded a radiocarbon age of 1,605 ± 238 cal yr BP (Table 1;

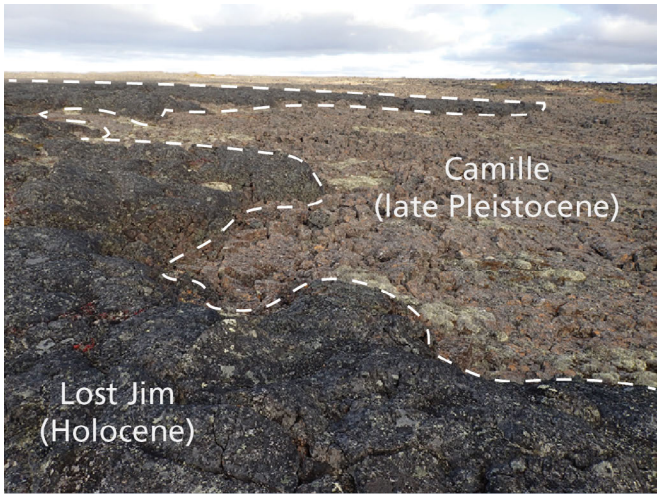


Figure 16. Photograph showing the contrasting Lost Jim and Camille lava flows.
The weathered Lost Jim lava flow (darker colored, on the left and in the foreground) contrasts the Camille lava flow (lighter colored, on the right).The Lost Jim flow is unoxidized and displays little frost shattering. The surface of the Camille flow is lighter colored due to oxidation and greater lichen cover; its surface has been broken up into angular blocks by frost action. NPS photograph by David Swanson (NPS Inventory and Monitoring Arctic Network).

Figure 17. Photograph of the Lost Jim cone.
The Lost Jim cone is composed of loose angular scoria. It is an unusually large cinder cone for the area, rising about 30 m (100 ft) above the surrounding plain. Its crater is 12 m (40 ft) deep and 30 m (100 ft) wide at the top; it contains a small lake. NPS photograph.

Hopkins 1988). The organic material may have been contaminated by younger roots, so this age represents the youngest estimate for the Lost Jim lava flow (Hopkins 1988).

The Camille lava flow is a pahoehoe flow that, unlike the older volcanic units around Imuruk Lake, was erupted from a single vent called the Camille Cone (Hopkins 1963). Stretching to the west for approximately 39 km (24 mi), the Camille lava flow is generally less than 8 m (25 ft) thick, but thickens to up to 30 m (100 ft) thick near the source vent. The Camille Cone is an agglomerate cone approximately 20 m (65 ft) tall (Hopkins 1963). The surface of the Camille lava flow has been fractured by frost to depths of as much as 2 m (5 ft), which contrasts with the thoroughly brecciated surfaces of the Gosling volcanics and the less-fractured surface of the Lost Jim lava flow (Figure 16).

The Lost Jim lava flow is the youngest of the volcanic formations in the Imuruk Lake area. Like the Camille lava flow, the Lost Jim lava flow stemmed from a singular volcanic vent called the Lost Jim cone (Figure 17; Hopkins 1963). The main body of lava flowed about 35 km (22 mi) westward from Lost Jim cone, which was primarily fed by a large lava tube (for more information about the lava tubes in the Lost Jim lava flow, see the "Cave Resources" section; Hopkin 1963; Marcucci et al. 2017). Smaller tongues of lava extended northward toward Imuruk Lake, where a large lava delta formed on the south shore of the lake (Figure 18; Hopkins 1963). The flow varies in thickness, ranging from less than 3 m (10 ft) thick in the valley of Andesite Creek, up to as much as 45 m (150 ft) thick near the Lost Jim cone (Hopkins 1963).

The Lost Jim lava flow displays features that are typical of pahoehoe lava flows, as well as uncommon features interpreted to be the result of lava-permafrost interactions. In areas that have not been broken by frost action, the surface of the lava flow is characterized by smooth, ropy textures typical of pahoehoe lava (Figure 19). Other features of the Lost Jim lava flow include lava channels and tubes, skylights, shatter rings, tumuli, and lava-rise plateaus (Figure 19; Hopkins 1963; Marcucci et al. 2017). Some irregularly shaped depression and collapse pit features around the periphery of the flow are thought to be formed by lava-induced permafrost thaw (Begét and Kargel 2008; Marcucci et al. 2017). Similar features exist near the margins of a lava flow on Mars, and the Lost Jim lava flow may be an informative proxy for lava-ground ice interactions on that planet (Marcucci et al. 2017).

Figure 18. Photograph of the Lost Jim lava delta.
Lost Jim Basalt (Qlj) erupted into Imuruk Lake, creating a lava delta on the southern shore. NPS photograph by Tahzay Jones (NPS Alaska Regional Office).

Espenberg Volcanic Field

The Espenberg volcanic field lies in the northern portion of the preserve and consists of five small shield volcanoes and four maars (Figure 20; Hopkins 1988; Begét et al. 1996). These volcanoes represent the northernmost volcanism of the "Bering Sea Volcanic Province," and are among the farthest north volcanoes in North America (see the "Bering Sea Volcanic Province" subsection for more details; Wood and Kienle 1990). The shield volcanoes appear to be older than the maars and may have formed in the absence of permafrost (Hopkins 1988).

The youngest of the shield volcanoes is Devil Mountain, which is a broad domed volcano formed by the eruption of multiple basaltic lava flows. The other shield volcanoes in the area are much more heavily vegetated than Devil Mountain, indicating that they were formed during older eruptions (Hopkins 1988). At the crest of Devil Mountain a west–northwest-trending swarm of cinder cones is preserved along with several short basaltic lava flows (Figure 21; Hopkins 1988). The lava flows are typical pahoehoe flows that have been fractured by frost action. Comparisons of the relatively well-preserved cinder cones on Devil Mountain to the preservation of cones in the Imuruk volcanic field suggest that the Devil Mountain eruption is probably on the younger end of volcanism that took place on the Seward Peninsula, which ranges from 28 million years ago to within the last few thousand years (Table 1; Hopkins 1988; Mukasa et al. 2007).

Near Cape Espenberg, large lakes occupy four of the maars (Figure 20; Hopkins 1988). Collectively called the Espenberg maars, these maars include (from west to east) the White Fish maar, the Devil Mountain maar, the South Killeak maar, and the North Killeak maar (Figure 20). The Espenberg maars are circular to slightly elliptical in outline, except for the Devil Mountain Maar, which is composed of a northern and southern crater (corresponding to the North and South Devil Mountain lakes) separated by a small spit-shaped accumulation of ejecta. The maars were formed by phreatomagmatic eruptions (volcanic eruptions caused by the explosive interaction of water and magma) during the Pleistocene. The youngest of the Espenberg maars is the Devil Mountain maar, which formed 17,500 years ago. The South Killeak and North Killeak maars are approximately 62,000 years old, and the White Fish maar is the oldest, dated to 160,000 years old (Table 1; Hopkins 1988; Begét et al. 1996, 2003, 2005).

The Espenberg maars are the four largest maars known on Earth (Table 2; Begét et al. 1996). The largest known

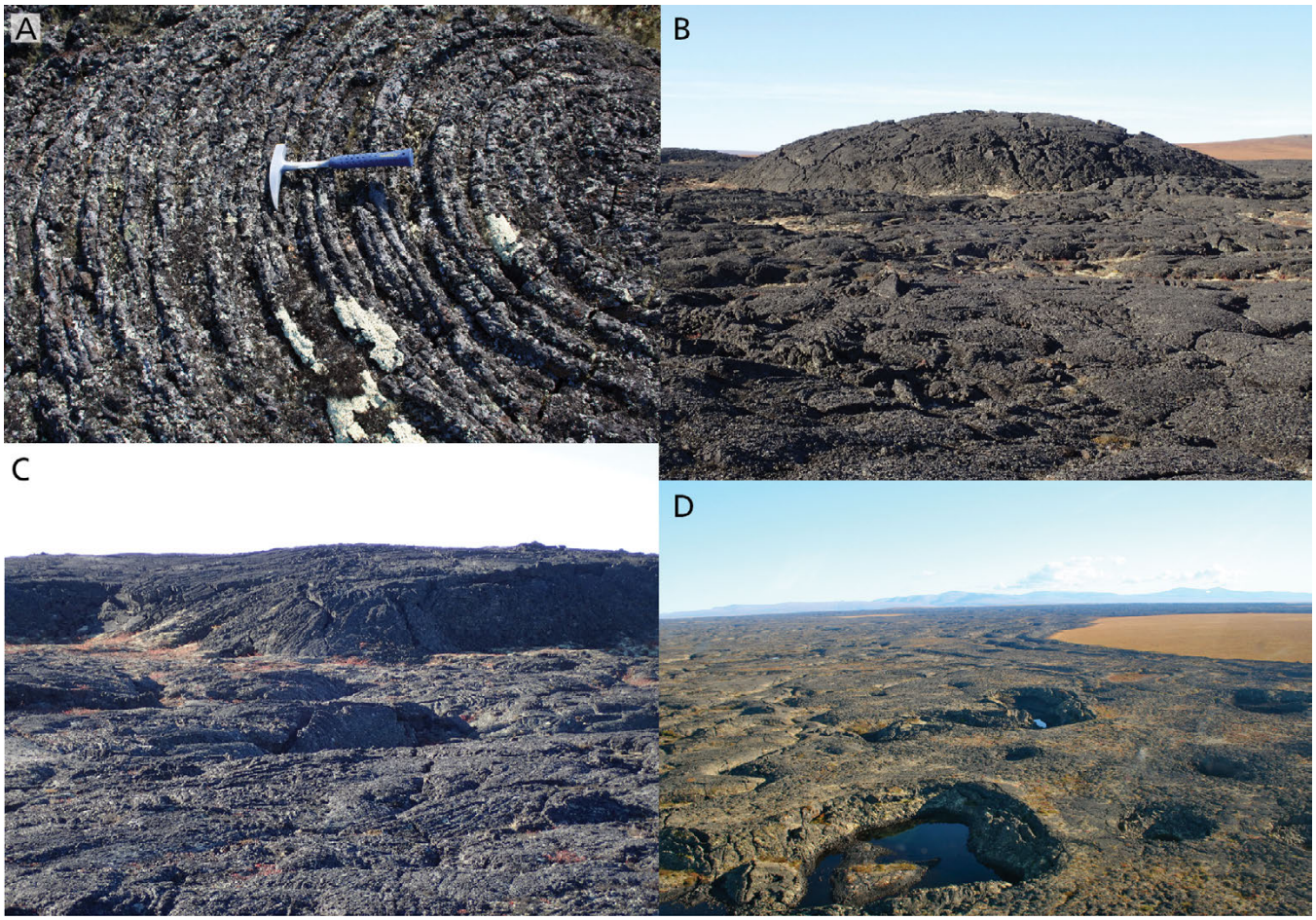


Figure 19. Photographs showing some of the features of the Lost Jim lava flow. (A) Ropy surface texture typical of pahoehoe lava. (B) A tumulus about 70 m (230 ft) long and 10 m (33 m) tall. Tumuli form by injection of lava and progressive thickening of the solid surface lava crust (Walker 1991). (C) Edge of a lava rise. This plateau feature formed by injection of lava and thickening of the solid surface crust, similar to tumuli but over an extensive area (Walker 1991). D: Lava flow collapse depressions. NPS photographs.

Table 2. Sizes of the Espenberg maars.

Note: Values of the maximum water depth represent the current depth of the lakes occupying the Espenberg maars. After taking into account the amount of sediment deposited in the lakes since the craters formed and the height of the bedrock cliffs surrounding the lakes, Begét et al. (1996) determined that, at the time of formation, each crater was excavated as much as 300 m (1,000 ft) into the underlying rock and sediments. Depths are from Begét et al. (1996), except for the depth of White Fish Maar, which was provided by Jonathan O'Donnell (NPS Inventory and Monitoring Arctic Network, aquatic ecologist, written communication, 10 September 10 2018).

Maar	Diameter	Total area	Maximum water depth
Devil Mountain Maar	8 x 6 km (5 x 4 mi)	> 30 km^2 (10 mi^2)	100 m (300 ft)
South Killeak Maar	5 km (3 mi)	An estimated 20 km^2 (8 mi^2)	> 60 m (200 ft)
White Fish Maar	4.3 km (2.7 mi)	15 km^2 (6 mi^2)	8-10 m (30 ft)
North Killeak Maar	4 km (3 mi)	An estimated 12 km^2 (5 mi^2)	25 m (80 ft)

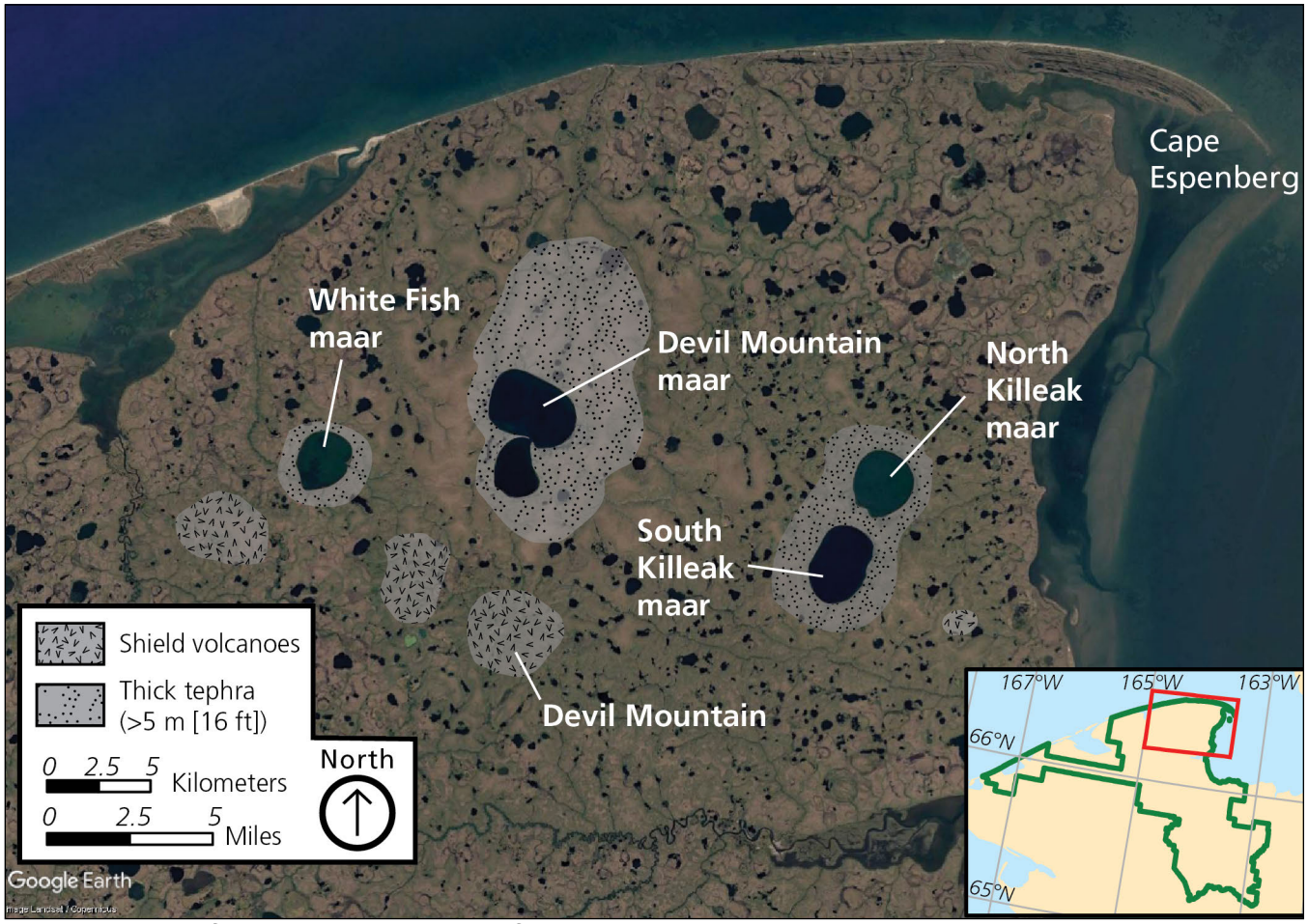


Figure 20. Map of the Espenberg volcanic field.
The large labeled lakes are the Espenberg maars, which are surrounded by thick ash deposits denoted by the light grey dotted areas. The shield volcanoes are denoted by light grey hatch-marked areas. Of the shield volcanoes, only Devil Mountain is labeled, as the other shield volcanoes are unnamed. GoogleEarth imagery © Landsat 2015. Tephra and shield volcano distribution is from Hopkins (1988).

maars outside the Espenberg maars are around 3 km (1.9 mi) in diameter and have a surface area of less than 8 km^2 (3 mi^2; Begét et al. 1996). The dimensions of the Espenberg maars are more comparable to small calderas (Begét and Mann 1992; Begét et al. 1996). The Devil Mountain maar has only a slightly smaller diameter than the Crater Lake caldera in Oregon (see GRI report by KellerLynn 2013). Moreover, all of the Espenberg maars are larger than the 2.5-km- (1.6-mi-) wide Katmai caldera in Katmai National Park and Preserve (Begét et al. 1996; Hults and Fierstein 2016).

The Espenberg maars are uniquely large because they formed as a result of interactions between magma and ice, rather than magma and liquid water (Begét et al. 1996). The Espenberg maars are the only known maars on Earth that formed where magma came into contact with ice-rich permafrost (Begét et al. 1996). Currently, permafrost is continuous (i.e., covers more than 90% of the landscape) on the northern part of the Seward Peninsula (Jorgenson et al. 2008) and was probably also continuous when the Espenberg maars erupted. Compared to liquid water, the thermodynamic properties of ice require about two to three times more energy to flash steam and cause a phreatomagmatic explosion (Begét et al. 1996). This effectively limits the amount of water reacting with the magma, keeping the water-to-magma ratio low. Phreatomagmatic eruptions with low water-to-magma ratios are more explosive (Begét et al. 1996). During phreatomagmatic eruptions with liquid water, the most explosive phase typically occurs early in the eruption (when initial groundwater is low) or towards the end of the eruption (when water supplies have been nearly exhausted) (Begét et al. 1996). By contrast, the high energy demands of melting ice of the Espenberg maars kept water-to-magma ratios continuously low while the abundance of ice provided an ample supply of water, resulting in prolonged and highly explosive eruptions.

Figure 21. Photograph of scoria from the cinder cones on Devil Mountain.
Scoria is a type of mafic (rich in iron and magnesium) igneous rock that is highly vesicular (containing voids where volcanic gas bubbles were trapped as the rock cooled). Boot for scale. NPS photograph by Chad Hults (NPS Alaska Regional Office).

In addition to excavating the craters, each maar-forming episode produced volcanic deposits and brought volcanic ejecta composed of fragments of older rocks and sediments up from depth (Figure 22; Hopkins 1988; Begét et al. 1996). The older rocks and sediments were sourced from the strata underlying the Espenberg maars. At the Devil Mountain maar, the "accidental rock fragments" (brought up from depth) include angular pieces of quartz and schist sourced from the Paleozoic basement rock (see the "Bedrock" section for more information), Eocene volcanic rocks formed by older eruptions in the region, and Pliocene and Pleistocene sedimentary rocks and sediments (see "Paleontological Resources" section for more information about the fossils recovered from these rocks). Juvenile volcanic deposits formed during the eruption of the Devil Mountain maar include sequences of massive pyroclastic flows (density currents of volcaniclastic particles and gases), bedded surge deposits (formed by low-density pyroclastic flows) (White and Ross 2011), scoria beds (extremely vesicular basaltic rock), and airfall lapilli (fine-grained pyroclastic material) (Figure 22; Begét et al. 1996). Each eruption deposited tephra, primarily volcanic ash, over an area of 1,000 km^2 (400 mi^2) or more (Figure 20; Hopkins 1988). These layers of tephra make effective stratigraphic marker beds, and at least one of the tephra layers (the Devil Mountain Lakes tephra, corresponding to the Devil Mountain maar eruption) preserves a paleosol beneath it (for more information about the Kitluk Paleosol, see the "Paleontological Resources" section; Hopkins 1988; Höfle and Ping 1996).

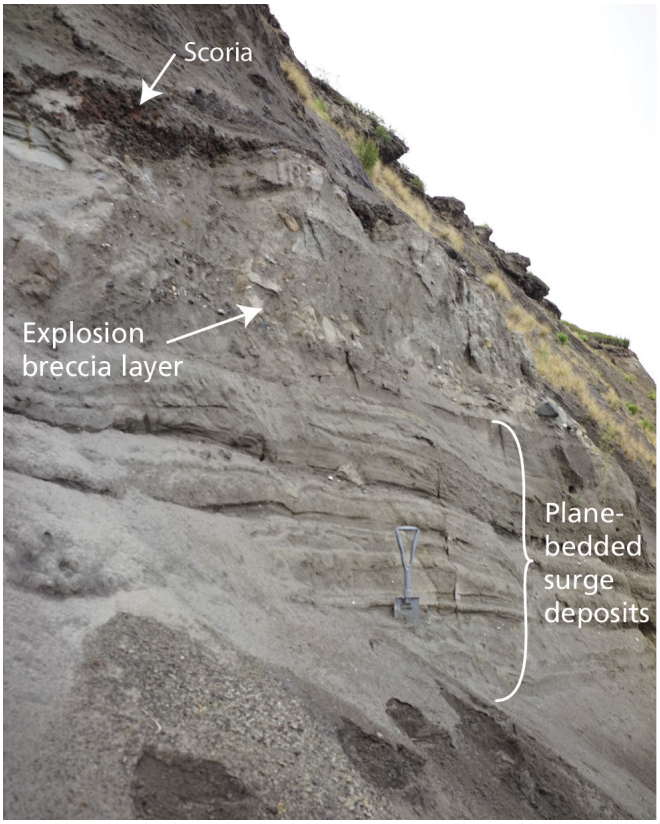


Figure 22. Photograph of maar-derived deposits found along the rim of the Devil Mountain maar. Plane-bedded surge deposits are overlain by a layer of explosion breccia, which is in turn overlain by a layer of scoria. Plane-bedded surge deposits were formed by low-density pyroclastic flows, which are density currents composed of volcaniclastic particles and gases. The explosion breccia contains accidental rock fragments brought up from depth, and the scoria layer is composed of vesicular mafic volcanic rocks (see Figure 21 for a photo of scoria from Devil Mountain). NPS Photograph by Chad Hults (NPS Alaska Regional Office).

Bering Sea Volcanic Province

Approximately 15 large late Cenozoic basaltic volcanic fields are scattered along the western coast of Alaska and on islands in the Bering Sea; these are collectively referred to as the Bering Sea volcanic province (Figure 23; Moll-Stalcup 1994; Winer et al. 2004). Both the Imuruk and the Espenberg volcanic fields are part of the Bering Sea volcanic province. The oldest basalts assigned to the Bering Sea volcanic province are the Kugruk volcanics, which date to 28 million–26 million years ago (Mukasa et al. 2007). This isolated eruption was followed by a pause in volcanic activity until about 6 million years ago when volcanism resumed on the Seward Peninsula (Mukasa et al. 2007) and began

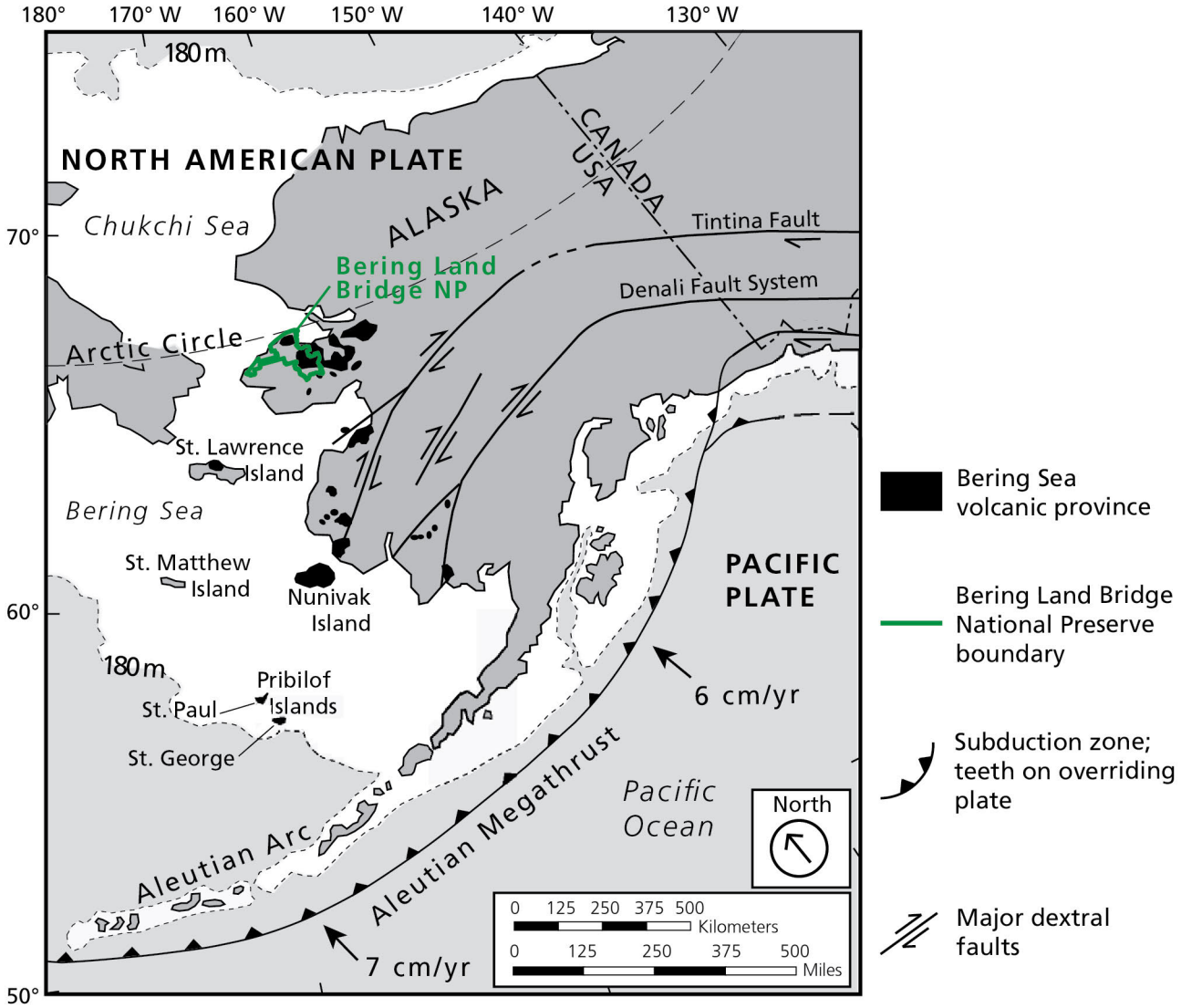


Figure 23. Map of the Bering Sea volcanic province distribution.
The Bering Sea volcanic province consists of approximately 15 large late Cenozoic basaltic volcanic fields, which are shown on the map in black. These volcanic fields are scattered along the western side of Alaska as well as on islands in the Bering Sea. Despite being located behind the Aleutian Megathrust, the Bering Sea volcanic province is not formed by typical back-arc volcanism, but is instead related to extension in the region. Modified from Winer et al. (2004).

elsewhere in the Bering Sea volcanic province (Moll-Stalcup 1994). Volcanism in the Bering Sea volcanic province has continued intermittently since 6 million years ago, with some eruptions, such as the Lost Jim lava flow, occurring during historic times (Hopkins 1963; Moll-Stalcup 1994; Mukasa et al. 2007). Mukasa et al. (2007) suggested that the Bering Sea volcanic province may essentially still be active (see the "Geohazards" section for more details on volcanic hazards in the preserve).

Unlike most of the recent volcanism in Alaska, the Bering Sea volcanic province does not occur at the boundary between the North American and Pacific plates but in the back-arc region of the Aleutian volcanic arc. Despite the location, the rocks of the Bering Sea volcanic province do not have a typical back-arc composition, nor do they occur along a spreading rift axis as would be expected for traditional back-arc volcanism (Moll-Stalcup 1994). The possibility that a mantle plume is the source of the volcanism, however, has been rejected because no clear progression or alignment of eruptive ages occurs along a hot spot trend (Mukasa et al. 2007). Most researchers instead

Figure 24. Photograph of one of the Trail Creek Caves.
NPS hydrologist Paul Burger is mapping the entrance of cave "C". Some of the caves, like the one pictured above, have shallow entrances that require crawling, whereas other caves have blocky entrances that are large enough for a person to stand. NPS photograph by Amanda Lanik (NPS Alaska Regional Office).

tie the presence of the Bering Sea volcanic province to extension within the region (Moll-Stalcup 1994; Wirth et al. 2002; Winer et al. 2004; Chang et al. 2009).

Wirth et al. (2002) suggested that the Bering Sea volcanic province fits the model for a diffuse igneous province, similar to that described for Cenozoic volcanism in Southeast Asia (Hoang and Flower 1998). The volcanism in the Bering Sea volcanic province and Southeast Asia are characterized by small volume and widely dispersed eruptions with similar compositions (tholeiitic to alkaline basalts; Wirth et al. 2002). Additionally, both areas are thought to be undergoing tectonic extrusion related to major collisional events: the accretion of terranes (including the modern collision of the Yakutat block) in southcentral Alaska (Mackey et al. 1997; Redfield et al. 2007) and the India-Asia collision in Asia (Hoang and Flower 1998). In Alaska, the southwestward extrusion of the "Bering Block" is accommodated by extensional and transtensional (oblique extension) faulting, which serve as conduits for magma to reach the surface (Chang et al. 2009). For more information about the history of extension in the Bering Strait region, see the "Geologic History" chapter of this report.

Cave Resources

Caves in the preserve occur in three contexts: (1) marble outcrops of the Nome Complex (**DOx**), (2) lava tubes in the Lost Jim lava flow (**Qlj**; Burger 2016), and (3) sea caves or alcoves present near the eastern end

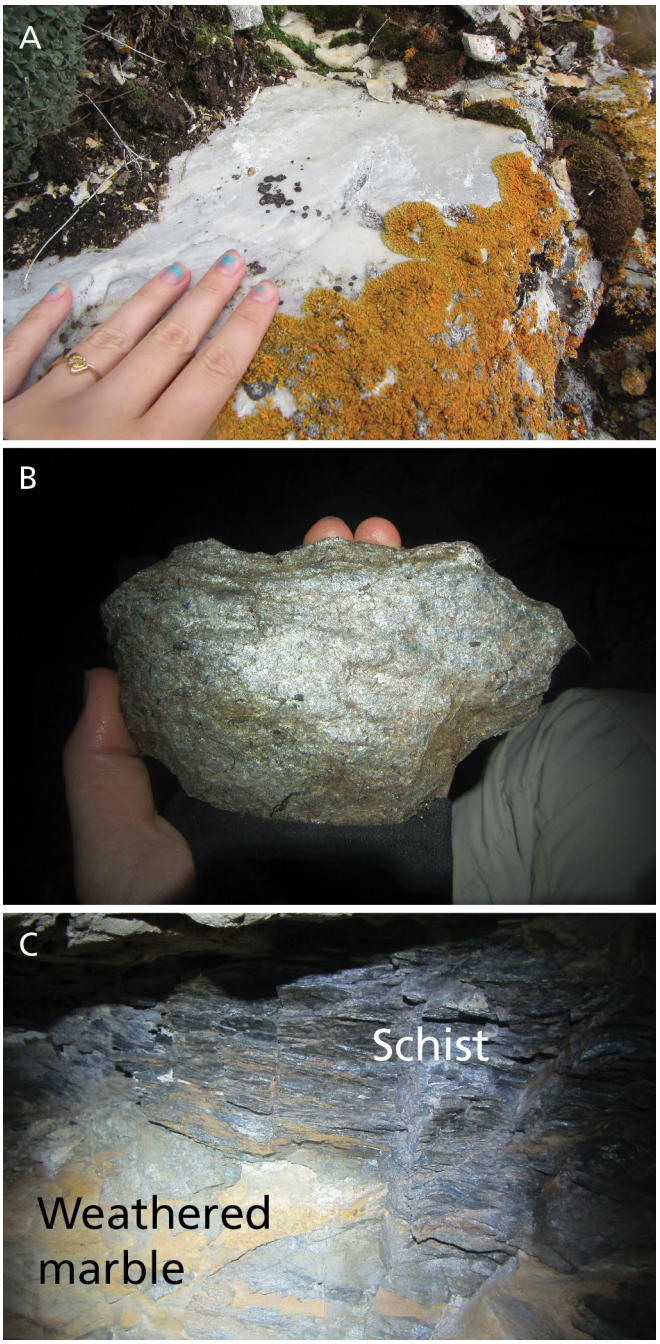


Figure 25. Photographs showing the different rock types found at Trail Creek caves.
(A) Photograph of the marble that makes up the majority of the outcrop. (B) and (C) Photographs of schist, which occurs as small pockets in the outcrop that is otherwise dominated by marble. (B) shows a schist cobble that was on the floor of Cave A; schist cobbles such as the one figured are commonly found littering the cave floors. (C) shows schist that occurs in the wall of Cave A. The common occurrence of schist in the cave walls may indicate that preferential weathering of this rock may be contributing to cave development. NPS photographs by Amanda Lanik (NPS Alaska Regional Office).

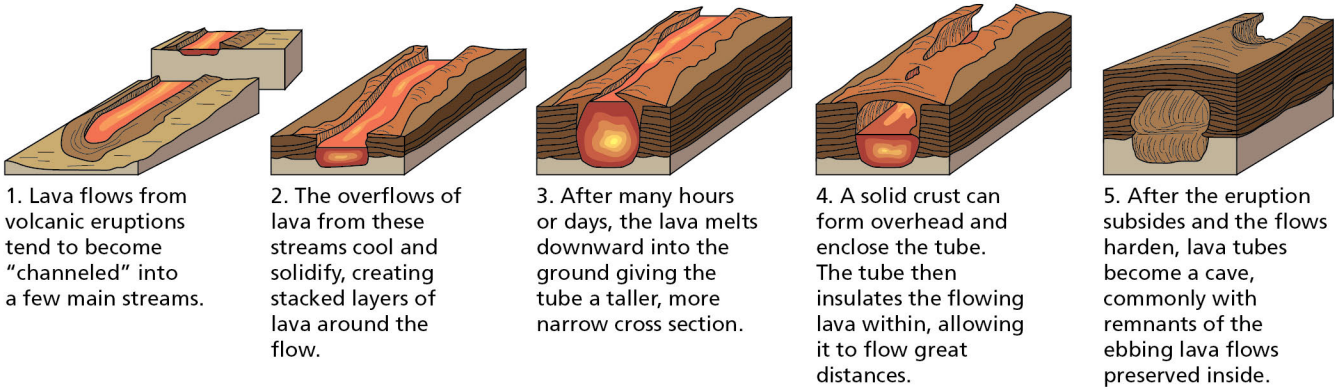


Figure 26. Series of diagrams showing how a lava tube forms.
The edges of a lava flow cool more quickly, and as the rock cools, it solidifies and builds up until it eventually encloses the still-liquid lava inside. Once the lava is drained from this structure, an underground void, or lava tube, remains. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after USGS graphic by Bruce Rogers.

of the preserve's coast. Caves are naturally occurring underground voids that can occur in rock, soil, or ice. Some of the most common cave types include solution caves (commonly associated with karst), lava tubes, sea caves, and glacier caves (ice-walled caves). Lava tubes or solution caves that contain perennial ice are sometimes called "ice caves." Both the Lost Jim lava tubes and Trail Creek caves have reports of perennial ice (Larsen 1968; Burger 2016).

Trail Creek Caves

The Trail Creek caves are of a set of 13 caves in an outcrop of marble, schist, and graphitic metasiliceous rock (**DOx**) belonging to the Nome Complex (Schaaf 1988). These caves were excavated by Danish archeologist Helge Larsen in 1949 and 1950 (Larsen 1968). Larsen focused his efforts on the two largest caves (Cave 2 and Cave 9) and found more than 300 archeologist artifacts and more than 25,000 faunal elements (Larsen 1968). The Trail Creek caves were investigated by NPS scientists in 1985, at which time five of the caves not excavated by Larsen were subjected to small-scale test excavations at the cave entrances

(Schaaf 1988, Vinson 1988). These excavations recovered more than 2,580 mammal and bird fossils (Vinson 1988), demonstrating that despite the thorough excavations of Caves 2 and 9 by Larsen (1968), the other caves still contain intact paleontological resources. During the summer of 2017, NPS scientists mapped five of the 13 caves in detail (Figure 24).

The Trail Creek caves are situated in a steep, southeast-facing rocky outcrop near the northeast boundary of the preserve. The 13 described caves range between 2.5 and 31 m (8.2 and 102 ft) long, but numerous additional small alcoves and other entrances exist in the same outcrop (Burger 2016). The outcrop is primarily composed of marble, but smaller lenses of schist are also present (Figure 25). Schist is common in the cave walls and in the rubble on the floors, and many of the caves terminate in pockets of schist. The preferred development of speleogenetic features in schist pockets could indicate that weathering and transport of the more friable schist contributed to the formation of the caves. No scallops or other erosional speleogens were observed during the 2017 cave mapping, but these features may have been removed by freeze-thaw weathering of the original walls. While the Trail Creek caves are the only currently known caves developed in carbonate rock in the preserve, marble and limestone crops out in other areas and could potentially contain caves that have yet to be discovered (Burger 2016).

Lava Tubes

The Lost Jim lava flow, which is composed of Lost Jim Basalt (**Qlj**), exhibits classic pahoehoe structures, including lava tubes (Hopkins 1963; Marcucci et al. 2017). A lava tube is a type of cave that forms during a volcanic eruption, as the outer portion of a lava channel cools and solidifies (see Figure 26 for a description of how lava tubes form). A large main lava tube with a length of more than 19 km (12 mi) fed the majority of the Lost Jim lava flow (Figure 27; Hopkins 1963). This main lava tube conveyed lava westward from the source vent beneath Lost Jim cone (Hopkins 1963). Skylights (formed either by incomplete roofing or roof collapse) overlie the main lava tube and mark its sinuous path (Hopkins 1963; Marcucci et al. 2017).

A three-day reconnaissance survey was conducted by NPS scientists during the summer of 2016 to document lava tubes in the Lost Jim lava flow (Figure 27; Burger 2016). During the survey, 34 cave features were documented while covering less than 10% of the

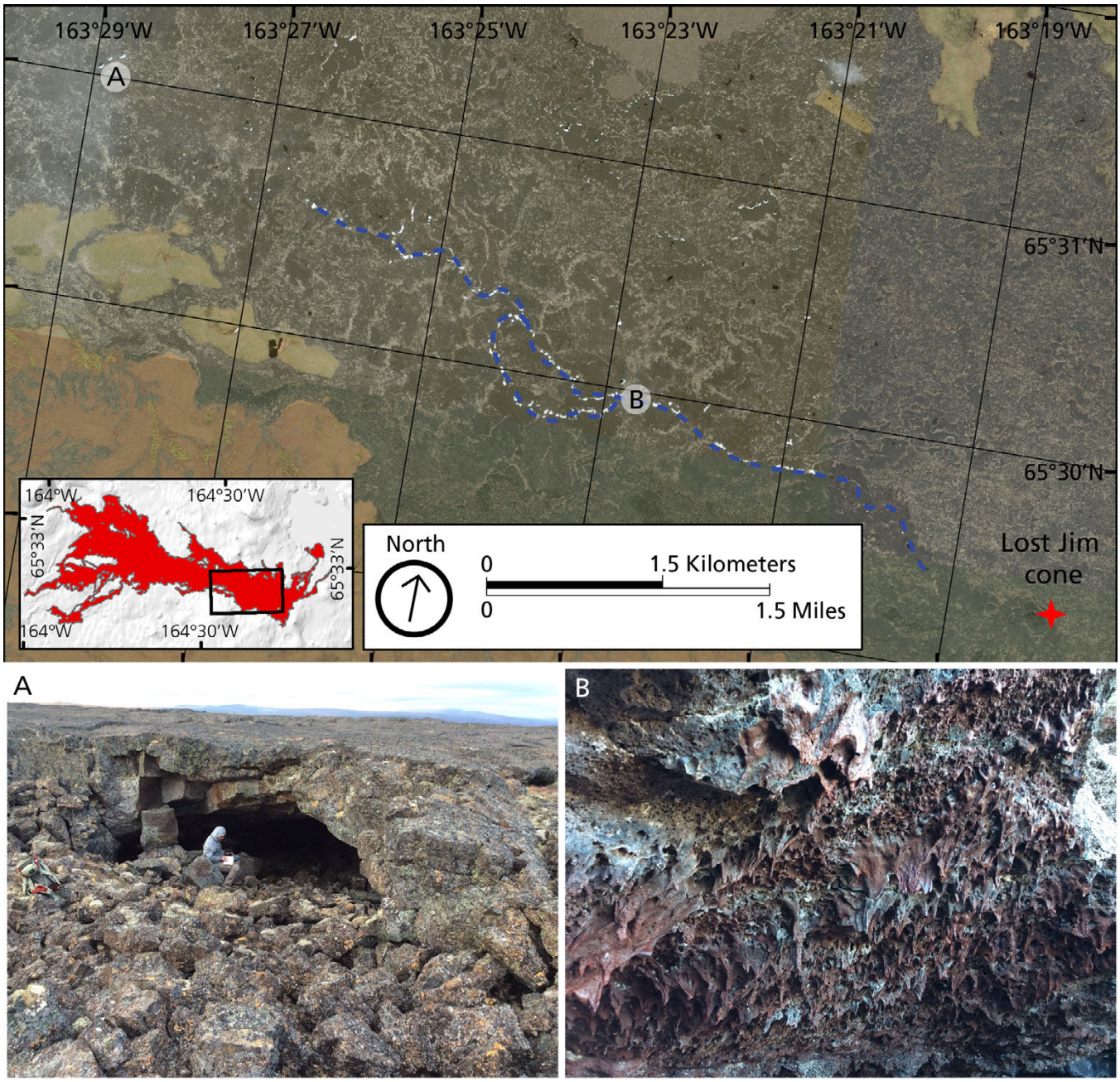


Figure 27. Map and photos of Lost Jim lava tubes.
Lettered dots indicate photograph locations and the red star marks the Lost Jim cone. The dotted blue line indicates the path of the skylights and the large main lava tube described by Hopkins (1963). A: Photograph of the entrance of one of the lava tubes. B: Photograph of lava stalactites formed by lava cooling as it dripped from the roof of the lava tube. NPS photographs by Tahzay Jones (NPS Alaska Regional Office).

total flow area (Burger 2016). The caves range in length from 10 m (30 ft) to 100 m (300 ft) or more; however, not all caves were explored to their full length (Burger 2016). Some of the caves documented as separate caves are part of the same lava tube network but were subsequently separated by roof collapse (Burger 2016). Several of the caves contained pools of water or flowing water perched on perennial ice (Burger 2016). A cairn was discovered at the entrance of one of these water-bearing caves; it may have been constructed to mark the location of the water hidden below (Burger 2016). The caves documented during the 2016 survey are smaller, tangential tubes that are not part of the large main lava tube described by Hopkins (1963) (Paul Burger, NPS Alaska Regional Office, hydrologist, personal communication, 3 January 2018). In the area that was investigated, the main lava tube that Hopkins (1963) discussed manifests as a large trench as much as 60 m (200 ft) wide, with no roofed sections.

Figure 28. Photograph of a sea cave or alcove.
Many sea caves have apparently developed in the Cambrian–Devonian schist (DCks) near the eastern end of the preserve's coast. ShoreZone photograph nw12_kz_03519 (latitude 66° 4′ 4″ N, longitude 163° 14′ 16″ W. NOAA Alaska ShoreZone database (https://alaskafisheries.noaa.gov/mapping/szflex/, accessed 6 September 2018).

Sea Caves

Sea caves or alcoves exist near the eastern end of the preserve's coast and are visible in imagery from the NOAA Alaska ShoreZone database (Figure 28). The sea caves have not yet been investigated, but numerous apparent caves are visible in ShoreZone imagery along the 4.5-km (2.8-mi) stretch of coast where units **DCks** (calcareous schist) and **DObm** (metalimestone and marble) (see poster, in pocket) crop out to form rocky cliffs. Sea caves form through the erosional action of waves and currents upon a cliff face unprotected by the buffering effects of a beach. To form caves, erosion cannot occur uniformly along the rock face, but must occur preferentially in preexisting weak areas of the rock (Moore 1954). The sea caves or alcoves are developed in Cambrian–Devonian calcareous schist (**DCks**; see poster, in pocket), and preferential weathering could be a result of dissolution of calcareous rock or erosion along bedding or foliation planes.

Serpentine Hot Springs

Serpentine Hot Springs is the only geothermal site within the preserve. It consists of two distinct thermal areas (Serpentine Hot Springs proper and Arctic Hot Springs) that are located approximately 600 m (2,000 ft) apart on Hot Springs Creek (Figure 29). The waters of Serpentine and Arctic Hot Springs are likely fed by the same source as evidenced by their virtually identical chemical compositions and similar maximum subsurface temperatures of 127 ± 3°C (260 ± 5°F; Nordstrom et al. 2015). Based on hydrogen and oxygen isotopes, the thermal waters are primarily meteoric in origin (Nordstrom et al. 2015), which is in line with other thermal springs in the region (Miller et al. 1975). The water at Serpentine Hot Springs contains a saline component, which also occurs in two other thermal springs on the Seward Peninsula: Pilgrim Hot Springs and Kwiniuk Hot Springs (Figure 29; Miller et al. 1975). Miller et al. (1975) interpreted the elevated salinity as a product of bedrock leaching whereas Nordstrom et al. (2015) suggested that, based on bromide and sodium

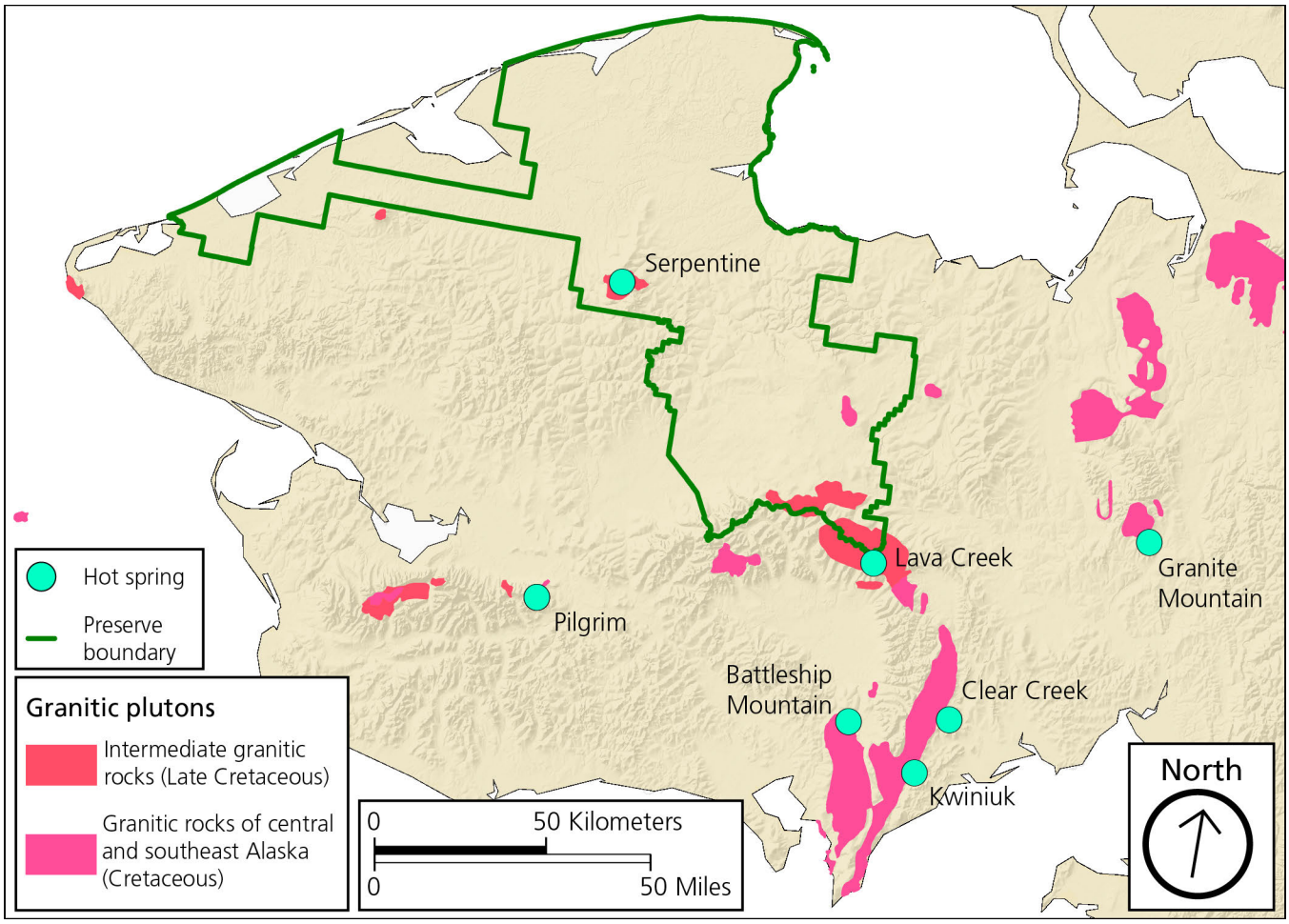


Figure 29. Map of hot springs and granitic plutons on the Seward Peninsula.
The hot springs are labeled by the green dots and the granitic plutons are colored pink. As the map shows, all of the hot springs on the Seward Peninsula, including Serpentine Hot Springs, are located either on top of a granitic pluton or close to one. Hot spring locations and names from Motyka et al. (1983). Granitic pluton distribution and description from Wilson et al. (2015).

concentrations at Serpentine Hot Springs, the salinity could represent a 7% seawater component.

Geothermal features, which are usually associated with recent volcanism or thermal springs, are found throughout Alaska (Figure 30). About half of the more than 100 geothermal features in Alaska are associated with volcanism along the Aleutian arc, while the other half are scattered across interior and southeastern Alaska and are not apparently associated with recent volcanism (Miller 1994). Instead, most are associated with granitic plutons (Waring 1917; Miller 1975), with 33 of the 36 thermal springs north of the Alaska Range occurring within 5 km (3 mi) of a granitic pluton margin (see Figure 29 for associations of thermal springs on the Seward Peninsula with granitic plutons; Miller 1994). The age, composition, or magmatic history of the plutons does not seem to correlate with development of thermal springs; ages of the plutons with thermal springs range from as old as 380 million years in the Brooks Range to as young as 60 million years in the Yukon-Tanana Upland (Miller 1994). Serpentine Hot Springs is associated with a 70 km^2 (27 mi^2) Late Cretaceous (80.2 million ± 3 million to 69.2 million ± 2 million year old; Hudson and Arth, 1983) biotite granite stock called the Oonatut Granite Complex (see the "Bedrock" section for more information; Hudson 1979).

Fractures in the granite plutons are thought to be the main driver in creating hot springs in northern Alaska. Based on the geochemistry and geology of these thermal springs, the heat is being derived from deep circulation of water derived from precipitation (Miller et al. 1975). Deep circulation is achieved by water percolating down through fractures in the granitic plutons, heating up because of the geothermal gradient (increase of temperature with depth), and moving back up to the surface along the fractured and faulted margins of

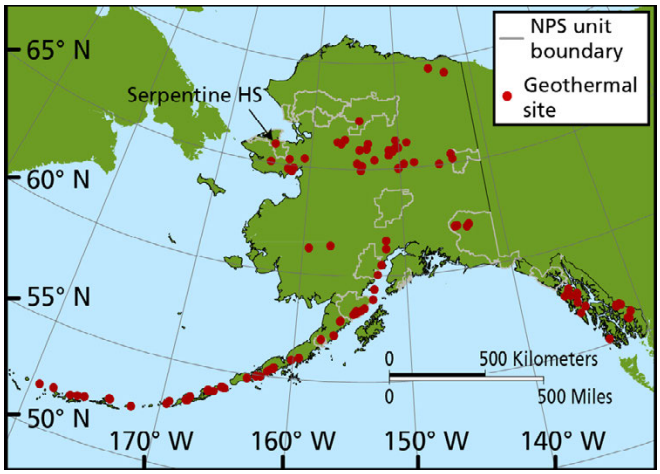


Figure 30. Map showing the location of geothermal sites in Alaska.
Many geothermal sites exist in the southern part of the state, and these are concentrated along the Aleutian volcanic arc. The hot springs in the northern part of the state are for the most part not associated with volcanism but rather with granitic plutons. The geothermal sites are marked by red dots, and national parks are outlined in grey. Serpentine Hot Springs is labeled. Geothermal site location from Motyka et al. (1983).

the granite plutons (Miller et al. 1975). Subsurface temperature estimates for Serpentine Hot Springs as well as 25 other thermal springs in west-central Alaska indicate that the thermal waters circulate to depths of 3.3–5.3 km (2.1–3.3 mi; Miller et al. 1975). This circulation depth was determined using a geothermal gradient of 30°C/km (80°F/mi) to 50°C/km (150°F/mi); however, if magma underlies the springs and is contributing heat to the system, these depths could be shallower.

Quaternary Surficial Deposits

Most of the preserve is covered by Quaternary surficial deposits (**Qs**; see poster, in pocket). Currently, no surficial geologic map is available for all of Bering Land Bridge National Preserve. Surficial geology has been mapped in the Shishmaref area (just outside preserve boundaries) by Mason (1996). The ecological subsection map (Jorgenson 2001) is another useful resource for understanding surficial geology in the preserve, as physiography and geology were factors used to define the various ecological land classifications. General types of Quaternary sediments in the preserve include eolian silt deposits called loess, slope deposits, alluvium, lacustrine sediment, and coastal marine deposits. These were grouped as "surficial deposits, undivided" by Till et al. (2011, the source map for the GRI GIS data). For more information on coastal marine deposits, see the "Coastal Features" section of this report.

Gently sloping surfaces that were exposed during the Pleistocene Epoch (2.58 million–11,700 years ago) are generally covered by a mantle of loess (windblown silt). Loess deposits cover most of the landscape across much of the northern half of the preserve. Jorgenson (2001), which mapped ecological subsections of the preserve, recognized "upper" coastal plain units (the Bering Straits and Goodhope Bay Upper Coastal Plains) and "lower" coastal plain units (the Bering Straits and Goodhope Bay Lower Coastal Plains). The two "upper" coastal plains contain significant areas of undisturbed Pleistocene loess deposits whereas on the "lower" coastal plains the Pleistocene loess has been reworked by thermokarst (discussed in the "Permafrost and Thermokarst" section in more detail) as well as lacustrine erosion and deposition. The eolian deposits of the "upper" coastal plains contain large amounts of ground ice. This ice accumulated while the loess was deposited, mainly in the form of large ice wedges in a polygonal network. The syngeneic (formed contemporaneously) accumulation of loess, ground ice, and permafrost resulted in tens of meters of ice-rich sediment known as "yedoma" (Figure 31; Kanevskiy et al. 2011; Shur et al. 2009, 2012). Thaw lakes in yedoma typically display conical mounds on their bottoms and along their shores that mark the centers of ice-wedge polygons where the ice has melted. Lakes in yedoma terrain are relatively deep, exceeding 10 m (33 ft), and can persist for thousands of years (Farquharson et al. 2016a). The eolian deposits of the preserve contain layers of tephra that are thickest in the vicinity of the maar lakes (see the "Volcanism" section for more details). Because yedoma has been frozen since the Pleistocene Epoch, it can be an excellent source of exceptionally preserved fossils (see the "Paleontological Resources" section for more information). In the Imuruk Lake area, Holocene lava flows (the Lost Jim and Camille flows) lack significant eolian deposits, but the older lavas (Kugruk, Imuruk, and Gosling volcanics) are partly covered by a mixture of loess and bedrock fractured by frost action (Hopkins 1963; see the "Volcanism" section in this report for more information). The eolian deposits were identified based on their good sorting and mineralogy, which includes minerals derived from alluvial source areas rather than the underlying bedrock (Hopkins 1963).

Slopes in the preserve contain a variety of colluvial (slope) deposits derived from both the underlying bedrock and eolian additions. These include talus and scree on the steepest mountain slopes, solufluction deposits, deposits from active-layer detachments (Swanson 2010, 2014), and mixtures of loess, peat, and frost-churned bedrock (Hopkins 1963).

Figure 31. Photograph of yedoma.
Yedoma (ice-rich sediment formed during the Pleistocene) is exposed along the coast of Bering Land Bridge National Preserve. NPS photograph by Tahzay Jones (NPS Alaska Regional Office).

Alluvium is present along all of the major streams in the preserve. Modern river floodplains generally contain most of the alluvium in the preserve because higher alluvial terraces and fans are mostly absent. Alluvium mixes with marine deposits in coastal estuaries and lagoons. Alluvial deposits consist of sand, gravel, and silt, commonly mantled by a layer of peat in lower energy areas. River channels are dominantly meandering (Figure 32), with oxbow lakes and wetlands formed in abandoned channels. Alluvial sediments from meandering streams consist of point-bar deposits from the migrating channel and finer-grained overbank sediments deposited across the floodplain during floods (Leopold et al. 1964). As permafrost becomes established in older alluvial deposits and ground ice accumulates, oxbow lakes and ponds become modified by thermokarst (see the "Permafrost and Thermokarst" section for more information; Péwé 1948).

Figure 32. Photograph of the Kuzitrin River.
The photograph highlights the meandering morphology of the Kuzitrin River, which is common in many of the rivers in the preserve. NPS photograph.

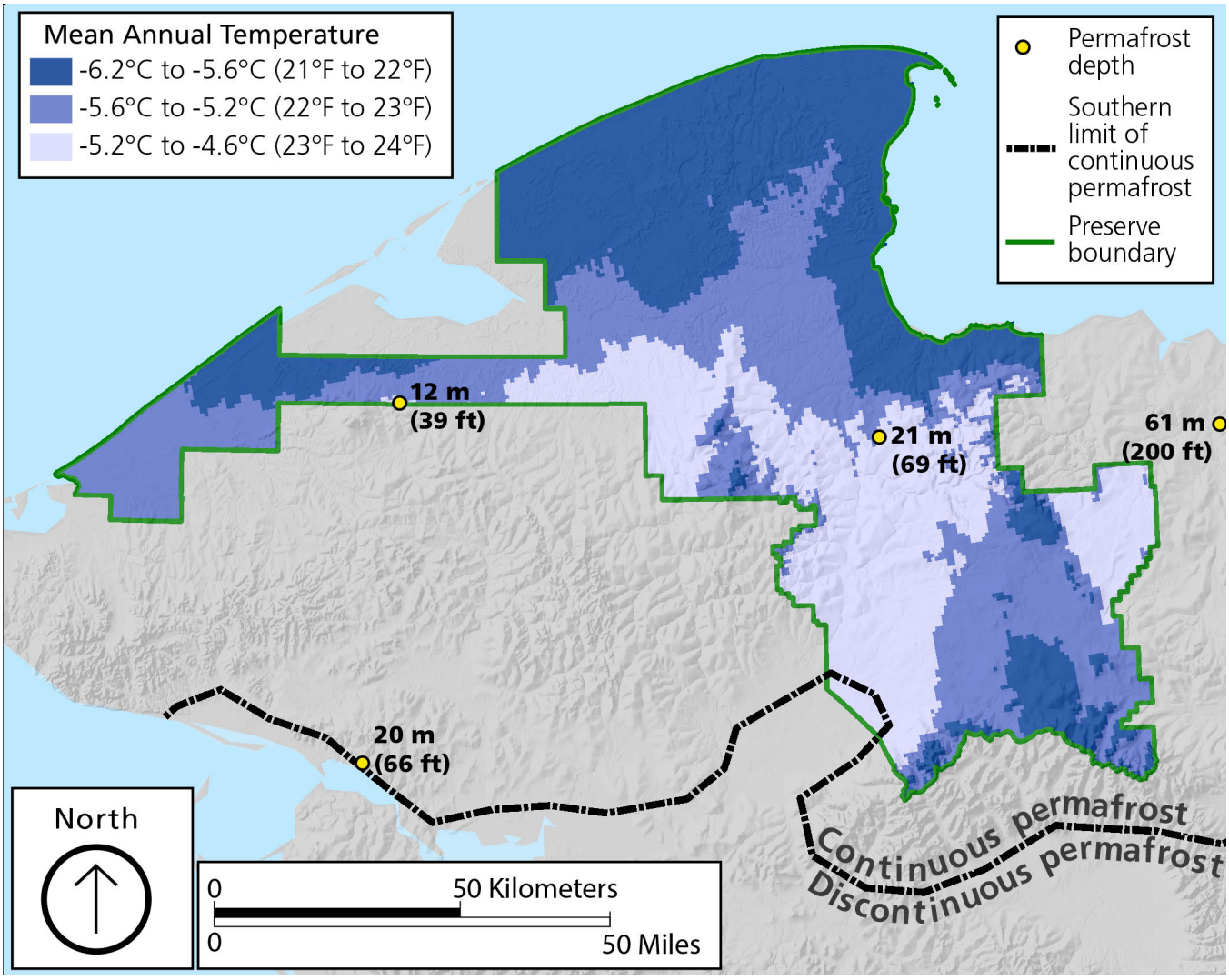


Figure 33. Map of mean annual temperature and permafrost in the preserve. Permafrost depths and the separation between the continuous permafrost zone and the discontinuous permafrost zone are shown. The continuous permafrost zone consists of more than 90% permafrost. The discontinuous permafrost zone has between 50% and 90% permafrost. Bering Land Bridge National Preserve is almost entirely in the continuous permafrost zone, with a small portion of the preserve in the discontinuous permafrost zone. Mean annual temperature is an estimate for the climatological period 1971–2000 and was created using the PRISM model (PRISM Climate Group 2009). The permafrost depth measurements (marked as yellow points) and the boundary between the continuous permafrost zone and discontinuous permafrost zone are from Jorgenson et al. (2008).

Most of the "lower" coastal plains mapped by Jorgenson (2001) are covered by lacustrine deposits and Holocene peat. The lacustrine deposits were mainly deposited in thermokarst lakes (see the "Permafrost and Thermokarst" section for more information). Existing lakes and outlines of former lakes that have drained cover essentially the entire landscape of the "lower" coastal plains. Peat deposits 0.5 m (2 ft) or more thick have formed under poorly drained conditions of the former thermokarst lake basins (Jones et al. 2012).

Permafrost and Thermokarst

The preserve is almost entirely in the zone of continuous permafrost, which means that permafrost underlies more than 90% of the landscape (Figure 33; Jorgenson et al. 2008). Permafrost is typically continuous in regions where the mean annual air temperature is about -5°C (23°F) or lower (Jorgenson et al. 2008). Mean annual air temperatures in the preserve are near -5°C to -6°C (23°F to 21°F) and thus permafrost is continuous, though near the warm limit for continuous permafrost (Figure 33).

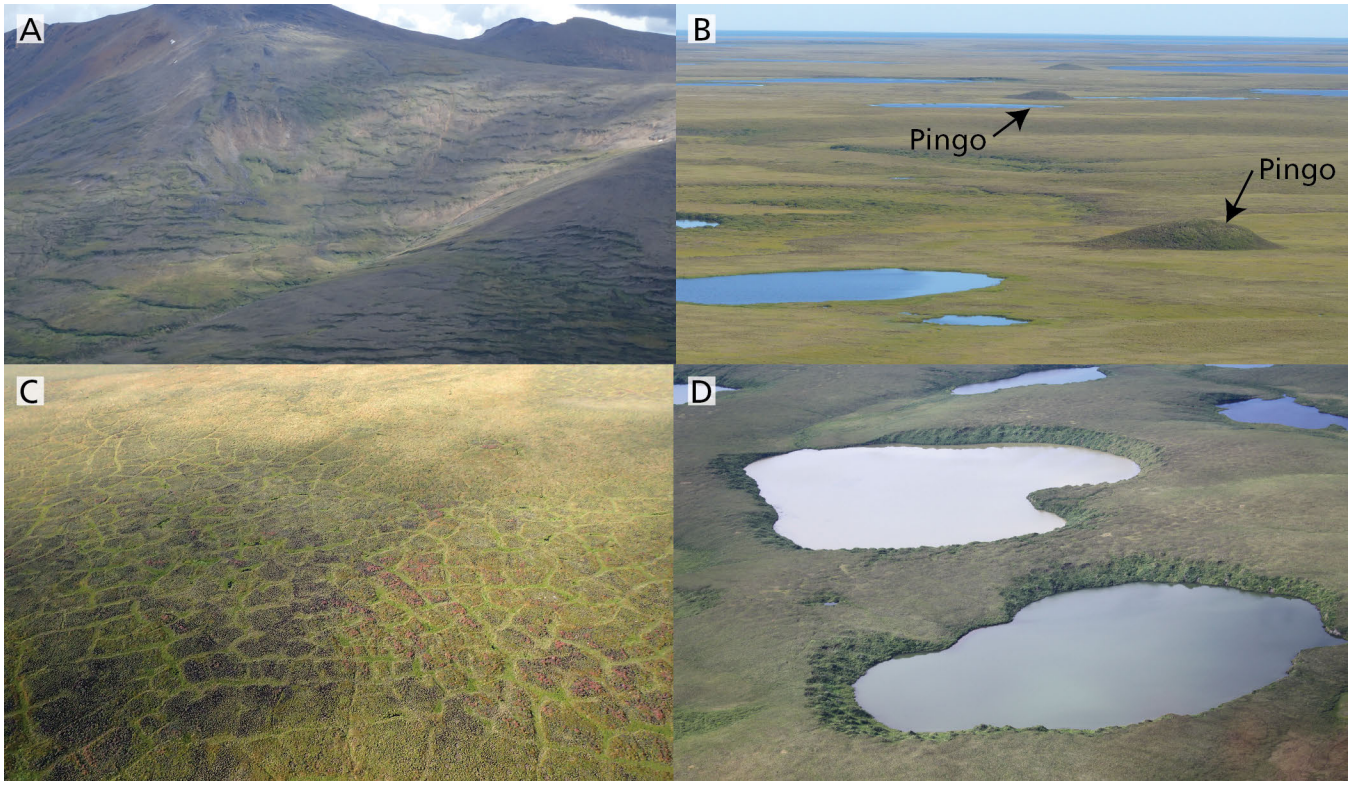


Figure 34. Photographs showing permafrost-related geomorphic features.
(A) Solifluction lobes. Solifluction lobes are marked by horizontal lines of vegetation. The downslope flow of wet, unfrozen material over frozen material. Refers to a slower process than that which produces active-layer detachments. The vegetation and organic soils surface mat on soliflucting material typically remains intact. (B) Pingos. Pingos are ice-cored hills that rise abruptly out of the flat landscapes of the Alaskan arctic. Pingos often form in drained thermokarst lake basins. After a lake drains, the previously unfrozen ground beneath the lake starts to freeze, nucleating around a core of ice that grows and pushes up the overlying ground to form a hill. (C) Ice-wedge polygons. These features are generally wedge-shaped bodies of ice present in permafrost that are produced by ice contraction cracking followed by infilling and freezing of water. Ice-wedges form in a polygonal pattern in map view, such as in this aerial photograph. (D) Thermokarst lake. Thermokarst lakes form when permafrost melts. Water in the lake is perched upon underlying ground ice. The lake water retains more heat than the surrounding ground, causing melt along the edges of the thermokarst lake and expansion. Thermokarst lakes occasionally drain rapidly when the edge of the lake is breached. NPS photographs.

Permafrost is ground (soil, sediment, or rock plus any ice or organic material) that remains frozen for at least two consecutive years. However, most of the permafrost in the preserve has been frozen for thousands of years. The upper portion of the ground that thaws each summer and refreezes each winter is known as the active layer and is 0.3–2 m (1–6.5 ft) thick (Panda et al. 2016). Permafrost exists between the active layer and the depth at which the geothermal gradient increases ground temperatures to above freezing. In the preserve, permafrost thickness is mostly unknown, but thicknesses measured in boreholes around the Seward Peninsula range from 5 to 107 m (16 to 350 ft) (Figure 33; Jorgenson et al. 2008). The thickest permafrost on the North Slope of Alaska is on the northern part of the coastal plain (Jorgenson et al. 2008), and the thickest permafrost on the Seward Peninsula is also likely on the northern coastal plain. Mean annual air temperatures on the coastal plain in the northern part of the preserve are lower than anywhere on the Seward Peninsula, and permafrost thickness in excess of 100 m (300 ft) may occur in these areas.

Permafrost and thawing of permafrost creates distinctive geomorphic features that are found throughout the preserve. These features include solifluction lobes, pingos, ice-wedge polygons, and thermokarst lakes (Hopkins 1949; Hopkins and Sigafoos 1951; Péwé 1975). See Figure 34 for descriptions of these features and how they form.

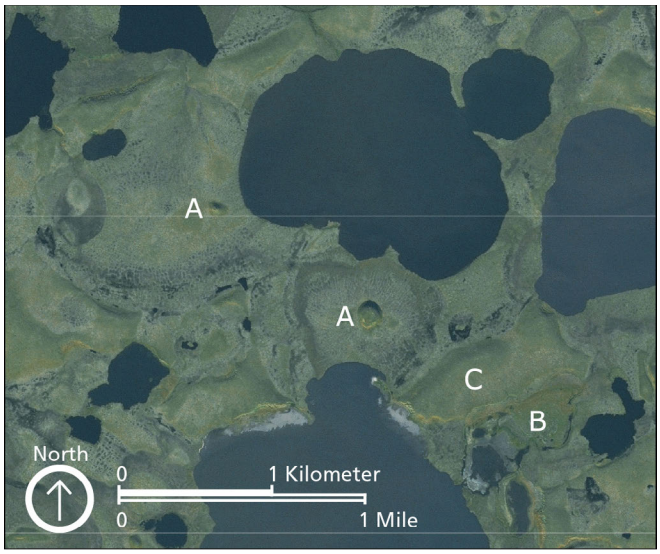


Figure 35. Map showing a satellite view of the thaw-lake plain.
"A"s mark old thaw lakes that drained and permafrost re-formed (note the polygons), resulting in a pingo in the center. "B" marks a recently drained thaw lake; it drained to the southwest into the bigger lake, but only partly so some water is still left. "C" marks remnant yedoma.

The term "thermokarst" refers to subsidence of the ground caused by thawing permafrost. One of the most conspicuous features created by thawing are thermokarst lakes (Figure 34). Themokarst lakes and evidence of past lakes are widespread in the coastal plains of the preserve (Figure 35). Many of the lakes in the northern portion of the preserve are thermokarst in origin (see poster, in pocket). Thermokarst lakes contain a distinctive set of sedimentary facies associated with growth of the lake (Hopkins and Kidd 1988; Farquharson et al. 2016b). These include a basal facies consisting of thawed material that subsided in place after the lake formed and a facies consisting of sediment eroded from the lakeshore and deposited in water. Remote sensing between 1950 and 2007 found that thermokarst lakes in the coastal plain south of Cape Espenberg expanded laterally at a rate of 0.35–0.39 m/yr (1.2–1.3 ft/yr); this expansion increased the likelihood for lake drainage (Jones et al. 2011). Consequently, despite the growth of individual lakes, the total area covered by lakes decreased by 15% during this time frame (Jones et al. 2011). Farther south in areas dominated by yedoma and volcanic deposits, decreases in lake area were less dramatic or absent (Swanson 2013).

Average permafrost temperatures in the preserve during the 2000–2009 decade were modeled to between -1.5°C and -4.5°C (29°F and 24°F) (Panda et al. 2016). Measurements of ground temperatures at three climate monitoring stations were in this same range (Swanson 2016a). Based on global circulation models, Panda et al. (2016) predicted an approximate 2°C (3.6°F) rise in average permafrost temperatures and a 5 to 20 cm (2 to 8 in) increase in active layer thickness by the 2050 decade. This would result in loss of only a small amount of the preserve's permafrost, though widespread thermokarst because of melting of ice in the upper permafrost is likely as the active layer thickens. The continued warming expected by the end of the current century would trigger widespread landscape change as ice-rich permafrost thaws. Changes are expected to be particularly dramatic in the ice-rich coastal plains of the northern part of the preserve, where tens of meters of subsidence as a result of thaw of ground ice is possible in some places. For more information about the results of permafrost thaw in the preserve today and what could be expected with further thaw, see the "Permafrost Monitoring" section of this report.

Coastal Features

The preserve contains 919 km (571 mi) of shoreline, which includes an outer coast as well as a substantial inner coast composed of large lagoons (Curdts 2011). The preserve encompasses much of the northern Seward Peninsula, with a portion of the coast facing east towards Kotzebue Sound and a larger portion facing northwest to the Chukchi Sea. Just to the west of the preserve lies the Bering Strait, which links the Chukchi Sea to the north with the Bering Sea to the south.

The bathymetry offshore of the preserve slopes gently, reaching depths of only 10 m (30 ft) between 3 and 15 km (2 and 9 mi) offshore (Jakobssen et al. 2012). The offshore waters are underlain by the submerged Bering-Chukchi shelf, which is a broad region of continental crust that connects North America and Asia (Miller et al. 2002). This continental shelf forms part of a crustal block called the Arctic Alaska-Chukotka microplate that stretches from northern Alaska to northeastern Russia (see the "Terrane Translation and Accretion" section for more information). Within the Bering-Chukchi shelf, sedimentary basins formed during Tertiary time (66 million–2.6 million years ago) as a result of extension related strike-slip faulting (Dumitru et al. 1995; Klemperer et al 2002); these include the Hope Basin (Chukchi Sea) to the north of the Seward Peninsula, and the Norton Basin (Bering Sea) to the south of the Seward Peninsula.

The Bering-Chukchi shelf has undergone periodic exposure and submergence in accordance with climate-driven fluctuations in global sea level. During glacial periods, widespread glaciation locked water on land in the form of ice. This lowered global sea level and caused

the Bering-Chukchi shelf to be subaerially exposed. The area that was exposed in the past by lowered sea level is called the Bering Land Bridge, which formed a terrestrial link between North America and Asia (Hopkins 1959). Conversely, glacial retreat during interglacial periods caused sea level to rise and large parts of the Bering-Chukchi shelf to be flooded. While this flooding severed the terrestrial link between North America and Asia, it opened up a marine connection between the Arctic and Pacific Oceans, allowing water, nutrients, and marine species to circulate between the two water bodies.

At least five major marine transgressions (periods of rising sea level) corresponding to interglacial periods occurred in the Bering Strait region during the Pliocene (5.3 million–2.58 million years ago) and Pleistocene (2.58 million–11,700 years ago) Epochs (Hopkins 1973; Kaufman and Brigham-Grette 1993; Khim et al. 2001). The "Pelukian Transgression" corresponds to the most recent interglacial period (approximately 120,000 years ago), and marine deposits that formed during this period can be found throughout the Bering Strait region at 8–10 m (26–33 ft) above modern sea levels (Hopkins 1967, 1973; Hamilton and Brigham-Grette 1991; Brigham-Grette and Hopkins 1995; Khim et al. 2001). Along the coast of the preserve and in ejecta from the Espenberg maars (see the "Volcanism" section for more information about the maars), investigators have found marine mollusks and marine sedimentary deposits that correspond to the Pelukian Transgression (Hopkins 1988; Hamilton and Brigham-Grette 1991; Brigham-Grette and Hopkins 1995). These marine deposits probably extend continuously throughout the Seward Peninsula at elevations of 10 m (30 ft) or less but are obscured in most areas by overlying Pleistocene terrestrial deposits (Brigham-Grette and Hopkins 1995).

During the Last Glacial Maximum (approximately 24,000–14,000 years ago), sea level was approximately 120 m (390 ft) lower that today (Hopkins 1973). Since that time, glacial retreat has caused sea level to rise to its present level (Dyke 2004). Rising sea level caused less and less of the Bering Land Bridge to be subaerially exposed; eventually North America and Asia were separated by the flooding of the Bering Strait around 11,000 years ago (Jakobsson et al. 2017). A level close to modern sea level was attained between 5,000 and 7,000 years ago, at which time sea level ceased to rise as rapidly as was seen during the Late Pleistocene and Early Holocene Epochs (Jakobsson et al 2017 and references therein).

Coastal Geomorphology

The northwest-facing coast of the preserve is dominated by several large lagoons protected by barrier islands and spits, and backed by ice-rich tundra bluffs. The east-facing coast is characterized primarily by narrow sand-dominated beaches in front of ice-rich tundra bluffs, but also contain the Nugnugaluktuk and Goodhope estuaries and bedrock sea cliffs to the east (see the "Cave Resources" section for a discussion on sea caves developed in the cliffs). Between the two coasts lies Cape Espenberg, a prominent spit composed of beach ridges. See Figure 36 for photographs and brief descriptions of some of the typical coastal geomorphology in the preserve.

Six major lagoons are distributed along the northwestern coast of the Seward Peninsula: (1) Lopp, (2) Ikpek (Figure 36A), (3) Arctic, (4) Shishmaref, (5) Kupik (or Cowpack), and (6) Espenberg (developing behind Cape Espenberg; see poster, in pocket). The lagoons are shallow and brackish, separated from the sea by barrier islands. The barrier island complexes are narrow strips of land, generally 0.5–2 km (0.3-1.2 mi) wide, consisting of active beach backed by active foredunes. Some of the barrier islands are locally low enough to be overtopped by storm surges. Some areas where overwash (flow of water over low areas during high tides or storms) events are frequent are marked by unvegetated bands that span the barrier from the beach to the lagoon, while other less frequently overwashed zones are vegetated by salt tolerant species. The barrier islands are breached entirely in places by tidal channels connecting the lagoons to the Chukchi Sea. These channels are persistent features, but the position of channels and adjacent sandbars constantly change as a result of erosional and depositional processes (Farquharson et al. 2018).

Cape Espenberg is a series of beach ridges that composes a spit, 1–2 km (0.6–1 mi) wide and 29 km (18 mi) long, located at the northern tip of the Seward Peninsula (Figure 36E). The longshore current transports sand derived from surrounding marine and terrestrial sources to Cape Espenberg, building up a spit platform and overlying beach ridges (Mason et al. 1997). Cape Espenberg began forming approximately 5,000 years ago, when sea level stabilized at about 2 m (7 ft) below modern levels (Mason et al. 1997). Since that time, Cape Espenberg has prograded east and north, depositing four distinct depositional units that correspond to changes in wind and storm intensity over time (Mason et al. 1997). The Aniakchak tephra, deposited by ashfall from the Aniakchak II eruption more than 1,500 km (930 mi) to the south, is found in the five oldest dunes, suggesting that these dunes formed between 4,000 and 3,400 years ago (Begét et al. 1992; see Hults and Neal 2015 for more information about the geology of Aniakchak National Park and Preserve). Archeological sites and accompanying

Figure 36. Photographs of coastal geomorphology found in the preserve.
(A) Barrier island outside Ikpek Lagoon. (B) stabilized dune. (C) eroding ice-rich tundra bluff. (D) salt marshes that occur in the Nugnugaluktuk estuary. (E) Cape Espenberg beach ridges. (F) Sullivan Bluffs bedrock cliffs. NPS photographs.

radiometric dates also help to constrain the timing of beach ridge formation and show that starting around 4,500 years ago, Cape Espenberg was occupied by people of the Arctic Small Tool tradition for at least 1,000 years (Tremayne 2017). With occasional periods of occupational hiatus, the archeology of the area shows humans continued to return to Cape Espenberg to hunt marine mammals up to the modern era.

Sea Ice

Sea ice currently exists throughout the year in the Arctic Ocean, growing in the winter and shrinking in

the summer (National Snow and Ice Data Center 2018). During the winter months when sea ice is at

its maximum, it envelopes the coast of the preserve. Sea ice acts to inhibit the strength of autumn storms in the Chukchi Sea (Thomson et al. 2016). The ice also provides biological habitat and is an important component in the global climate system (Mahoney 2017). Along the coast, landfast sea ice (sea ice that connects to land) protects the coast from autumn and winter storms, acting to decrease coastal erosion.

The extent of sea ice in the Arctic has been documented with satellite imagery since 1979 (Vihma 2014). Sea ice in the Arctic Ocean has declined significantly in the last few decades (Figure 37; National Snow and Ice Data Center 2018). Ice has a higher albedo than water, meaning it reflects more solar radiation. As sea ice melts, more solar radiation is absorbed and the Arctic Ocean becomes warmer, resulting in a positive feedback relationship. The extent of Arctic sea ice in September (sea ice minimum) has declined by approximately 40% since late 1978 (Serreze and Stroeve 2015) and summer sea ice will be almost gone in the Arctic Ocean by the 2030s (Wang and Overland 2012).

The amount of time sea ice exists along the coast in the winter is also decreasing. Recent analysis of sea ice located just offshore Bering Land Bridge National Preserve found that, between 1982 and 2014, the length of time that the ocean was free of sea ice increased by about five weeks per year, from 19 to 24 weeks (Farquharson 2018). Sea ice fluctuated from year to year during this period, with some seasons exhibiting longer ice seasons than others; however, the overall trend was that of shorter sea ice seasons (Farquharson 2018). Landfast sea ice acts to inhibit coastal erosion during storms, so the lack of landfast sea ice in the fall and early spring results in the coast being vulnerable to a greater number of storms and increased erosion.

Erosion and Accretion

The processes of erosion (removal of sediment) and accretion (addition of sediment) occur along the coast of the preserve, resulting in a continually changing coastline (Figure 38). Erosion and accretion have been monitored primarily through remote sensing since the 1950s (Jordan 1988; Manley and Lestak 2012; Holt et al. 2016; Farquharson 2018). Mean rates of change were a loss of 0.68 m/yr (2.2 ft/yr) of land between 1950 and 1980, a loss of 0.26 m/yr (0.85 ft/yr) between 1980 and 2003, and a loss of 0.68 m/yr (-2.2 ft/yr) between 2003 and 2014 (Farquharson 2018). In addition, coastal processes became more dynamic, with 2003–2014 displaying the greatest range and variability in rates of change (Farquharson 2018). Change in erosion and accretion over time appears to be a response to climate change–related factors, such as a decline in sea ice (Farquharson 2018).

Coastal processes in the Arctic are tied to climate in various ways: sea ice protects the coast from winter storms and also acts to reduce the strength of storms (Thomson et al. 2016); permafrost is present throughout coastal areas, and thawing could cause increased erosion (see the "Permafrost and Thermokarst" section for more details; Swanson 2017a); and the global retreat of glaciers is causing sea level rise (Meier et al. 2007). Despite the magnitude of sea ice reduction since the 1980s (see the "Sea Ice" section), the effect on coastal erosion rates has been surprisingly subtle to date, although both erosion and deposition rates appear to have increased in the past decade (Farquharson 2018). For information on the impact climate change has on the coastal regions of the preserve, see the "Coastal Issues" section of this report.

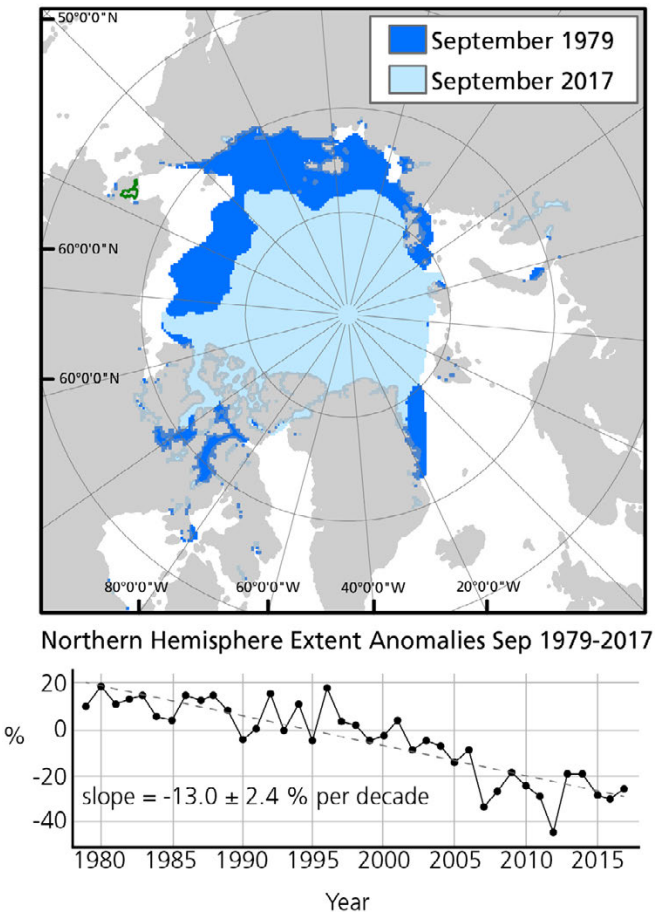


Figure 37. Map and graph showing the decline of September sea ice during the 1979–2017 period. The graph shows monthly sea ice extent anomalies plotted as a time series of percent difference between the September extent in a given year and the mean September extent between 1981 and 2010. Created with data from the National Snow and Ice Data Center (2018).

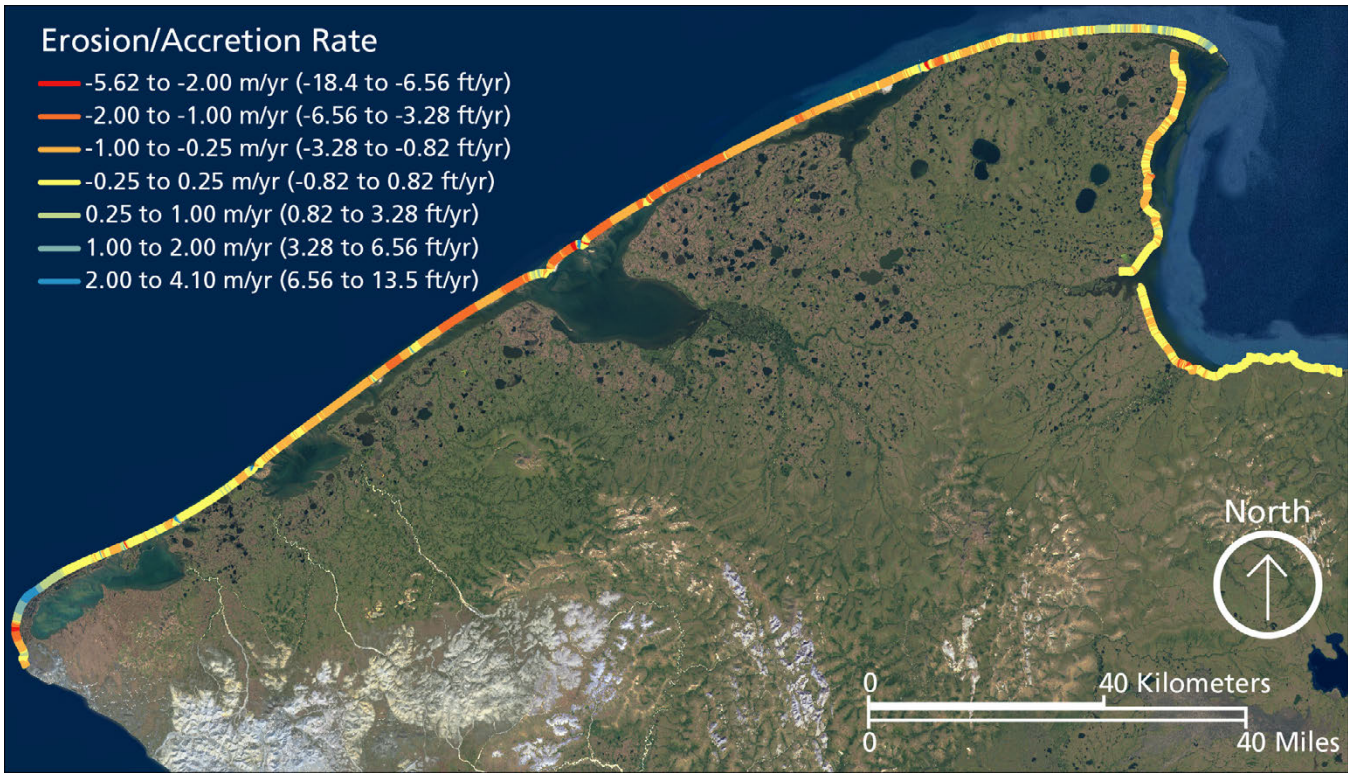


Figure 38. Map of erosion and accretion rates through the period of 1950–2003. Erosion and accretion rates along the coast through this time range from -5.62 m/yr (-18.4 ft/yr) to 4.10 m/yr (13.5 ft/yr). Erosion and accretion rate data from Manley et al. (2010).

Paleontological Resources

The preserve contains paleontological resources, or "fossils," in both bedrock and surficial deposits. The fossils that date to the Cenozoic Era (the past 66 million years) record the exchange of flora and fauna across the Bering Land Bridge, and their protection and study is noted in the preserve's enabling legislation (ANILCA 1980). The Paleontological Resources Preservation Act, which was signed into law in 2009, defines paleontological resources as "any fossilized remains, traces, or imprints of organisms, preserved in or on the earth's crust, that are of paleontological interest and that provide information about the history of life on earth." For more detailed information about fossils in the preserve, Elder et al. (2009) inventoried the fossils in the Arctic Inventory and Monitoring Network parks (including Bering Land Bridge), and Lanik et al. (In press) assessed the condition of the paleontological resources in the Arctic Inventory and Monitoring Network.

Paleozoic fossils occur in two of the units that crop out in the preserve: the Nome Complex and York terrane (see the "Bedrock" section for more information about these units; Till et al. 2011). The rocks of the Nome Complex range in age from the late Proterozoic Eon to the Devonian Period (1.0 billion–359 million years ago) and have been subjected to heat and pressure, resulting in metamorphism. This metamorphism destroyed many of the fossils that may have originally been present and, for the most part, only sparse, poorly preserved fossils remain (Till et al. 2014). The remaining fossils include corals, stromatoporoids (Paleozoic reef-building invertebrates thought to be related to sponges), bryozoa (colonial invertebrates composed of many tiny individuals or "zooids"), brachiopods (primarily Paleozoic shelled invertebrates that superficially resemble bivalves), graptolites (extinct colonial animals that form serrated structures), conodonts (microscopic teeth belonging to an extinct, eel-like organism), radiolarians (single-celled organisms that produce microscopic skeletons composed of silica), lapworthellids (enigmatic cone-shaped fossils), and ichthyoliths (fish remains) (Till et al. 1986, 2011, 2014; Till and Dumoulin 1994; Harris et al. 1995; Dumoulin et al. 2002, 2014). The York terrane is split into the Ordovician–Devonian (485 million–359 million years ago) York Mountains succession, which is located to the south of the preserve, and older rocks, which extend into the preserve. These older rocks, which are not as well understood as the York Mountains succession, range in age from the latest Proterozoic Eon to the Ordovician Period (1.0 billion–444 million years

ago) and have yielded poorly preserved conodonts, chitinozoans (enigmatic microscopic flask-shaped fossils), and brachiopods (Till et al. 2011).

In addition to the older Paleozoic fossils found in bedrock, the preserve also contains younger Cenozoic fossils that record the history of a landmass called "Beringia." Beringia is the area stretching from eastern Russia to western Canada that remained largely unglaciated during the last Pleistocene glacial period (for more information see the "Geologic Setting and Significance" section of this report). During glacial periods sea level fell and exposed the shallow marine platform between North America and Asia. This exposed area, called the "Bering Land Bridge," created a migration corridor through which animals and plants moved from one continent to the other (Hopkins et al. 1982).

Fossils are key to understanding the ecology of Beringia and tracking how past ecosystems in the Arctic responded to events such as the migration of new species (including humans) and climate change (e.g., warming at the end of the Pleistocene Epoch). In the preserve, remains of organisms that once called Beringia home include mammals (e.g., mammoths, horses, and bison) (Figure 39; Quackenbush 1909; Larsen 1962, 1968; Dixon and Smith 1986; Vinson 1988, 1993; Höfle et al. 2000; Rasic 2012; Pasda 2012; Goebel et al. 2013), palynomorphs (pollen and spores) (Colinvaux 1967; Wetterich et al. 2012), plant macrofossils (Figure 40; Goetcheus and Birks 2001; Wetterich et al. 2012), insects (Elias 2000; Kuzmina et al. 2008), arachnids (Kuzmina et al. 2008), ostracods (crustaceans that live within a small calcareous shell), mollusks, charophytes (freshwater green algae), rhizopods (testate amobae), and diatoms (single-celled algae with a siliceous shell) (Wetterich et al. 2012; Lenz et al. 2016; Palagushkina et al. 2017). Pliocene–Pleistocene (5.3-million–11,700-year-old) marine mollusks, which were deposited between glacial periods (called interglacial periods) when higher sea level drowned areas that are dry land today, have also been found (Hopkins 1988; Hamilton and Brigham-Grette 1991; Brigham-Grette and Hopkins 1995).

The Kitluk Paleosol is one of the most well-studied and significant fossil-bearing deposits within the preserve. The Kitluk Paleosol is a soil horizon containing fossils such as plant macrofossils (Goetcheus and Birks 2001) and insects (Kuzmina et al. 2008) that formed on the Seward Peninsula 21,500 years ago, during the last glacial maximum (Höfle et al. 2000). The soil was preserved by an ash layer called the Devil Mountain Lakes tephra deposited during the eruption of the Devil Mountain maar (see the "Volcanism" section of

Figure 39. Photograph of a mammoth tooth. Discovered in a lake in Bering Land Bridge National Preserve by NPS aquatic ecologist Amy Larsen and pilot Eric Sieh (Rasic 2012), this mammoth tooth was radiometrically dated using carbon-14 isotopes, producing an age of 12,330 radiocarbon years before present. A semi-articulated mammoth humerus and ulna, two mammoth vertebra, a mammoth rib fragment, and possible mammoth cranial bones were discovered in proximity to the tooth. Because these bones were found clustered together, they likely originated from a single individual. Finds of multiple mammoth bones from the same skeleton are relatively uncommon in Alaska, making this one of the more complete mammoth skeletons known from the state. A three-dimensional model of this fossil can be found at https://sketchfab.com/alaska_nps_geology. NPS photograph by Jeff Rasic (Gates of the Arctic National Park and Preserve and Yukon-Charley Rivers National Preserve).

this report for more details; Hopkins 1988). This thick layer of ash buried the soil in the area surrounding the Devil Mountain maar, causing permafrost to advance upward rapidly and freezing the soil in place (Höfle and Ping 1996). The Kitluk Paleosol is now exposed along the perimeters of many of the thermokarst lakes on the northern coastal plain of the preserve. The characteristics and fossils of the Kitluk Paleosol provide a window into the paleoenvironment of central Beringia, an area that is now almost entirely under water due to subsequent sea level rise (Höfle et al. 2000). This is important because scientists have long debated the environmental conditions that existed in Beringia during the last glacial period. Termed the "productivity paradox" by Hopkins et al. (1982), vertebrate fossil records that indicate that Beringia contained a diverse and productive environment, while plant fossil records indicate that Beringia was much harsher and only

Figure 40. Photograph of petrified wood. This specimen was found in volcanic ejecta along the shore of Devil Mountain Lakes. Because no surficial deposit in the area is known to contain fossilized wood, the specimen was likely brought up from depth by the eruption of the Devil Mountain maar. Fossil mollusks from the last interglacial have also been reported in Devil Mountain maar ejecta, which indicates that marine deposits corresponding to the Pelukian Transgression exist beneath the maar at depth (see the "Coastal Features" section for more information; Hopkins 1988). While the petrified wood has not yet been dated, it likely corresponds to one of the interglacial periods when climate on the Seward Peninsula was warm enough to support trees. A three-dimensional model of this fossil can be found at https://sketchfab.com/alaska_nps_geology. Length of wood: 13.5 cm (5.3 in). NPS photograph by Charles Linneman (NPS Alaska Regional Office).

supported sparse plants and animals. Goetcheus and Birks (2001) found that the Kitluk Paleosol formed in a dry herb-rich tundra-grassland, which contrasts with the wetter environment interpreted for parts of the central Bering Land Bridge by Elias et al. (1996, 1997). These findings support the interpretation that Beringia contained a mosaic of differing environments during full-glacial times (Goetcheus and Birks, 2001).

Two notable fossil localities, Elephant Point and Cape Deceit, found just outside of the preserve represent valuable datasets to combine with paleontological records in the preserve. Elephant Point, located about 85 km (53 mi) east of the preserve on the coast of Escholtz Bay, was named for the numerous mammoth fossils (including a lower jaw, teeth, tusks, and bones) collected by Royal Navy Captain Frederick William Beechey in 1826 (Beechey 1831). These finds spurred expeditions to this location for the next 100 years and prompted some of the earliest Alaskan paleontological research (see Appendix A for a history of geologic research on the Seward Peninsula). Cape Deceit is also located to the east of the preserve (see Figure 1) and is formed by a Pleistocene outcrop that captures an unusually long record for the area. The Cape Deceit section contains three stratigraphic units (Cape Deceit Formation, Inmachuk Formation, and Deering Formation) from which fossil vertebrates, insects, and pollen have been collected (Guthrie and Matthews 1971; Matthews 1974; Giterman et al. 1982; Elias and Matthews 2002; Elias et al. 2006). The fossil vertebrates collected from Cape Deceit include new species of pika (*Ochotoma*), vole (*Pliomys* and *Microtus*), and a new genus and species *Predicrostyonyx hopkins*i, which was a predecessor to modern collared lemmings (Guthrie and Matthews 1971).

One of the most important characteristics of many of the Pleistocene fossils in terms of scientific value and management concern is that, rather than being preserved in sediment or rock like most fossils, these fossils are frozen in permafrost. During the Pleistocene Epoch (2.58 million–11,700 years ago), ice-rich permafrost called "yedoma" formed in areas where silty sediment deposition and permafrost formation occurred simultaneously (Kanevskiy et al. 2011; Shur et al. 2012). Consequently, yedoma contains fossils that have been continuously frozen since the Pleistocene Epoch. Rapid freezing of organisms after burial tends to result in exceptional fossil preservation, which can include the preservation of ancient DNA and organic material. The ancient DNA preserved in yedoma-derived fossils represents an opportunity for scientists to study ancient organisms in a way that is usually impossible, and future fossil discoveries in the preserve could potentially be suitable for ancient DNA testing. For a discussion of the management issues associated with paleontological resources preserved in permafrost, see the "Paleontological Resources Inventory, Monitoring, and Protection" section.

Geologic History

The following is a brief chronology of the geologic events leading to the present landscape of the preserve. The "Geologic Features and Processes" chapter provides additional details for the geologic map units and features mentioned here. See Figure 5 for the dates associated with the geologic time periods discussed in this section.

Terrane Translation and Accretion

Alaska is a collage of displaced rocks called "terranes" (Figure 41). A terrane is a fault-bounded package of rocks that has a different geologic history than surrounding rocks. Alaskan terranes have been tectonically transported from where they originally formed and accreted to the edge of the North American craton. Only a small portion 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 (see Figure 41). The rest of Alaska consists either of pieces of crust that arrived from elsewhere or are offset portions of the North American craton.

The bedrock of the preserve belongs to two terranes: the Arctic Alaska terrane and the York terrane (Figure 38). Rocks in the preserve mostly belong to the Arctic Alaska terrane, but some rocks belonging to the York terrane (unit **OPRI**) crop out in a small area in the western portion of the preserve (see poster, in pocket). The York terrane has undergone little metamorphism, while the Arctic Alaska terrane on the Seward Peninsula has undergone penetrative deformation and metamorphism (Till et al. 2011). Despite the differing metamorphic histories, lithological and paleontological evidence indicate that rocks of the York terrane and the western portion of the Arctic Alaska terrane were originally part of the same late Proterozoic–Paleozoic carbonate platform (Dumoulin et al. 2014). As such, the early geologic history of these two terranes on the Seward Peninsula is similar but diverges in the Mesozoic with the formation of the Brooks Range in northern Alaska (Mull 1982).

The Arctic Alaska terrane is one of the biggest terranes in Alaska, encompassing a large part of northern Alaska, from the Yukon to the Seward Peninsula (Figure 41). The Arctic Alaska terrane is a composite terrane; this means that some of the rocks have an earlier geologic history that differs from other rocks assigned to the terrane, but at some point all these rocks came together and evolved as one terrane thereafter. In the past, geologists had split out rocks on the Seward Peninsula into the "Seward terrane," (Silberling et al. 1992). However, recent work has shown that these rocks correlate with the more metamorphosed portions of the Arctic Alaska terrane (Till 2016).

Late Proterozoic Eon to Devonian Period

The Arctic Alaska terrane consists of at least two crustal blocks that evolved independently until the mid-Paleozoic Era: the eastern Arctic Alaska terrane and western Arctic Alaska terrane. The eastern portion of the Arctic Alaska terrane (eastern Brooks Range) contains early Paleozoic rocks with similarities to Laurentia (North American craton, seen in light blue on Figure 41). These similarities include fossils with Laurentian paleogeographic affinity and late Proterozoic–Cambrian detrital zircons with ages that correlate with those found in Laurentia (Dutro et al. 1972; Strauss et al. 2013, 2017; Lane et al. 2016; Cox et al. 2015). In contrast, the western portion of the Arctic Alaska terrane (central and western Brooks Range and the Seward Peninsula) contains early Paleozoic rocks that differ from Laurentia in terms of fossil paleogeographic affinity (Blodgett et al. 2002; Dumoulin et al. 2002, 2014) and geochronological signatures (Amato et al. 2009; Miller et al. 2011; Hoiland et al. 2018). These data suggest that the eastern Arctic Alaska terrane evolved as part of, or close to, Laurentia during the early Paleozoic Era, while the western Arctic Alaska terrane has exotic origins with respect to Laurentia. These disparate portions accreted together and were joined to North America by the Devonian Period (Strauss et al., 2013; Hoiland et al. 2018). The accretion event may be recorded by the widespread evidence for pre-Mississippian deformation in eastern Arctic Alaska strata, referred to as the Romanzof and Ellesmerian orogenies (Moore et al. 1994; Lane 2007).

While the western Arctic Alaska terrane has a distinct early Paleozoic geologic history when compared to eastern Arctic Alaska and Laurentia, it does correlate well with some of the other exotic terranes of Alaska and northeastern Russia. Similar early Paleozoic fossil assemblages with a Siberian or mixed Siberian/Laurentian biogeographic affinity have been collected from the western Arctic Alaska, York, Farewell, and Alexander terranes (Figure 41; Blodgett et al. 2002; Dumoulin et al. 2002, 2014). Lithologic features have been correlated between the western Arctic Alaska, York, and Farewell terranes, and similarities in strata have been noted with the Alexander terrane and Paleozoic strata of northeastern Russia (Natal'in et al. 1999; Dumoulin et al. 2002, 2014). Igneous and

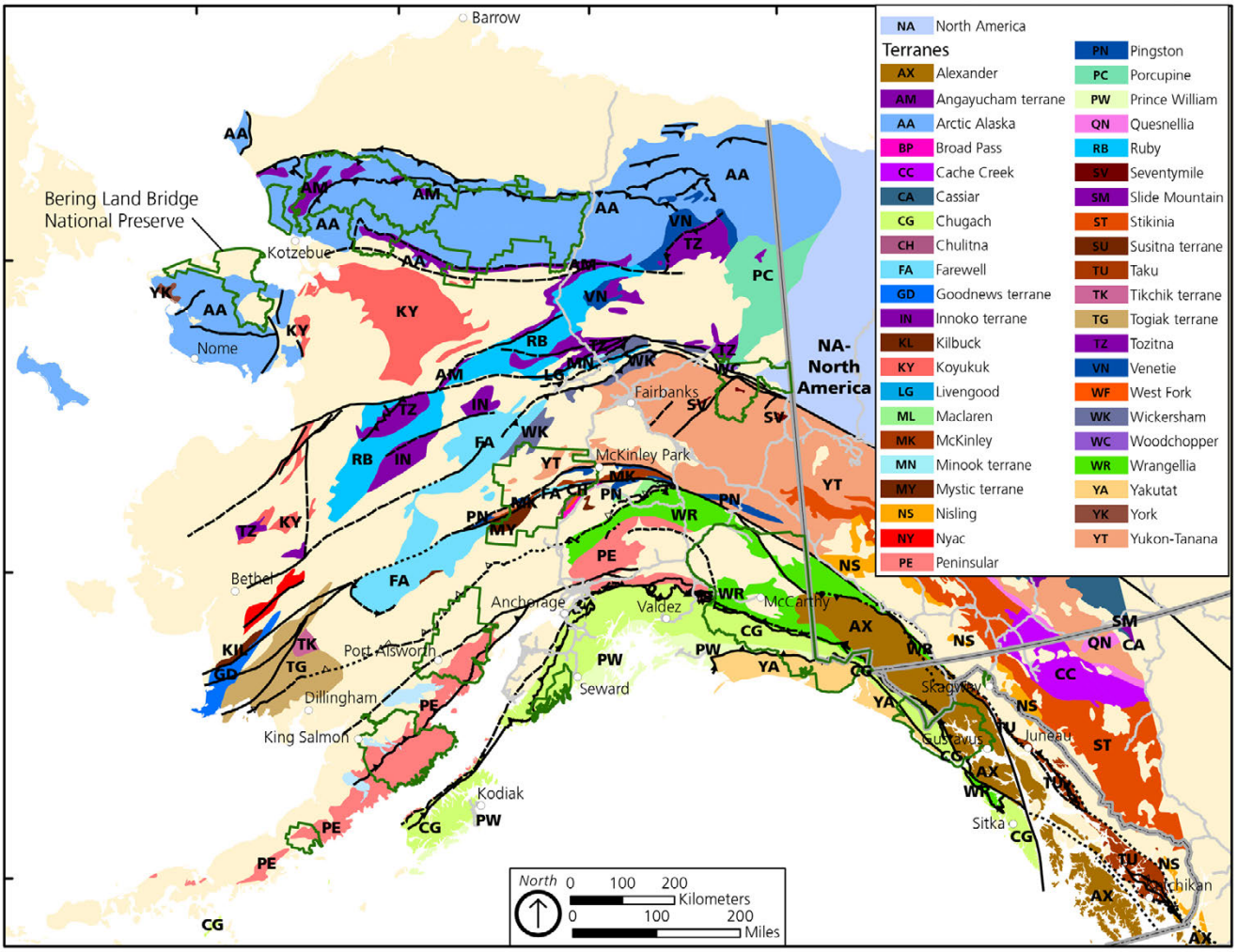


Figure 41. Map of the terranes of Alaska.
Park boundaries are outlined in dark green, roads in light grey, and major faults in black. The bedrock units on the poster (in pocket) correspond to the Arctic Alaska terrane (AA; colored light blue) and the York terrane (YK; colored brown). Modified from Silberling et al. (1992).

detrital zircon ages demonstrate links between the Farewell, Kilbuck, and Arctic Alaska terranes (Figure 41; Bradley et al. 2014), and protolith evaluations suggest correlation of the metasedimentary rocks on the Seward Peninsula (Arctic Alaska terrane) and the Ruby terrane (Figure 41; Hoiland et al. 2018). Overall, these data indicate the western Arctic Alaska terrane formed in proximity to some of the other exotic terranes in Alaska and Russia (mentioned above) during the early Paleozoic, probably in the vicinity of Siberia or Baltica (Figure 42).

Late Jurassic to Earliest Cretaceous Periods

After docking with North America in the Devonian Period (419 million–359 million years ago), the next big tectonic event to affect the Arctic Alaska terrane was the Mesozoic Brooks Range orogeny (mountain building event) and coinciding opening of the Canada basin (Figure 43). During the Late Jurassic–Early Cretaceous Periods, closure of the Angayucham Ocean (Angayucham terrane in Figure 41) caused the Koyukuk arc (Koyukuk terrane in Figure 41) and the Arctic Alaska terrane to collide (Moore et al. 1994). This resulted in subduction of the southern margin of the Arctic Alaska terrane, emplacement of the Angaycham terrane onto the Arctic Alaska terrane, and folding and thrusting of strata northward (Moore et al. 1994; Till 2016). Subduction and crustal thickening caused blueschist-facies metamorphism of the Nome Complex (see the "Nome Complex" subsection for more details). The Canada basin, situated between northern Alaska and the Canadian Arctic Islands, opened during this same timeframe (Figure 43). Although multiple models have been put forth (see Lawver and Scotese 1990

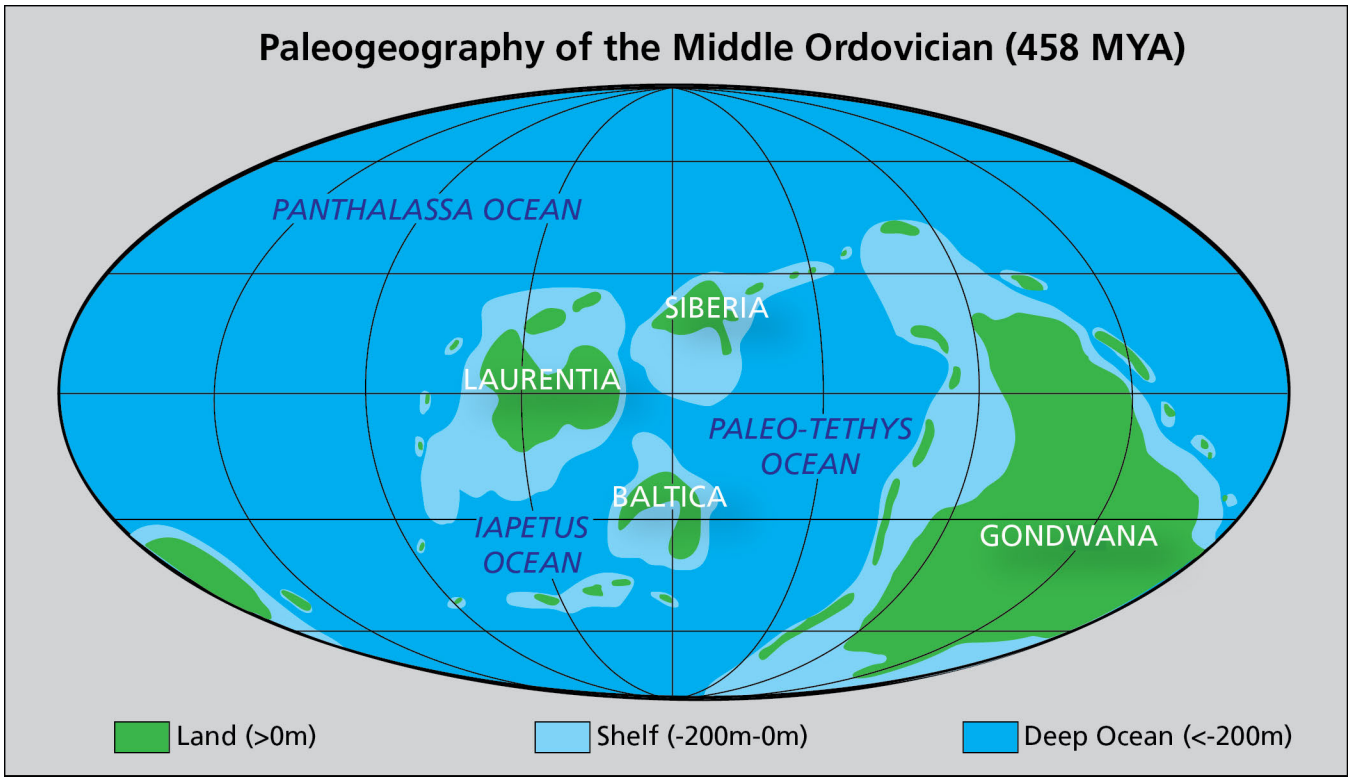


Figure 42. Map showing the paleogeography of the Middle Ordovician (approximately 458 million years ago).
Most researchers place western Arctic Alaska next to Siberia, next to Baltica, or in some intermediate position during the early Paleozoic Era (Blodgett et al. 2002; Dumoulin et al. 2002; Amato et al. 2009; Colpron and Nelson 2009; Strauss et al. 2017).

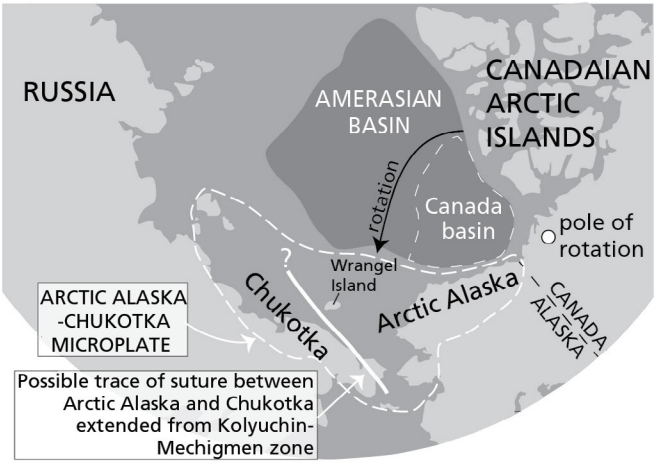


Figure 43. Map of the Arctic Alaska-Chukotka microplate and the Canada and Amerasian basins. The opening of the Canada basin rotated the Arctic Alaska-Chukotka microplate away from its prior position near the Canadian Arctic Islands, to its modern position in northern Alaska/Siberia. Modified from Till (2016).

for a review), the most widely accepted theory for the opening of the Canada basin involves counterclockwise rotation of the Arctic Alaska terrane away from the Canadian Arctic Islands (e.g., Lawver et al. 2002; Mickey et al. 2002; Gottlieb et al. 2014; Till 2016).

Cretaceous Period

Following this Late Jurassic–Early Cretaceous contractional deformation, the Bering Strait region (including the Seward Peninsula) switched to an extensional regime. The Bering Strait region has gone through at least three episodes of extension: (1) Cretaceous Period, (2) Eocene–early Oligocene Epochs, and (3) Pliocene–Holocene Epochs, though the Pliocene start date is uncertain (Dumitru et al. 1995).

Extension during the Cretaceous Period is evidenced by the exhumation and cooling of blueschist- and greenschist-facies rocks belonging to the Nome Complex between 120 million and 70 million years ago (see “Nome Complex” subsection for more details) and by the rise of high-grade gneiss domes in the Kigluaik, Bendeleben, and Darby Mountains around 90 million years ago (Amato et al. 1994; Dumitru et al. 1995; Hannula et al. 1995; Amato and Wright 1997; Amato

et al. 2002; Amato and Miller 2004). Extension caused crustal thinning in the Bering Strait region to the extent that, instead of the topographic highs that characterize the Brooks Range to the east, most of the continental crust in the region is below sea level (i.e., the Bering-Chukchi shelf) (Dumitru et al. 1995; Klemperer et al. 2002). Cretaceous extension also was accompanied by magmatism on the Seward Peninsula, which formed granitic plutons, stocks, and dikes (see the "Cretaceous Igneous Rocks" subsection for more details). These rocks are part of a Cretaceous magmatic belt that extends more than 6,000 km (4,000 mi) through eastern Russia, Alaska, and the Canadian and US cordillera (Rubin et al. 1995; Amato et al. 2003).

Eocene to Early Oligocene Epochs

During the Eocene–early Oligocene Epochs, extension caused the formation of the Hope basin (north of the Seward Peninsula; see the "Oil and Gas Potential" section for more details) and Norton basin (south of the Seward Peninsula) (Dumitru et al. 1995).

Late Oligocene to Holocene Epochs

Extension caused by the tectonic extrusion (escape of a tectonic block due to collision in other areas) of the "Bering Block" has continued into the Holocene Epoch (the last 11,700 years) (Dumitru et al. 1995; McDannell et al. 2014), causing normal faulting and volcanism of the Bering Sea volcanic province. The Bering Sea volcanic province began erupting at 28 million years ago, with the formation of the Kugruk volcanics on the Seward Peninsula (Hopkins 1963; Swanson et al. 1981; Moll-Stalcup 1994). About 20 million years ago, the extrusion of the Kugruk volcanics was followed by a hiatus in volcanic activity. Eruptions resumed around 6 million years ago with the formation of the Imuruk volcanics on the Seward Peninsula and began elsewhere in the Bering Sea volcanic province at this time (Moll-Stalcup 1994; Mukasa et al. 2007). Volcanism in the Bering Sea volcanic province has continued intermittently until the present day, and according to Mukasa et al. (2007) may essentially still be active. The most recent volcanism in the preserve was the eruption of the Lost Jim lava flow about 1,605 years ago (Hopkins 1988).

During the Pleistocene Epoch (2.58 million–11,700 years ago), sea level fluctuations related to glacial and interglacial periods caused the periodic exposure and submergence of the Bering Land Bridge (Hopkins 1959). Alaska and Siberia are separated by shallowly submerged continental crust known as the Bering-Chukchi shelf. When sea level is lower, this shelf becomes subaerially exposed and creates a land bridge, known as the Bering Land Bridge, connecting Asia and North America. The Bering Land Bridge allowed for the exchange of terrestrialf flora and fauna between the two continents, including the first humans in North America.

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management to address visitor safety needs and preservation of natural and cultural resources in Bering Land Bridge National Preserve.

Two meetings were held to discuss the GRI products, geology of the preserve, and resource management issues. These meetings were held with NPS natural resources managers, NPS Arctic Network staff, NPS Alaska Region specialists, and geologists with experience in the preserve. A scoping meeting was held in 2008 (see scoping summary by Thornberry-Ehrlich 2008); a report kick-off meeting was held in 2017. Attendees of the scoping meeting and the report kick-off meeting are listed in Appendix A.

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

- Geohazards
- Abandoned mineral lands
- Oil and gas development potential
- Geothermal features inventory and monitoring
- Caves and associated landscape management
- Permafrost monitoring
- Coastal issues
- Paleontological resources inventory, monitoring, and protection

Geologic Resource Management

In addition to this report, the park's foundation statement (NPS 2009), natural resource condition assessment (NPS in preparation), and state of the park report (NPS 2016) are all sources that provide more information concerning resource management within the preserve.

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

Geoscience-focused internships can be arranged to help park managers carry out geologic resource-related projects. The Geoscientists-in-the-Park (GIP) and Mosaics in Science programs are internship opportunities that place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. As of March 2019, past projects at Bering Land Bridge National Preserve have included a paleontology inventory conducted in 2016 (Lanik et al. In press). Products created by the program participants may be available on that website or by contacting the Geologic Resources Division (http://go.nps.gov/grd). Refer to the programs' websites at http://go.nps.gov/gip and http://go.nps.gov/mosaics for more information.

Geohazards

This section describes the potential geologic hazards ("geohazards") for the preserve. Geohazards are the result of active geologic processes. They can be hazardous to people or infrastructure, or they may occur naturally in remote areas with no hazardous impact. Geohazards that are present in the preserve include volcanic eruptions, earthquakes, landslides, and permafrost thaw-related land collapses (described in more detail in the "Permafrost Monitoring" section of this report).

Volcanic Eruptions

Two areas in the preserve contain rocks formed by volcanism during the Cenozoic Era: the Imuruk and Espenberg volcanic fields (Figure 44; for more information about these volcanic fields, see the "Volcanism" section of this report or visit http://avo.alaska.edu). The oldest volcanic rocks in these fields date to 28 million–26 million years ago, but most of the volcanism has taken place within the last 6 million years. Neither of the volcanic fields has been active within historical time (since about 1760 CE), and they are not monitored by the USGS Alaska Volcano Observatory. Additional information about monitoring volcanoes in NPS areas can be found in Smith et al. (2009).

The most recent volcanic activity in the preserve was the eruption of the Lost Jim lava flow 1,605 ± 238 years ago (Hopkins 1988). This event likely correlates to a dramatic eruption described in the oral history of the Inupiat-speaking Kaweruk people native to central Seward Peninsula (Oquilluk and Bland 1981; Hopkins 1988). Other recent volcanism in the Bering Sea volcanic province has occurred on St. Paul Island (youngest eruption 3,230 ± 40 years ago; Winer et al. 2004), and St. Michael Island (possibly as young as

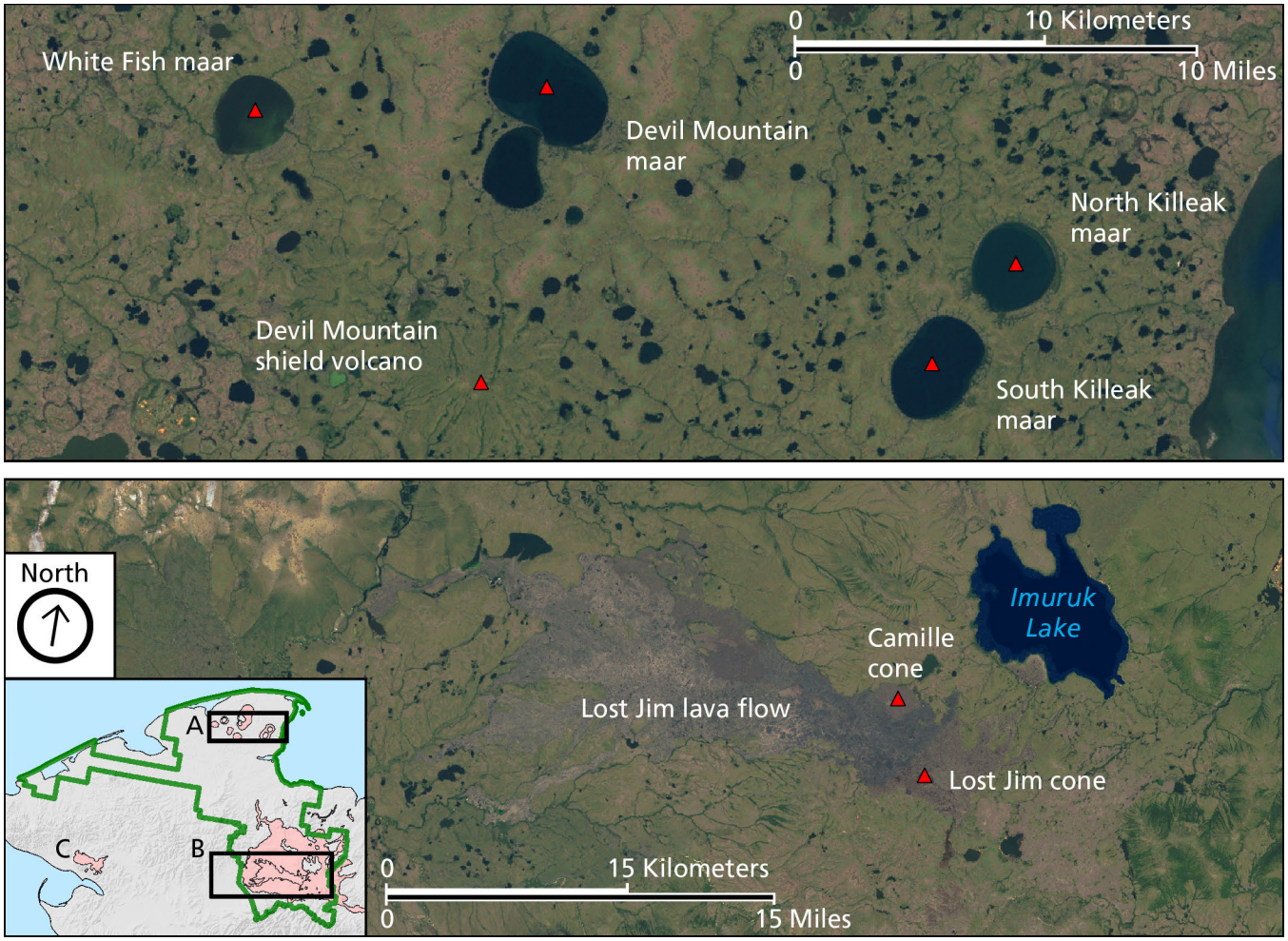


Figure 44. Map showing the two volcanic areas in the preserve.
The Espenberg volcanic field (top) is in the northern part of the preserve (A). The Imuruk volcanic field (bottom) is in the southern part of the preserve (B). Maps made using the satellite image map created by the National Park Service (2011).

3,000–2,000 years ago; Mukasa et al. 2007). Based on the eruptive ages, Mukasa et al. (2007) suggested that the Bering Sea volcanic province may essentially still be active today.

Feeley and Winer (2009) performed a study to assess the volcano hazards and potential risks on St. Paul Island. The volcanoes on that island are part of the same volcanic province and have characteristics similar to the volcanoes in the preserve; therefore, this study may be a good resource for considering volcanic hazard in the preserve and could provide a model for a future volcanic hazard and risk analysis.

An important step in assessing volcanic hazard is understanding the frequency of volcanic eruptions in the area. On St. Paul Island, 40 separate eruptions occurred during the period 360,000–3,230 years ago, making the average eruptive interval approximately 8,900 years and the probability of an eruption within the next five years 0.06% (Feeley and Winer 2009). Over the last 160,000 years, six or possibly seven individual eruptions (uncertainty is due to the poor constraint on the timing of the Devil Mountain eruption) have occurred within the preserve (Table 1). Including the Devil Mountain eruption, seven eruptions in 160,000 years gives an eruptive interval of about 23,000 years, which is more than double the eruptive interval calculated for St. Paul Island. This indicates that the probability of an eruption in the preserve in the next five years would be less than the 0.06% calculated for St. Paul Island.

Two main eruptive styles have occurred in the preserve: (1) explosive phreatomagmatic (water-magma interaction) eruptions that formed the Espenberg maars and (2) effusive eruptions that formed the shield volcanoes near Cape Espenberg (such as Devil Mountain) and the lava flows around Imuruk Lake. No evidence of large maar-forming phreatomagmatic eruptions in the past exists around Imuruk Lake, so

future eruptions in this area would likely be of the more effusive style. Near Cape Espenberg, phreatomagmatic eruptions occurred during glacial periods (marine isotope stage [MIS] 2, 4, and 6), while shield volcanoes were formed during interglacial periods (MIS 7 and 9; Begét et al. 2003). Because the Earth is currently in an interglacial period, the occurrence of an effusive eruption instead of a phreatomagmatic eruption would be in line with past trends. However, the presence of permafrost around the Espenberg maars has been considered to be the key condition for producing exceptionally large phreatomagmatic eruptions in the past (Begét et al. 1996). Since permafrost is currently continuous on the northern Seward Peninsula, the possibility of a future phreatomagmatic eruption in the Cape Espenberg area cannot be discounted.

The main volcanic hazards identified by Feeley and Winer (2009) for St. Paul Island are effusion of pahoehoe lava flows, tephra fallout, and base surges. These hazards are similar to those that would be associated with volcanic eruption in the preserve. Additionally, Feeley and Winer (2009) noted that the remote location of St. Paul Island may exacerbate risks related to volcanic hazards. Bering Land Bridge National Preserve is also quite remote; no roads or trails lead to the preserve and access is limited to foot, boat, or aircraft in the summer, with the added option of snowmobile travel in the winter. This limited access could complicate relief efforts in the event of an eruption.

The deposition of tephra (called "fallout") both close to the vent and farther afield could pose a volcanic risk in the preserve. Tephra is composed of rock fragments expelled during explosive eruptions, and the smallest of these fragments (volcanic ash) can be carried by wind a significant distance from the source vent. Depending on the accumulation of tephra, impacts can range from eye and respiratory irritation to heavy infrastructure damage and loss of plants and animals (Table 3; https://www.avo.alaska.edu/volcanoes/hazards.php). The risk from tephra fallout would be significantly higher if a phreatomagmatic eruption was to occur (e.g., Espenberg maar eruptions) and lower if more effusive volcanism prevailed (e.g., Espenberg shield volcanoes or lava flows around Imuruk Lake). A phreatomagmatic eruption would be expected to produce more tephra with a widespread dispersal. For example, each of the Espenberg maars produced tephra that was deposited over an area of up to 1,000 km^2 (380 mi^2; Hopkins 1988). In contrast, Feeley and Winer (2009) concluded that tephra fallout from shield volcanoes on St. Paul Island would be restricted to deposition of coarse pyroclastic material within a few hundred meters of the vents, and this also is likely true for effusive eruptions in the preserve.

Table 3. Impacts of tephra fallout.

Note: Table modified from the Alaska Volcano Observatory (https://www.avo.alaska.edu/volcanoes/hazards.php; accessed 4 February 2019).

Term	Accumulation	Key Impact Thresholds (cumulative)
Trace or dusting	<0.08 mm (0.031 in)	Eye and respiratory irritant, very low level impacts for most people.
Minor	0.8–6.4 mm (0.031–0.25 in)	Possible crop, animal equipment, and infrastructure problems; widespread clean-up likely.
Moderate	6.4–25.4 mm (0.25–1.0 in)	Ash removal efforts significant.
Heavy	25.4–100 mm (1.0–4.0 in)	Weaker roofs can fail at about 10–12 centimeters (4–5 inches) of compacted, wet ash accumulation ~200 kg/m2 (~40 lb/ft2).
Very Heavy	100–300 mm (4.0–12.0 in)	Danger of roof collapse increases, damage to trees, essential services interrupted.
Severe	>300 mm (>12 in)	Roads impassable, severe infrastructure damage, heavy plant and animal loss.

Base surges are pyroclastic flows that result from phreatomagmatic eruptions. Although base surges are a significant hazard, the chance for loss of property or life as a result of base surges is not great because the area in which they would occur is remote (Figure 45). The Espenberg maars produced base surges, and base surge deposits can be seen around the perimeter of the Devil Mountain maar (Figure 23). Because bases surges can propagate with a velocity of up to 100 m/s (300 ft/s), they have the potential to cause extensive damage and loss of life (Feeley and Winer 2009). However, they typically do not travel more than 10 km (6 mi) away from the source vent (Feeley and Winer 2009). No infrastructure is within 10 km (6 mi) of any of the Espenberg maars, and this area is not frequently visited by humans.

The risks associated with an active lava flow are relatively low because very little infrastructure is present in the preserve and the majority of it is located away from the Imuruk or Espenberg volcanic fields (Figure 45). Lava flows erupted at Hawaiian volcanoes, which we are using as an example of typical lava flow rates, flow at a rate of 1–5 km/day (0.6–3 mi/day) on gentle terrain, and associated risks are typically related to infrastructure destruction rather than loss of life (Feeley and Winer 2009). The Cottonwood Creek shelter cabin overlies previous lava flows, but it is far removed from

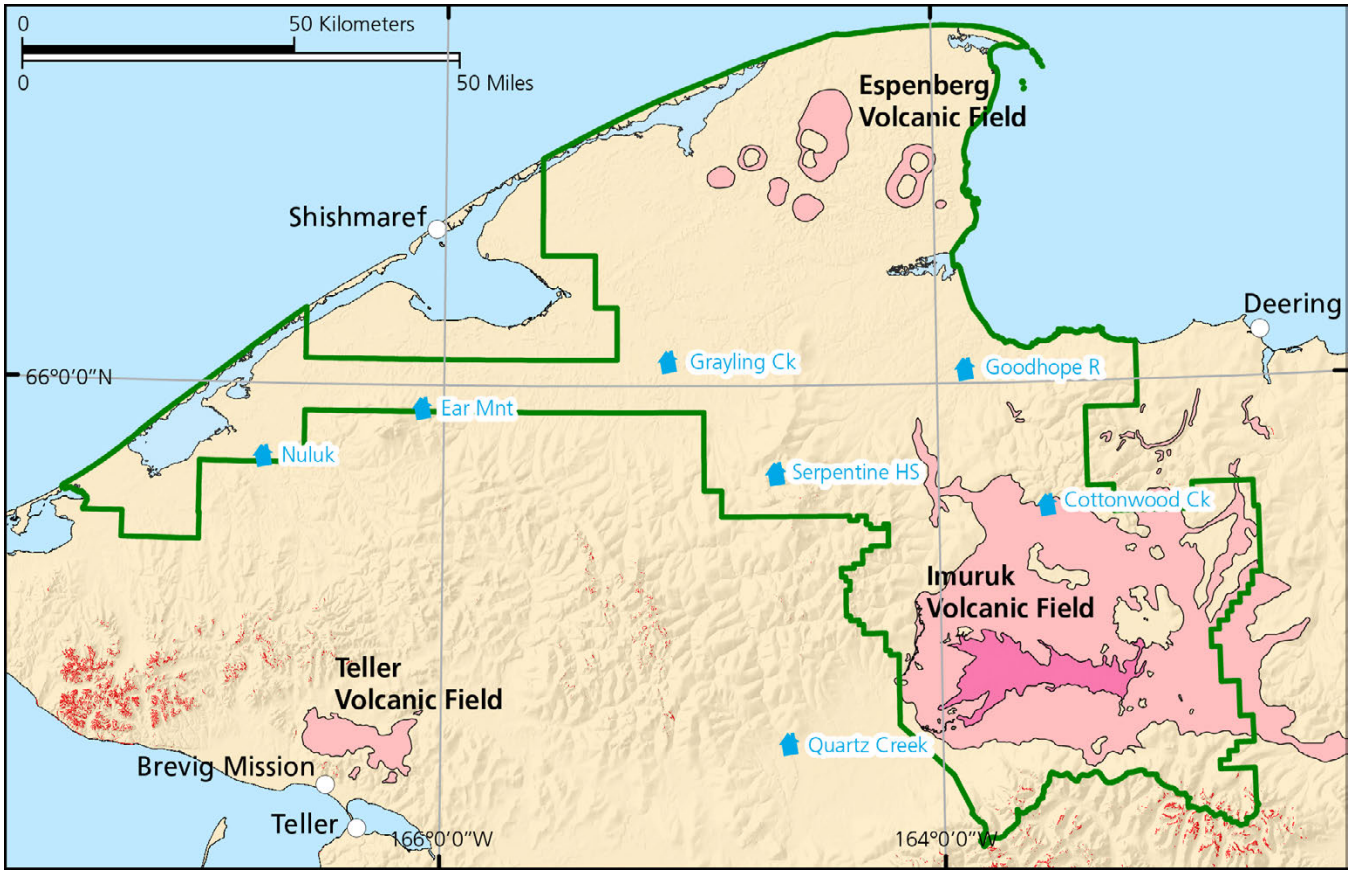


Figure 45. Geohazard map.
The map shows the location of Cenozoic volcanic rocks (light and dark pink), public shelter cabins (blue symbols and labels), towns (white dots and black labels), and slopes greater than 30° (shown in red). All Cenozoic volcanic rocks are shown in pink, with the Lost Jim lava flow shown in dark pink. Two volcanic fields exist in the preserve: the Espenberg volcanic field and the Imuruk volcanic field. The Teller volcanic field is to the west of the preserve. The preserve's boundary is shown in green.

Figure 46. Photograph of a large piece of ice-rich ground detaching from the coast.
For more information on coastal erosion and the management concerns associated with it, see the "Coastal Issues" section of this report. NPS photograph by Tahzay Jones (NPS Alaska Regional Office).

the two most recent flows in the area (Camille and Lost Jim lava flows); a modern eruption of the Imuruk volcanic field would either have to produce more lava or erupt in a different location than the last two lava flows to pose a threat to the Cottonwood Creek shelter cabin.

Slope Movement

Slope movements are a common type of geologic hazard; they can be a natural or human-caused condition that may impact park resources, infrastructure, or visitor safety. Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. These processes and the

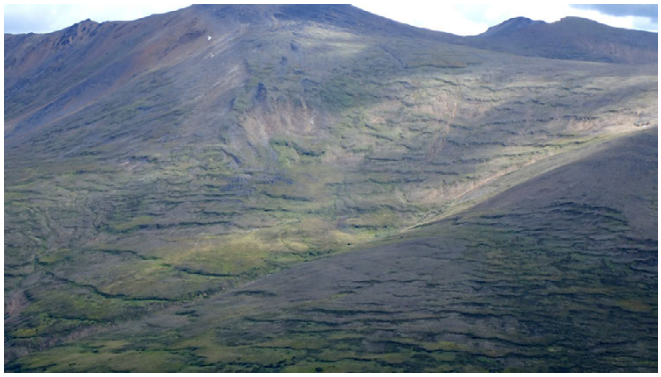


Figure 47. Photograph showing solifluction lobes in the Bendeleben Mountains.
The solifluction lobes in the photograph are marked by the horizontal lines of vegetation. Solifluction is the downslope flow of wet, unfrozen material over frozen material. Solifuction, which typically allows vegetation and soils to remain intact, is a slower process than an active-layer detachment. NPS photograph by David Swanson (NPS Inventory and Monitoring Arctic Network).

resultant deposits are also known as "mass wasting" and commonly grouped as "landslides." Over-steepened slopes (greater than 30°) are one of the primary causes for landslides. Information on monitoring slope movements can be found in Wieczorek and Snyder (2009).

The majority of the preserve has gentle relief; only limited slopes in the southernmost portion reach or exceed 30° (shown in red on Figure 45). Most slope movements in the preserve are related to permafrost thaw, such as detachment of blocks along the coast (Figure 46), solifluction (Figure 47), active-layer detachments, and retrogressive thaw slumps (for more information on active-layer detachments and retrogressive thaw slumps see the "Permafrost Monitoring" section).

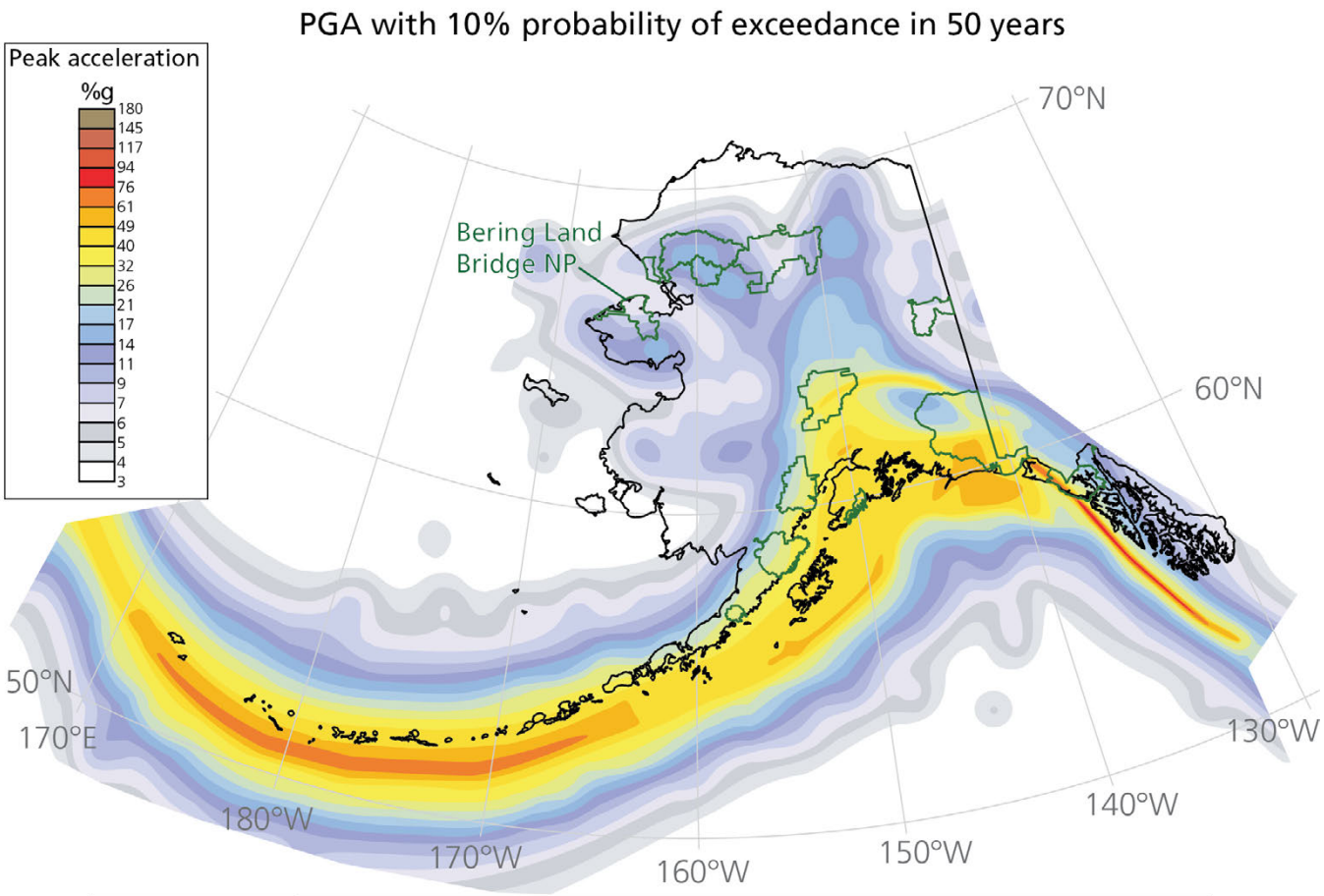
Earthquakes

The Alaska Earthquake Center maintains seismic monitoring stations near the preserve and actively monitors earthquake hazards in conjunction with the USGS. The closest stations are at Kotzebue, Nome, and Wales (see http://earthquake.alaska.edu/). According to the USGS 2007 seismic hazard map of Alaska (Figure 48), the preserve has a 10% probability for an earthquake to cause peak ground acceleration of between 6% and 17% of the acceleration of gravity (9.8 m/s^2 [32 ft/s^2]) in the next 50 years (Wesson et al. 2007). This amount of peak horizontal acceleration would be perceived as moderate to strong shaking, and could potentially cause very light to light damage. Additional information on seismic monitoring can be found in Braile (2009).

The preserve does not experience large subduction-zone megathrust earthquakes like those generated in southern Alaska, but instead the seismic activity on the Seward Peninsula is primarily associated with normal faulting (Figure 49; Page et al. 1991). Normal faults form in extensional settings. Extension in the Bering Strait Region started during the mid-Cretaceous Period and has continued to the present day (Dumitru et al. 1995). The distribution of seismic activity in western Alaska and eastern Russia outlines the "Bering Block," which is a crustal block that is undergoing northeast–southwest extension related to tectonic extrusion (escape of a tectonic block caused by collision in another area) (Biswas et al. 1983; Mackey et al. 1997; Redfield et al. 2007).

During historic times at least four earthquakes with magnitude 6.0 or greater occurred in western Alaska and four in the Chukchi Sea (Page et al. 1991). The largest of these events was a magnitude 7.3 earthquake that occurred in 1958 near Huslia, Alaska, approximately 300 km (190 mi) east of the preserve (Davis 1960; Page et al. 1991). The residents of Huslia felt continuous shaking for approximately two hours and sand dune deposits near the epicenter were heavily fissured (Davis 1960). Smaller earthquakes (magnitude 2.0–5.0) have been broadly distributed in western Alaska, with no prominent linear trends (Page et al. 1991). The diffuse distribution indicates that seismicity is not concentrated along one or two major faults, but distributed over many active faults (Page et al. 1991). Recently active faults mapped on the Seward Peninsula include the Bendeleben and Kigluaik faults, which were active within the last 15,000 years (USGS 2018).

Within the preserve, the direct impacts of an earthquake to human development would be limited because of a lack of major infrastructure. A large earthquake in the vicinity of Nome, where park headquarters and visitor center are located, could pose a more substantial threat to park infrastructure and staff. Earthquake-induced landslides and tsunamis are common, dangerous, indirect effects of an earthquake with the potential to impact park resources and visitors. However, the gentle relief in the majority of the preserve and the shallowly submerged Bering-Chukchi shelf reduce the probability for large earthquake-induced landslides and tsunamis, respectively.



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

Figure 48. Earthquake probability map of Alaska.
The map shows the peak ground acceleration (PGA) with 10% probability of exceedance in 50 years. This means the map is showing the greatest amount of ground acceleration (as a percentage of the acceleration of gravity) produced by an earthquake that has the probability of 10% to occur in the next 50 years. Green outlines are National Park System units. Bearing Land Bridge National Preserve (NP) is labelled. Map modified from Wesson et al. (2007). Table values from Wald et al. (1999), which were developed for southern California but provide a general sense of perceived shaking and damage for earthquakes elsewhere.

Abandoned Mineral Lands Mitigation

The USGS Alaska Resource Data File (http://ardf.wr.usgs.gov/) lists 13 metalliferous mineral occurrences in the preserve, including three inactive mines that are documented in the NPS Abandoned Mineral Lands (AML) database. According to the AML database and Burghardt et al. (2014), the preserve contains four AML features at three sites. Abandoned mineral lands are lands, waters, and surrounding watershed that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation. The NPS takes action under various authorities to mitigate, reclaim, or restore AML features in order to reduce hazards and impacts to resources.

Much of the mining associated with the Nome Gold Rush (see "Park Establishment and History") was located on the southern portion of the peninsula, but as the number of miners increased and deposits were exhausted, miners ventured northward. Several small-scale placer gold mines (Humbolt Creek, Esperanza Creek, and Goose Creek mines) operated in what is now the preserve. The Humbolt Creek mining claim was valid as recently as the late 2000s (Figure 50; NPS 2016). The abandoned placer gold mines and mining features that still exist are considered cultural resources,

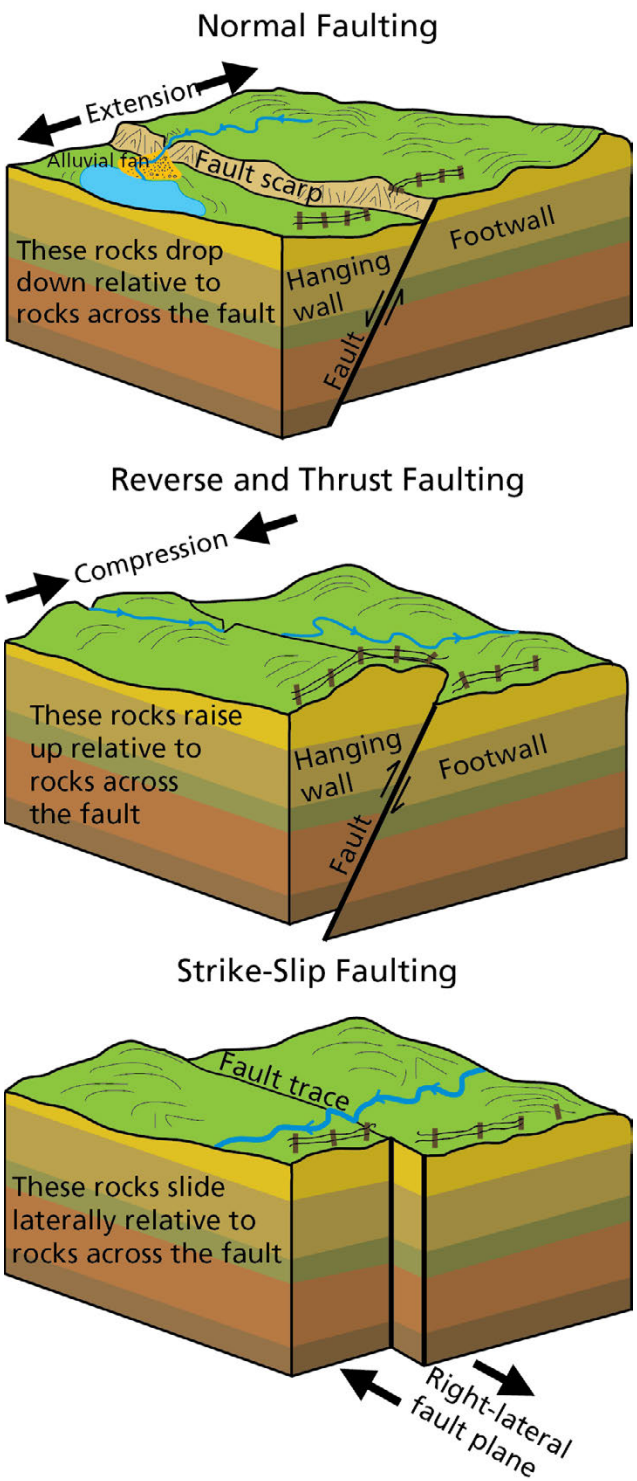


Figure 49. Diagram showing different types of faults.
Faulting in the preserve has mainly been normal faulting (top) related to extension in the region. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 50. Photograph of the miners cabin and partially full barrel at Humbolt Creek mine. NPS photograph.

and 14 sites in the preserve are related to historic placer gold mining (NPS 2016). One of these sites is the Fairhaven Ditch historic canal, which is a 38-mi- (61-km-) long ditch used to transport water from Imuruk Lake to placer mining sites. The ditch is listed in the National Register of Historic Places and is one of several such canals dug without the benefit of heavy equipment on the Seward Peninsula during the Nome Gold Rush (NPS 2016).

A 2007 environmental site assessment at the Humbolt Creek mine noted a small amount of petroleum released into the ground from one of the barrels left on site (Figure 50). Mercury in a quantity near the clean-up limit of the Alaska Department of Environmental Conservation was also present in the soils beneath the blacksmith shop. The preserve's state of the park report (NPS 2016) recommended that the barrel be removed to prevent further release of petroleum into the environment.

Oil and Gas Development Potential

The Kotzebue and Hope basins (combined into the Hope basin in Figure 51) are Tertiary extensional basins located to the north of the Seward Peninsula. These basins contain an estimated mean volume of 0.2 billion barrels (90% confidence interval: 0, 0.6) of undiscovered oil and an estimated mean volume of 3.8 trillion cubic feet (90% confidence interval: 0, 15.0) of undiscovered gas (Figure 51; Houseknecht and Bird 2005). Deposits assigned to these basins occur in the subsurface in the northern part of the preserve as well as offshore beneath the Kotzebue Sound and Chuckchi Sea (BOEM 2006). During the 1970s, two exploratory

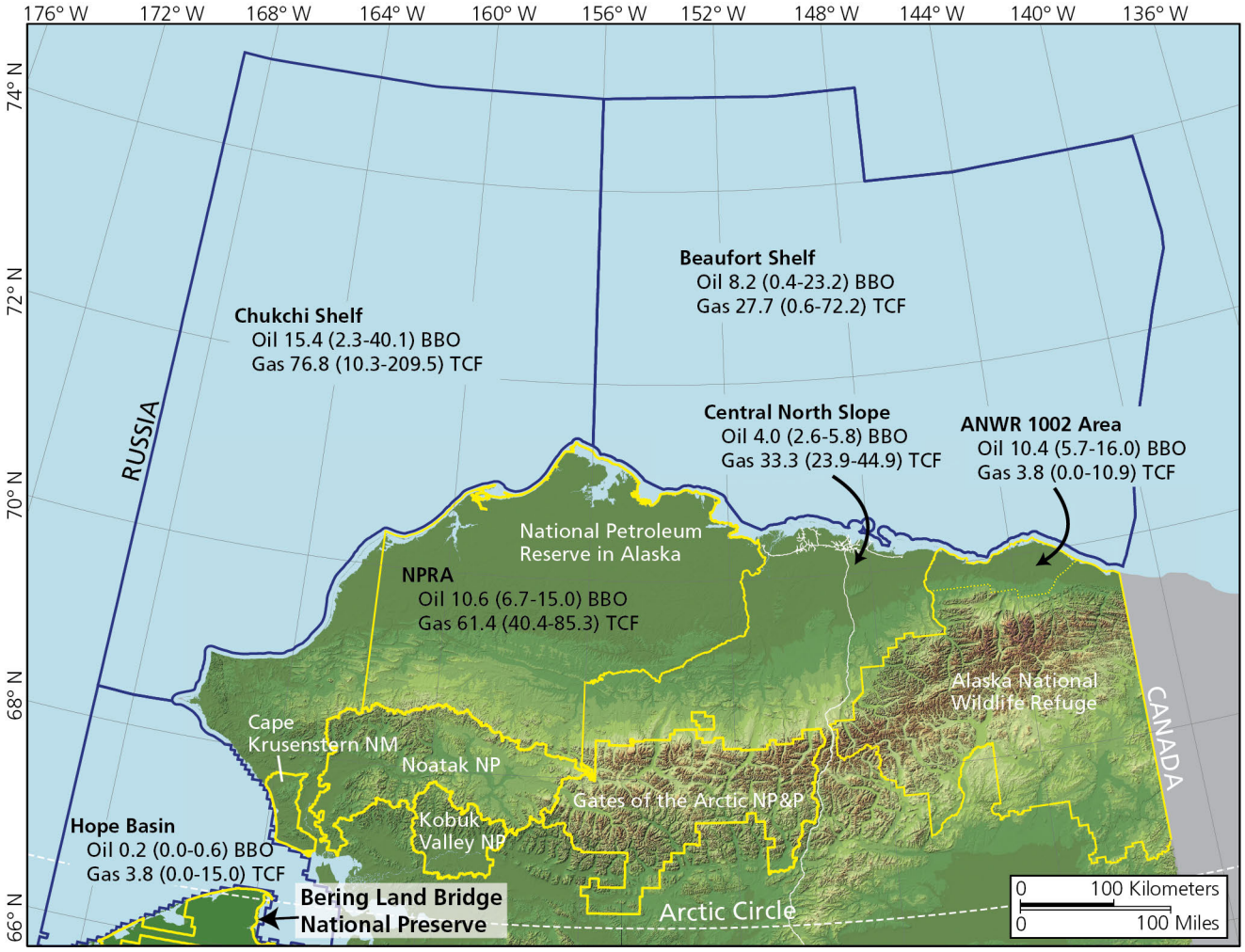


Figure 51. Map showing estimated undiscovered oil and gas.
The map shows the estimates of undiscovered oil (in billions of barrels [BBO]) and gas (in trillions of cubic feet [TCF]) for federal onshore and offshore assessment areas in northern Alaska. The oil and gas estimates are the mean (first number) and range (in parentheses) of the 90% confidence interval. The Hope basin in this figure combines both the Kotzebue and Hope basins, which are managed together under the Hope Basin Planning Area. Modified from Houseknecht and Bird (2005).

onshore wells were drilled within the Kotzebue basin: Cape Espenberg Well No. 1 (located within what is now Bering Land Bridge National Preserve) and Nimiuk Point Well No. 1. The mudlogs for both of these wells depicted small amounts of methane, but no oil or gas was recovered and they were abandoned as dry holes (Troutman and Stanley 2003).

The Kotzebue and Hope basins compose the Hope Basin Planning Area. the Bureau of Ocean Energy Management (BOEM) manages oil and gas development in the Hope Basin Planning Area. The Hope Basin Planning Area was offered for oil and gas lease sales in 1988, 1991, and 2002–2007. No bids were attracted during the 1988 and 1991 lease sales, and no interest was expressed in obtaining exploration rights during the 2002–2007 period (BOEM 2006). A new Outer Continental Shelf Oil and Gas Leasing Program is being developed to replace the 2017–2022 program. The new 2019–2024 draft proposed program (the first in a series of three draft documents before the final 2019–2024 program is approved) proposes making the Hope Basin Planning Area available to consider for oil and gas leasing during 2023 (BOEM 2018).

There is potential for oil and gas development in the preserve in areas where the surface and subsurface rights are non-federally owned near Cape Espenberg, and for offshore development adjacent to the preserve if the final BOEM 2019–2024 program contains lease sales in the Hope Basin Planning Area. However, failure of the Cape Espenberg and Nimiuk Point wells to recover oil or gas makes the probability for renewed efforts to

Figure 52. Photograph of Serpentine Hot Springs.
The photograph shows the bunkhouse (right) and bathhouse (left) at Serpentine Hot Springs. Granitic tors (in the background) are described in more detail in the "Cretaceous Igneous Rocks" section of this report. NPS photograph.

drill within the preserve relatively low. Additionally, the disinterest in past lease sales in the Hope basin (BOEM 2006) combined with the low resource estimates compared to other assessment areas of northern Alaska (Figure 51; Houseknecht and Bird 2005) reduces the probability of offshore oil and gas development if the Hope Basin Planning Area. In the 2019–2024 draft proposed program, the Hope Basin Planning Area is noted as having measured resource potential, but "an estimated negligible development value" (BOEM 2018).

Geothermal Features Inventory and Monitoring

The preserve is one of the 16 units in the National Park System 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. 28,790–28,800), Serpentine Hot Springs is a significant thermal feature in the National Park System, constituting the only hot springs in the region and a culturally significant site to Alaska Natives. The recreational importance of Serpentine Hot Springs is acknowledged in the preserve's enabling legislation (ANILCA 1980) and the preserve's foundation statement identified protecting "the integrity of Serpentine Hot Springs, its natural setting, and its cultural and spiritual significance" as a significant part of the preserve's mission (NPS 2009).

Serpentine Hot Springs is the most visited location within the preserve. The Inupiat have used the springs for religious, medicinal, subsistence, and recreational purposes for hundreds, perhaps thousands of years (Curran 2008). The traditional Inupiat name for the site is "Iyat." Infrastructure at Serpentine Hot Springs includes a bunkhouse, bathhouse, privy, and 400 m (1,300 ft) airstrip (Figure 52). The bunkhouse and bathhouse are surrounded by water and are only accessible via boardwalk; the proximity of these structures to the water could potentially pose water-quality risks associated with inadequate human-waste disposal and grey-water effluent from the bathhouse (Nordstrom et al. 2015). In 2010, sampling found that total coliform bacteria were elevated at sites closest

to the structures, though fecal coliform levels were within the range of Alaska's drinking water and water recreation standards (Nordstrom et al. 2015). The timing of this sampling did not coincide with peak visitation, so coliform bacteria levels may be higher at other times of the year.

The Geothermal Steam Act of 1970 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 science-informed inventorying and monitoring of significant geothermal features of the park. In 2009, NPS managers and park planners began developing a management plan for Serpentine Hot Springs, but the process was stymied by a lack of baseline data (Nordstrom et al. 2015). To address the data gaps, a study was undertaken to describe the hydrology, geochemistry, water chemistry, and microbiology of Serpentine Hot Springs, the results of which are summarized by Nordstrom et al. (2015). Information about monitoring geothermal systems and hydrothermal features can be found in Heasler et al. (2009).

Caves and Associated Landscape Management

Bering Land Bridge National Preserve currently contains 48 documented caves (Burger 2016). These include caves developed in the Nome Complex (Trail Creek caves), lava tubes in the Lost Jim lava flow, and sea caves or alcoves along the coast. Some of the cave resources in the preserve have been well documented, while others are relatively poorly known.

Cave features are non-renewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act request (also see Appendix B). The chapter in *Geological Monitoring* about caves (Toomey 2009) provides more information about inventorying and monitoring cave-related vital signs, and the "Cave Resources" section of this report provides more information about the geologic context of caves in the preserve. Other resources focused on the preserve's caves include a cave and karst resource summary (Burger 2016) and a Trail Creek caves survey and reconnaissance field report (Burger et al. In preparation).

Trail Creek caves has received the most study of the preserve's caves. Excavated by Danish archeologist Helge Larsen in 1949 and 1950, Trail Creek caves are known for their important archeological and paleontological resources (Larsen 1968; Dixon and Smith 1986; Pasda 2012). These resources were investigated by NPS archeologists in 1985, and the caves were revisited by NPS scientists during the summer of 2017. The purpose of the 2017 visit was to conduct detailed cave mapping and ascertain the potential for additional archeological and paleontological deposits. Maps were completed for five of the 13 known caves in the Trail Creek region. Future work could include mapping the remaining known caves and investigating the rest of the marble outcrop for additional cave sites. Although carbonate-hosted caves have not yet been reported outside Trail Creek, carbonate units occur in other areas of the preserve (see poster, in pocket). Most of these outcrops have not been checked specifically for caves or karst features, but a survey may potentially uncover additionally cave resources (Burger 2016).

The Lost Jim lava flow contains 34 known lava tubes and likely many more that have yet to be documented. During a 2016 reconnaissance trip, NPS scientists documented 34 caves while covering less than 10% of the total flow area (Burger 2016). Another lava tube mapping project occurred during the summer of 2018, which involved detailed mapping of previously identified caves, as well as documentation and mapping of newly discovered lava tubes. Given the size of the Lost Jim lava flow, multiple similar surveys may be required to fully inventory the lava tubes.

Imagery from the NOAA Alaska ShoreZone database shows sea caves or alcoves developed in Cambrian-Devonian (**DCks**) calcareous schist near the eastern end of the preserve's coast. This area is likely the only area where sea caves exist within the preserve because it is the only area where bedrock crops out along the coast (see poster, in pocket). The caves have not yet been investigated or mapped by NPS staff.

Permafrost Monitoring

Continuous permafrost underlies almost all of the preserve (Figure 33) and has been selected as one of the "vital signs" subjected to long-term monitoring by the Arctic Network Inventory and Monitoring Program (for more information about permafrost, see the "Permafrost and Thermokarst" section of this report; Lawler et al. 2009). Future climate change is likely to cause permafrost thaw in the preserve. The consequences of significant thaw could include creation and drainage of thermokarst lakes, mass wasting, release of methane and carbon dioxide, and changes in hydrology, soil temperature, and sedimentation that

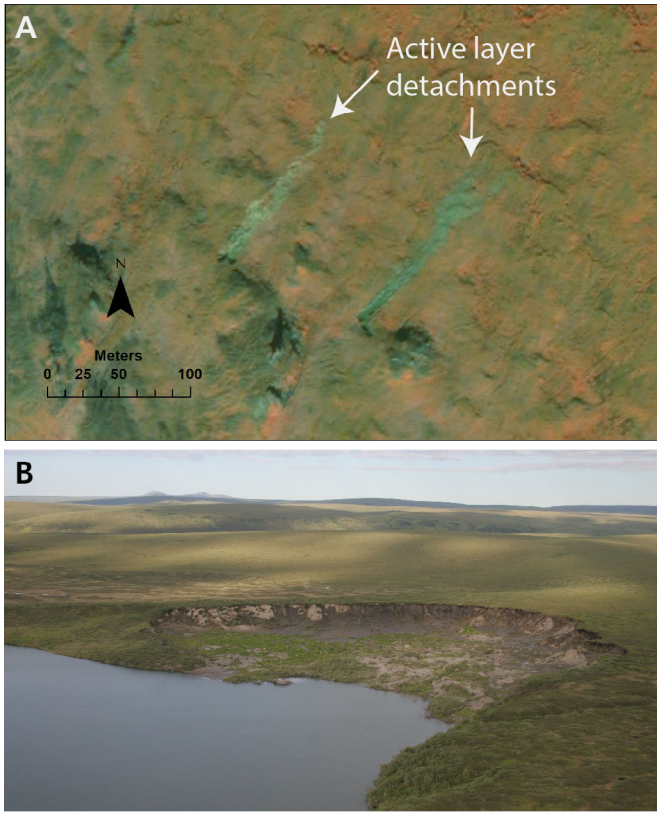


Figure 53. Photographs showing erosional features related to thawing permafrost.
(A) An active-layer detachment from Bering Land Bridge National Preserve. Active-layer detachments are mass movement features that consist of active-layer material (see the "Permafrost and Thermokarst" section for a description of the active layer) that slides along a slip surface of saturated fine-grained material that usually develops at the interface between permafrost and the active layer, resulting in an exposed area of bare soil with a deformed mat of soil and vegetation at its lower end. (B) A retrogressive thaw slump from Noatak National Preserve. A retrogressive thaw slump is a mass movement caused by thaw of permafrost, consisting of an escarpment that advances upslope as material thaws and is transported away by viscous flow and water erosion. No retrogressive thaw slumps were identified during the 2006–2009 period. NPS photographs by David Swanson (NPS Inventory and Monitoring Arctic Network).

will affect nutrient cycling and vegetation communities. In the Arctic Network Inventory and Monitoring permafrost monitoring protocol, Swanson (2017a) outlines two areas of focus for long-term monitoring: (1) ground temperatures, which will be monitored at climate monitoring stations; and (2) permafrost-related landforms, which will be monitored with remote sensing. Monitoring of permafrost-related landforms

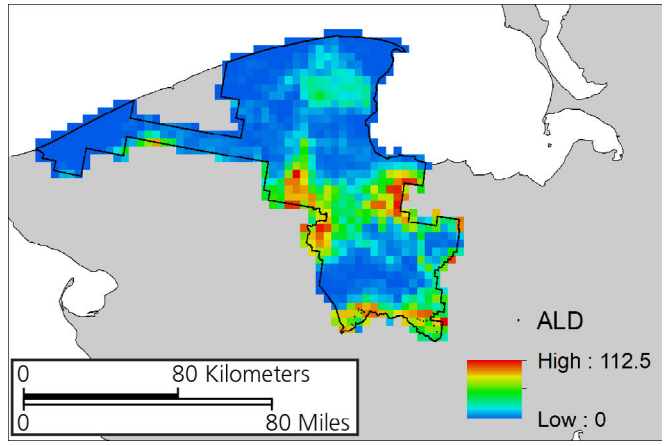


Figure 54. Map showing susceptibility of terrain to active-layer detachments.
Red areas have a relatively high proportion of the landscape that is susceptible to active-layer detachment (ALD) formation, up to 112.5 parts per million (0.01%). Previous ALD (dots) were all in the Bendeleben Mountains in the south, but conditions appear right for slides to also occur in the hills of the central part of the preserve. From Swanson (2014).

will be split into comprehensive mapping of erosional features produced by permafrost thaw (active-layer detachments and retrogressive thaw slumps), focused monitoring of selected retrogressive thaw slumps, and monitoring of ice-wedge degradation and other thermokarst features (Swanson 2017a).

Active-layer detachments and retrogressive thaw slumps (erosional features produced by permafrost thaw) in the preserve have been mapped on satellite images from 2006–2009 (Figure 53; Swanson 2010, 2014). Twenty-two active-layer detachments were identified by this mapping, exposing a total area of 2.9 ha (7.2 ac); all the active-layer detachments occurred in the southeastern portion of the preserve, either in the Bendeleben Mountains or Bendeleben Foothills (Swanson 2010). This part of the preserve has the right conditions for occurrence of active-layer detachments; that is, long slopes (at least 100 m [330 ft]) with moderate steepness (10% to 33%) and fine-grained sediments that are susceptible to ice accumulation (Swanson 2014). Active-layer detachments occur in groups during years with unusual weather (warm and/or rainy summers), such as 2004 (Swanson 2014, Balser 2015). They are most effectively monitored by acquisition of imagery as soon as possible after an event, followed by mapping as outlined by Swanson (2017a, 2017b). Retrogressive thaw slumps were also mapped on satellite images from 2006–2009, but none were found in the preserve (Swanson 2010).The lack of retrogressive thaw slumps

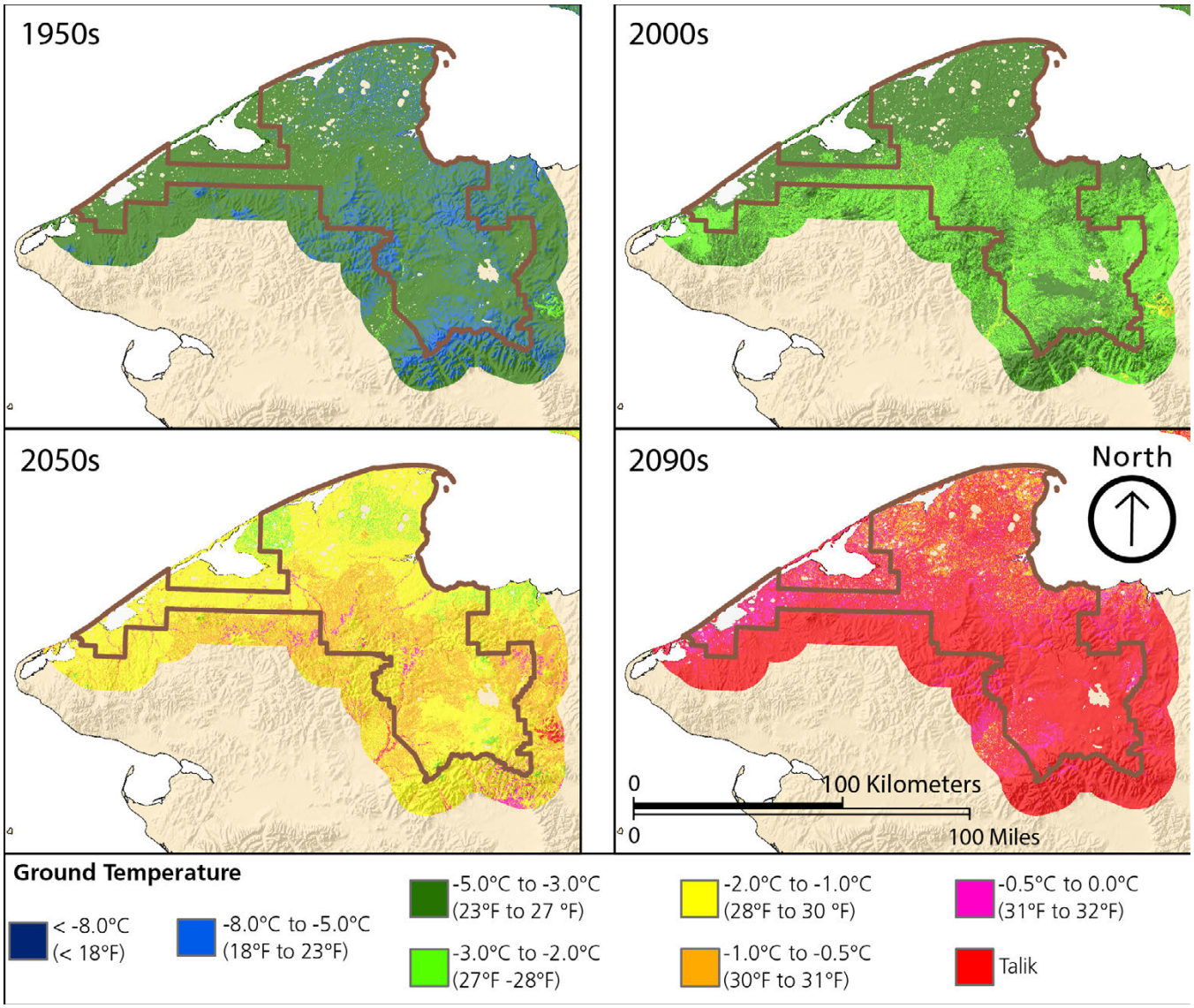


Figure 55. Maps showing projected ground temperature for the 1950s, 2000s, 2050s, and 2090s. "Talik" means ground temperatures above 0° C. Modified from Panda et al. (2016).

is probably due to the fact that the very ice-rich material (e.g., yedoma) exists only in places with nearly level slopes. Thermokarst is locally active along lakeshores and the coast, but it tends to stabilize unless wave erosion continues to remove material from the foot of the slump.

Current environmental impacts of active-layer detachments and retrogressive thaw slumps in the preserve are limited due to the relatively small area affected (Swanson 2014). Active-layer detachments revegetate rapidly in most cases, and no retrogressive thaw slumps were observed in the preserve (Swanson 2014). Many of the 22 active-layer detachments identified in the preserve probably were triggered by the unusually warm summer of 2004 (Swanson 2010). Similar triggering events could be a concern in the future, especially if they become more severe or frequent with projected climate change (Figure 54).

With continued climate warming, thermokarst, particularly in the form of ice wedge thawing, is likely to become widespread in the preserve. If the permafrost warming predicted by Panda et al. (2016) occurs (see Figures Figure 55 and Figure 56), wedge ice will thaw and the ground over the wedges will subside across vast expanses of the preserve's lowland terrain. This will result in the formation of small ponds, some of which will expand to form larger water bodies as thawing continues. Meanwhile, linear thaw features along ice wedges will breach the shores of existing lakes, causing them to drain suddenly (Jones et al. 2011; Swanson 2013). NPS scientists have monitored

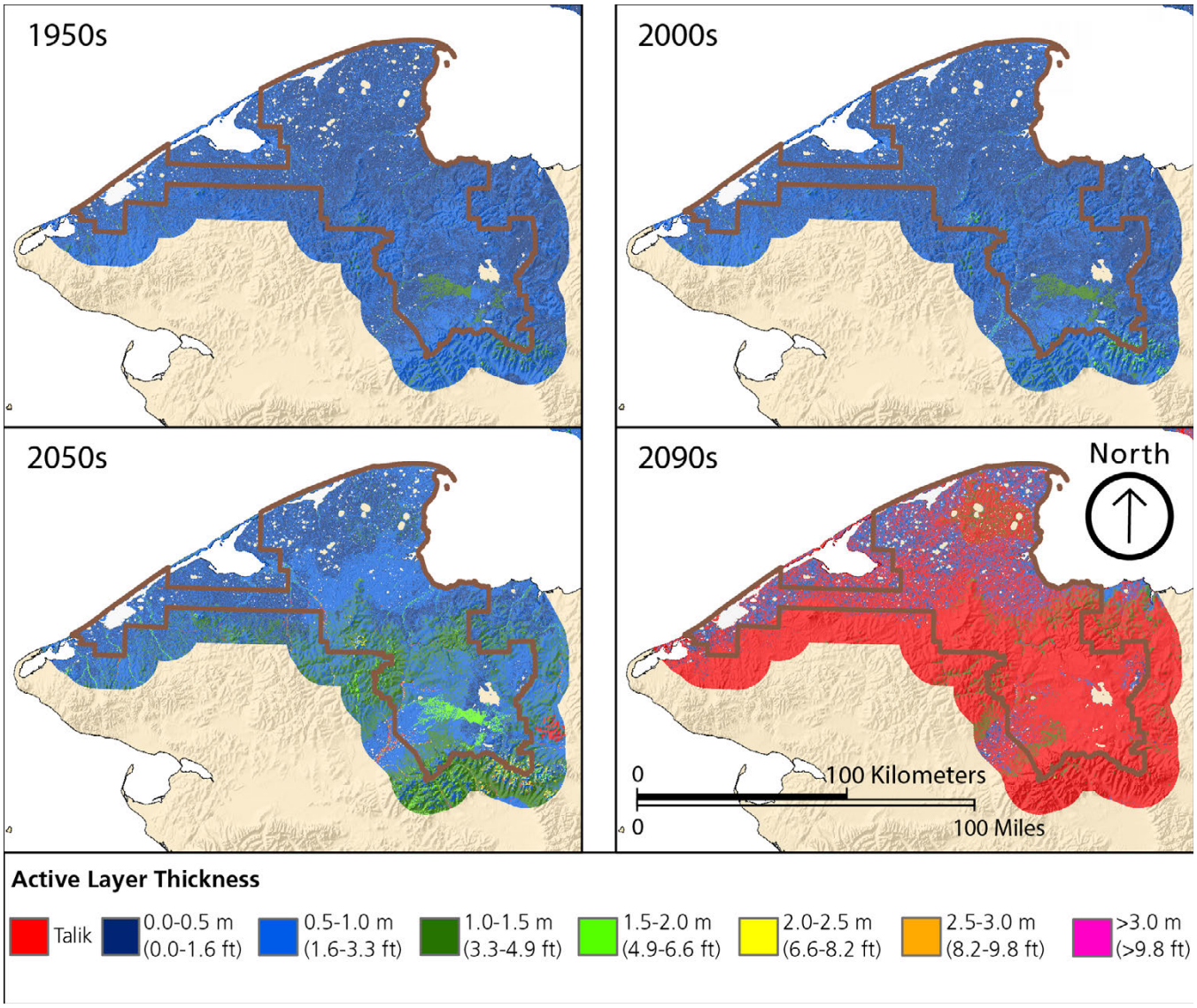


Figure 56. Maps showing projected active layer thickness for the 1950s, 2000s, 2050s, and 2090s. "Talik" means ground temperatures above 0°C. Modified from Panda et al. (2016).

degradation of ice-wedge polygons in the Noatak National Preserve and Kobuk Valley National Park (Swanson 2016b), but not Bering Land Bridge National Preserve because suitable historical imagery was not present. With acquisition of suitable images in the future, monitoring will be extended to include Bering Land Bridge National Preserve. The area of surface water in the preserve, which is affected by lake drainage, lake expansion by thermokarst, and non-thermokarst lake size changes (e.g., shrinkage because of drying) is monitored as a part of the Arctic Network Inventory and Monitoring Program's terrestrial landscape dynamics vital sign (Swanson 2017a, 2017b)

Coastal Issues

The preserve covers 919 km (571 mi) of shoreline and 35,534 ha (87,808 ac) of water, primarily in the form of large coastal lagoons (Curdts 2011). Surficial deposits along the coast contain archeological and paleontological resources (Holt et al. 2016) and the preserve's coastal zone hosts productive ecosystems that are rich in biological resources. These coastal ecosystems play an essential role in the subsistence lifestyle of Inupiat peoples who have lived in the region for hundreds of generations (Neitlich et al. 2017). The protection and interpretation of coastal formations, as well as protection of populations of fish and marine mammals, were identified as a central part of the preserve's mission by its enabling legislation (ANILCA 1980).

Because the coast of the preserve contains biological, archeological, and paleontological resources, understanding how the coast is changing is critical. Coastal erosion is monitored by the Arctic Network Inventory and Monitoring program (Lawler et al. 2009). Warming temperatures in the Arctic will cause a reduction in sea ice and permafrost (see the "Coastal Features" and "Permafrost and Thermokarst" sections for more details), which is expected to increase future rates of erosion along the coast. To date, coastal change has been mapped for three time intervals: 1950–1980, 1980–2003, and 2003–2014 (Jordan 1988; Manley and Lestak 2012; Farquharson 2018). During these time intervals, mean rates of coastal change were losses 0.68 m/yr (2.2 ft/yr), 0.26 m/yr (0.85 ft/yr), and -0.68 m/yr (2.2 ft/yr), respectively. Overall coastal processes became increasingly dynamic through time; Farquharson (2018) attributed the increasingly dynamic coastal processes to climate change-related factors such as sea ice decline. Monitoring efforts have largely been focused on the outer coast, and as a result the erosion and deposition patterns of the inner coast (inner part of the coastal lagoons) are comparatively less understood.

Climate change is expected to increase storm strength in the Arctic, which will contribute to future erosion. One of the factors projected to increase storm strength is a decline in Arctic sea ice (Bader et al. 2011). This relationship has already been observed; analysis shows that over the last 30 years, the extent of September ice coverage is positively correlated to storm strength in the Arctic basin (Simmonds and Keay 2009). Furthermore, the increasingly late development of landfast sea ice leaves the preserve's coast vulnerable to fall and early winter storms and the erosion caused by these events (Farquharson 2018).

The preserve is one of the 118 parks in the National Park System that have been identified as potentially vulnerable to sea level change (Caffrey et al 2018). Relative (local) sea level change is the combination of vertical movements of the land and eustatic (global) sea level rise. Modern eustatic sea level rise is primarily caused by the addition of freshwater from melting continental ice and thermal expansion of ocean water (Caffrey et al. 2018). The vertical motion of land varies geographically as a result of regional tectonic strain, isostatic rebound, or natural subsidence caused by crustal loading. Unlike southcentral Alaska where land is rising fast enough to outpace eustatic sea level rise, relative sea level in in western Alaska is rising approximately 0.79 mm/yr (0.03 in/yr) (DeGrandpre 2015). This is because the coast of northwest Alaska has not been recently glaciated and is not significantly affected by tectonic strain associated with the Aleutian megathrust. The preserve is expected to experience future sea level rise, with a recent study projecting rise of 0.18–0.21 m (0.59–0.70 ft) by 2050 and 0.37–0.6 m (1.2–2.0 ft) by 2100 (Caffrey et al. 2018).

While no NPS infrastructure is present along the coast of the preserve, archeological and paleontological resources in coastal sediments are threatened by sea level rise, increased storm strength, and increased erosion caused by climate change. Schupp et al. (2015) and Holt et al. (2016) provide summaries of this issue and the steps already taken to address it. One area with significant infrastructure that is entirely surrounded by the preserve is Shishmaref; this village has been affected by high erosion rates that are predicted to intensify with continued warming. Erosion has undermined some of the infrastructure, causing homes to be relocated and several buildings to fall into the Chukchi Sea. With assistance from the State of Alaska, Shishmaref has investigated the option of building an access road across the preserve to extract construction material from Native-owned lands at Ear Mountain. These materials would be used to reinforce the existing village site or a future village site.

The NPS coastal adaptation handbook (Beavers et al. 2016) provides climate change adaptation guidance to coastal park managers in parks that are potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts. Case studies of the many ways that park managers are implementing adaptation strategies for threatened resources, including a case study for Bering Land Bridge National Preserve, are available in Schupp et al. (2015). An additional reference manual that guides coastal resource management is NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction, which can provide insight for managers in parks with boundaries that may shift with changing shorelines; this manual is available at https://home.nps.gov/applications/npspolicy/DOrders.cfm. For more information on monitoring coastal resources, see Bush and Young (2009). The NPS Water Resources Division, Ocean and Coastal Resources Branch website (https://www.nps.gov/orgs/1439/ocrb.htm) has additional information about servicewide programs and resources.

Paleontological Resources Inventory, Monitoring, and Protection

Paleontological resources, or fossils, occur within the preserve's bedrock and surficial deposits. The fossils in the preserve can broadly be divided into two

groups: (1) Paleozoic fossils found in bedrock and (2) Cenozoic fossils mainly found in surficial deposits (see the "Paleontological Resources" section of this report for more details). The Cenozoic fossils record the migration of flora and fauna across the Bering Land Bridge; protection of this record is cited in the enabling legislation as a primary purpose of the preserve (ANILCA 1980; NPS 2009). Bering Land Bridge National Preserve and Yukon-Charley Rivers National Preserve are the only park units in Alaska expressly established to protect paleontological resources.

Paleontological resources are important because they represent a non-renewable record of life on our planet; once a fossil is destroyed it can never be recovered, and that piece of Earth's history is lost forever. As such, science-informed inventory, monitoring, protection, and interpretation of paleontological resources is mandated on all federal lands by the Paleontological Resources Preservation Act. NPS *Management Policies 2006* (p. 54) states, "Superintendents will establish programs to inventory paleontological resources and systematically monitor for newly exposed fossils, especially in areas of rapid erosion. Scientifically significant resources will be protected by collection or by on-site protection and stabilization. The Service will encourage and help the academic community to conduct paleontological field research in accordance with the terms of a scientific research and collecting permit."

Fossils are faced with the potential for damage and destruction from both natural and human sources. Natural processes, primarily weathering and erosion, are responsible for exposing fossils at the surface of the Earth, enabling their discovery and study. However, the progression of these same processes leads to the eventual destruction of exposed fossils. Fossil sites that are especially vulnerable to destructive erosional events are located along streams or rivers, lakeshores, the coast or on slopes prone to mass movements. In addition, warming climate in the Arctic is intensifying natural erosional processes, putting vulnerable fossil localities at even greater risk (Holt et al. 2016). Anthropogenic threats to paleontological resources include unauthorized disturbance or removal of fossils, or an increase in rates of erosion as a result of visitor traffic. Fossil sites especially prone to human disturbance are those easiest to access or proximal to areas frequented by visitors. These include fossils exposed along river banks, coastal bluffs, or near roads and trails.

The predicted future widespread thawing of permafrost (see the "Permafrost Monitoring" section for more details) poses the most significant threat to frozen Pleistocene fossils in the preserve. Fossil material frozen in permafrost commonly displays exceptional preservation, which can include intact soft tissue and ancient DNA; however, this type of preservation also means that fossils degrade quickly once removed from their frozen state. Once frozen fossil material is exposed, it must be either collected or stabilized within a limited window of time before that material is destroyed. In addition, the frozen nature of these deposits will cause natural rates of erosion to accelerate as temperatures rise. The unusual environmental circumstances that preserved these frozen fossils (i.e., continuous permafrost since the Pleistocene Epoch) are predicted to disappear; thus these valuable resources will be lost if they are not documented, collected, or stabilized.

Pleistocene mammal fossils are particularly vulnerable to loss via unauthorized collection. This is because they are highly desirable, can be relatively easy to collect, and are most often exposed in areas that receive frequent human visitation (e.g., along rivers and the coast). The sale of fossils collected from Native and privately owned lands is legal, but the Paleontological Resources Preservation Act prohibits unpermitted fossil collection is prohibited on NPS land. One factor that could exacerbate this issue is the heightened monetary value of fossil ivory due to the 2016 embargo on ivory sourced from African elephants. Pleistocene bones, especially mammoth tusks and teeth, can be sold for thousands of dollars (Vigne and Martin 2014). Evidence of apparent fossil collection–related behavior in the preserve includes the presence of human footprints systematically arrayed along the bluffs in the vicinity of the Nugnugaluktuk River that appear to be left by people looking for fossils (Chad Hults, NPS Alaska Regional Office, regional geologist, personal communication, 15 November 2017). Other unauthorized fossil collecting incidents may be occurring but have gone unrecognized due to a low NPS presence in the preserve.

Due to their intrinsic value and non-renewable status, baseline documentation of the paleontological resources is an important first step toward management. An inventory of fossils in the preserve was completed by Elder et al. (2009), and a paleontological resource condition assessment was completed by Lanik et al. (In press). Both of these documents provide a primarily literature-based overview of fossils in the preserve, and much of this information has been incorporated into an Alaska-wide NPS paleontology database. A field-based inventory to assess areas where fossils have previously been found and explore areas for new fossils is planned for the summer of 2019. For a more in-depth discussion of paleontological resource management for the preserve, see the "Paleontological Resources" chapter of the Arctic Network natural resource condition assessment (Lanik et al. In press).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. A poster (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. NPS employees can also obtain GRI GIS data via the Alaska Region NPS Theme Manager, under the BELA Themes folder, in the Geologic Resources Inventory folder.

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.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. GRI produced a bedrock map for Bering Land Bridge National Preserve.

Source Maps

The GRI team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following sources to produce the GRI GIS data set for Bering Land Bridge National Preserve:

Hudson, T. 1998. Alaska Resource Data File, Bendeleben Quadrangle, Alaska. Open-File Report 99-332 (1:250,000). US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr99332.

Hudson, T. 1998. Alaska Resource Data File, Teller Quadrangle, Alaska. Open-File Report 98-328 (1:250,000). US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr98328.

Till, A. B., J. A. Dumoulin, M. B. Werdon, and H. A. Bleick. 2011. Bedrock geologic map of the Seward Peninsula, Alaska, and accompanying conodont data. Scientific Investigations Map 3131 (1:500,000). US Geological Survey, Reston, Virginia.

Till, A. B., J. A. Dumoulin, M. B. Werdon, and H. A. Bleick. 2010. Preliminary bedrock geologic map of the Seward Peninsula, Alaska, and accompanying conodont data. Open-File Report 2009-1254 (1:500,000). US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr20091254.

Williams, A. 2000. Alaska Resource Data File, Kotzebue Quadrangle, Alaska. Open-File Report 99-579 (1:250,000). US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr99579.

Wilson, F. H., N. B. Shew, G. D. DuBois, and S. Dadisman, 1999. Alaska Radiometric Ages, Alaska. Unpublished Data (1:250,000). U.S. Geological Survey, 1999 (release date),

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Bering Land Bridge National Preserve was compiled using data model version 2.2, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

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

The following components are part of the data set:

- A GIS readme file (bela_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 4).
- Federal Geographic Data Committee (FGDC)–compliant metadata.
- An ancillary map information document (bela_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 (bela_geology.mxd) that displays the GRI GIS data.
- A version of the data viewable in Google Earth (bela_geology.kmz).

GRI Map Poster

A poster of the GRI GIS draped over a shaded relief image of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (Table 4). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

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 the poster.

Table 4. GRI GIS data layers for Bering Land Bridge National Preserve.

Data Layer	On Poster?	Google Earth Layer?
Mine Point Features	No	No
Geologic Sample Localities	No	No
Linear Dikes	Yes	Yes
Faults	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Literature Cited

These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.

Amato, J. M., and E. L. Miller. 2004. Geologic map and summary of the evolution of the Kigluaik Mountains gneiss dome, Seward Peninsula, Alaska. Pages 295–306 in D. L. Whitney, C. Teyssier, and C. S. Siddoway, editors. Gneiss domes in orogeny. Special Paper 380. Geological Society of America, Boulder, Colorado.

Amato, J. M., E. L. Miller, and K. A. Hannula. 2002. Orthogonal flow directions in extending continental crust: an example from the Kigluaik gneiss dome, Seward Peninsula, Alaska. Pages 133–146 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Amato, J. M., E. L. Miller, J. E. Wright, and W. C. McIntosh. 2003. Dike swarms on Seward Peninsula, Alaska, and their implications for the kinematics of Cretaceous extension in the Bering Strait region. Canadian Journal of Earth Science 40:865–886.

Amato, J. M., J. Toro, E. L. Miller, G. E. Gehrels, G. Lang Farmer, E. S. Gottlieb, and A. B. Till. 2009. Late Proterozoic-Paleozoic evolution of the Arctic Alaska-Chukotka terrane based on U-Pb igneous and detrital zircon ages: implications for Neoproterozoic paleogeographic reconstructions. Geological Society of America Bulletin 121(9/10):1219–1235.

Amato, J. M., and J. E. Wright. 1997. Potassic mafic magmatism in the Kigluaik gneiss dome, northern Alaska: a geochemical study of arc magmatism in an extensional tectonic setting. Journal of Geophysical Research 102(B4):8065–8084.

Amato, J. M., J. E. Wright, P. B. Gans, and E. L. Miller. 1994. Magmatically induced metamorphism and deformation in the Kigluaik gneiss dome, Seward Peninsula, Alaska. Tectonics 13(2):515–527.

Anderson, E. 1943. Pargon Mountain muscovite prospect, Seward Peninsula, Alaska. Mineral Investigation 44-1. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/619.

ANILCA (Alaska National Interest Lands Conservation Act). 1980. Public Law 96–487, 94 Statute 2371, 2 December 1980. https://www.nps.gov/locations/alaska/anilca.htm.

Bader, J., M. D. S. Mesquita, K. I. Hodges, N. Keenlyside, S. Østerhus, and M. Miles. 2011. A review on Northern Hemisphere sea-ice, storminess and the North Atlantic oscillation: observations and projected changes. Atmospheric Research 101:809–834.

Basler, A. W. 2015. Retrogressive thaw slumps and active layer detachment slides in the Brooks Range and foothills of northern Alaska: terrain and timing. Dissertation. University of Alaska Fairbanks, Fairbanks, Alaska.

Beavers, R. L., A. L. Babson, and C. A. Schupp. 2016. Coastal adaptation strategies handbook. NPS 999/134090. National Park Service, Washington, DC. https://www.nps.gov/subjects/climatechange/coastaladaptation.htm.

Becker, J. J., D. T. Sandwell, W. H. F. Smith, J. Braud, B. Binder, J. Depner, D. Fabre, J. Factor, S. Ingalls, S-H. Kim, R. Ladner, K. Marks, S. Nelson, A. Pharaoh, R. Trimmer, J. Von Rosenberg, G. Wallace, P. Weatherall. 2009. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. Marine Geodesy 32(4):355–371.

Beechey, F. W. 1831. Narrative of a voyage to the Pacific and Beering's Strait, to co-operate with the Polar Expeditions: performed in his majesty's ship *Blossom*, under the command of Captain F. W. Beechey, R. N. F. R. S. &c. in the years 1825, 26, 27, 28. Lords Commissioners of the Admiralty, London, England.

Begét, J. E., D. M. Hopkins, and S. D. Charron. 1996. The largest known maars on Earth, Seward Peninsula, Northwest Alaska. Arctic 49(1):62–69.

Begét, J. E., and J. S. Kargel. 2008. Volcanoes and permafrost in Bering Land Bridge National Preserve, Arctic Alaska. Alaska Park Science 7(1):33–37.

Begét, J. E., J. Kargel, and R. Wessels. 2005. Landforms produced by permafrost-volcano interactions, Arctic Alaska. Abstract V12B-07. American Geophysical Union, Fall Meeting, 5–9 December 2005, San Francisco, California.

Begét, J. E., P. Layer, and M. Keskinen. 2003. Interactions between volcanism, permafrost, Milankovitch cycles, and climate change on the Seward Peninsula. Geological Society of America Abstracts with Programs 35(6):546.

Begét, J. E., and D. Mann. 1992. "Caldera" formation by unusually large phreatomagmatic eruptions through permafrost in Arctic Alaska. Eos 73(43):636.

Berryhill, R. V. 1962. Reconnaissance sampling of beach and river-mouth deposits, Norton Bay and Kotzebue Sound, Seward Peninsula, Alaska. Open-File Report 1. US Bureau of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/21301.

Biswas, N. N., J. Pujol, G. Tytgat, and K. Dean. 1983. Synthesis of seismicity studies for western Alaska. Final report. [Conducted by] Outer Continental Shelf Environmental Assessment Program, Research Unit 486. University of Alaska Fairbanks, Geophysical Institute, Fairbanks, Alaska.

Blodgett, R. B., D. M. Rohr, and A. J. Boucot. 2002. Paleozoic links among some Alaskan accreted terranes and Siberia based on megafossils. Pages 273–290 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

BOEM (Bureau of Ocean Energy Management). 2006. Hope Basin Planning Area (Alaska)—Province Summary. 2006 Oil and Gas Assessment. Bureau of Ocean Energy Management, Alaska OCS Region, Anchorage, Alaska. https://www.boem.gov/About-BOEM/BOEM-Regions/Alaska-Region/Resource-Evaluation/2006-assessment-AK.aspx.

Bureau of Ocean Energy Management (BOEM). 2018 [access date]. 2019–2024 National Outer Continental Shelf Oil and Gas Leasing: Draft Proposed Program. Online information. Bureau of Ocean Energy Management, Washington, D. C. https://www.boem.gov/National-Program/.

Bouma A. H. 1962. Sedimentology of some flysch deposits: a graphic approach to facies interpretation. Elsevier, Amsterdam.

Bradley, D. C., W. C. McClelland, R. M. Friedman, P. O'Sullivan, P. W. Layer, M. L. Miller, J. A. Dumoulin, A. B. Till, J. G. Abbott, D. B. Bradley, and J. L. Wooden. 2014. Proterozoic geochronological links between the Farewell, Kilbuck, and Arctic Alaska terranes. The Journal of Geology 122:237–258.

Braile, L. W. 2009. Seismic monitoring. Pages 229–244 in R. Young, and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Braje, T. J., T. D. Dillehay, J. M. Erlandson, R. G. Klein, and T. C. Rick. 2017. Finding the first Americans. Science 358(6363):592–594.

Brigham-Grette, J., and D. M. Hopkins. 1995. Emergent marine record and paleoclimate of the last interglaciation along the northwest Alaskan coast. Quaternary Research 43:159–173.

Brooks, A. H. 1903. Stream tin in Alaska. Pages 92–93 in S. F. Emmons, and C. W. Hayes, editors. Contributions to economic geology. Bulletin 213. US Geological Survey, Washington DC. https://pubs.er.usgs.gov/publication/b213.

Brooks, A. H. 1905. Administrative reports on investigations of mineral resources of Alaska. Pages 13–17 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1904. Bulletin No. 259. US Geological Survey, Washington DC. https://pubs.er.usgs.gov/publication/b259.

Brooks, A. H. 1906. The mining industry in 1905. Pages 4–9 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1905. Bulletin 284. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b284.

Brooks, A. H. 1907a. Administrative report. Pages 11–18 in A. H. Brooks, editor Report on progress of investigations of mineral resources of Alaska in 1906. Bulletin 314. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b314.

Brooks, A. H. 1907b. The mining industry in 1906. Pages 19–38 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1906. Bulletin 314. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b314.

Brooks, A. H., G. B. Richardson, A. J. Collier, and W. C. Mendenhall. 1901. Reconnaissances in the Cape Nome and Norton Bay regions, Alaska, in 1900. US Geological Survey, Washington, DC. http://dggs.alaska.gov/pubs/id/21021.

Burand, W. M. 1957. A report on the Hannum Creek lead deposit. Prospect Evaluation 44-2. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/1923.

Burand, W. M. 1958. Itinerary report, summer of 1958, trips to Shungnak, Ruby Creek, and Kougarok. Itinerary Report 195-1. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/543.

Burch, E. S. Jr. 2006. Social life in northwest Alaska. University of Alaska Press, Fairbanks, Alaska.

Burger, P. 2016. Cave and karst resource summary—Bering Land Bridge National Preserve. National Park Service, Anchorage, Alaska.

Burger, P., C. P. Hults, A. Lanik, and A. H. Tremayne. In preparation. Trail Creek Caves Survey and Reconnaissance: 2017 Field Report. National Park Service, Anchorage, Alaska.

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2014. Abandoned mineral lands in the National Park System—comprehensive inventory and assessment. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2215804.

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Caffrey, M. A., R. L. Beavers, and C. Hawkins Hoffman. 2018. Sea level rise and storm surge projections for the National Park Service. Natural Resource Report Series NPS/NRSS/NRR—2018/1648. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2253283.

Carlson, T. H. 1946. The discovery of gold at Nome, Alaska. Pacific Historical Review 15(3):259–278.

Cathcart, S. H. 1922. Metalliferous lodes in southern Seward Peninsula. Pages 163–261 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1920. Bulletin 722. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b722.

Chang, J. M., T. C. Feeley, and M. R. Deraps. 2009. Petrogenesis of basaltic volcanic rocks from the Pribilof Islands, Alaska, by melting of metasomatically enriched depleted lithosphere, crystallization differentiation, and magma mixing. Journal of Petrology 50(12):2249–2286.

Chapin, T. 1914a. Placer mining on Seward Peninsula. Pages 385–395 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1913. Bulletin 592. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b592.

Chapin, T. 1914b. Lode developments on Seward Peninsula. Pages 397–407 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1913. Bulletin 592. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b592.

Clark, W. E. 1910. Alaska. Pages 1477–1669 in G. W. Browne and N. H. Dole, editors. The new America and the Far East. Marshall Jones Company, Boston.

Colinvaux, P. A. 1962. The environment of the Bering Land Bridge. Dissertation. Duke University, Durham, North Carolina.

Colinvaux, P. A. 1964. The environment of the Bering Land Bridge. Ecological Monographs 34(3):297–329.

Collier, A. J. 1902. A reconnaissance of the northwestern portions of Seward Peninsula, Alaska. Professional Paper 2. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp2.

Collier, A. J. 1904. The tin deposits of the York region, Alaska. Bulletin 229. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b229.

Collier, A. J. 1905. Recent development of Alaskan tin deposits. Pages 120–127 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1904. Bulletin 259. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b259.

Collier, A. J., F. L. Hess, P. S. Smith, and A. H. Brooks. 1908. The gold placers of parts of Seward Peninsula, Alaska. Bulletin 328. US Geological Survey, Washington DC. https://pubs.er.usgs.gov/publication/b328.

Colpron, M., and J. L. Nelson. 2009. A Palaeozoic Northwest Passage: incursion of Caledonian, Baltican and Siberian terranes into eastern Panthalassa, and the early evolution of the North American Cordillera. Pages 273–307 in P. A. Cawood and A. Kröner, editors. Earth accretionary systems in space and time. Special Publications 318. The Geological Society, London, England.

Cook, J. 1821. The three voyages of Captain James Cook round the world. Longman, Hurst, Rees, Orme, and Brown, London. https://www.biodiversitylibrary.org/bibliography/6760#/summary.

Cowan, M. 1916. Report of Morgan Cowan on the Ward Copper Company in the Seward Peninsula. Miscellaneous Report 43-2. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/762.

Cox, G. M., J. V. Strauss, G. P. Halverson, M. D. Schmitz, W. C. McClelland, R. S. Stevenson, and F. A. Macdonald. 2015. Kikiktat volcanics of Arctic Alaska-Melting of harzburgitic mantle associated with the Franklin large igneous province. Lithosphere 7(3):275–295.

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and great lake parks: updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2180595.

Curran, M. 2008. National Park Service, cultural landscapes inventory, 2003: Iyat (Serpentine Hot Springs), Bering Land Bridge National Preserve. National Park Service, Alaska Regional Office, Anchorage, Alaska. https://irma.nps.gov/DataStore/Reference/Profile/2227706.

Dall, W. H. 1870. Alaska and its resources. Lee and Shepard, Boston. https://archive.org/details/1870alaskaitsres00dalluoft/page/n5.

Davis, T. N. 1960. A field report on the Alaska earthquakes of April 7, 1958. Bulletin of the Seismological Society of America 50(4):489–510.

DeGrandpre, K. G. 2015. Relative sea level change in western Alaska estimated from satellite altimetry and repeat GPS measurements. Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.

Dixon, E. J., and G. S. Smith. 1986. Broken canines from Alaskan cave deposits: Re-evaluating evidence for domesticated dog and early humans in Alaska. American Antiquity 51(2):341–351.

Dumitru, T. A., E. L. Miller, P. B. O'Sullivan, J. M. Amato, K. A. Hannula, A. T. Calvert, and P. B. Gans. 1995. Cretaceous to recent extension in the Bering Strait region, Alaska. Tectonics 14(3):549–563.

Dumoulin, J. A., and A. B. Till. 1985. Seacliff exposures of metamorphosed carbonate and schist, northern Seward Peninsula. Pages 18–22 in S. Bartsch-Winkler and K. M. Reed, editors. The United States Geological Survey in Alaska: accomplishments during 1983. Circular 945. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/70180236.

Dumoulin, J. A., A. G. Harris, M. Gagiev, D. C. Bradley, and J. E. Repetski. 2002. Lithostratigraphic, conodont, and other faunal links between lower Paleozoic strata in northern and central Alaska and northeastern Russia. Pages 291–312 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Dumoulin, J. A., A. G. Harris, and J. E. Repetski. 2014. Carbonate rocks of the Seward Peninsula, Alaska: their correlation and paleogeographic significance. Pages 59–110 in J. A. Dumoulin and A. B. Till, editors. Reconstruction of a late Proterozoic to Devonian continental margin sequence, northern Alaska, its paleogeographic significance, and contained base-metal sulfide deposits. Special Paper 506. Geological Society of America, Boulder, Colorado.

Dutro Jr., J. T. 1972. Significance of recently discovered Cambrian fossils and reinterpretation of Neruokpuk Formation, northeastern Alaska. AAPG Bulletin 56(4):808–815.

Dyke, A. 2004. An outling of North America deglaciation with emphasis on central and northern Canada. Pages 373–442 in J. Ehlers and P. L. Gibbard, editors. Quaternary glaciations–extent and chronology, part II. Elsevier, Amsterdam.

Eakin, H. M. 1915. Tin mining in Alaska. Pages 81–94 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1914. Bulletin 622. U. S. Geological Survey, Washington D. C. https://pubs.er.usgs.gov/publication/b622.

Ehlers, J., P. L. Gibbard, and P. D. M. Hughes, editors. 2011. Quaternary glaciations—extent and chronology: a closer look. Developments in Quaternary Science 15. Elsevier, Amsterdam.

Elder, W., V. L. Santucci, J. P. Kenworthy, R. B. Blodgett, and R. T. P. McKenna. 2009. Paleontological resource inventory and monitoring—Arctic Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/276. National Park Service, Fort Collins, Colorado.

Elias, S. A. 2000. Late Pleistocene climates of Beringia, based on analysis of fossil beetles. Quaternary Research 53:229–235.

Elias, S. A., S. Kuzmina, and S. Kiselyov. 2006. Late Tertiary origins of the Arctic beetle fauna. Palaeogeography, Palaeoclimatology, Palaeoecology 241:373–392.

Elias, S. A., and J. V. Matthews. 2002. Arctic North American seasonal temperatures from the latest Miocene to the early Pleistocene, based on mutual climatic range analysis of fossil beetle assemblages. Canadian Journal of Earth Sciences 39:911–920.

Elias, S. A., S. K. Short, H. H. Birks. 1997. Late Wisconsin environments of the Bering Land Bridge. Palaeogeography, Palaeoclimatology, Palaeoecology 136:293–308.

Elias, S. A., S. K. Short, C. H. Nelson, and H. H. Birks. 1996. Life and times of the Bering Land Bridge. Nature 382:60–63.

Eterlein, C. E., R. E. Davis, W. P. Williams, R. B. Johnson, and W. L. Emerick. 1962. Preliminary results of a survey for thick high-calcium limestone deposits in the United States, with a section on possible Alaskan sites for nuclear reaction experiment in limestone. Open-File Report 62-36. US Geological Survey, Washington, D. C.

Farquharson, L. M., D. H. Mann, G. Grosse, B. M. Jones, and V. E. Romanovsky. 2016a. Spatial distribution of thermokarst terrain in Arctic Alaska. Geomorphology 273:116–133.

Farquharson, L., K. W. Anthony, N. Bigelow, M. Edwards, and G. Grosse. 2016b. Facies analysis of yedoma thermokarst lakes on the northern Seward Peninsula, Alaska. Sedimentary Geology 340:25–37.

Farquharson, L. M., D. H. Mann, D. K. Swanson, B. M. Jones, R. M. Buzard, and J. W. Jordan. 2018. Temporal and spatial variability in coastline response to declining sea-ice in northwest Alaska. Marine Geology 404:71–83.

Feeley, T. C., and G. S. Winer. 2009. Volcano hazards and potential risks on St. Paul Island, Pribilof Islands, Bering Sea, Alaska. Journal of Volcanology and Geothermal Research 182:57–66.

Gault, H. R. 1953. Candle Creek area, 1945. Pages 11–16 in H. R. Gault, P. L. Killeen, W. S. West, R. F. Black, J. B. Lyons, M. G. White, and J. J. Matzko. Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945-47 and 1951. Circular 250. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir250.

Gault, H. R., R. F. Black, and J. B. Lyons. 1953. Sweepstakes Creek area, 1945. Pages 1–14 in H. R. Gault, P. L. Killeen, W. S. West, R. F. Black, J. B. Lyons, M. G. White, and J. J. Matzko. Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945–47 and 1951. Circular 250. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir250.

Giterman, R. E., A. V. Sher, and J. V. Matthews. 1982. Comparison of the development of steppe-tundra environments in west and east Beringia: pollen and macrofossil evidence from key sections. Pages 43–74 in D. M. Hopkins, J. V. Matthews, C. E. Schweger, and S. B. Young, editors. Paleoecology of Beringia. Academic Press, New York.

Goebel, T., H. L. Smith, L. DiPietro, M. R. Waters, B. Hockett, K. E. Graf, R. Gal, S. B. Slobodin, R. J. Speakman, S. G. Driese, and D. Rhode. 2013. Serpentine Hot Springs, Alaska: results of excavations and implications for the age and significance of northern fluted points. Journal of Archaeological Science 40:4222–4233.

Goetcheus, V. G., and H. H. Birks. 2001. Full-glacial upland tundra vegetation preserved under tephra in the Beringia National Park, Seward Peninsula, Alaska. Quaternary Science Reviews 20:135–147.

Goodfellow, B. W., A. Skelton, S. J. Martel, A. P. Stroeven, K. N. Jansson, and C. Hättestrand. 2014. Controls of tor formation, Cairngorm Mountains, Scotland. Journal of Geophysical Research: Earth Surface 119:225–246.

Gottlieb, E. S., and J. M. Amato. 2007. Geologic mapping, structural analysis, and geochronology of the Bendeleben Mountains metamorphic complex, Seward Peninsula, Alaska. Geological Society of America Abstracts with Programs 39(4):5.

Gottlieb, E. S., and J. M. Amato. 2008. Structural evolution, transition from anatectic to mantle-derived magmatism, and timing of exhumation: Bendeleben metamorphic complex, Seward Peninsula, Alaska. Geological Society of America Abstracts with Programs 40(1):97.

Gottlieb, E. S., K. E. Meisling, E. L. Miller, and C. G. Mull. 2014. Closing the Canada basin: detrital zircon geochronology relationships between the north slope of Arctic Alaska and the Franklinian mobile belt of Arctic Canada. Geosphere 10(6):1366–1384.

Gunnell, Y., D. Jarman, R. Braucher, M. Calvet, M. Delmas, L. Leanni, D. Bourlès, M. Arnold, G. Aumaître, and K. Keddaouche. 2013. The granite tors of Dartmoor, southwest England: rapid and recent emergence revealed by Late Pleistocene cosmogenic apparent exposure ages. Quaternary Science Reviews 61:62–76.

Guthrie, R. D. 2001. Origin and causes of the mammoth steppe: a story of cloud cover, woolly mammal tooth pits, buckles, and inside-out Beringia. Quaternary Science Reviews 20:549–574.

Guthrie, R. D., and J. V. Matthews. 1971. The Cape Deceit fauna; early Pleistocene mammalian assemblage of the Alaskan Arctic. Quaternary Research 1:474–510.

Hall, A. M., and W. M. Phillips. 2006. Glacial modification of granite tors in the Cairngorms, Scotland. Journal of Quaternary Science 21(8):811–830.

Hamilton, T. D., and J. Brigham-Grette. 1991. The last interglaciation in Alaska: stratigraphy and paleoecology of potential sites. Quaternary International 10/12:49–71.

Hannula, K. A., E. L. Miller, T. A. Dumitru, J. Lee, C. M. Rubin. 1995. Structural and metamorphic relations in the southwest Seward Peninsula, Alaska: crustal extension and the unroofing of blueschists. Geological Society of America Bulletin 107(5):536–553.

Harrington, G. L. 1919. The gold and platinum placers of the Kiwalik-Koyuk region. Pages 369–400 in G. C. Martin, editor. Mineral resources of Alaska, report on progress of investigations in 1917. Bulletin 692. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b692.

Harris, A. G., J. A. Dumoulin, J. E. Repetski, and C. Carter. 1995. Correlation of Ordovician rocks of northern Alaska. Pages 21–26 in J. D. Cooper, M. L. Droser, and S. C. Finney, editors. Ordovician odyssey: short papers for the 7th International Symposium on the Ordovician system. Society for Sedimentary Geology, Pacific Section, Fullerton, California.

Harrison, E. S. 1905. Nome and Seward Peninsula: history, description, biographies and stories. The Metropolitan Press, Seattle.

Heasler, H. P., C. Jaworowski, and D. Foley. 2009. Geothermal systems and monitoring hydrothermal features. Pages 105–140 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Heide, H. E. 1946. Investigation of the Lost River tin deposit, Seward Peninsula, Alaska. Report of Investigations 3902. US Bureau of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/21507.

Heide, H. E., and F. A. Rutledge. 1949. Investigation of Potato Mountain tin placer deposits, Seward Peninsula, northwestern Alaska. Report of Investigations 4418. US Bureau of Mines, Juneau, Alaska. http://dggs.alaska.gov/pubs/id/21538.

Heide, H. E., and R. S. Sanford. 1948. Churn drilling at Cape Mountain tin placer deposits, Seward Peninsula, Alaska. Report of Investigations 4345. US Bureau of Mines, Juneau, Alaska. http://dggs.alaska.gov/pubs/id/21529.

Henshaw, F. F. 1908. Water supply of the Nome and Kougarok regions. Pages 272–286 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1907. Bulletin 345. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b345.

Henshaw, F. F. 1909. Mining in the Fairhaven precinct. Pages 355–369 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1908. Bulletin 379. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b379.

Henshaw, F. F. 1910. Water-supply investigations in Seward Peninsula in 1909. Pages 372–418 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1909. Bulletin 442. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b442.

Hess, F. L. 1906. The York tin region. Pages 145–157 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1905. Bulletin 284. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b284.

Hoang, N., and M. Flower. 1998. Petrogenesis of Cenozoic basalts from Vietnam: implication for origins of a "diffuse igneous province." Journal of Petrology 39(3):369–395.

Hoffecker, J. F., S. A. Elias, D. H. O'Rourke, G. R. Scott, and N. H. Bigelow. 2016. Beringia and the global dispersal of modern humans. Evolutionary Anthropology 25:64–78.

Höfle, C., and C.-L. Ping. 1996. Properties and soil development of Late-Pleistocene paleosols from Seward Peninsula, northwest Alaska. Geoderma 71:219–243.

Höfle, C., M. E. Edwards, D. M. Hopkins, D. H. Mann, and C.-L. Ping. 2000. The full-glacial environment of the northern Seward Peninsula, Alaska, reconstructed from the 21,500-year-old Kitluk Paleosol. Quaternary Research 53:143–153.

Hoiland, C. W., E. L. Miller, V. Pease, and J. K. Hourigan. 2018. Detrital zircon U-Pb geochronology and Hf isotope geochemistry of metasedimentary strata in the southern Brooks Range: constraints on Neoproterozoic-Cretaceous evolution of Arctic Alaska. Pages 121–158 in V. Pease and B. Coakley, editors. Circum-Arctic Lithosphere Evolution. Special Publication 460. The Geological Society, London, England.

Holt, M. J., L. Farquharson, T. Urban, and D. Davenport. 2016. The vulnerabilities of cultural and paleontological resources to coastal climate change processes in northwest Alaska. Alaska Park Science 15(1):11–21.

Hopkins, D. M. 1949. Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. The Journal of Geology 57(2):119–131.

Hopkins, D. M. 1959. Cenozoic history of the Bering Land Bridge. Science 129:1519–1528.

Hopkins, D. M. 1963. Geology of the Imuruk Lake area, Seward Peninsula, Alaska. Bulletin 1141-C. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b1141C.

Hopkins, D. M. 1967. The Bering Land Bridge. Stanford University Press, Stanford, California.

Hopkins, D. M. 1973. Sea level history in Beringia during the past 250,000 years. Quaternary Research 3:520–540.

Hopkins, D. M. 1988. The Espenberg maars: a record of explosive volcanic activity in the Devil Mountain-Cape Espenberg area, Seward Peninsula, Alaska. Pages 262–321 in J. Schaaf, editor. Bering Land Bridge National Preserve, an archaeological survey. Volume I. National Park Service, Anchorage, Alaska.

Hopkins, D. M., and J. G. Kidd. 1988. Thaw lake sediments and sedimentary environments. Pages 790–795 in Fifth International Conference on Permafrost, 2–5 August 1988, Trondheim, Norway.

Hopkins, D. M., J. V. Matthews, C. E. Schweger, and S. B. Young. 1982. Paleoecology of Beringia. Academic Press, New York, New York.

Hopkins, D. M., and R. S. Sigafoos. 1951. Frost action and vegetation patterns on Seward Peninsula, Alaska. Bulletin 974-C. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b974C.

Houseknecht, D. W., and K. J. Bird. 2005. Oil and gas resources of the Arctic Alaska petroleum province. Professional Paper 1732-A. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp1732A.

Hoyt, J. C., and F. F. Henshaw. 1907. Water supply of the Nome region, Seward Peninsula. Pages 182–185 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1906. Bulletin 314. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b314.

Hudson, T. 1979. Igneous and metamorphic rocks of the Serpentine Hot Springs area, Seward Peninsula, Alaska. Professional Paper 1079. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp1079.

Hudson, T., and J. G. Arth. 1983. Tin granites of Seward Peninsula, Alaska. Geological Society of America Bulletin 94:768–790.

Hulten, E. 1937. Outline of the history of arctic and boreal biota during the Quaternary Period. Bokforlags Aktiebolaget, Thule, Stockholm.

Hults, C. P., and J. Fierstein. 2016. Katmai National Park and Preserve and Alagnak Wild River: geologic resources inventory report. Natural Resources Report NPS/NRSS/GRD/NRR—2016/1314. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2235401.

Hults, C., and C. A. Neal. 2015. Aniakchak National Monument and Preserve: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1033. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2224165.

Jakobsson, M., C. Pearce, T. M. Cronin, J. Backman, L. G. Anderson, N. Barrientos, G. Björk, H. Coxall, A. de Boer, L. A. Mayer, C. Mörth, J. Nilsson, J. E. Rattray, C. Stranne, I. Semiletov, and M. O'Regan. 2017. Post-glacial flooding of the Bering Land Bridge dated to 11 cal ka BP based on new geophysical and sediment records. Climate of the Past: 13:991–1005.

Jones, B. M., G. Grosse, C. D. Arp, M. C. Jones, K. M. Walter Anthony, and V. E. Romanovsky. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. Journal of Geophysical Research 116, G00M03. doi:10.1029/2011JG001666.

Jones, M. C., G. Grosse, B. M. Jones, and K. W. Anthony. 2012. Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. Journal of Geophysical Research: Biogeosciences 117, G00M07. doi:10.1029/2011JG001766.

Jordan, J. W. 1988. Erosion characteristics and retreat rates along the north coast of Seward Peninsula. Pages 322–361 in J. Schaaf, editor. Bering Land Bridge National Preserve, an archaeological survey. Volume I. National Park Service, Anchorage, Alaska.

Jorgenson, M. T. 2001. Landscape-level mapping of ecological units for the Bering Land Bridge National Preserve (final report). ABR, Inc.—Environmental Research and Service, Fairbanks, Alaska.

Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones. 2008. Permafrost characteristics of Alaska (scale 1:7,200,000). University of Alaska Fairbanks, Institute of Northern Engineering, Fairbanks, Alaska.

Kanevskiy, M., Y. Shur, D. Fortier, M. T. Jorgenson, and E. Stephani. 2011. Cryostratigraphy of Late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure. Quaternary Research 75(3):584–596.

Kaufman, D. S., and J. Brigham-Grette. 1993. Aminostratigraphic correlations and paleotemperature implications, Pliocene-Pleistocene high-sea-level deposits, northwestern Alaska. Quaternary Science Reviews 12:21–33.

KellerLynn, K. 2013. Crater Lake National Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2013/719. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2204475.

Khim, B. K., D. E. Krantz, and J. Brigham-Grette. 2001. Stable isotope profiles of last interglacial (Pelukian transgression) mollusks and paleoclimate implications in the Bering Strait region. Quaternary Science Review 20:463–483.

Killeen, P. L. 1945. Tin deposits in western Seward Peninsula, Alaska. News Release, Technical Data Unit classification number 21. US Geological Survey, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/10429.

Killeen, P. L., and R. J. Ordway. 1955. Radioactivity investigations at Ear Mountain, Seward Peninsula, Alaska, 1945. Bulletin 1024-C. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b1024C.

Killeen, P. L., and M. G. White. 1953. South fork of Quartz Creek. Pages 17–18 in H. R. Gault, P. S. Killeen, and W. S. West, editors. Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945–47 and 1951. Circular 250. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir250.

Kindle, E. M. 1911. The faunal succession in the Port Clarence limestone, Alaska. American Journal of Science 32:335–349.

Klemperer, S. L., E. L. Miller, A. Grantz, and D. W. Scholl. 2002. Crustal structure of the Bering and Chukchi shelves: deep seismic reflection profiles across the North American continent between Alaska and Russia. Pages 1–37 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic Margin and Adjacent Landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Knopf, A. 1908a. Geology of the Seward Peninsula tin deposits, Alaska. Bulletin 358. US. Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b358.

Knopf, A. 1908b. The mineral deposits of the Lost River and Brooks Mountain region, Seward Peninsula, Alaska. Pages 268–271 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1907. Bulletin 345. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b345.

Kotzebue, O. 1821. A voyage of discovery into the South Sea and Beering's Straits for the purpose of exploring a north-east passage, undertaken in the years 1815–1818. Longman, Hurst, Rees, Orne, and Brown, London. https://archive.org/details/voyageofdiscover01kotz/page/n5.

Kuzmina, S., S. Elias, P. Matheus, J. E. Storer, A. Sher. 2008. Paleoenvironmental reconstruction of the Last Glacial Maximum, inferred from insect fossils from a tephra buried soil at Tempest Lake, Seward Peninsula, Alaska. Palaeogeography, Palaeoclimatology, Palaeoecology 267:245–255.

Lane, L. S. 2007. Devonian-Carboniferous paleogeography and orogenesis, northern Yukon and adjacent Arctic Alaska. Canadian Journal of Earth Science 44:679–694.

Lane, L. S., G. E. Gehrels, and P. W. Layer. 2016. Provenance and paleogeography of the Neruokpuk Formation, northwest Laurentia: an integrated synthesis. Geological Society of America Bulletin 128(1/2):239–257.

Lanik, A., C. P. Hults, and J. Rasic. In press. Condition assessment of paleontological resources within Alaska's Arctic National Park Network. Chapter 12 in Western Alaska Parklands, Bering Land Bridge National Preserve, and Gates of the Arctic National Park and Preserve: natural resource condition assessment. Natural Resource Report. Fort Collins, Colorado.

Larsen, H. 1962. The Trail Creek caves on Seward Peninsula, Alaska. Pages 284–291 in Proceedings of the 34th International Congress of Americanists, 18–25 July 1960, Vienna, Austria.

Larsen, H. 1968. Trail Creek: final report on the excavation of two caves on Seward Peninsula, Alaska. Acta Arctica 15:7–79.

Lawler, J. P., J. Ver Hoef, and S. B. Young. 2009. Arctic Network vital signs monitoring plan. Natural Resource Report NPS/ARCN/NRR—2009/088. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/661340.

Lawver, L. A., A. Grantz, and L. M. Gahagan. 2002. Plate kinematic evolution of the present Arctic region since the Ordovician. Pages 333–358 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Lawver, L. A., and C. R. Scotese. 1990. A review of tectonic models for the evolution of the Canada Basin. Pages 593–618 in G. Plafker and H. C. Berg, editors. The geology of Alaska. The Geology of North America, Volume G-1. Decade of North American Geology (DNAG) Project, Geological Society of America, Boulder, Colorado.

Lenz, J., G. Grosse, B. M. Jones, K. M. Walter Anthony, A. Bobrov, S. Wulf, and S. Wetterich. 2016. Mid-Wisconsin to Holocene permafrost and landscape dynamics based on a drained lake basin core from the northern Seward Peninsula, Northwest Alaska. Permafrost and Periglacial Processes 27:56–75.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial Processes in Geomorphology. Dover Publications, New York.

Levensaler, L. A., and E. Anderson. 1944. Kogruk galena mine and associated properties, Seward Peninsula, Alaska , silver lead property, statement of development. Miscellaneous Report 44-3. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/769.

Linton, D. L. 1955. The problem of tors. The Geographical Journal 121(4):470–487.

Mackey, K. G., K. Fujita, L. V. Gunbina, V. N. Kovalev, V. S. Imaev, B. M. Koz'min, and L. P. Imaeva. 1997. Seismicity of the Bering Strait region: Evidence for a Bering block. Geology 25(11):979–982.

Mahoney, A. R. 2017. Understanding Arctic sea ice in a period of rapid climate change. Alaska Park Science 16(1): 11–13.

Manley, W. F. and L. R. Lestak. 2012. Protocol for high-resolution geospatial analysis of coastal change in the Arctic Network of Parks. Natural Resource Report NPS/ARCN/NRR—2012/537. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2185931.

Manley, W. F., E. G. Parrish, and L. R. Lestak. 2010. Digital shorelines and analysis for the coastal areas of Bering Land Bridge NP (BELA) and Cape Krusenstern NM (CAKR), Northwest Alaska. National Park Service, Arctic Network Inventory and Monitoring Program, Fairbanks, Alaska.

Marcucci, E. C., C. W. Hamilton, and R. R. Herrick. 2017. Remote sensing evidence of lava–ground ice interactions associated with the Lost Jim lava flow, Seward Peninsula, Alaska. Bulletin of Volcanology 79:89.

Mason, O. K. 1996. Geologic Map of Portions of the Shishmaref A-3, B-3, and Teller D-3 Quadrangles, Alaska (scale 1:63,380). Report of Investigations 96-7. Alaska Division of Geological & Geophysical Surveys, Fairbanks, Alaska. http://www.dggs.alaska.gov/pubs/id/2536.

Mason, O. K., D. M. Hopkins, and L. Plug. 1997. Chronology and paleoclimate of storm-induced erosion and episodic dune growth across Cape Espenberg spit, Alaska, U.S.A. Journal of Coastal Research 13(3): 770–797.

Matthews, J. V. 1974. Quaternary environments at Cape Deceit (Seward Peninsula, Alaska): Evolution of a tundra ecosystem. Geological Society of America Bulletin 85:1353–1384.

McDannell, K. T., J. Toro, J. K. Hourigan, and D. Harris. 2014. Thermochronological constraints on Late Cretaceous to Cenozoic exhumation of the Bendeleben Mountains, Seward Peninsula, Alaska. Geochemistry, Geophysics, Geosystems 15:4009–4023.

Meier, M. F., M. B. Dyurgerov, U. K. Rick, S. O'Neel, W. T. Pfeffer, R. S. Anderson, S. P. Anderson, and A. F. Glazovsky. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. Science 317(5841):1064–1067.

Mendenhall, W. C. 1902. Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska, by way of Dall, Kanuti, Allen and Kowak Rivers. Professional Paper 10. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp10.

Mertie, J. B. Jr. 1918a. Lode mining and prospecting on Seward Peninsula. Pages 425–449 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1916. Bulletin 662. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b662.

Mertie, J. B. Jr. 1918b. Placer mining on Seward Peninsula. Pages 451–458 in A. H. Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1916. Bulletin 662. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b662.

Mickey, M. B., A. P. Byrnes, and H. Haga. 2002. Biostratigraphic evidence for the prerift position of the North Slope, Alaska. Pages 67–76 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Miller, T. P. 1994. Geothermal resources of Alaska. Pages 979–987 in G. Plafker and H. C. Berg, editors. The geology of Alaska. The Geology of North America, Volume G-1. Decade of North American Geology (DNAG) Project, Geological Society of America, Boulder, Colorado.

Miller, T. P., I. Barnes, and W. W. Patton Jr. 1975. Geologic setting and chemical characteristics of hot springs in west-central Alaska. Journal of Research of the US Geological Survey 3(2):149–162.

Miller, T. P., and C. M. Bunker. 1976. A reconnaissance study of the uranium and thorium contents of plutonic rocks of the southeastern Seward Peninsula, Alaska. Journal of Research of the US Geological Survey 4(3):367–377.

Miller, E. L., A. Grantz, and S. L. Klemperer. 2002. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Miller, E. L., N. Kuznetsov, A. Soboleva, O. Udoratina, M. J. Grove, and G. Gehrels. 2011. Baltica in the Cordillera? Geology 39(8):791–794.

Moffit, F. H. 1905. Fairhaven gold placers, Seward Peninsula, Alaska. Bulletin 246. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b247.

Moffit, F. H. 1906. Gold mining on Seward Peninsula. Pages 132–144 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1905. Bulletin 284. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b284.

Moffit, F. H. 1913. Geology of the Nome and Grand Central quadrangles, Alaska. Bulletin 533. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b533.

Moll-Stalcup, E. J. 1994. Latest Cretaceous and Cenozoic magmatism in mainland Alaska. Pages 589–619 in G. Plafker and H. C. Berg, editors. The geology of Alaska. The Geology of North America, Volume G-1. Decade of North American Geology (DNAG) Project, Geological Society of America, Boulder, Colorado.

Moore, D. G. 1954. Origin and development of sea caves. The American Caver: Bulletin of the National Speleological Society 16:71–76.

Moore, T. E., W. K. Wallace, K. J. Bird, S. M. Karl, C. G. Mull, and J. T. Dillion. 1994. Geology of northern Alaska. Pages 49–140 in G. Plafker and H. C. Berg, editors. The geology of Alaska. The Geology of North America, Volume G-1. Decade of North American Geology (DNAG) Project, Geological Society of America, Boulder, Colorado.

Motyka, R. J., M. A. Moorman, and S. A. Liss. 1983. Geothermal Resources of Alaska. Miscellaneous Publication 8. State of Alaska, Department of Natural Resources, Division of Geological and Geophysical Surveys, Fairbanks, AK. http://dggs.alaska.gov/metadata/MP8.faq.html.

Moxham, R. M., and W. S. West. 1953. Radioactivity investigations in the Serpentine-Kougarok area, Seward Peninsula, Alaska, 1946. Circular 265. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir265.

Muir, J. 1917. The cruise of the Corwin: Journal of the Arctic Expedition of 1881 in Search of De Long and the Jeanette. Houghton Mifflin Company, Boston and New York.

Mukasa, S. B., A. V. Andronikov, and C. M. Hall. 2007. The 40Ar/39Ar chronology and eruption rates of Cenozoic volcanism in the eastern Bering Sea volcanic province, Alaska. Journal of Geophysical Research 112:B06207. doi:10.1029/2006JB004452.

Mull, C. G. 1982. Tectonic evolution and structural style of the Brooks Range, Alaska: an illustrated summary. Pages 1–45 in R. B. Powers, editor. Geologic studies of the Cordilleran thrust belt, Volume I. Rocky Mountain Association of Geologists, Denver Colorado.

Mulligan, J. J. 1959a. Sampling stream gravels for tin, near York, Seward Peninsula, Alaska. Report of Investigations 5520. US Bureau of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/21202.

Mulligan, J. J. 1959b. Tin placer and lode investigations, Ear Mountain area, Seward Peninsula, Alaska. Report of Investigations 5493. US Bureau of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/21201.

Natal'in, B. A., J. M. Amato, J. Toro, and J. E. Wright. 1999. Paleozoic rocks of northern Chukotka Peninsula, Russian Far East: implications for the tectonics of the Arctic region. Tectonics 18(6):977–1003.

NPS (National Park Service). 2009. Bering Land Bridge National Preserve foundation statement. National Park Service, Anchorage, Alaska. http://npshistory.com/agency_history.htm#foundation-documents.

NPS (National Park Service). 2016. State of the park report for Bering Land Bridge National Preserve. State of the Park Reports 40. National Park Service, Washington DC. https://irma.nps.gov/DataStore/Reference/Profile/2240571.

NPS (National Park Service). 2019 [access date]. National Park Service Visitor Use Statistics. Online Information. Bering Land Bridget National Preserve, Alaska. https://irma.nps.gov/Stats/Reports/Park/BELA.

National Snow and Ice Data Center. 2018 [access date]. Sea ice data. Online information. National Snow and Ice Data Center, University of Colorado, Boulder, Colorado. https://nsidc.org/.

Neitlich, P., T. Jones, and J. Lawler. 2017. Synthesis of coastal issues and projects in the western Arctic national parklands. Alaska Park Science 16(1):95–99.

Nordstrom, D. K., L. Hasselbach, S. E. Ingebritsen, D. Skorupa, R. B. McCleskey, and T. McDermott. 2015. An environmental survey of Serpentine Hot Springs: geology, hydrology, geochemistry, and microbiology. Natural Resource Report NPS/BELA/NRR—2015/1019. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2224027.

Oquilluk, W. A., and L. L. Bland. 1981. People of Kauwerak: legends of the northern Eskimo. Alaska Pacific University Press, Anchorage, Alaska.

Page, R. A., N. N. Biswas, J. C. Lahr, and H. Pulpan. 1991. Seismicity of continental Alaska. Pages 47–68 in D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell, editors. Neotectonics of North America, Decade Map Volume 1. Geological Society of America, Boulder Colorado.

Palagushkina, O., S. Wetterich, B. K. Biskaborn, L. Nazarova, L. Schirrmeister, J. Lenz, G. Schwamborn, and G. Grosse. 2017. Diatom records and tephra mineralogy in pingo deposits of Seward Peninsula, Alaska. Palaeogeography, Palaeoclimatology, Palaeoecology 479:1–15.

Palmer, J. A., and R. A. Nielsen. 1962. The origin of granite tors on Dartmoor, Devonshire. Proceedings of the Yorkshire Geological Society 33(3):315–340.

Panda, S. K., V. E. Romanovsky, and S. S. Marchenko. 2016. High-resolution permafrost modeling in the Arctic Network national parks, preserves and monuments. Natural Resource Report NPS/ARCN/NRR—2016/1366. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2237720.

Pasda, K. 2012. Seward Peninsula Alaska: Trail Creek caves 2 and 9 revisited, the skeletal remains. BAR International Series 2374. British Archaeological Reports, Oxford, England.

Patrick, B. E. 1988. Synmetamorphic structural evolution of the Seward Peninsula blueschist terrane, Alaska. Journal of Petrology 30:531–556.

Patrick, B. E., and B. W. Evans. 1989. Metamorphic evolution of the Seward Peninsula blueschist terrane. Journal of Petrology 30(3):531–555.

Péwé, T. L. 1948. Terrain and permafrost of the Galena Air Base. Permafrost Progress Report 7. US Geological Survey, Military Geology Branch, Alaska Terrain and Permafrost Section, Washington, DC.

Péwé, T. L. 1975. Quaternary geology of Alaska. Professional Paper 835. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp835.

Potter, B. A., J. F. Baichtal, A. B. Beaudoin, L. Fehren-Schmitz, C. V. Haynes, V. T. Holliday, C. E. Holmes, J. W. Ives, R. L. Kelly, B. Llamas, R. S. Malhi, D. S. Miller, D. Reich, J. D. Reuther, S. Schiffels, and T. A. Surovell. 2018. Current evidence allows multiple models for the peopling of the Americas. Science Advances Review 4:1–8.

PRISM Climate Group. 2009. Annual Mean Average Temperature for Alaska 1971-2000. Oregon State University, Corvallis, Oregon. http://prism.oregonstate.edu.

Quackenbush, L. S. 1909. Notes on Alaskan mammoth expeditions of 1907 and 1908. Bulletin of the American Museum of Natural History 26(9):87–130.

Rasic, J. T. 2012. Mammoth site reconnaissance in BELA. National Park Service field notes. Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve, Fairbanks, Alaska.

Ray, J. D. 1975. The Eskimos of Bering Strait, 1650–1898. University of Washington Press, Seattle, Washington.

Redfield, T. F., D. W. Scholl, P. G. Fitzgerald, and M. E. Beck. 2007. Escape tectonics and the extrusion of Alaska: Past, present, and future. Geology 35(11):1039–1042.

Reed, I. M. 1929a. Report on mining conditions on Seward Peninsula for 1929. Miscellaneous Report 192-2. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/959.

Reed, I. M. 1929b. Report on the status of the coal and lode prospects of Seward Peninsula in the summer of 1929. Miscellaneous Report 192-3. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/960.

Reed, I. M. 1933. Report on the coal and gold placer deposit of the lower Kugruk River valley, Seward Peninsula. Miscellaneous Report 44-1. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/767.

Richardson, J. 1854. The zoology of the voyage of *H. M. S. Herald*, under the command of Captain Henry Kellet: during the years 1845–1851. Lovell Reeve, London.

Roehm, J. C. 1940. Some operations and geology—Seward Peninsula. Miscellaneous Report 192-5. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/962.

Roehm, J. C. 1942. Preliminary report of certain potential placer areas on Seward Peninsula—economic aspects and problems. Miscellaneous Report 192-7. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/962.

Roeske, S. M., C. Dusel-Bacon, J. N. Aleinikoff, L. W. Snee, and M. A. Lanphere. 1995. Metamorphic and structural history of continental crust at a Mesozoic collisional margin, the Ruby terrane, central Alaska. Journal of Metamorphic Geology 13:25–40.

Rubin, C. M., E. L. Miller, and J. Toro. 1995. Deformation of the northern circum-Pacific margin: variations in tectonic style and plate-tectonic implications. Geology 23(10):897–900.

Ryherd, T. J., C. Carter, and M. Churkin Jr. 1995. Middle through Upper Ordovician graptolite biostratigraphy of the Deceit Formation, northern Seward Peninsula, Alaska. Geological Society of America Abstracts with Programs 27(5):75.

Ryherd, T. J., and C. E. Paris. 1987. Ordovician through Silurian carbonate base-of-slope apron sequence, northern Seward Peninsula, Alaska. Abstract. Pages 347–348 in I. L. Tailleur and P. Weimer, editors. Alaskan North Slope Geology. Book 50, Volume I. Society for Sedimentary Geology, Pacific Section, Bakersfield, California.

Sainsbury, C. L. 1969. Geology and ore deposits of the central York Mountains, western Seward Peninsula, Alaska. Bulletin 1287. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b1287.

Sainsbury, C. L., R. G. Coleman, and R. Kachadoorian. 1970. Blueschist and related greenschist facies rocks of the Seward Peninsula, Alaska. Pages B33–B42 (Chapter B) in Geological Survey Research 1970. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp700B.

Sandvik, P. O. 1956. Report on diamond drilling for radioactive material near Candle, northeast Seward Peninsula. Mineral Investigation 44-2. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/620.

Schaaf, J. 1988. Bering Land Bridge National Preserve, an archaeological survey. Volume I. National Park Service, Anchorage, Alaska.

Schaaf, J., and T. Smith. 1996. Ublasaun, first light: Inupiaq hunters and herders in the early twentieth century, northern Seward Peninsula, Alaska. National Park Service, Anchorage, Alaska. https://irma.nps.gov/DataStore/Reference/Profile/2227471.

Schrader, F. C., and A. H. Brooks. 1900. Preliminary report on the Cape Nome gold region, Alaska. US Geological Survey, Washington, DC. http://www.dggs.alaska.gov/pubs/id/21041.

Schupp, C. A., R. L. Beavers, and M. A. Caffrey. 2015. Coastal adaptation strategies: case studies. NPS 999/129700. National Park Service, Fort Collins, Colorado.

Seemann, B. C. 1852–1857. The botany of the voyage of *H. M. S. Herald* under the command of Captain Henry Kellett, R. N., C. B., during the years 1845–51. Lovell Reeve, London.

Seemann, B. C. 1853. Narrative of the voyage of *H. M. S. Herald* during the years 1845–51, under the control of Captain Henry Kellett, R. N, C. B.: being a circumnavigation of the globe, and three cruizes to the Arctic regions in search of Sir John Franklin. Reeve and Co., London.

Serreze, M. C., and J. Stroeve. 2015. Arctic sea ice trends, variability, and implications for seasonal ice forecasting. Philosophical Transactions of the Royal Society 373(2045), 20140159. doi:10.1098/rsta.2014.0159.

Shallit, A. B. 1938a. Placer operations in second division – 1938. Miscellaneous Report 192-4. Alaska Territorial Department of Mines, Juneau, Alaska. http://dggs.alaska.gov/pubs/id/961.

Shallit, A. B. 1938b. Tin deposits on Seward Peninsula. Miscellaneous Report 43-4. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/764.

Shallit, A. B. 1941a. The placer deposits in the upper Kougarok, Seward Peninsula, Alaska. Miscellaneous Report 44-2. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/768.

Shallit, A. B. 1941b. Report on Ward Copper Company property, Seward Peninsula, Alaska. Prospect Evaluation 43-1. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/1919.

Shur, Y., M. Kanevskiy, T. Jorgenson, M. Dillon, E. Stephani, M. Bray, and D. Fortier. 2012. Permafrost degradation and thaw settlement under lakes in yedoma environment. Pages 383–388 in Tenth International Conference on Permafrost, 25–29 June 2012, Salekhard, Russia.

Shur, Y., M. Z. Kanevskiy, M. T. Jorgenson, D. Fortier, M. Dillon, E. Stephani, and M. Bray. 2009. Yedoma and thermokarst in the northern part of Seward Peninsula, Alaska. Abstract C41-0443. American Geophysical Union (AGU), Fall Meeting, 14–18 December 2009, San Francisco, California.

Silberling, N. J., D. L. Jones, J. W. H. Monger, and P. J. Coney. 1992. Lithotectonic terrane map of the North America Cordillera (scale 1:5,000,000). Miscellaneous Investigations Series Map I-2176. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publicationi2176.

Simmonds, I., and K. Keay. 2009. Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008. Geophysical Research Letters 36, L19715. doi: 10.1029/2009GL039810

Smith, J. G., J. Dehn, A. L. Mims, R. P. Hoblitt, R. G. LaHusen, J. B. Lowenstern, S. C. Moran, L. McClelland, K. A. McGee, M. Nathenson, P. G. Okubo, J. S. Pallister, M. P. Poland, J. A. Power, D. J. Schneider, and T. W. Sisson. 2009. Volcano monitoring. Pages 273–305 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Smith, P. S. 1907a. Gold fields of the Solomon and Niukluk River basins. Pages 146–156 in A. H. Brooks, editor Report on progress of investigations of mineral resources of Alaska in 1906. Bulletin 314. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b314.

Smith, P. S. 1907b. Geology and mineral resources of Iron Creek. Pages 157–163 in A. H. Brooks, editor. Report on progress of investigations of mineral resources of Alaska in 1906. Bulletin 314. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b314.

Smith, P. S. 1908. Investigations of the mineral deposits of Seward Peninsula, Alaska. Pages 206–250 in A. H. Brooks, editor. Mineral Resources of Alaska, report on progress of investigations in 1907. Bulletin 345. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b345.

Smith, P. S. 1910. Geology and mineral resources of the Solomon and Casadepaga quadrangles, Seward Peninsula, Alaska. Bulletin 433. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b433.

Smith, P. S. 1912. Notes on mining in Seward Peninsula. Pages 334–339 in A. H Brooks, editor. Mineral resources of Alaska, report on progress of investigations in 1911. Bulletin 520. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b520.

Strauss, J. V., C. W. Hoiland, W. P. Ward, B. G. Johnson, L. L. Nelson, and W. C. McClelland. 2017. Orogen transplant: Taconic-Caledonian arc magmatism in the central Brooks Range of Alaska. Geological Society of America Bulletin 129(5/6):649–676.

Strauss, J. V., F. A. Macdonald, J. F. Taylor, J. E. Repetski, and W. C. McClelland. 2013. Laurentian origin for the North Slope of Alaska: implications for the tectonic evolution of the Arctic. Lithosphere 5:477–482.

Swanson, D. K. 2010. Mapping of erosion features related to thaw of permafrost in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, and Kobuk Valley National Park. Natural Resource Data Series NPS/ARCN/NRDS—2010/122. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2166895.

Swanson, D. K. 2013. Surface water area change in the Arctic Network of national parks, Alaska, 1985–2011: analysis of landsat data. Natural Resource Data Series NPA/ARCN/NRDS—2013/445. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2193078.

Swanson, D. K. 2014. Mapping of erosion features related to thaw of permafrost in the NPS Arctic Inventory and Monitoring Network, Alaska. Natural Resource Technical Report NPS/ARCN/NRTR—2014/912. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2216465.

Swanson, D. K. 2016a. Soil temperatures in Alaska's Arctic national parks, 2011–2015, and implications for permafrost stability. Natural Resource Report NPS/ARCN/NRR—2016/1109. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2226036.

Swanson, D. K. 2016b. Stability of ice-wedge polygons in Kobuk Valley National Park and the Noatak National Preserve, 1951–2009. Natural Resource Report NPS/ARCN/NRR—2016/1248. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2230516.

Swanson, D. K. 2017a. Permafrost monitoring protocol for the Arctic Network: narrative. Natural Resource Report NPS/ARCN/NRR—2017/1396. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2238783.

Swanson, D. K. 2017b. Permafrost monitoring protocol for the Arctic Network: standard operating procedures. Natural Resource Report NPS/ARCN/NRR—2017/1397. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2238788.

Swanson, S. E., D. L. Turner, and R. B. Forbes. 1981. Petrology and geochronology of Tertiary and Quaternary basalts from the Seward Peninsula, western Alaska. Geological Society of America Abstracts with Programs 13:563.

Thomson, J., Y. Fan, S. Stammerjohn, J. Stopa, W. E. Rogers, F. Girard-Ardhuin, F. Ardhuin, H. Shen, W. Perrie, H. Shen, S. Ackley, A. Babanin, Q. Liu, P. Guest, T. Maksym, P. Wadhams, C. Fairall, O. Persson, M. Doble, H. Graber, B. Lund, V. Squire, J. Gemmrich, S. Lehner, B. Holt, M. Meylan, J. Brozena, J. R. Bidlot. 2016. Emerging trends in the sea state of the Beaufort and Chukchi seas. Ocean Modelling 105:1–12.

Thornberry-Ehrlich, T. 2008. Geologic resource evaluation scoping summary arctic network. Geologic Resources Inventory Scoping Report, Colorado State University, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Thurston, S. P. 1985. Structure, petrology, and metamorphic history of the Nome Group blueschist terrane, Salmon Lake area, Seward Peninsula, Alaska. Geological Society of America Bulletin 96:600–617.

Till, A. B. 2016. A synthesis of Jurassic and Early Cretaceous crustal evolution along the southern margin of the Arctic Alaska-Chukotka microplate and implications for defining tectonic boundaries active during opening of Arctic Ocean basins. Lithosphere 8(3):219–237.

Till, A. B., and Dumoulin, J. A. 1994. Geology of Seward Peninsula and Saint Lawrence Island. Pages 141–152 in G. Plafker and H. C. Berg, editors. The geology of Alaska. The Geology of North America, Volume G-1. Decade of North American Geology (DNAG) Project, Geological Society of America, Boulder, Colorado.

Till, A. B., J. A. Dumoulin, B. M. Gamble, D. S. Kaufman, and P. I. Carroll. 1986. Preliminary geologic map and fossil data, Solomon, Bendeleben, and southern Kotzebue quadrangles, Seward Peninsula, Alaska (scale 1:250,000). Open-File Report OFR-86-276. US Geological Survey, Anchorage, Alaska. https://pubs.er.usgs.gov/publication/ofr86276.

Till, A. B., J. A. Dumoulin, M. B. Werdon, and H. A. Bleick. 2011. Bedrock geologic map of the Seward Peninsula, Alaska, and accompanying conodont data (scale 1:500,000). Scientific Investigations Map SIM-3131. US Geological Survey, Anchorage, Alaska. https://pubs.usgs.gov/sim/3131/.

Till, A. B., J. A. Dumoulin, R. A. Ayuso, J. N. Aleinikoff, J. M. Amato, J. F. Slack, and W. C. P. Shanks III. 2014. Reconstruction of an early Paleozoic continental margin based on the natural of protoliths in the Nome Complex, Seward Peninsula, Alaska. Pages 1–28 in J. A. Dumoulin and A. B. Till, editors. Reconstruction of a late Proterozoic to Devonian continental margin sequence, northern Alaska, its paleogeographic significance, and contained base-metal sulfide deposits. Special Paper 506. Geological Society of America, Boulder, Colorado.

Toomey, R. S. III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Tremayne, A. H. 2017. Investigating the Arctic Small Tool tradition at Cape Espenberg, Bering Land Bridge National Preserve, Alaska. Cultural Resources Report NPS/BELA/CRR—2017/004. National Park Service, Anchorage, Alaska.

Tremayne, A. H. 2018. A survey of human migration in Alaska's national parks through time. Alaska Park Science 17(1):5–15.

Troutman, S. M., and R. G. Stanley. 2003. Maps showing sedimentary basins, surface thermal maturity, and indications of petroleum in the central Alaska province. Miscellaneous Field Studies Map MF–2428. US Geological Survey, Denver, Colorado. https://pubs.er.usgs.gov/publication/mf2428.

US Census Bureau. 2017. American community survey 5-year estimates. Online Information. https://censusreporter.org/profiles/16000US0254920-nome-ak/.

USGS (United States Geological Survey). 2018 [access date]. Quaternary Faults Database. Online information. USGS Geologic Hazards Science Center, Golden, Colorado. https://earthquake.usgs.gov/hazards/qfaults/.

Vigne, L., and E. Martin. 2014. China faces a conservation challenge: the expanding elephant and mammoth ivory trade in Beijing and Shanghai. Save the Elephants, Kairobi, Kenya; The Aspinall Foundation, Kent, United Kingdom.

Vihma, T. 2014. Effects of Arctic sea ice decline on weather and climate: a review. Surveys in Geophysics 35:1175–1214.

Vinson, D. M. 1988. Preliminary report on faunal identifications from Trail Creek caves. Pages 410–438 in J. Schaaf, editor. Bering Land Bridge National Preserve, an archaeological survey. Volume I. National Park Service, Anchorage, Alaska.

Vinson, D. M. 1993. Taphonomic analysis of faunal remains from Trail Creek caves, Seward Peninsula, Alaska. Thesis. University of Alaska Fairbanks, Fairbanks, Alaska.

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori. 1999. Relationships between peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity in California. Earthquake Spectra 15(3):557–564.

Walker, G. P. 1991. Structure, and origin by injection of lava under surface crust, of tumuli, “lava rises,”, “lava-rise pits,” and “lava-inflation clefts” in Hawaii. Bulletin of Volcanology 53(7):546–558.

Wang, M., and J. E. Overland. 2012. A sea ice free summer Arctic within 30 years: an update from CMIP5 models. Geophysical Research Letters 39, L18501. doi: 10.1029/2012GL052868.

Waring, G. A. 1917. Mineral springs of Alaska. Water-Supply Paper 418. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/wsp418.

Wesson, R. L., O. S. Boyd, C. S. Mueller, C. G. Bufe, A. D. Frankel, and M. D. Petersen. 2007. Revision of time-independent probabilistic seismic hazard maps for Alaska. Open-File Report OFR-2007-1043. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2007/1043/.

West, W. S. 1953. Headwaters of the Peace River. Pages 28–31 in H. R. Gault, P. L. Killeen, and W. S. West. Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945–47 and 1951. Circular 250. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir250.

West, W. S., and J. J. Matzko. 1953. Buckland-Kiwalik district, 1947. Pages 21–27 in H. R. Gault, P. L. Killeen, and W. S. West. Reconnaissance for radioactive deposits in the northeastern part of the Seward Peninsula, Alaska, 1945–47 and 1951. Circular 250. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir250.

West, W.S., and M. G. White. 1952. The occurrence of zeunerite at Brooks Mountains, Seward Peninsula, Alaska. Circular 214. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir214.

Wetterich, S., G. Grosse, L. Schirrmeister, A. A. Andreev, A. A. Bobrov, F. Kienast, N. H. Bigelow, and M. E. Edwards. 2012. Late Quaternary environmental and landscape dynamics revealed by a pingo sequence on the northern Seward Peninsula, Alaska. Quaternary Science Reviews 39:26–44.

White, J. D. L., and P.-S. Ross. 2011. Maar-diatreme volcanoes: a review. Journal of Volcanology and Geothermal Research 201:1–29.

White, M. G., and W. S. West. 1952. Seward Peninsula. Pages 1–6 in M. G. White, W. S. West, G. E. Tolbert, A. E. Nelson, and J. R. Houston, editors. Preliminary summary of reconnaissance for uranium in Alaska, 1951. Circular 196. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir196.

White, M. G., W. S. West, and J. J. Matzko. 1953. Reconnaissance for radioactive deposits in the vicinity of Teller and Cape Nome, Seward Peninsula, Alaska, 1946–47. Circular 244. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/cir244.

Whitney, D. L., C. Teyssier, O. Vanderhaeghe. 2004. Gneiss domes and crustal flow. Special Paper 380. Geological Society of America, Boulder, Colorado.

Wieczorek, G. F., and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 in R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Williams, J. A. 1952. Field trip made by Robert H. Saunders and James A. Williams through the Fairbanks, Circle, Cape Nome, and Valdez precincts, July 21 to September 2, 1952. Itinerary Report 195-52. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/594.

Williams, J. A. 1953. Field trip by J.A. Williams and R.H. Saunders to Seward Peninsula, 26 June to 14 July 1953. Itinerary Report 192-1. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/540.

Williams, J. A., and R. H. Saunders. 1954. Magnetic exploration of the Cape Mountain placer tin deposits. Prospect Evaluation 43-3. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/1921.

Williss, G. F. 1986. "It is a hard country, though": historic resource study—Bering Land Bridge National Preserve. US Department of Interior, National Park Service, Anchorage, Alaska. https://irma.nps.gov/DataStore/Reference/Profile/2188868.

Wilson, F. H., C. P. Hults, C. G. Mull, and S. M. Karl. 2015. Geologic map of Alaska (scale 1:1,584,000). Scientific Investigations Map SIM-3340. US Geological Survey, Anchorage, Alaska. https://pubs.er.usgs.gov/publication/sim3340.

Wimmler, N. L. 1924. Placer mining in Alaska in 1924. Miscellaneous Report 195-7. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/996.

Wimmler, N. L. 1926. Placer mining in Alaska in 1926. Miscellaneous Report 195-11. Alaska Territorial Department of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/1000.

Winer, G. S., T. C. Feeley, and M. A. Cosca. 2004. Basaltic volcanism in the Bering Sea: geochronology and volcanic evolution of St. Paul Island, Pribilof Islands, Alaska. Journal of Volcanology and Geothermal Research 134:277–301.

Winter, J. 2001. An introduction to igneous and metamorphic petrology. Prentice Hall, New Jersey.

Wirth, K. R., J. Grandy, K. Kelley, and S. Sadofsky. 2002. Evolution of crust and mantle beneath the Bering Sea region: evidence from xenoliths and late Cenozoic basalts. Pages 167–194 in E. M. Miller, A. Grantz, and S. L. Klemperer, editors. Tectonic evolution of the Bering Shelf–Chukchi Sea–Arctic margin and adjacent landmasses. Special Paper 360. Geological Society of America, Boulder, Colorado.

Wood, C. A., and J. Kienle. 1990. Volcanoes of North America, United States and Canada. Cambridge University Press, New York.

Wright, W. S. 1947. Ward copper deposit, Seward Peninsula, Alaska. Report of Investigations 4110. US Bureau of Mines, Juneau, Alaska. http://www.dggs.alaska.gov/pubs/id/21520.

Young, R., and L. Norby. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Additional References

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

Geology of National Park Service Areas

- NPS Alaska Regional Office (Anchorage, Alaska) Active Geology: https://www.nps.gov/subjects/aknatureandscience/activegeology.htm
- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- 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 Resource Management Guidance and Documents

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

Climate Change Resources

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

Geological Surveys and Societies

- Alaska Division of Geological & Geophysical Surveys: http://dggs.alaska.gov/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- US Geological Survey Reference Tools
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: History of Geologic Exploration

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

Pre-European contact – Alaskan Natives occupied and explored the Seward Peninsula for thousands of years before European contact and possessed intimate knowledge of the geography and natural resources of the area. The inhabitants were well aware of the presence of mammoth fossils, as Captain Frederick William Beechey traded for a large scoop carved from fossil ivory during his visit in 1826 (Beechey 1831).

21 August 1732 – A Russian expedition led by Mikhail Gvozdez and Ivan Fedorov sailed within view of the Seward Peninsula near the village of Wales (Williss 1986).

1767 – A secret Russian discovery expedition led by Lieutenant Synd landed to the south of Cape Prince of Wales (Dall 1870).

1778 – Captain Cook made the first survey of the coastline of the Seward Peninsula (Clark 1910). On August 5, Cook landed on Sledge Island. He described the surface of the island as being "composed chiefly of large loose stones." On 9 August 1778, Cook saw Cape Prince of Wales and noted that he thought he saw people and huts on shore. On 10 September 1778, Cook, accompanied by Mr. King, landed at Bald Head in Norton Bay in search of wood and fresh water. They described the area where they landed as "where the coast projects out into a bluff head composed of perpendicular strata of a rock of a dark blue colour, mixed with quartz and glimmer" (Cook 1821).

1791 – Billings and Sarycheff, in search of a fabled lost Russian military garrison, sailed from Petropavlovsk (Russia) to the American coast near Cape Prince of Wales (Dall 1870; Williss 1986).

1816 – In late July, an expedition commanded by Otto von Kotzebue approached Cape Prince of Wales and from their ship observed Alaska Natives and several dwellings on the beach. Continuing north, Kotzebue and naturalist Adelbert von Chamisso visited Shishmaref and briefly explored the Cape Espenberg area. In August, they continued to Kotzebue Sound on their quest to discover a passage across the Arctic Ocean. During their exploration of the area, they noted extensive permafrost half a foot under the surface of the ground. Later, while exploring the eastern portion of Kotzebue Sound, the expedition physician and assistant naturalist Dr. Johann Friedrich Eschscholtz discovered what he described as a body of massive ground ice 30 m (100 ft) thick exposed by an eroding cliff along the water. This prompted a more thorough examination of the cliff by the party, which resulted in the discovery of a significant quantity of mammoth teeth, tusks, and bones exposed by melting ice and collapsing of the cliff; the party used some of the fossil ivory to fuel their watch fire. They described the ice as being overlaid by a bluish clay (or loam). Dr. Eschscholtz described Chamisso Island as being composed of flinty slate. Two rock samples collected by Dr. Eschscholtz in Kotzebue Sound were later examined and identified by German mineralogist Moritz von Engelhardt as silvery-white mica-slate and porphyritic syenite. Today, many geographic feature of the area in and around Bering Land Bridge National Preserve bear the names given by the expedition, including the high points of Asses Ears and Devils Mountain (Kotzebue 1821).

14 July 1820 – Gleb S. Shishmarev anchored near Chamisso Island and set out to explore the ice mountain described by Kotzebue in 1816, but encountered hostility from the Native people (Williss 1986).

1822 – A Russian-American company expedition led by Kramchenko, Etolin, and Wasilieff examined the coasts of Norton Sound, describing Golofnina Bay and Golovin Sound (Dall 1870).

1826 – An expedition led by Frederick William Beechey entered Kotzebue Sound. In late July, Beechey and his crew explored the area where Kotzebue found mammoth tusks, and named the area Elephant Point. They searched the area and could not find the massive ice formation described by Kotzebue. Beechey surmised that the cliffs must have significantly melted and changed in the intervening decade; furthermore, Kotzebue may have possibly been mistaken, overestimating the extent and scale of the ice. Beechey described the geology of the Choris Peninsula as "composed of a green-coloured mica slate, in which the mica predominated, and contained garnets, veins of feldspar, enclosing crystals of schorl, and had its fissures filled with quartz" (Beechey 1831, p. 404). In September, the expedition's surgeon Mr. Collie found many fossils along the cliffs and shore at Elephant Point, including tusks, teeth, and bone of elephant (mammoth), deer,

horse, and musk ox. The largest tusk collected weighed 73 kg (160 lbs). Mr. Collie named the Buckland River for Dr. William Buckland, a professor of geology and mineralogy at the University of Oxford who described the fossils in Beechey's report. On 8 September 1826, Beechey explored Spafarief Bay and climbed the 200 m- (640 ft-) tall hill on the northeast side of Kiwalik Lagoon to further survey the area. Beechey described the geology between Spafarief Bay and Cape Esenberg in detail, identifying volcanic rocks (including blocks of porous vesicular lava and lava containing olivine), slaty limestone, talcaceous slate, limestone, and slate. He also noted the dip of the limestone beds at several locations. The following September (1827), Beechey and his crew explored Port Clarence and described the area as "cliffs composed of fine and talcy mica slate, intersected by veins of calcareous spar of a pearly lustre, mixed with grey quartz" (Beechey 1831, p. 544).

1830 – Etolin, Vasilief, and others explored more thoroughly the coasts of Norton Sound and Golovin Sound (Dall 1870).

1848 – Following the loss of an Arctic expedition led by Sir John Franklin in 1845, several groups began to search for the lost Franklin expedition. On 14 September 1848, the *Herald*, captained by Henry Kellett, arrived in Kotzebue Sound and anchored off Chasmisso Island. The *Plover*, which was commanded by Thomas E. L. Moore, was delayed and did not make it north in time to join the *Herald* in the search in 1848. The *Herald* departed the Kotzebue Sound on 29 September 1848 (Seemann 1852–1857, 1853).

1849 – In July, the *Herald* (Captain Henry Kellett) returned to Kotzebue Sound and rendezvoused near Chamisso Island with the *Plover* (Commander Thomas E.L. Moore) and the yacht *Nancy Dawson* (owned by Robert Shedden, Esq). The three ships remained in Kotzebue Sound until 18 July 1849 and then commenced their search effort along the Arctic coast for the lost Franklin expedition. On 2 September 1849, all of the ships met back at Kotzebue Sound. They spent the remainder of season exploring Eschscholtz Bay and the Buckland River. Several days were spent at Elephant Point, where Dr. John Goodridge, J. Hudsishon, Berthold Carl Seemann (naturalist on *Herald*), and T. Woodward researched the nature of the ice-cliffs and collected many fossils. In September, Kellett and Moore ascended the Buckland River. The heavier boats were stopped by rapids about 50 km (30 mi) upstream, so Kellett returned to the ship and Moore continued on for about another 50 km (30 mi). In the upper portion of the Buckland River, Moore noted fine basaltic columns. At the end of the season, the *Herald* headed for Mazatlán, Mexico, and the Plover and crew wintered in Kotzebue Sound (Seemann 1852–1857, 1853).

1850 – On 15 July 1850, the *Herald* returned to Chamisso Island to rejoin the *Plover* in the search for Franklin. After a fruitless summer of searching, the *Herald* accompanied the *Plover* to Grantley Harbor where the *Plover* wintered. The *Herald* departed on 23 September 1850, continuing south and arriving at Honolulu on 16 October 1850 (Seemann 1852–1857). Berthold Seemann, naturalist of the *Herald*, took every opportunity to explore Norton Sound, Kotzebue Sound, and the Buckland River in 1848, 1849, and 1850. In 1848, he collected eight tusks, one (with broken tip) measuring 3.5 m (11.5 ft) long and 0.5 m (1.75 ft) in circumference (around the base) and weighing 110 kg (243 lbs). They also found mammoth molars, thigh and rib bone, and other fragments and bones from many other animals (Figures 57, 58). Seemann claimed to have found fossils from the following species: mammoth (*Elephas primigenius*), fossil horse (*Equus fossilis*), moose deer (*Cervus Alces*), reindeer (*Cervus Tarandus*), fossil musk ox (*Ovibos moschatus*, *Ovibos maximus*), fossil bison (*Bison priscus* [though the species *priscus* is uncertain]), heavy-horned fossil bison (*Bison crassicornis*), and bighorn sheep (*Ovis montana*) (Seemann 1853). Sir John Richardson described the fossils collected by Seemann (Richardson 1854).

9 February 1854 to 27 March 1854 – The search for the lost Franklin expedition continued. William R. Hobson, Henry Toms, and William Lee of the sloop *Rattlesnake* under Captain Collinson traveled overland from Port Clarence to Chamisso Island on 5 March 1854 (and back, 560 miles roundtrip) to leave a notice that they were wintering in Port Clarence and the *Plover* crew was wintering at Point Barrow (Williss 1986).

1866 – The Western Union Telegraph Exploring Expedition of 1865–1867 attempted to route telegraph lines through British Columbia, Alaska, and then across the Bering Strait to Russia. Although this Russian-American telegraph expedition ultimately failed, a party in the charge of Baron Otto von Bendeleben explored parts of the Seward Peninsula during the exploration. Bendeleben ascended the Niukluk River, crossed the divide to the Kruzgamepa River (or Pilgrim River) and continued to Port Clarence. On the Niukluk River, Bendeleben discovered placer gold deposits (Clark 1910). Local Alaska Native inhabitants showed Captain Daniel B. Libby rich gold and silver ore, but they would not reveal the source of the ore. Libby discovered gold on Ophir Creek; he made notes, a rough map, and plans to return sometime in the future (Harrison 1905; Carlson 1946).

Figure 57. Painting of the ice cliffs of Eschscholtz Bay.
Plate I from the Botany of the Voyage of H.M.S. Herald (Seemann 1852–1857).

1880 – In census report of 1880, Petrof mentioned occurrence of silver ore in Golofnin Bay (Brooks et al. 1901).

1881 – John Muir, during his voyage aboard the US Revenue steamer *Thomas Corwin*, visited Golofnin Bay. On 10 July 1881, Muir noted that a party of prospectors from San Francisco was up river searching for "a mountain of solid silver" (Muir 1917, p. 114). That party of 10 prospectors, which as associated with the Alaska Mining Company, was led by John C. Green. The prospectors chartered the schooner *W.F. March* and sailed from San Francisco, California, on 5 May 1881. They were lured to the area by specimens of silver ore exhibited in Oakland that assayed $150 per ton said to be from a mine near Golofnin Bay. Muir surmised, "They will not find the mountain to be solid silver, but some far commoner mineral" (Muir 1917, p. 114). While hiking in the area, Muir found rocks composed of "mica, slate, and a good deal of quartz" and thought it seemed favorable for finding gold. The group of prospectors found promising galena and said they found rich silver deposits, but the mine was about 50 km (30 mi) from the coast. On 11 July 1881, Muir noted that Sledge Island was made of granite and seemed to have been scoured by glacier ice. Muir continued exploring the Seward Peninsula: on 13 July 1881, he visited Cape Espenberg and on 14 July 1881, he explored the head of Kotzebue Sound and about 10 km (8 mi) up Kiwalik River. Muir noted that he found a portion of fossil ivory tusk and a few bones and that the gravel consisted of quartz, mica, slate, and lava. Muir also noted many lava cones and ridges on the sides of the estuary. Near the end of the expedition, Muir spent a week exploring the area near Chamisso Island and described the buried ice formations, "fossil elephant tusks," and "bones of elephants, buffaloes, musk oxen, etc." at Elephant Point (Muir 1917, p. 225). Muir also describes the glacier dynamics and the presence and formation of permafrost–related patterned ground in the Kuuk River area (Muir 1917).

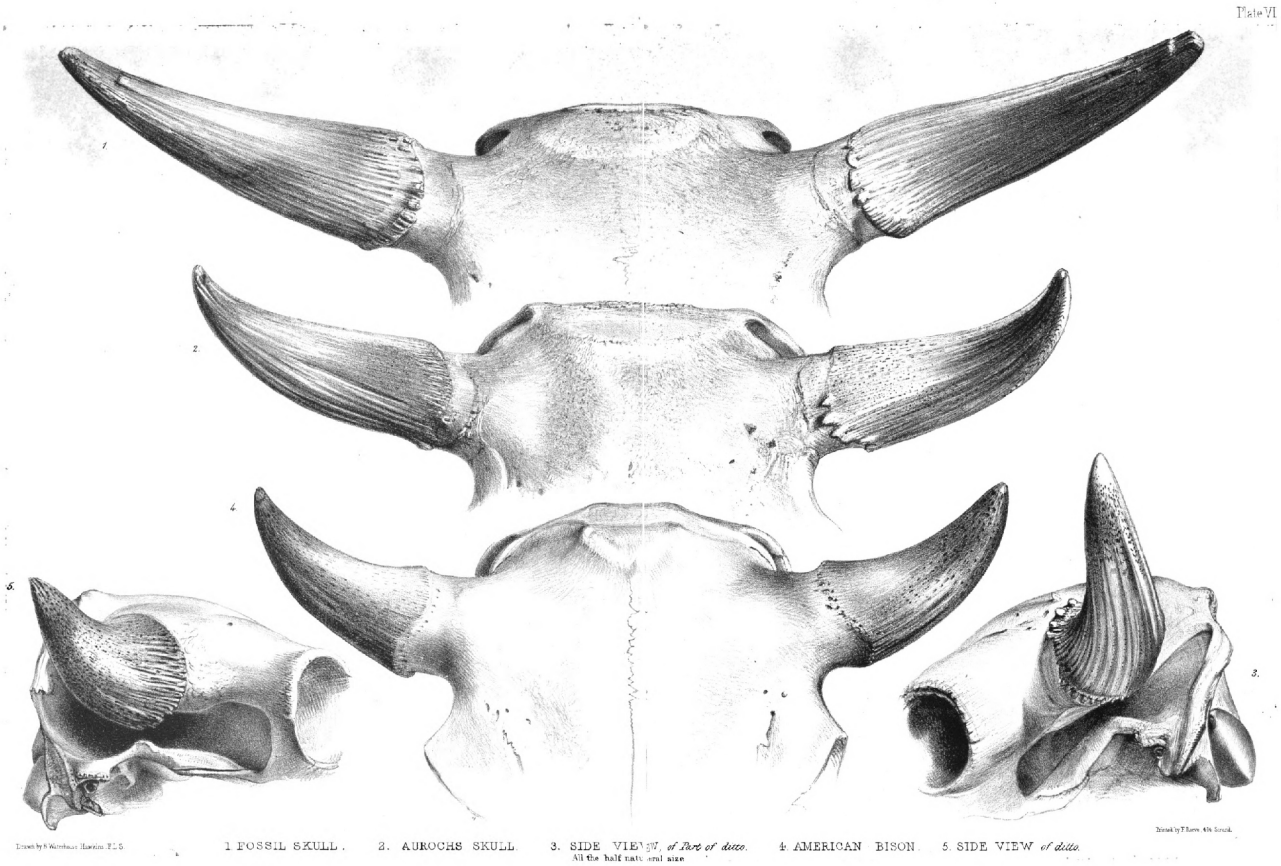


Figure 58. Fossil illustration by Richardson (1854).
Plate VII from Richardson (1854) compares a fossil steppe bison skull from Elephant Point (top) with an aurochs skull (middle) and an American bison skull (bottom). Original plate description: "Comparative views of the horn-cores and forehead of a fossil skull from Eschscholtz Bay, with those of a Lithuanian bull Aurochs and Mustush-bull, all reduced to half their linear dimensions. Fig. 1. Fossil skull, No. 24,589 (Bison priscus?), British Museum: half nat. size. Fig. 2. Adult bull Aurochs (figured in Plate VI. fig. 1): half nat. size (Pages 33–43, passim, and 64.) Fig. 3. Lateral aspect of the same Aurochs skull: half nat. size. Fig. 4. Skull of the adult Mustush (Bison americanus), also figured in Plate VI. Fig. 3: half nat. size. (Page 35, and 33-43, passim.) Fig. 5. Lateral aspect of the same Mustush skull: half nat. size."

1884-1886 – In 1884, Omalik mine (northern edge of Fish River basin) produced 30–40 sacks of high-quality silver ore, which were sent to San Francisco on the steamer *Corwin*. In 1885, 100,000 kg (125 tons) of silver ore shipped out from Omalik mine, and in 1886, 30,000 kg (30 tons) of silver ore were shipped. The ore assayed 70%–85% lead and 100–250 ounces of silver per ton (Brooks et al. 1901).

1895 – Alaska Natives showed a Swedish missionary Nels Olsen Hultberg, who was stationed at Golovin Bay, rich samples of gold said to be from the Nome River. In spring of 1895, a prospector from California named Johansen found gold on the Neukluk River, Casadepoga River, Melsing Creek, and Ophir Creek. In December, a man named Howard prospected the Fish River area and found gold but did not develop any of the prospects (Harrison 1905).

1897 – D. B. Libby, who was the discoverer of gold during the Russian-American Telegraph Expedition in 1866, decided to return to the Niukluk River area in search of gold. Libby, A. P. Mordaunt, L. F. Melsing, and H. L. Blake sailed aboard the *North Fork* from San Francisco with prospecting gear and four years' worth of supplies, reaching Golovin Bay 18 September 1897. They traveled up the Fish River for 50 km (30 mi), then 20 km (10 mi) up the Niukluk River, and set up camp at Council City. During the fall, Blake found gold on Ophir Creek, Melsing found gold on Melsing Creek, and Mordaunt and Libby made other discoveries. In December, an Alaska Native named Too rig Luck showed Blake some ore he found at Cape Nome. On 28 December 1897, Luck, Blake, and Hultberg set out

for Cape Nome with six of the best sled deer from the government reindeer herd. They found rich gold in the area and planned to return in the spring to stake claims. On 24 April 1898, they staked claims on Ophir Creek, Melsing Creek, and other claims in the area. These were the first claims staked on the Seward Peninsula (Harrison 1905; Carlson 1946). On 5 August 1898, Blake and Hultberg, along with John Brynteson, John L. Hagelin, Christ Kimber, and Henry L. Porter, returned to the Cape Nome area and prospected on Moonlight, Anvil, and Rock Creeks and the Snake River. Hultberg found rich concentrations of placer gold on Anvil Creek, including a pan with 169 colors. On 25 August 1898, Hultberg persuaded Brynteson, Jafet Leneberg, and Eric Lindblom to go back and continue prospecting. Between 22 September and 28 September 1898, the group staked 11 claims on Anvil Creek and other claims on Nakkila Gulch, Rock Creek, Snow Creek, Dry Creek, and Quartz Gulch. On 15 October 1898, the men returned along with P. H. Anderson, Gabriel W. Price, and Dr. A. N. Kittilsen and set up camp at the mouth of the Snake River. They immediately organized the Cape Nome Mining District, which would prove to be the richest mining district in northern Alaska (Harrison 1905; Carlson 1946). By the end of December 1898, 300 claims were recorded and more were located in the Cape Nome Mining District. By April 1899, 1,200 additional claims were staked, and by July 1899, about 2,000 had been recorded. By December 1899, about 4,500 claims were recorded, and by December 1900, 30 mining districts had been established on the Seward Peninsula (Carlson 1946).

1899 – The US Geological Survey (USGS) began investigations on the Seward Peninsula. Frank C. Schrader and Alfred H. Brooks spent several weeks in October 1899 collecting topographic and geologic data in the newly discovered Nome gold-mining region. After completing their regular fieldwork in the Yukon and awaiting a steamer to Seattle, Schrader and Brooks conducted fieldwork in the Nome area. Topographic work was done under the direction of T .G. Gerdine by D. C. Witherspoon (Schrader and Brooks 1900).

1900 – As a result of public interest sparked by the discovery of gold in the area, the USGS began a concerted topographic and geologic reconnaissance of the southern half of the Seward Peninsula. The area was divided into two portions: one extending east and from Golofnin Bay and Fish River, and one extending west from Golofnin Bay and Fish River. In the western area, Alfred H. Brooks led the geologic work, with assistant geologists George B. Richardson and Arthur J. Collier. Meanwhile, E. C. Barnard led the topographic mapping effort, assisted by D. L. Reaburn, H. G. Hefty, and R. B. Robertson. The mapped area focused on the more important gold fields on the Seward Peninsula (Brooks et al. 1901). Brooks also noted the occurrence of placer tin (cassiterite) on Buhner Creek (tributary of the Anikovik River) and on the Anikovik River (Brooks 1903). Work in the eastern area was conducted by topographer W. J. Peters, geologist W. C. Mendenhall, and field assistant J. H. Knowles (Brooks et al. 1901). They produced the first general geology map of the southwestern portion of Seward Peninsula (see Brooks et al. 1901, plate 3).

1901 – W. C. Mendenhall and D. L. Reaburn examined and mapped part of the northern coast of the Seward Peninsula (Mendenhall 1902). They published a crude geologic map from their season, which included a portion of the area surrounding Kotzebue Sound (see Mendenhall 1902, plate 5). In the interest of investigating the northern extension of the gold fields, the USGS dispatched a geologic and topographic reconnaissance expedition to the northwestern part of the Sewared Peninsula. This party included geologist Arthur J. Collier, topographer T. G. Gerdine, and assistant topographer D. C. Witherspoon (Collier 1902). The fieldwork resulted in a geologic map of the northwest portion of the Seward Peninsula. The mapped area extended from Granley Harbor in the south, to Harris Dome in the east, to Shishmaref Inlet in the north (see Collier 1902, plate 3).

1903 – USGS geologic and topographic reconnaissance work continued and shifted to the northeastern part of the peninsula. The reconnaissance party included geologist Fred H. Moffit, field assistant C. E. Hill, and topographer D. C. Witherspoon. A second party composed of geologist J. Collier and assistant Frank L. Hess continued the investigation of the western and northern area (Collier et al. 1908). Collier also examined the tin deposits in the York region (Collier 1904). This season completed the initial phase of USGS reconnaissance work on the Seward Peninsula (Moffit 1905).

1904 – The USGS continued work on the Seward Peninsula. Topographer T. G. Gerdine with assistants R. B. Oliver and W. R. Hill completed a 1:45,000 scale topographic map of the gold producing areas around Nome (Brooks 1905). Arthur J. Collier examined the tin deposits of the York region (Collier 1905). T. F. Ward staked the Excelsior Group of copper mining claims on Kougarok Mountain on 25 July 1904 (Cowan 1916). Tom Rous and associates discovered gold in economically viable quantities on the Kugruk River (Reed 1933).

1905 – The USGS continued work on the Seward Peninsula. Geologists Fred H. Moffit and Frank L.

Hess mapped half the geology of the Nome and Grand Central special maps. T. G. Gerdine with assistants W. B. Corse and B.A. Yoder completed a 1:45,000 scale topographic survey in the Solomon and Casadepaga regions (Brooks 1906). Hess visited the tin deposits of the York region (Hess 1906). Moffit and Hess also collected information on gold production (Moffit 1906).

1906 – Fred H. Moffit and P. S. Smith completed the geologic mapping of the Nome and Grand Central quadrangles (Brooks 1907a) and studied the occurrence and distribution of placer gold (Smith 1907a, 1907b). Hoyt and assistant F. F. Henshaw conducted hydrographic surveys in the Nome region (Hoyt and Henshaw 1907). A. H. Brooks spent September on the Seward Peninsula with the Moffit and Hoyt parties, and spent time studying the Kougarok placer district (Brooks 1907a, 1907b).

1907 – USGS geologist Adolph Knopf studied the tin deposit of the Seward Peninsula in the Ear Mountain, Buck Creek, Cape Mountain, and Lost River areas (Knopf 1908a, 1908b). P. S. Smith, assisted by George I. Finlay and F. J. Katz, mapped the geology of the Solomon and Casadepaga quadrangles and investigated mining in other districts (Smith 1908). F. F. Henshaw and assistant Raymond Richards continued stream gauging work, focusing on the Kougarok district but with other work in neighboring areas (Henshaw 1908).

1907 and 1908 – The American Museum of Natural History conducted a paleontology expedition in Alaska led by L. S. Quackenbush. In 1907, this expedition included a visit to Eschscholtz Bay, with time spent at Elephant Point and the Buckland River. Mammoth fossils and some skin and hair were found embedded in the bluff near Elephant Point. The next year (1908), a second field season (3 July to 20 August 1908) was devoted to a more detailed exploration of the area (Quackenbush 1909).

1908 – USGS geologist Fred F. Henshaw spent about seven weeks examining the Fairhaven mining district (Henshaw 1909).

1909 – F. F. Henshaw and G. L. Park conducted stream gauging research on the Fish, Solomon, Nome, Sinuk, Cobblestone, Kruzgamepa, Kuzitrin, Kougarok, Noxapaga, Goodhope, Inmachuk, Kugruk, and Kiwalik Rivers, and Iron Creek (Henshaw 1910).

1910 – Edward M. Kindle collected fossils and studied the stratigraphy of the Port Clarence region (Kindle 1911).

1911 – After finishing fieldwork in the Alatna-Noatak region, Philip S. Smith spent several days in Nome waiting for the steamer. During this time, he gathered information on mining operations in the area (Smith 1912).

September 1913 – Theodore Chapin visited the Seward Peninsula and reported on placer and lode mining (Chapin 1914a, 1914b).

1914 – Henry M. Eakin spent two weeks examining tin mining in the York district, mining developments near Nome, and the Sinrock basin iron deposits (Eakin 1915).

1916 – Between 19 September and 13 October 1916, J. B. Mertie investigated the lode and placer mining developments in the Seward Peninsula districts (Mertie 1918a, 1918b).

August 1917 – USGS geologist George L. Harrington spent a few days examining the area near Candle, two days on Bear Creek, and about two weeks studying the gold and platinum placers of Sweepstakes and Dime Creeks (Harrington 1919).

1920 – USGS geologist S. H. Cathcart spent 3 July to 19 September 1920 studying mineral deposits of the Seward Peninsula, with a focus on mineral bearing lodes. Cathcart examined 110 prospects between Council and the Cripple River and studied the country rock around the richest placer deposits (Cathcart 1922).

1924 – John A. Davis (US Bureau of Mines) conducted placer mining investigations on the Seward Peninsula in the Koyuk, Candle, Inmachuck, Nome, Solomon, and Council districts (Wimmler 1924).

1926 – Norman L. Wimmler (USGS mining engineer) conducted placer mining investigations on the Seward Peninsula in the Nome, Solomon, Casadepaga, Bluff, Council, Koyuk, Fairhaven (Candle and Inmachuck areas), Kougarok, Iron Creek-Dahl Creek, and Port Clarence districts (Wimmler 1926).

1929 – During the summer, Irving M. Reed (Alaska Territorial Department of Mines) reported on the status of the placer mining conditions and coal and lode prospects of Seward Peninsula in the Nome, Solomon, Casadepaga, Bluff, Council, Koyuk, Candle, Inmachuck, Kougarok, Iron Creek-American Creek, and Nulato districts (Reed 1929a, 1929b).

1931 – Between 25 September and 27 September 1931, Irving M. Reed examined the Kugruk, Superior, and Chicago Creek coal mines and Coffin hydraulic mine (Reed 1933).

1938 – During the summer, A. Ben Shallit (Alaska Territorial Department of Mines associate engineer) examined placer gold operations in the Council and Teller districts and the Norton Bay area (Shallit 1938a)

and stream tin developments in the York region (Shallit 1938b).

1939 – USGS geologist J. B. Mertie Jr. examined tin deposits in the Cape Mountain (Heide and Sanford 1948) and Potato Mountain areas (Heide and Rutledge 1949).

1940 – A. Ben Shallit and J. C. Roehm (Alaska Territorial Department of Mines associate engineers) visited the upper and lower Kougarok drainages, the Krugruk drainage, the Inmachuk drainage, the Lower Solomon drainage, and other areas of the northcentral Seward Peninsula (Roehm 1940, 1942). Shallit conducted a detailed placer gold study of the area around the confluence of the Kougarok River and Taylor Creek (Shallit 1941a).

1941 – Between 23 September and September 26 1941, Shallit studied the copper claims near Kougarok Mountain (Shallit 1941b).

1942 – In July, Harold E. Heide (Bureau of Mines mining engineer) examined the Lost River tin mines in the valley of Cassiterite Creek to determine the possibility of using these deposits to support the war effort (Heide 1946).

1943 – Between 25 July 25 and 2 August 1943, Eskil Anderson (Alaska Territorial Department of Mines associate engineer) and L. E. Ost (claim owner from the Council district) investigated the Pargon Mountain muscovite prospect near Oregon Creek (Anderson 1943). Eskil also visited the Kugruk galena mines (Levensaler and Anderson 1944).

1944 – The USGS investigated tin deposits in the Lost River and Cape Mountain areas that had been identified by geologist P. L Killeen in 1943 (Killeen 1945).

1945 – USGS geologists H. R. Gault and R. F. Black investigated radioactive minerals in the Sweepstakes Creek area (Gault et al. 1953). Gault also evaluated the Candle Creek area (Gault 1953), and P. L. Killeen and R. J. Ordway studied the Ear Mountain area (Killeen and Ordway 1955).

1946 – In September, Lowell B. Moon (US Bureau of Mines, Mining Branch chief) made a preliminary examination of the Ward Copper Deposit at the head of the Serpentine River (Wright 1947). P. L. Killeen and M. G. White (USGS) evaluated radioactive minerals on the south fork of Quartz Creek in the Candle district (Killeen and White 1953), Moxham and West investigated the Serpentine-Kougarok area (Moxham and West 1953), and M. G. White evaluated the Teller area (White et al. 1953).

1947 – W. S. West and J. J. Matzko (USGS) evaluated radioactive minerals in the Buckland-Kiwalik district (West and Matzko 1953).

1947–1949 – USGS scientists D. M. Hopkins and R. S. Sigafoos spent three summers conducting geomorphic and biologic studies to understand the relationship of frost action and vegetation patterns around Imuruk Lake and in other areas of the Seward Peninsula (Hopkins and Sigafoos 1951).

1949–1950 – Larsen excavated Trail Creek caves.

1951 – During July and August, USGS geologists Walter S. West and Max G. White examined the York, Nome, and Koyuk districts for uranium deposits (White and West 1952). They made note of the occurrence of zeunerite at Brooks Mountain (West and White 1952), and West evaluated radioactive minerals in the headwaters of the Peace River (West 1953).

1952 – Pemberton Killeen and Charles Hummel of the USGS and Robert H. Saunders and James A. Williams, associate mining engineers of the Alaska Territorial Department of Mines, investigated tin production at Lost River (Williams 1952).

1953 – James A. Williams and Robert H Saunders (Territory of Alaska Department of Mines mining engineers) led a field trip to the Seward Peninsula. Their objective was to conduct magnetometer surveys of tin placer ground in the vicinity of Cape Mountain (Williams and Saunders 1954), a safety examination at Lost River tin mine, and a mineral investigation of Hirk Edward's antimony prospect on Big Hurrah Creek (Williams 1953). During the 1953 and 1954 field seasons, John J. Mulligan (Bureau of Mines mine examination and exploration engineer) conducted placer and lode sampling of tin deposits of the Ear Mountain area (Mulligan 1959b).

1956 – During the periods 20–29 May and 13–22 June 1956, Peter O. Sandvik (Territory of Alaska Department of Mines engineer-assayer) led a field trip to an area approximately 21 km (13 mi) south of the village of Candle. The objective of the trip was to assist C. C. Taylor and R. E. Young in investigating lode claims in the Fairhaven mining and recording district, which were staked based on a radioactive anomaly detected by airborne radiometric work (Sandvik 1956).

1957 – Willow M. Burand (Alaska Territorial Department of Mines assay-engineer) investigated the Hannum Creek lead deposit (Burand 1957). John J. Mulligan evaluated tin bearing stream gravels near the previously worked tin deposits at Lost River and Potato Mountain (Mulligan 1959a).

1958 – Between 30 July and 6 August 1958, Burand visited various placer mines in the Kougarok River area (Burand 1958).

1959 – In August, Robert V. Berryhill (US Bureau of Mines mine examination and exploration engineer) collected samples to determine heavy mineral content of beach and river mouth deposits on the south shore of the Seward Peninsula between Golovia and Koyuk, and on the north shore of the peninsula between the Goodhope River and Alder Creek (Berryhill 1962).

1960 – Paul A. Colinvaux (Duke University graduate [PhD] student) sampled sediment cores from Imuruk Lake to reconstruct and study the Pleistocene environment of the Bering Land Bridge (Colinvaux 1962).

1961 – USGS geologist G. Donald Eterlein evaluated the Port Clarence limestone in the Lost River area and the Mount Distin limestone in the Nome area as potential host rocks for a proposed nuclear test site (Eterlein et al. 1962).

Appendix B: Scoping Participants

The following people attended the GRI scoping meeting, held on 8–10 May 2007, or the follow-up report writing conference call, held on 2 August 2017. 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.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Robert Blodgett	USGS	Paleontologist
Mary Booth	NPS Arctic Network	Ecologist
Greta Burkart	NPS Arctic Network	Ecologist
Jobe Chakuchin	NPS Arctic Network	Resource Manager
Tim Connors	NPS Geologic Resources Division	Geologist
Bruce Giffen	NPS Alaska Regional Office	Geologist
Tom Hamilton	USGS	Emeritus Geologist
Tom Heinlein	NPS Bering Land Bridge National Preserve	Superintendent
Bruce Heise	NPS Geologic Resources Division	Geologist
Torre Jorgenson		
Rus Kucinski	NPS Alaska Regional Office	Geologist
Jim Lawler	NPS Arctic Network	Coordinator
Owen Mason	INSTAAR (Institute of Arctic and Alpine Research)	Geoarcheologist
Scott Miller	NPS Arctic Network	Arctic Network Data Manager
David Mills	NPS Yukon-Charley Rivers National Preserve and Gates of the Arctic National Park and Preserve	Superintendent
Kumi Rattenburg	NPS Arctic Network	Biotechnician
Robert Swenson	Alaska Geologic Survey	State Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Research Associate
Alison Till	USGS Alaska Science Center	Geologist
Tara Whitesell	NPS Arctic Network	Biotechnician
Ric Wilson	USGS Alaska Science Center	Geologist

2017 Conference Call Participants

Name	Affiliation	Position
Ken Adkisson	NPS Bering Land Bridge National Preserve	Resources Program Manager
Chad Hults	NPS Alaska Regional Office	Regional Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Jeanette Koelsch	NPS Bering Land Bridge National Preserve	Superintendent
Amanda Lanik	NPS Alaska Regional Office	Geologist, GRI Report Author
Jim Lawler	NPS Alaska Regional Office	Regional I&M Program Manager
Dave Swanson	NPS Arctic Network	Terrestrial Ecologist
Andy Tremayne	NPS Alaska Regional Office	Archeologist
Sarah Venator	NPS Alaska Regional Office	Geologist
Dale Vinson	NPS Alaska Regional Office	Archeologist

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 NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2018. Contact the NPS Geologic Resources Division for detailed guidance

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/ submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. 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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: ● only for park administrative uses; ● after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; ● after finding the use is park's most reasonable alternative based on environment and economics; ● parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; ● spoil areas must comply with Part 6 standards; and ● NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**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. *See also "Climate Change"*	**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 new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

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 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **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. *Continued in 2006 Management Policies column*	**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. (2016). *NPS guidance, continued:* **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
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. *2006 Management Policies, continued:* **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.	**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. *continued in Regulations column*

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).

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

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