Geologic Map of the Emmons Lake Volcanic Center, Alaska

By Thomas P. Miller, Christopher F. Waythomas, Margaret T. Mangan, Frank A. Trusdell, and Andrew T. Calvert

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Cover. Aerial photograph (to the southwest) of Emmons Lake and the west-northwest side of Emmons Lake volcanic center. Lava flows along the east shore of Emmons Lake were erupted from cone A and are of Holocene age. Photograph by Chris Waythomas, U.S. Geological Survey, July 23, 2017.

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Discussions with Chris Nye (Alaska Division of Geological and Geophysical Surveys [AKDGGS]) and Tom Sisson, Charlie Bacon, and Wes Hildreth (all U.S. Geological Survey [USGS]) over a number of years provided valuable geologic and geochemical insight. John Power (USGS) provided geophysical information that helped us develop our interpretation of the subsurface geology. We wish to thank past and present staff at the Izembek National Wildlife Refuge for their many years of interest and support. We are also grateful for the field assistance of Chris Nye (AKDGGS) and Kristi Wallace, Elizabeth Yount, and Don Richter (all USGS). Charlie Bacon and Cynthia Gardner (both USGS) provided very helpful reviews of the map and report; their comments are greatly appreciated.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F – 32) / 1.8.

Datum

Elevation, as used in this report, refers to distance above sea level (a.s.l.), unless otherwise noted.

Abbreviations

μm	micrometer
σ	sigma (standard deviation)
$^{40}Ar/^{39}Ar$	argon-argon
a.s.l.	above sea level
°C	degrees Celsius
^{14}C	carbon-14
ELVC	Emmons Lake volcanic center
ka	kilo-annum (or, thousand years ago)
K-Ar	potassium-argon
lat	latitude
LGM	Last Glacial Maximum
long	longitude
Ma	mega-annum (or, million years ago)
NAD 27	North American Datum of 1927
UTM	Universal Transverse Mercator
USGS	U.S. Geological Survey
yr	year
yr B.P.	years before present

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Introduction

The Emmons Lake volcanic center (ELVC) is a spatially clustered group of stratovolcanoes and calderas on the Alaska Peninsula near Cold Bay, Alaska (figs. 1, 2). The volcanic center is characterized by several ice- and snow-clad stratovolcanoes located within and along the margins of a nested-caldera complex that includes Emmons Lake. A shieldlike ancestral edifice (ancestral Mount Emmons) is truncated by the caldera complex and forms a broad volcanic platform around the center. The main stratovolcanoes of the ELVC (from northeast to southwest) are Pavlof Sister, Pavlof Volcano, Little Pavlof, Double Crater, Mount Hague, and Mount Emmons (fig. 1). Several small unnamed cinder cones and vents also are located within ELVC and on the east flank of Pavlof Volcano (fig. 1). Many of these cones and vents have been the source of the young lava flows that mantle the floor of the caldera. Pavlof Volcano, in the northeastern part of the ELVC, is one of the most historically (that is, the past about 300 years [yr]) active volcanoes in Alaska (see https://avo.alaska.edu/), and eruptions from Pavlof Volcano pose the greatest hazards to the region (Waythomas and others, 2006).

The Emmons Lake volcanic center is located about 40 kilometers (km) east of Cold Bay, about 34 km northeast of King Cove, and about 95 km west of Sand Point (fig. 2); Cold Bay and King Cove are the largest towns and villages in the region. Nelson Lagoon, a small village on the Bering Sea coast, is located about 93 km northeast of Pavlof Volcano. Most of the area around the ELVC is uninhabited treeless wilderness adjacent to the Izembek National Wildlife Refuge. The area is rugged and largely inaccessible except by aircraft or on foot. Because of its remote location, recreational use of the area is minimal, although small groups of people visit in the summer and occasionally in winter.

The purpose of this report is to describe the geology and eruptive history of the ELVC. A main contribution of this multiyear study of the volcanic geology of the area is a 1:100,000-scale geologic map and cross section of the volcanic center. The spatial database (Waythomas and others, 2026) contains detailed information about geologic-unit compositions, faults, and contacts. Also included in this report are photographs and figures illustrating key geologic relations, as well as argon-argon ($^{40}Ar/^{39}Ar$) and potassium-argon (K-Ar) age determinations (table 1.1, in appendix 1), major- and trace-element geochemical analyses of the major rock units (table 2.1, in appendix 2), and radiocarbon ages (table 3.1, in appendix 3). Thin-section photographs and brief descriptions (figs. 4.1 through 4.82, in appendix 4), as well as data (table 4.1, in appendix 4), are also provided.

Geologic Setting

The Emmons Lake volcanic center is located in the southwestern part of the Alaska Peninsula, in a section of the Aleutian Arc that is underlain primarily by continental crust of the tectonostratigraphic Peninsular terrane (Jones and others, 1987). The axis of the Aleutian Trench is located about 250 km southeast of the ELVC, and the rate of northwestward convergence between the North America and Pacific Plates in this area is about 60 to 70 millimeters (mm) per yr (Keleman and others, 2003). The thickness of the continental crust in the vicinity of the ELVC is about 15 to 35 km (Fliedner and Klemperer, 2000; Lizarralde and others, 2002).

Volcanic rocks of the ELVC overlie continental and marine sedimentary rocks of chiefly Late Jurassic to early Tertiary age (Detterman and others, 1996). The oldest rocks in the area are those of the Naknek Formation (not shown in map area), a widespread rock unit on the Alaska Peninsula that consists of volcaniclastic sandstone, siltstone, and conglomerate of Late Jurassic age (McLean, 1979; Detterman and others, 1996). Rocks of the Naknek Formation crop out in the Black Hill area, located along the Bering Sea coast north of the ELVC, just outside the map area (fig. 2). The southern part of the area includes rocks of the Belkofski Formation (not shown in map area), a 1.8-km-thick sequence of volcaniclastic sandstone, siltstone, and conglomerate of middle Tertiary age (Oligocene to Miocene) (Detterman and others, 1996). Lava flows, volcanic breccia, and fluvial volcaniclastic rocks of late Miocene age, which unconformably overlie the Belkofski Formation south of the ELVC, are primarily exposed on the islands just south of the Alaska Peninsula, between Pavlof Bay and King Cove (fig. 2).

The ELVC was affected multiple times by glaciation associated with the glacier expansion that characterized the Quaternary. An evaluation of Quaternary glaciation in the region was beyond the scope of our mapping effort; however, glaciation has played a key role in shaping the present-day (2021) landscape, and much of the eruptive history of the ELVC has involved interactions with glacier ice. Thus, a brief review of the Quaternary glacial history of the area is provided to establish the physical context for ELVC eruptive activity.

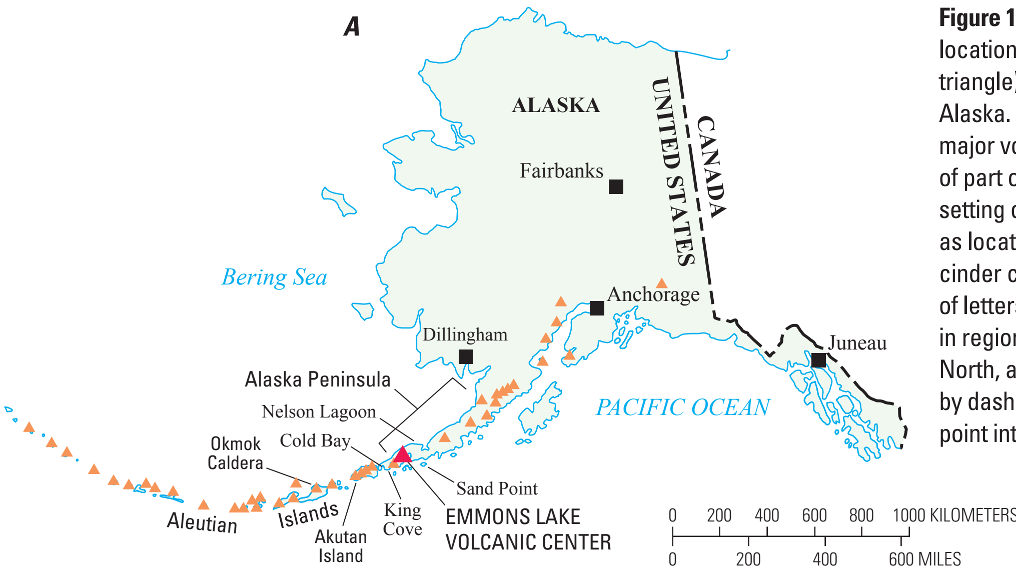
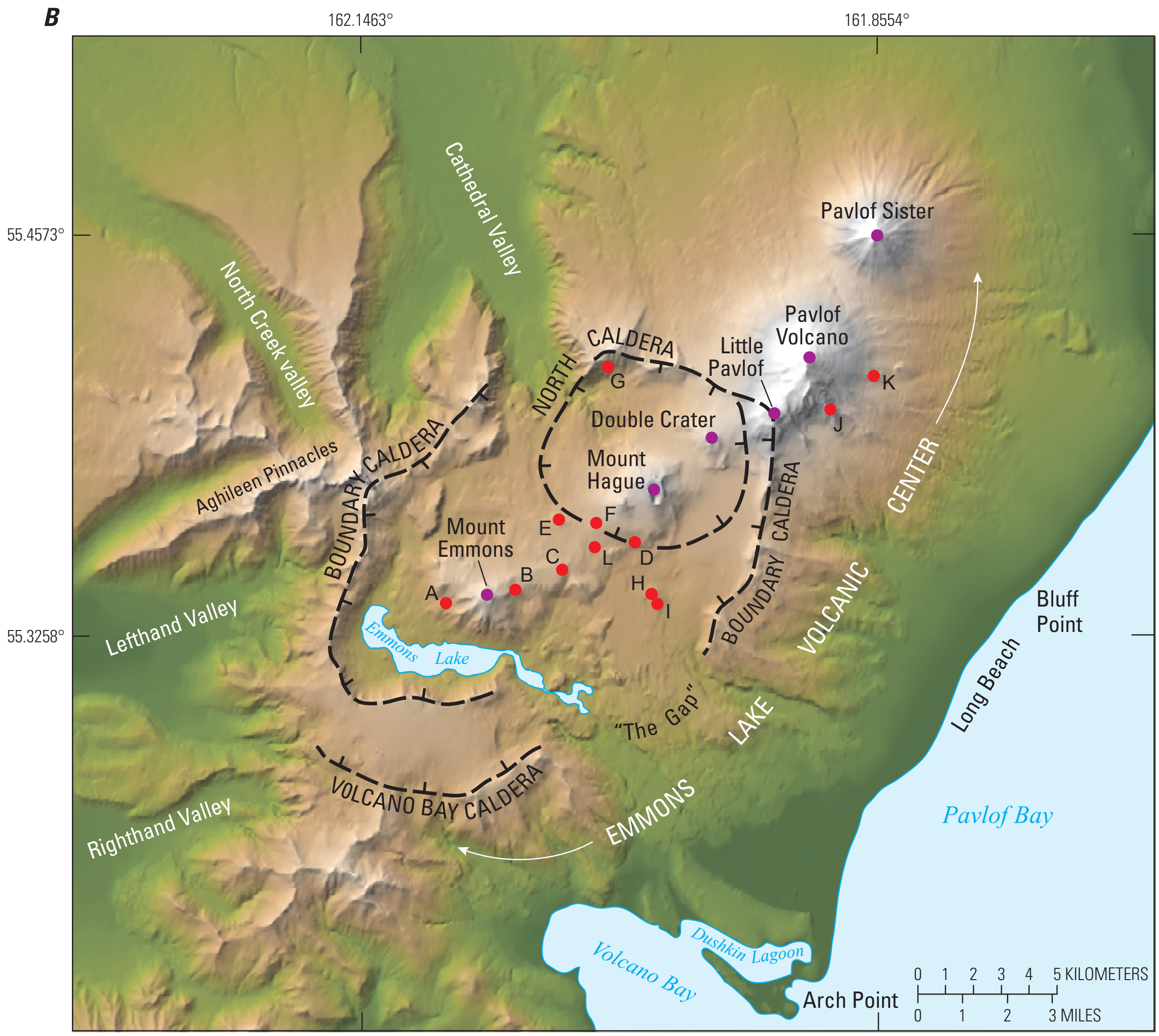


Figure 1. *A*, Index map of Alaska, showing location of Emmons Lake volcanic center (red triangle) on Alaska Peninsula, in southwestern Alaska. Orange triangles show locations of other major volcanoes. *B*, Colored shaded-relief map of part of Alaska Peninsula, showing geographic setting of Emmons Lake volcanic center, as well as locations of major stratocones (purple dots), cinder cones (red dots; see text for discussion of letters [A–L]), and other geographic features in region. Outlines of calderas (Boundary, North, and Volcano Bay calderas) are shown by dashed and hachured black lines; hachures point into calderas.



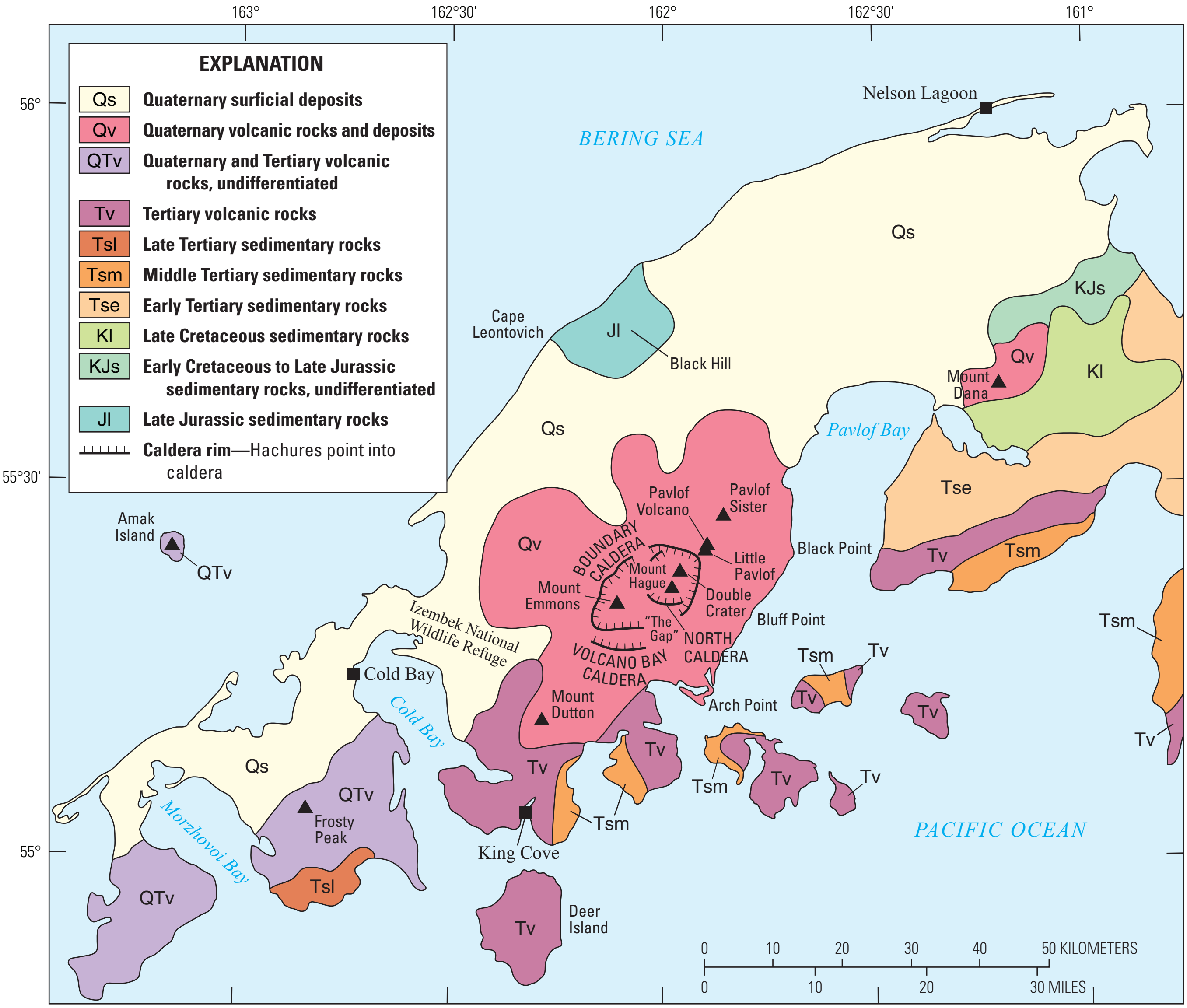


Figure 2. Generalized geologic map of southwestern part of Alaska Peninsula in vicinity of Emmons Lake volcanic center (ELVC); see Description of Map Units for full unit descriptions. Black triangles indicate locations of main Quaternary volcanoes in region, both inside and outside of ELVC. Outlines of calderas (Boundary, North, and Volcano Bay calderas) are shown by hachured black lines; hachures point into calderas. Modified from Detterman and others (1996).

Previous Studies

Geologic investigations of the Emmons Lake area have been relatively limited, and much of the previous work has been primarily reconnaissance mapping (for example, McLean and others, 1978; Wilson and others, 1992, 1997). Prior to this study, the only focused geologic study of the ELVC area was conducted in the summer of 1946 by Kennedy and Waldron (1955). The principal outcome of this work was the first geologic map of Pavlof Volcano and parts of the ELVC. Kennedy and Waldron (1955) did not recognize the significance of the caldera structures in the Emmons Lake area; rather, they suggested that some kind of rift structure had cut the region and that this structure may have been the source of the lava flows and cinder cones that they had mapped near Emmons Lake. Kennedy and Waldron (1955) mapped a widespread, dark, 50- to 600-meter (m)-thick, columnar-jointed, multivent sequence of lava flows, which they named the Dushkin Basalt. They suggested, with reservations, that the concentric depression partly filled by Emmons Lake may have been a "sunken block or part of a caldera" that formed as a result of the eruption of the Dushkin Basalt (Kennedy and Waldron, 1955). Although Kennedy and Waldron (1955) described the Dushkin Basalt as having a "streaked" appearance and containing numerous remelted and "dragged out" inclusions, they concluded that the unit was erupted as a series of lava flows from multiple vents located along a northeast-trending fissure between Mount Emmons and Pavlof Sister. As a result of our work, the Dushkin Basalt has been reinterpreted, and it is herein documented as a sequence of andesite to dacite, welded, columnar-jointed, rheomorphic tuffs of multiple ages (this report; see also, Mangan and others, 2009).

Because of its prolific historical eruptive history, Pavlof Volcano has been the subject of a variety of studies over the past 60 yr. At the time of this writing (2021), the volcano had last erupted in March 2016; however, it has been intermittently active for at least the past 300 yr, and it has had 40 to 50 historically recorded eruptions (McNutt, 1987; Waythomas, 2015; Waythomas and others, 2017; see also, www.avo.alaska.edu).

The present study, which was undertaken in piecemeal fashion, spanned a period from the mid-1970s to the present (2021). The Alaska Volcano Observatory supported a multiyear geologic study of the ELVC from 1999 to 2003, during which time a concerted effort was made to map and sample the primary eruptive units and to investigate their geologic relations; data for the present report were largely obtained during this period. Also assessed during this time were the hazards associated with eruptive activity of the ELVC (Waythomas and others, 2006).

Geologic Overview of the Emmons Lake Volcanic Center

Volcanic Rocks

The Emmons Lake volcanic center (ELVC) is one of the largest volcanic centers in the 2,600-km-long Aleutian Arc. It is the largest (19×12 km) nested-caldera complex in the Aleutian Arc, and it includes the most historically active volcano in Alaska (Pavlof Volcano). It has an estimated volume of 350 cubic kilometers (km^3) (Miller and Richter, 1994), and it contains an extensive assemblage of densely welded tuffs. Studies of the ELVC show that, at about 29 kilo-annum (ka), eruption of basaltic andesite lava at Pavlof Volcano was essentially synchronous with the voluminous eruption of rhyolitic, pumiceous pyroclastic flows from the ELVC, only 5 km away (Mangan and others, 2009).

The ELVC consists of a nested and overlapping series of calderas (165 square kilometer [km^2] area) superimposed in a northeastern-southwestern direction onto one or more large, deeply dissected, andesitic stratovolcanoes (fig. 3). Geologic mapping, petrologic studies, and $^{40}Ar/^{39}Ar$ dating indicate that silicic volcanism at the volcanic center has been long lived and dominated by at least three—and perhaps as many as six—major caldera-forming eruptions between about 300 and 27 ka (Mangan and others, 2009). In addition, we identify at least two periods of andesitic volcanism: one period resulted in at least four andesitic lava flows between the caldera rims in the southernmost part of caldera, one of which is dated at about 126 ka; the other period resulted in a northeast-southwest-trending series of stratovolcanoes and associated cinder cones and lava flows, located both inside and outside the caldera complex during eruptive activity of latest Pleistocene to Holocene age.

Outflow products from all silicic eruptive events, except the youngest (27 ka), consist of lavalike, columnar-jointed, welded tuffs (fig. 4), commonly rheomorphic in character. Such tuffs, which are found as far as 35 km from their source caldera, range

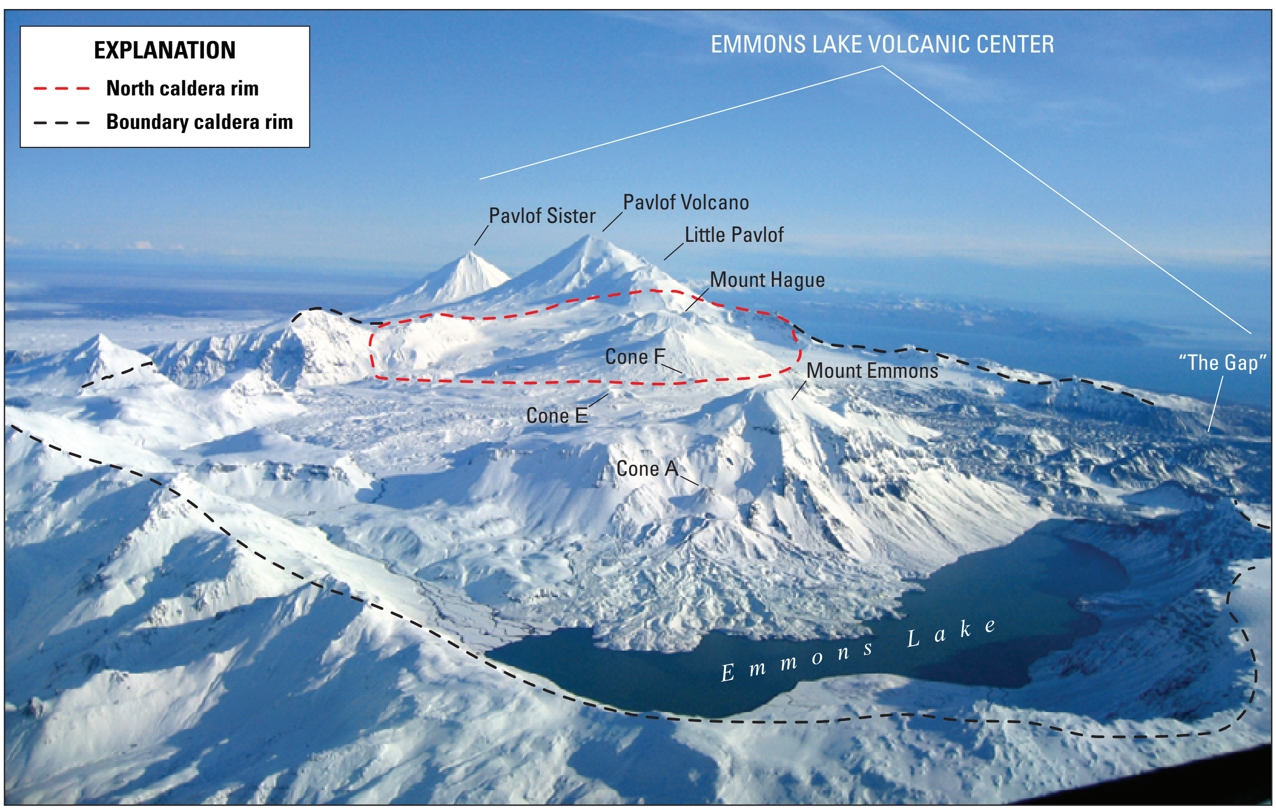


Figure 3. Aerial photograph (to east-northeast) of Emmons Lake volcanic center (ELVC), showing major stratocones and also intracaldera cinder cones A, E, and F. Dashed lines show approximate (partial) traces of two (of three) calderas that make up ELVC (black, Boundary caldera; red, North caldera). Photograph by R. Hazen, Peninsula Airways, October 21, 2008.

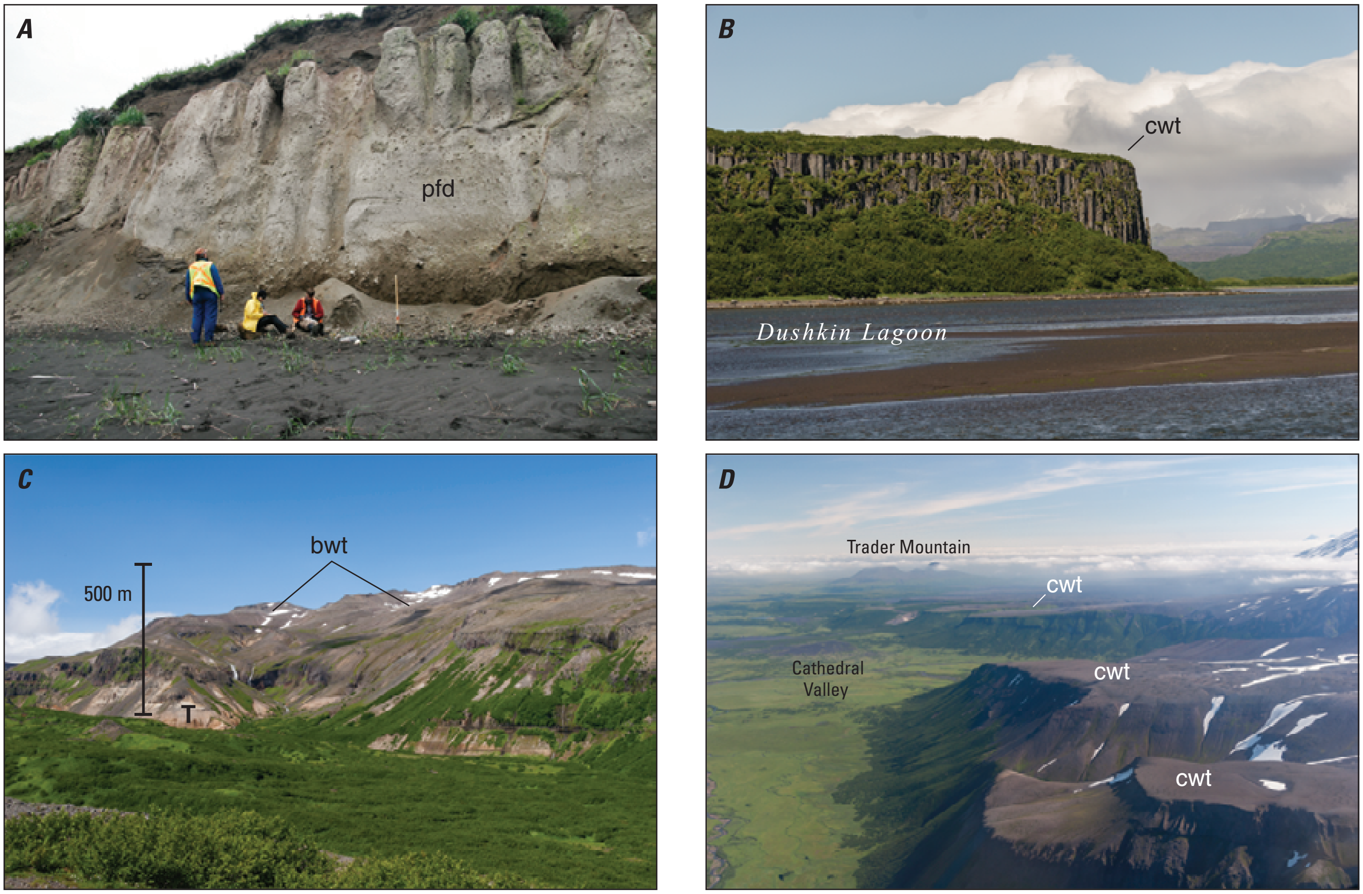


Figure 4. Photographs showing examples of pyroclastic-flow deposits and welded tuffs of Emmons Lake volcanic center (ELVC). Photographs by Chris Waythomas, U.S. Geological Survey. *A*, View (to south) of pumiceous pyroclastic-flow deposits associated with 27-kilo-annum (ka) caldera-forming eruption (the rhyolite pyroclastic-flow deposits [unit pfd]) in typical sea-cliff exposure along Bering Sea coast, about 38 kilometers (km) north-northwest of ELVC. Photograph taken July 23, 2005. *B*, View (to north) of columnar-jointed Cathedral welded tuff (the rhyolite rheomorphic tuff, agglutinate, and breccia of upper Cathedral River drainage [unit cwt]) at Dushkin Lagoon, about 16 km south of ELVC. Photograph taken July 28, 2005. Unit cwt is about 50 meters (m) thick at this location. *C*, View (to north) of "The Butte" welded tuff (the dacite rheomorphic tuff and agglutinate of "The Butte" [unit bwt]) on south flank of caldera complex. Photograph taken July 29, 2005. Area labeled T is underlying section of pumiceous airfall tephra emplaced just prior to welded tuff; relief from T to skyline, about 500 m. *D*, View (to north) of flat-topped mesas of Cathedral welded tuff (unit cwt) in upper Cathedral River drainage on north flank of caldera complex. Photograph taken August 6, 2005.

in composition from dacite to rhyolite. These welded tuffs, which are confined to the areas southeast and northwest of the caldera complex, represent infilling of ancestral drainages and lowlands (for example, ancestral Cathedral River and ancestral Emmons Lake). The youngest (27 ka) event, in contrast, is associated with highly mobile, nonwelded, rhyolitic pumice-flow deposits that slope away from the ELVC; these deposits are exposed over a 3,000-km^2 area around the ELVC and are as much as 60 km from the caldera. A rhyolitic ash-fall deposit (the Dawson tephra of Naeser and others [1982]), located 1,700 km beyond the ELVC in the Klondike region of western Canada, has been correlated with the youngest (27 ka) ELVC event (Mangan and others, 2003).

Morphology of the Caldera Complex

The caldera complex is defined morphologically as the discontinuous rim breached on its north side by the 3-km-wide Cathedral River drainage and on the southeast side by a 9-km-wide breach informally known as "The Gap" (figs. 1, 2), which contains an unnamed river that drains Emmons Lake. At least four known silicic welded-tuff units flowed through "The Gap" between 234 and 32 ka. The elevation of the discontinuously breached rim ranges from about 915 m (3,000 feet [ft])[1] in the southwest to 2,060 m (6,762 ft) at Little Pavlof volcano at the northeast end. Overlapping caldera rims along and near the south edge of the caldera complex suggest the presence of at least three collapse calderas (fig. 1).

Interior of the Caldera Complex

The interior of the caldera complex is dominated topographically by three prominent andesitic stratovolcanoes, Mount Emmons (mapped as the volcanic rocks of Mount Emmons [unit ev]; 1,326 m), Double Crater (the volcanic rocks and pyroclastic deposits of Double Crater [unit dv]; 1,356 m), and

[1]Elevations, as given in this report, refer to distance above sea level (a.s.l), unless otherwise noted.

Mount Hague (the volcanic rocks and pyroclastic deposits of Mount Hague [unit hv] and four Mount Hague volcanic-rock subunits [hlf1, hlf2, hlf3, and hlf4]; 1,540 m), all aligned in a northeast-southwest direction across the floor of the caldera complex. Mount Hague volcano and four scattered cinder cones have been the source of at least 20 andesitic lava flows that moved across parts of the caldera floor and out through “The Gap,” to within 3 km of the North Pacific Ocean. These lava flows cover a total area of about 70 km^2. We have no radiometric ages for the lava flows, but they are all unglaciated and, therefore, likely are latest Pleistocene to Holocene age. At least four older glaciated lava flows (the four lava-flow subunits on the south caldera rim [olf1, olf2, olf3, and olf4]) are present along the southern margin of the complex between two overlapping caldera rims. The lava flow of subunit olf1 yielded $^{40}Ar/^{39}Ar$ ages of 197.0±21.5, 136.7±1.3, and 131.6±1.0 ka, and the lava flow of subunit olf4 yielded an $^{40}Ar/^{39}Ar$ age of 128.5±4.3 ka (table 1.1, in appendix 1).

A series of flat-topped, mesa-like domes crops out over a large area that extends east-west across the caldera complex, north and east of Emmons Lake (fig. 5). The domes consist of massive, black, glassy andesite to dacite (the dacite to andesite lava domes, flows, coulees, and welded tuff [unit ida]) that contains well-developed ice-contact features such as strongly contorted columnar jointing. An altered, light-tan hyaloclastite phase east of the lake and a welded tuff just outside the caldera are correlated in this report to unit ida on the basis of chemistry (table 2.1, in appendix 2). These domes, coulees, and associated lava flows yielded $^{40}Ar/^{39}Ar$ ages of about 100 ka (table 1.1, in appendix 1). No older rocks have been found north of these domes, indicating that the boundary of the northernmost (and youngest) caldera collapse must lie to the north.

A persistent bicarbonate thermal spring is present on the north shore of Emmons Lake in the western part of the caldera (latitude [lat] 55.337151° N., longitude [long] 162.141129° W.; 350 m elevation). Intermittent temperature measurements made over the past 30 yr indicate that the spring has attained a maximum temperature of about 185 degrees Celsius (°C); associated gases contain magmatic volatiles (Motyka and others, 1994; Mangan and others, 2009).

Individual Calderas

Three individual calderas have been identified by location, morphology, and $^{40}Ar/^{39}Ar$ dating (fig. 1). The outermost caldera, herein named the Volcano Bay caldera, is best represented by a prominent scarplike, northeast-trending topographic ridge that is truncated at its east edge by the Emmons Lake drainage and “The Gap.” The scarp is less clearly defined at the extreme south edge of the complex, as it decreases in elevation and is hidden

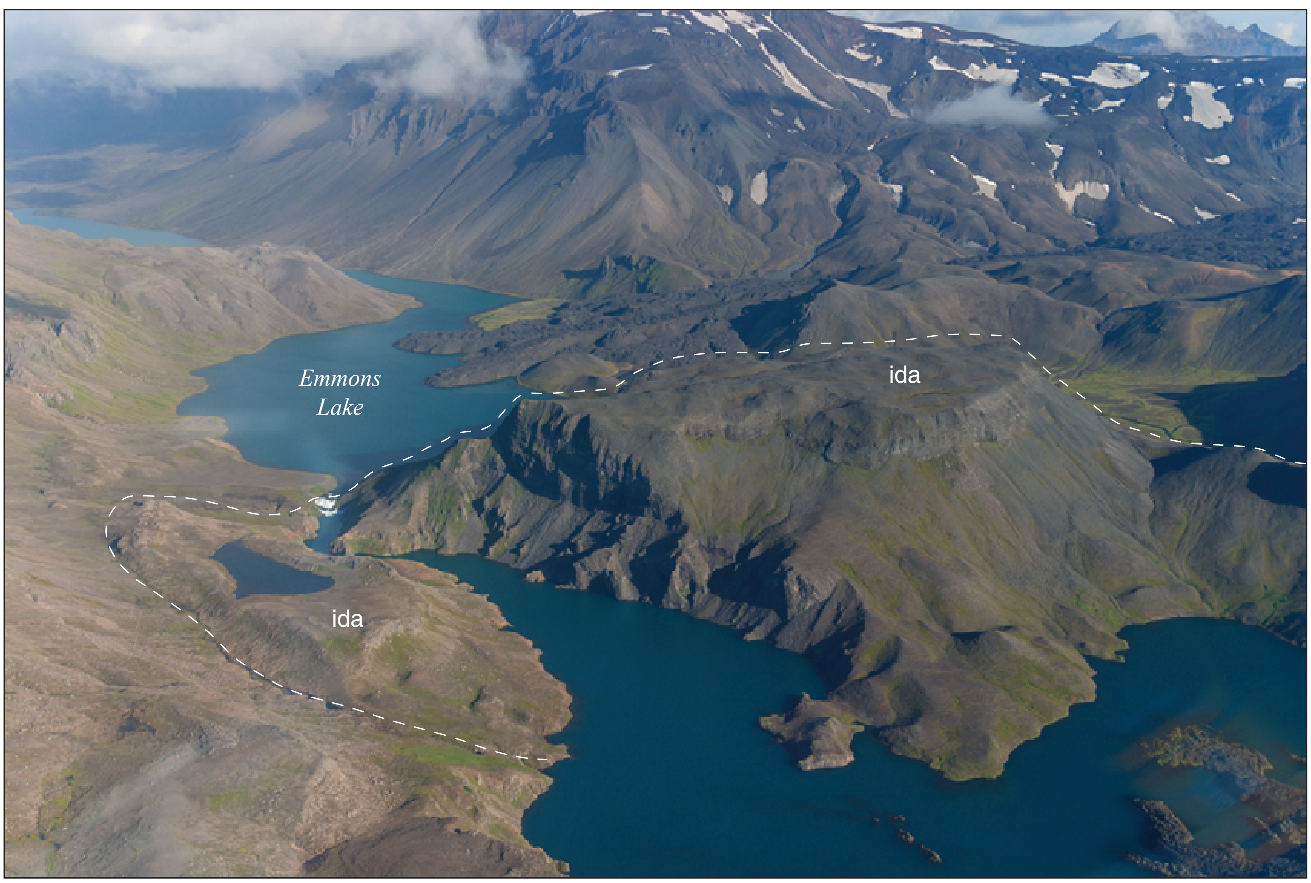


Figure 5. Aerial photograph (to northwest) toward Mount Emmons (on skyline), showing example of intracaldera ice-contact andesite dome of the dacite to andesite lava domes, flows, coulees, and welded tuff (unit ida). Dashed white line indicates approximate location of contact between unit ida and other units. Photograph by Chris Waythomas, U.S. Geological Survey, August 15, 2003.

beneath a permanent snow-and-ice field; it is older than, and is truncated by, the scarp of a younger caldera, herein named the Boundary caldera. The ridge that forms the Volcano Bay caldera scarp truncates intrusive basement rocks and ELVC cone-building volcanic rocks (mapped as the andesite of ancestral Mount Emmons [unit cbl]). The scarplike feature that outlines the western margin of the caldera complex from Emmons Lake to the Cathedral River drainage and Cathedral Valley is probably part of the Volcano Bay caldera, for the reasons stated below. The Volcano Bay caldera may be associated with the welded tuffs (mapped as the rhyolite rheomorphic tuff, agglutinate, and breccia of upper Cathedral River drainage [unit cwt]; 234 ka) found outside the caldera boundary.

The Boundary caldera is defined by a spectacular 600-m-high scarp that forms the west-southwest side of Emmons Lake and extends northward to the Cathedral River drainage (fig. 6*D*). The scarp north of Emmons Lake exposes 600 m of thick-bedded lava flows and volcaniclastic rocks of the cone-building phase of ancestral Mount Emmons (mapped as the andesitic volcaniclastic rocks of ancestral Mount Emmons [unit cbv] and the andesite of ancestral Mount Emmons [unit cbl]). At least four thick andesite lava flows (subunits olf1, olf2, olf3, and olf4) crop out in the largely ice-covered valley between the Boundary and Volcano Bay caldera scarps, and they extend as far as the unnamed outlet stream that drains Emmons Lake. A source vent for these flows is not apparent, but it is assumed to have been part of an ancestral cone located above the Boundary caldera scarp that later was destroyed during the collapse that formed the Boundary caldera.

A glacially scoured, columnar-jointed lava flow (subunit olf4) that lies just north of the Volcano Bay caldera scarp yielded an ^{40}Ar/^{39}Ar age of 128.5±4.3 ka. Several glassy dacite domes (unit ida) are scattered across the caldera floor. The domes have whole-rock geochemistry that is similar to that of the lava flows and are probably associated with the same eruptive period. A sample from one of the domes (sample no. 99S15M1, table 1.1, in appendix 1) yielded an ^{40}Ar/^{39}Ar age of 100.7±7.1 ka. This result suggests that the Boundary caldera formed between 126 and 100 ka and may be associated with the welded tuffs exposed in the northern part of “The Gap” (mapped as the rhyodacite rheomorphic tuff, agglutinate, and ignimbrite of “The Gap” [unit gwt]), which have ^{40}Ar/^{39}Ar ages of between 125 and 123 ka.

Figure 6. Aerial photographs showing examples of intracaldera lava flows and cinder cones of Emmons Lake volcanic center. Photographs by Chris Waythomas, U.S. Geological Survey. *A*, View (to north) across middle of caldera, showing setting of cones C, D, and E. Cone D lava flow 5 (subunit dfl5) shown in foreground. Photograph taken August 5, 2003. *B*, View (to southwest) at terminus of cone D lava flow 5 (dfl5) where it enters Emmons Lake. Photograph taken August 18, 2003. *C*, View (to southwest) at cone E and associated lava flows. Photograph taken July 23, 2017. *D*, View (to west-southwest) at cone A and associated lava flows at north end of Emmons Lake. Mount Dutton volcano and prominent scarp of Boundary caldera also shown. Photograph taken July 23, 2017.

The youngest caldera, herein named the North caldera, is clearly defined along its northern and eastern margins by a prominent, 15-km-long topographic scarp that reaches an elevation of 2,061 m near the crest of Little Pavlof and cuts volcanic units as young as 123 ka. The southern and western margins are not topographically well expressed, but they lie north and east of the dacite dome belt (unit ida; 100 ka) and are covered by late Pleistocene and Holocene lava flows. About one-third of the floor of the North caldera (~20 km^2) is covered by modern glacier ice and glacial deposits of Holocene age. The thickest and most extensive deposits of the widespread pumiceous pyroclastic flows (unit pfd) lie adjacent to the North caldera, suggesting, therefore, that its age is about 27 ka.

Intracaldera Cinder Cones and Associated Lava Flows

Previous studies by Kennedy and Waldron (1955) identified 11 cinder cones in the Emmons Lake–Pavlof Volcano area, and our work has identified one more (cone L), for a total of 12 in the Emmons Lake volcanic center. These cinder cones (unit cc, labeled A–L) are found inside the Boundary and North calderas and on the southeast flank of Pavlof Volcano. All are Holocene, but we only have age control on cone J; soil organic matter from a buried soil below the cone J lava flow (unit plh) yielded a radiocarbon age of 4,560±130 years before present (yr B.P.) (table 3.1, in appendix 3).

Blocky basaltic andesite to andesite lava flows have issued from at least four of these cones, in some cases repeatedly, in the Holocene (fig. 6). The lava flows are composed of dark, grayish-black, porphyritic basaltic andesite to andesite (53–59 percent SiO_2) that contains phenocrysts of plagioclase, clinopyroxene, and orthopyroxene and small amounts of olivine, in a groundmass of microlites and glass.

We have informally designated 10 cones within the caldera as cones A through I and L (fig. 1). Cone D has been particularly active, and at least five lava flows (subunits dlf1, dlf2, dlf3, dlf4, and dlf5) have originated from the cone. The lengths of individual cone D lava flows range from 1 to 10 km, and some lava flows extend outside the caldera complex, almost to the North Pacific Ocean. Cone D lava flows cover a total area of about 50 km^2; however, at least two of the flows overlap, and so the maximum total area is probably at least 60 km^2. Therefore, if an average lava-flow thickness of 10 m is assumed, the total volume of lava is about 0.6 km^3.

The absolute ages of the cone D lava flows are unknown, but they have not been glaciated, and they have a fresh, unaltered surface morphology, and, thus, they are likely of Holocene age. Relative ages have been determined by superposition and differences in vegetation cover. Organic material suitable for carbon-14 (^{14}C) dating has not been found in association with the cone D lava flows, and no historically recorded eruptive activity has been reported from inside the ELVC caldera complex. Fumarolic activity does occur on the southeast flank of Mount Hague, as well as inside its summit crater where an ephemeral lake commonly is present. Other known sites of anomalous heat flux are the bicarbonate thermal spring near the northeast end of Emmons Lake and a possible fumarole site just south of Little Pavlof where yellow coloration in a crevassed glacier has been reported (Flowers, 1997).

Mount Hague

Mount Hague volcano (lat 55.377581° N., long 161.981327° W.; summit elevation, 1,540 m) is the largest (volume, about 5 km^3) and most prominent of the intracaldera volcanic vents, and it is presumed to have largely filled the North caldera soon after it formed (fig. 7). Mount Hague consists of a twin-peaked, basaltic andesite to dacite (53–64 percent SiO_2) stratovolcano, about 5 km wide at its base and about 750 m high (fig. 8). The flanks are largely snow and ice covered and are scalloped by glacial erosion. Some older lava flows from Mount Hague contain ice-contact features (fig. 7). The summit area is marked by two overlapping, circular craters, each about 400 m in diameter (fig. 9). The rim of the north crater reaches an elevation of 1,540 m but is cut by the south crater, indicating that the south crater is younger. The south crater is about 250 m deep, and a fumarole field is visible when the crater floor is exposed; however, by midsummer, the bottom of the crater is commonly covered by a seasonal lake (fig. 9). A satellitic circular knob, located about 1 km southwest of the summit vents at an elevation of about 1,366 m (fig. 9), probably represents an older, eroded vent.

Another fumarole field on Mount Hague is located in a steep, incised ravine on its southeast flank, at an elevation of between 975 and 1,160 m (fig. 8). At least six vigorously steaming vents are found in the ravine, and large amounts of native sulfur have been deposited in pinnaclelike columns; sulfur gases are also present. The fumarolic field in the ravine is only about 700 m from the summit-crater fumaroles that are at roughly the same elevation.

The timing of eruptive activity at Mount Hague is unknown. Some of its distal lava flows have been glaciated, suggesting that Mount Hague may have been active during the late Pleistocene and likely into the Holocene. No historically recorded activity has occurred at Mount Hague.

Mount Emmons

Mount Emmons volcano (lat 55.352203° N., long 162.098568° W.; summit elevation, 1,325 m) is a relatively small, andesite to dacite edifice (55–64 percent SiO_2) that covers an area of about 10 km^2 (fig. 10). The volcano, which has a volume of about 1 km^3, is located in the south-central part of the caldera, along the east side of Emmons Lake; it is the westernmost stratocone within the volcanic center. The edifice is situated on a plateaulike feature that consists chiefly of dacite-andesite domes and coulees (unit ida) dated ($^{40}Ar/^{39}Ar$) at about 100 ka. Lava flows from Mount Emmons (unit ev) drape over these domes on the north side of the volcano (fig. 10). The volcano currently supports small glaciers and snowfields, but it was more extensively glaciated during the late Pleistocene. Two samples of lava from Mount Emmons (unit ev) yielded $^{40}Ar/^{39}Ar$ ages of 18.0±0.8 and 17.1±0.9 ka (table 1.1, in appendix 1).

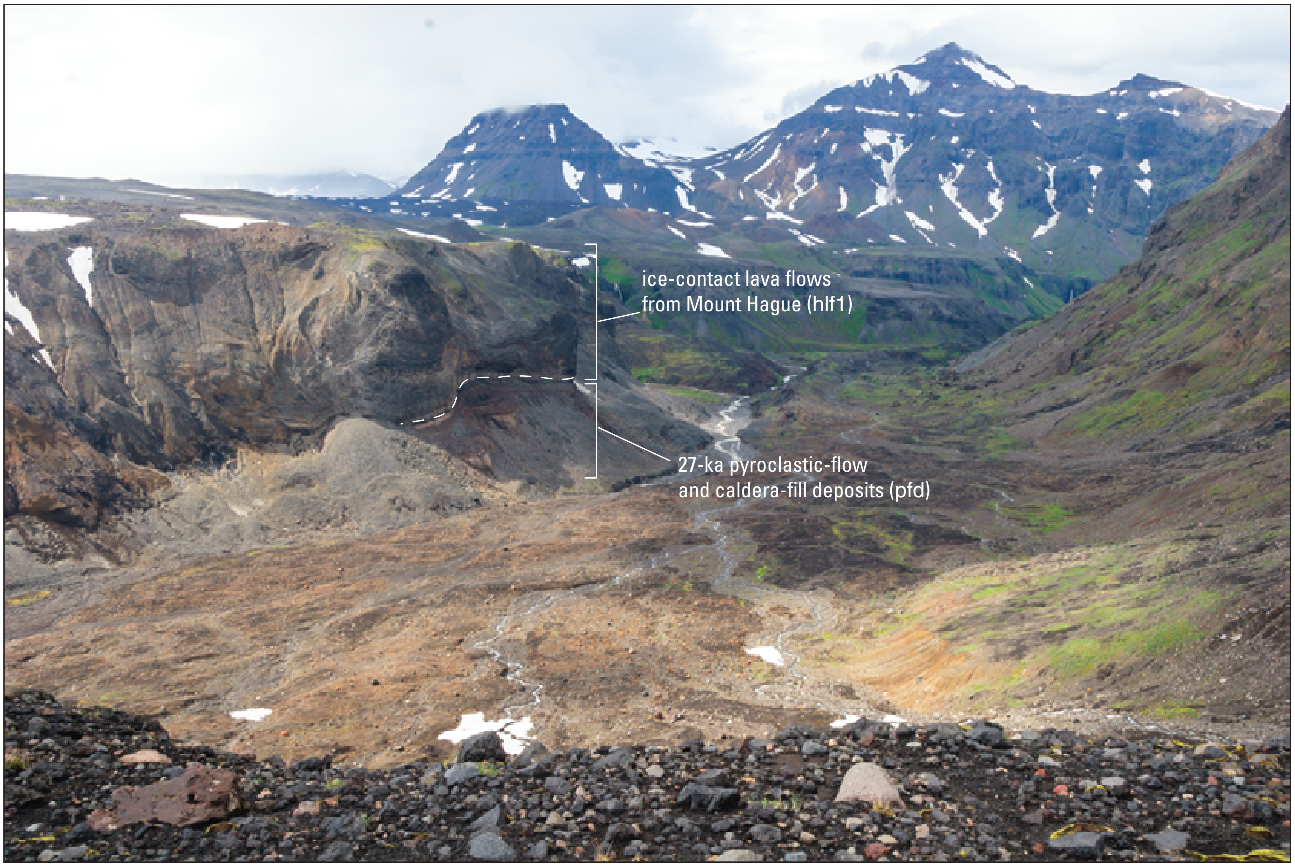


Figure 7. Photograph (to west) of outcrop of ice-contact lava flows from Mount Hague volcano (mapped as the volcanic rocks of Mount Hague [subunit hlf1]) overlying pumiceous pyroclastic-flow and caldera-fill deposits (pfd) associated with 27-kilo-annum (ka) caldera-forming eruption; dashed white line indicates approximate location of contact. These relations indicate that lava flows from Mount Hague began to develop within North caldera relatively soon after its formation. Braided stream in middle background is part of upper Cathedral River drainage. Photograph by Chris Waythomas, U.S. Geological Survey, July 23, 2005.

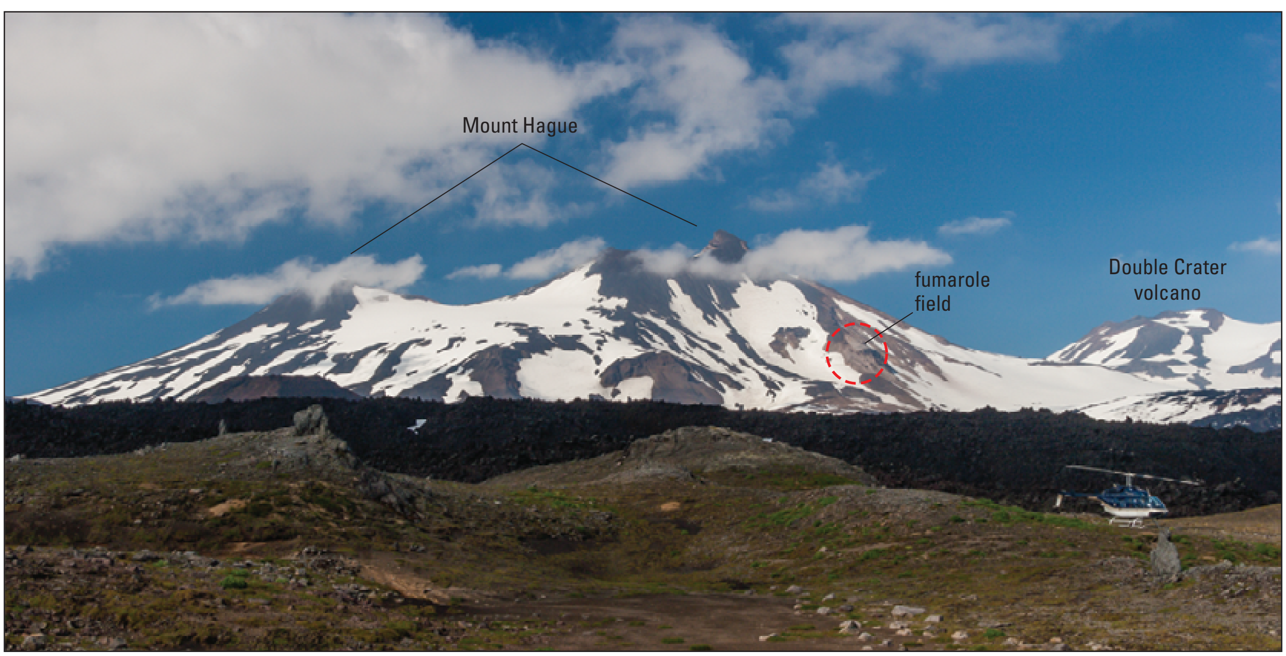


Figure 8. Photograph (to north) of two-peaked summit of Mount Hague volcano; dashed red circle outlines active fumarole field on southeast flank of Mount Hague. Dark lava flow in middle ground is from cone D (cone D lava flow 1 [subunit dlf1]). Also shown is Double Crater volcano to right. Photograph by Chris Waythomas, U.S. Geological Survey, August 7, 2005.

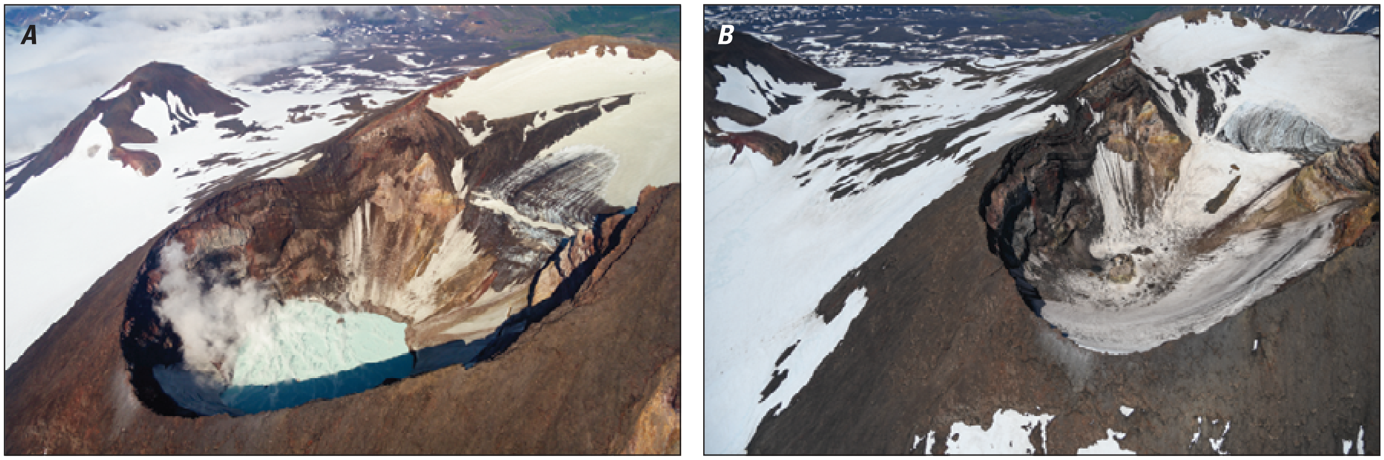


Figure 9. Aerial photographs (to north), showing two overhead views of summit craters of Mount Hague volcano; peak visible in upper left of each image is second (lower) summit peak of volcano. Photographs by Chris Waythomas, U.S. Geological Survey. *A*. Summit craters on August 6, 2005. *B*. Summit craters on July 22, 2017.

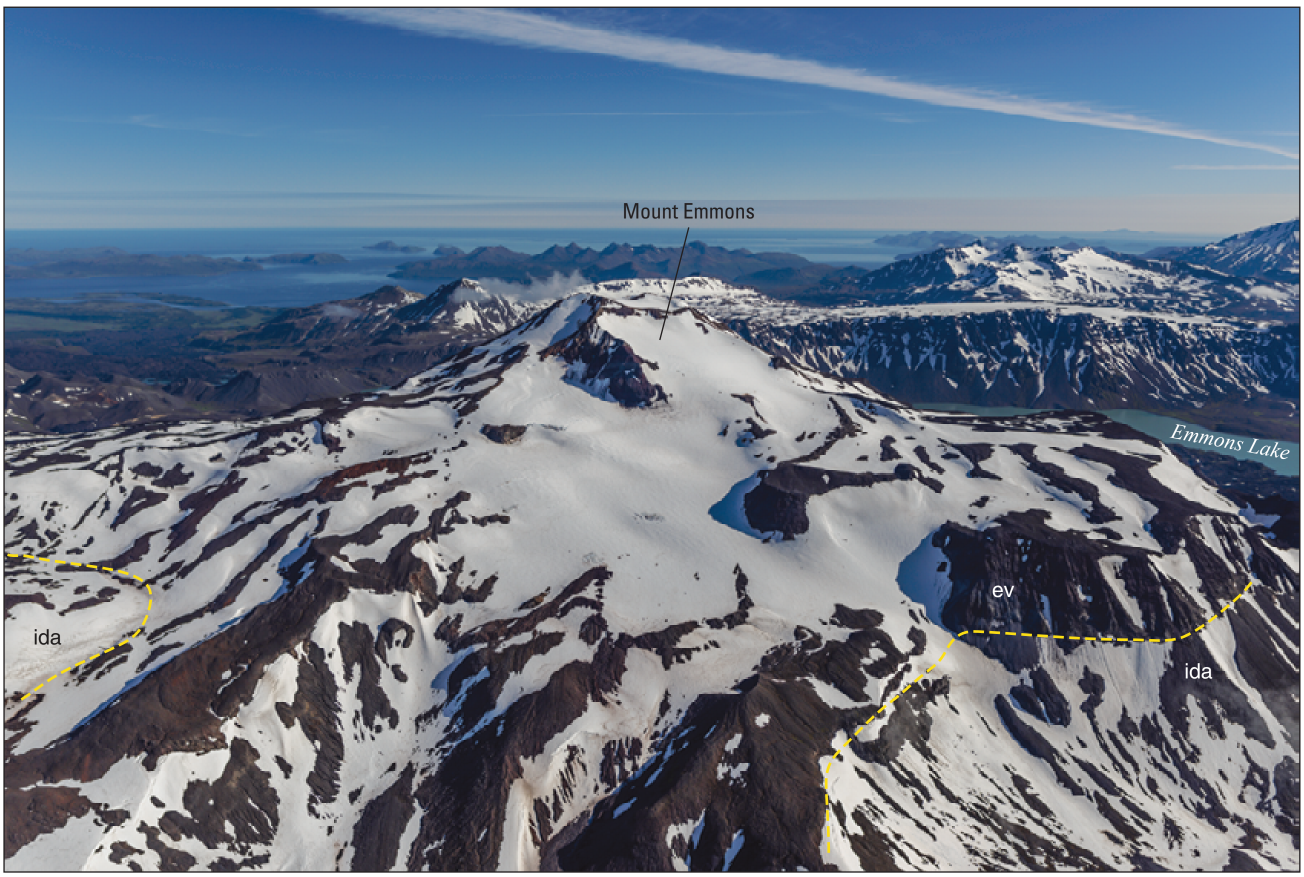


Figure 10. Aerial photograph (to southwest) of Mount Emmons volcano. Mount Emmons andesite lava flows (the volcanic rocks of Mount Emmons [unit ev]) developed on platform of underlying dacite-andesite flows and domes (the dacite to andesite lava domes, flows, coulees, and welded tuff [unit ida]); dashed yellow line indicates approximate location of contact between units ev and ida. Basal lava flows of Mount Emmons yielded argon-argon ($^{40}Ar/^{39}Ar$) ages of about 18 to 17 kilo-annum (ka). Emmons Lake is in middle background to right. Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

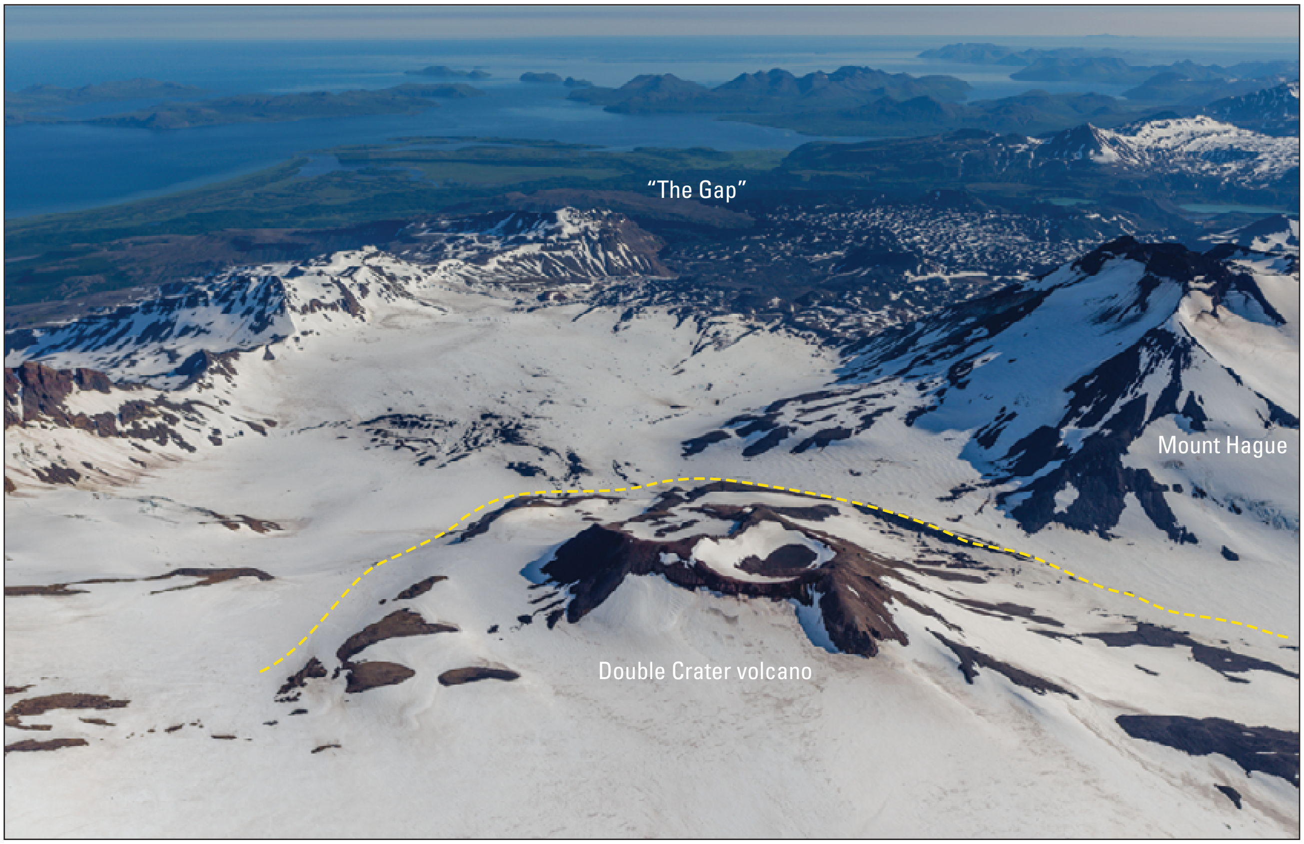


Figure 11. Aerial photograph (to southwest) of Double Crater volcano (dashed yellow outline), across southwestern part of Emmons Lake volcanic center toward "The Gap." Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

Double Crater

Double Crater volcano (lat 55.391841° N., long 161.946362° W.; summit elevation, 1,357 m) is a mostly ice- and snow-covered edifice in the eastern part of Emmons Lake volcanic center (fig. 1). The top of the edifice is characterized by two adjacent craters, each about 200 m in diameter (fig. 11). Lava flows from the volcano (unit dv) extend northward and southward of the twin craters, but they soon disappear beneath glacier ice and snow, which is ubiquitous in this part of the caldera. No historically recorded activity has occurred from this vent, but Holocene activity is suspected because of the fresh-appearing morphology of the summit craters. The lavas that make up Double Crater are andesitic to dacitic in composition (56–65 percent SiO_2).

Little Pavlof

Little Pavlof volcano (lat 55.400118° N., long 161.946362° W.; summit elevation, 2,042 m) is also an ice- and snow-covered edifice on the eastern margin of Emmons Lake volcanic center (fig. 1). The volcano overlies the east rim of North caldera, and, thus, its formation postdates the last caldera-forming eruption about 27 ka. Little Pavlof is largely inaccessible owing to its extensive ice and snow cover (fig. 12). One sample of lava was basaltic in composition (51 percent SiO_2), and most of the edifice consists of lava flows interbedded with deposits of coarse volcanic breccia and scoriaceous material. Local zones of hydrothermally altered material are evident on the upper part of the edifice (fig. 12). It is not known if Little Pavlof volcano and Pavlof Volcano had contemporaneous eruptive activity.

Pavlof Volcano

Pavlof Volcano (lat 55.418261° N., long 161.898802° W.; summit elevation, 2,518 m) is one of the most frequently active volcanoes in the Aleutian Arc, having erupted more than 40 times since observations were first recorded in the early 1800s (see https://www.avo.alaska.edu/volcanoes/volcinfo.php?volcname=Pavlof). Pavlof Volcano is a symmetrically shaped stratocone that has about 2,300 m of relief. The volcano supports a cover of glacial ice and perennial snow roughly 2 to 4 km^3 in volume, which is mantled by variable amounts of tephra fall, rockfall debris, and pyroclastic-flow deposits produced during historically recorded eruptions. Typical historically recorded eruptions of Pavlof Volcano are characterized by moderate amounts of ash emission, lava fountaining, and explosions, resulting in spatter-fed lava flows and the accumulation of unstable mounds of spatter on the

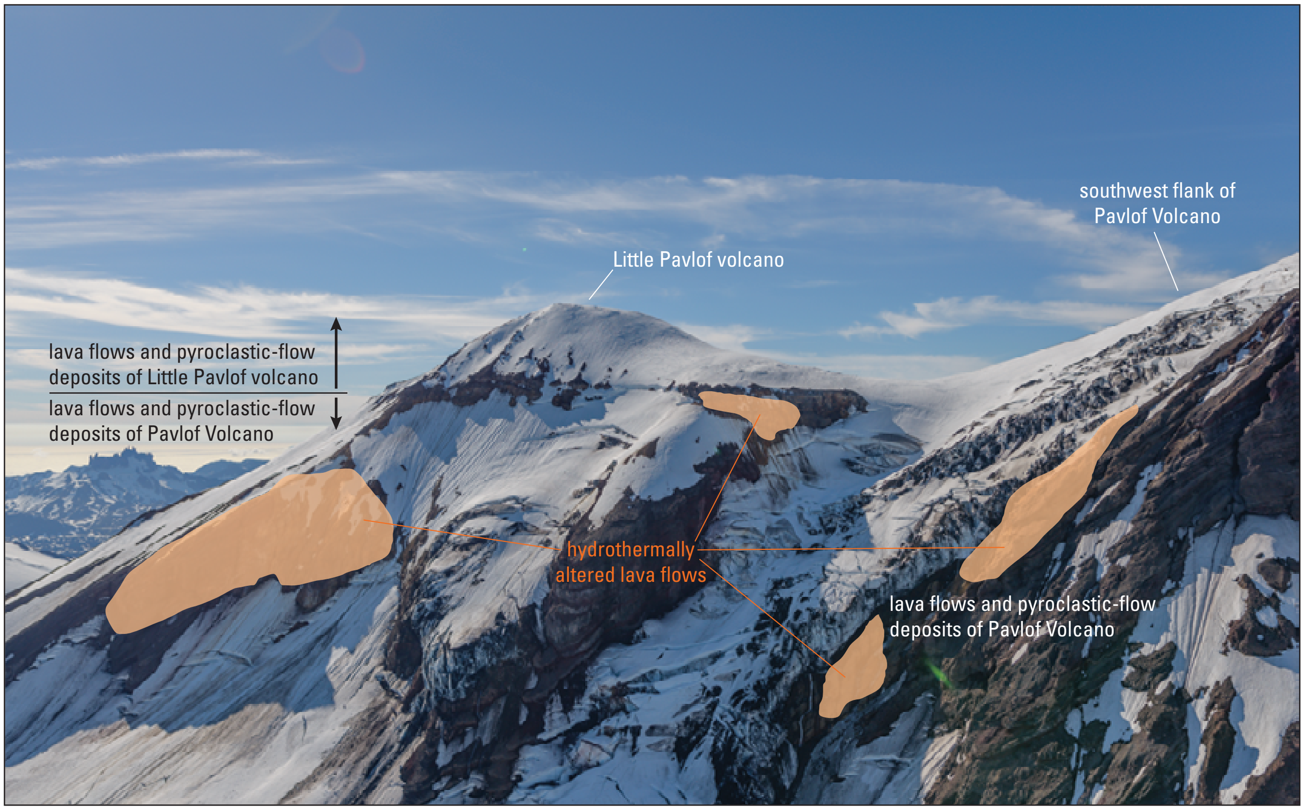


Figure 12. Aerial photograph (to northwest) of Little Pavlof volcano. Exposure consists of lava flows interbedded with pyroclastic debris, all of which dip steeply toward viewer. Deposits from Little Pavlof volcano can be visually traced eastward where they underlie southwest-dipping lava flows and pyroclastic-flow deposits from Pavlof Volcano that are younger than those shown in photograph. Pale-orange shading highlights zones of hydrothermal alteration. Photograph by Chris Waythomas, U.S. Geological Survey, July 23, 2017.

upper flanks of the volcano (McNutt, 1987; Waythomas and others, 2014). The accumulation and subsequent collapse of spatter piles on the upper flanks of the volcano create hot granular avalanches, which erode and melt snow and ice, thereby generating watery debris-flow and hyperconcentrated-flow lahars (Waythomas and others, 2014).

Most lava flows on Pavlof Volcano are basaltic to basaltic andesite in composition (51–54 percent SiO_2) and are commonly covered by a thick mantle of tephra, pyroclastic debris, and drift of Holocene age. Historically recorded eruptions have occurred from both southward- and northward-oriented vents (fig. 13). Lava flows associated with historically recorded eruptions are commonly clastogenic (Sumner, 1988; Waythomas and others, 2014) and consist of various accumulations of spatter and agglutinate (fig. 14) produced during sustained lava fountaining.

The Holocene basalt to andesite lava flows of Pavlof Volcano (unit plh) are exposed only on the east-southeast flank of the volcano, and they are primarily thin, ribbonlike ‘a‘ā flows. Three samples of charcoal collected from the base of two lava flows yielded (uncalibrated) radiocarbon ages of 4,500 to 3,500 yr B.P. (table 3.1, in appendix 3), indicating a middle Holocene eruption for the lavas.

Pavlof Sister

Pavlof Sister volcano (lat 55.456608° N., long 161.853988° W.; summit elevation, 2,142 m) is also a snow- and ice-covered, symmetrical, cone-shaped stratovolcano located just east of Pavlof Volcano (figs. 1, 15). Pavlof Sister is similar in many regards to Pavlof Volcano; however, it is smaller and has had no historically recorded eruptions. Its flanking slopes are mantled by an extensive cover of tephra from Pavlof Volcano (mapped as the tephra deposits of historically recorded eruptions of Pavlof Volcano [unit pt]) and pyroclastic debris, and the volcano is slightly dissected by glacier ice and stream erosion. Lava flows from Pavlof Sister (mapped as the basaltic andesite lava flows, breccia, and scoria of Pavlof Sister volcano [unit pslf]) are basaltic andesite in composition (52–54 percent SiO_2), and many are clastogenic, similar to those observed on Pavlof Volcano. The volcano is probably of late Quaternary age, but none of its lava flows or other eruptive products has been radiometrically dated.

Aghileen Pinnacles

The Aghileen Pinnacles, located a few kilometers northwest of Emmons Lake volcanic center, are a cluster of near-vertical,

Figure 13. Aerial photograph (to north) of summit and upper southeast flank of Pavlof Volcano, showing vent area (triangular-shaped feature just below summit) for 2007 eruption. Below vent area, note steep chute (dashed white outline; orange arrow shows direction of flow path) developed in ice and snow that conveyed hot granular-mass flows; chute is associated with formation, and subsequent failure, of spatter piles that developed just below erupting vent. These granular-mass flows interacted dynamically with snow and ice on volcano to form watery lahars (the lahar deposits of historically recorded eruptions of Pavlof Volcano [unit pvl]) that flowed to North Pacific Ocean coast. Upper part of edifice is almost always snow free and steaming slightly, as shown in photograph. Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

minaretlike spires of volcaniclastic rocks (fig. 16) within the ancestral Mount Emmons cone-building sequence. The pinnacles are a prominent landform in the area and are visible from both the Bering Sea and North Pacific Ocean sides of the Alaska Peninsula. According to Dall (1918), the name Aghileen is a Native Alaskan name, and the Aghileen Pinnacles have captured the attention of visitors to the area for many years (Hubbard Alaskan Expedition, 1935). A diorama of Alaskan brown bears in the American Museum of Natural History in New York City features the Aghileen Pinnacles in the background (https://lbry-web-007.amnh.org/digital/index.php/items/show/40837).

Glaciation

Pleistocene Glaciation

During Pleistocene glaciation, almost all of the Aleutian Arc was covered by a continuous glacial complex that extended eastward and was contiguous with the great Cordilleran ice sheet (Hamilton and Thorson, 1983; Kaufman and Manley, 2004). The crest of the Aleutian Range likely supported the bulk of the Pleistocene ice masses, and many of these areas also coincide with major volcanoes and volcanic complexes on the Alaska Peninsula. Paleoglacier reconstructions of the Last Glacial Maximum (LGM), roughly between 22 and 17 ka (Mann and Hamilton, 1995), indicate that glacier ice was thicker and more extensive to the south and slightly less extensive and thinner to the north (Mann and Peteet, 1994; Kaufman and Manley, 2004). The LGM ice sheet that covered the Alaska Peninsula was asymmetric: the ice divide was located south of the axis of the Aleutian Range over the continental shelf (Kaufman and Manley, 2004). During the LGM, ice flow in many areas was to the north but particularly along cross-peninsula lowlands, which are now major bays on the Alaska Peninsula.

The most extensive and morphologically distinct glacial deposits in the ELVC area are those associated with the LGM, known locally as the Brooks Lake glaciation (Muller, 1952; Detterman and Reed, 1973; Detterman, 1986). These deposits make up the prominent arcuate moraine complexes of fresh-appearing, hummocky kettle-kame topography at the heads of Pavlof Bay, Cold Bay, and Morzhovoi Bay, as well as in the lowland of the lower Cathedral River valley (fig. 17).

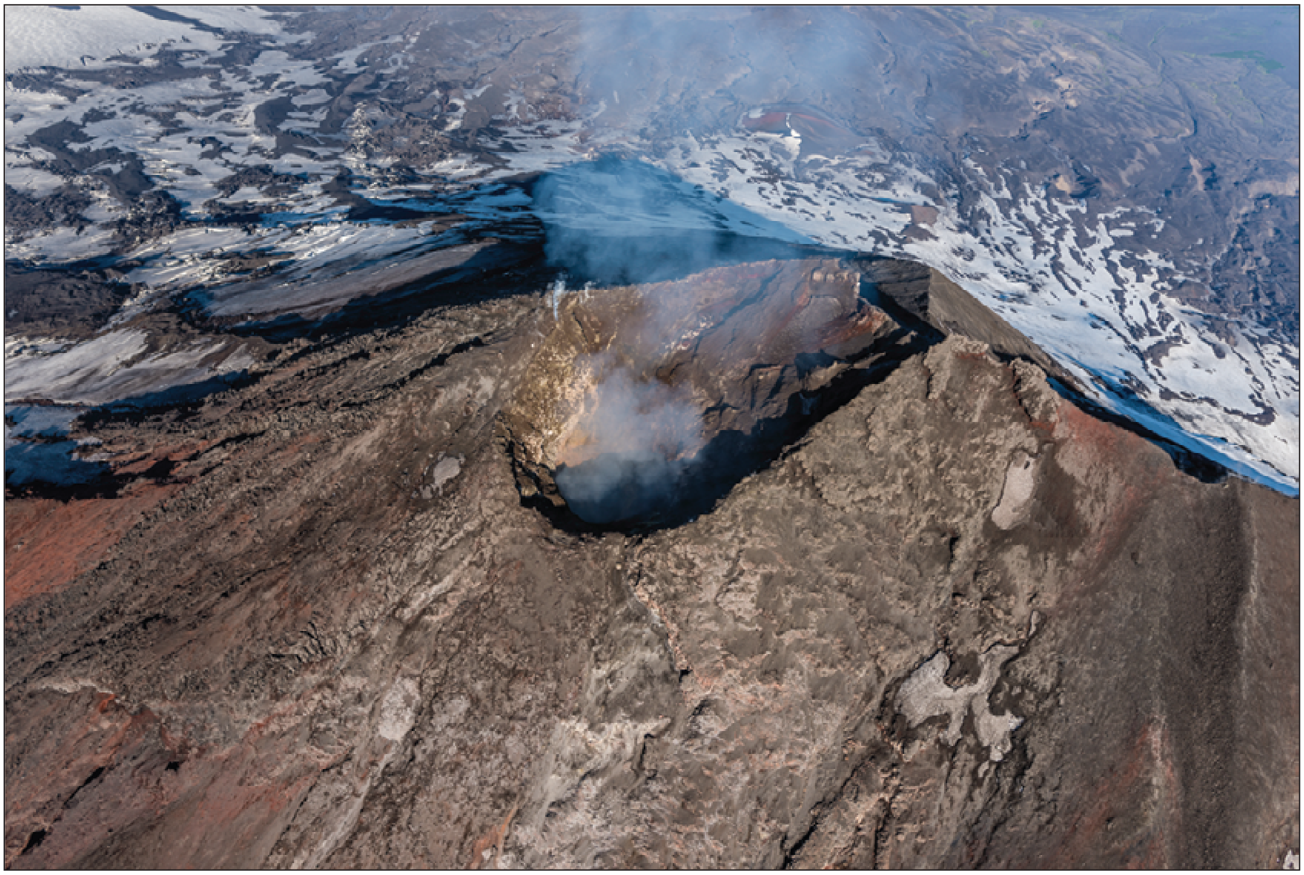


Figure 14. Aerial photograph (to southeast) showing overhead view of summit of Pavlof Volcano. Summit crater is about 200 meters in diameter and was enlarged to this size during 2016 eruption. Note various accumulations of spatter and agglutinate around summit. Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

Figure 15. Aerial photograph (to northeast) of Pavlof Sister volcano, which has cover of scoriaceous tephra from Pavlof Volcano (mapped as the tephra deposits of historically recorded eruptions of Pavlof Volcano [unit pt]) on most of its flanking slopes; east flank of Pavlof Volcano can be seen in left foreground. Pavlof Sister volcano has had no confirmed historically recorded eruptions, but its symmetrical shape and its undissected, rather youthful-appearing cone suggests that volcano is relatively young, perhaps of late Quaternary age. Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

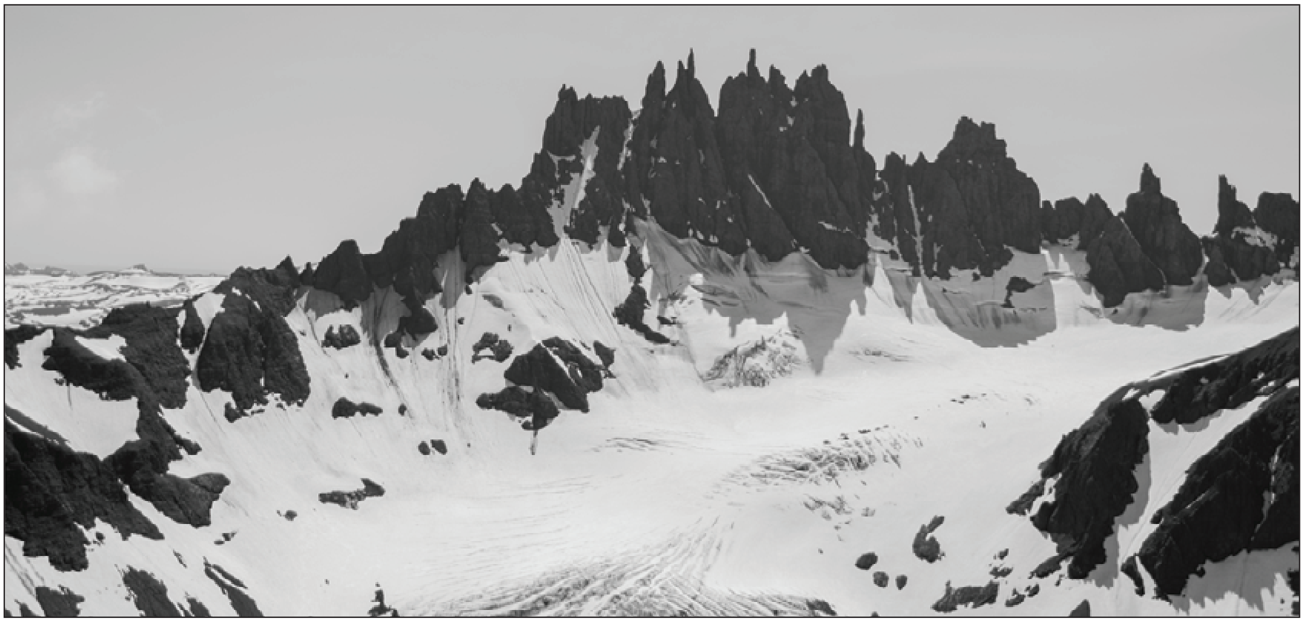


Figure 16. Photograph (to northwest) of Aghileen Pinnacles. Photograph by Chris Waythomas, U.S. Geological Survey, July 2017.

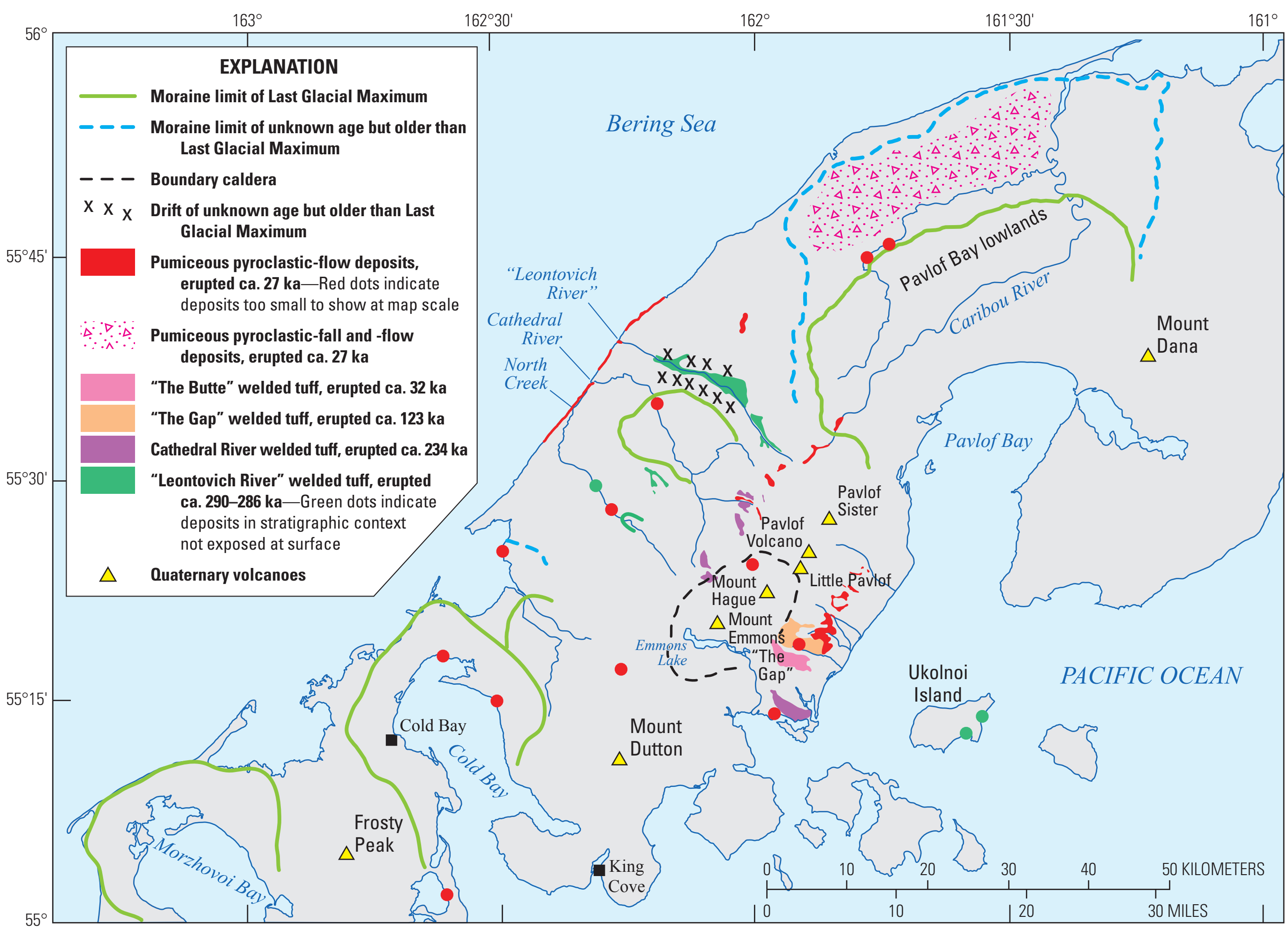


Figure 17. Map of southwestern part of Alaska Peninsula in vicinity of Emmons Lake volcanic center (ELVC; approximate outline is Boundary caldera [dashed black line]), showing generalized extent of major moraine belts of late Pleistocene age (Last Glacial Maximum) in relation to outcrops of several dated pyroclastic-flow deposits and welded-tuff units erupted from ELVC. Abbreviation: ka, kilo-annum.

Throughout the map area, glacial deposits are interbedded with pyroclastic-flow, welded-tuff, and tephra deposits erupted from the ELVC (fig. 18), providing a level of age control on the glacial deposits not typically available elsewhere on the Alaska Peninsula. Glacial deposits presumed to have formed during the Brooks Lake glaciation are depicted on various reconnaissance-level maps of the region, including Detterman (1986), Wilson and others (1992, 1997), and Kaufman and Manley (2004).

Holocene Glaciation

Holocene glacial deposits are present in areas of sufficient relief that either formerly or presently support glacier ice. Most major volcanic edifices of the ELVC were glaciated during the Holocene, and some volcanoes (for example, Pavlof Volcano, Little Pavlof) support modern glaciers. The Holocene glacial history of the ELVC was not addressed during our study. The only local study of Holocene glaciation in the region is by Funk (1973), who described Holocene glacial advances on Frosty Peak volcano west of the ELVC (figs. 2, 17).

Modern Glaciers

Modern glacier ice covers an area of about 126 km^2 within the ELVC (fig. 19). Most modern glacier ice is situated on the highest upland terrain around Pavlof Volcano. No glaciological studies of the ice masses within the ELVC have been undertaken, and, thus, the thickness of glacier ice in the area is not known. Using an estimate of average ice thickness of 75 m for the extent of ice shown on figure 19 gives an approximate ice volume of about 9.5 km^3.

Modern loss of glacier ice and snow in parts of the ELVC has been significant, and some glacier termini have retreated several hundred meters or more over the past 30 to 40 yr. In other locations, such as on the flanks of Pavlof Volcano and Pavlof Sister, an extensive cover of surficial debris has inhibited ice ablation, and significant amounts of glacier ice are situated well below regional glacier-equilibrium lines (Waythomas, 2015).

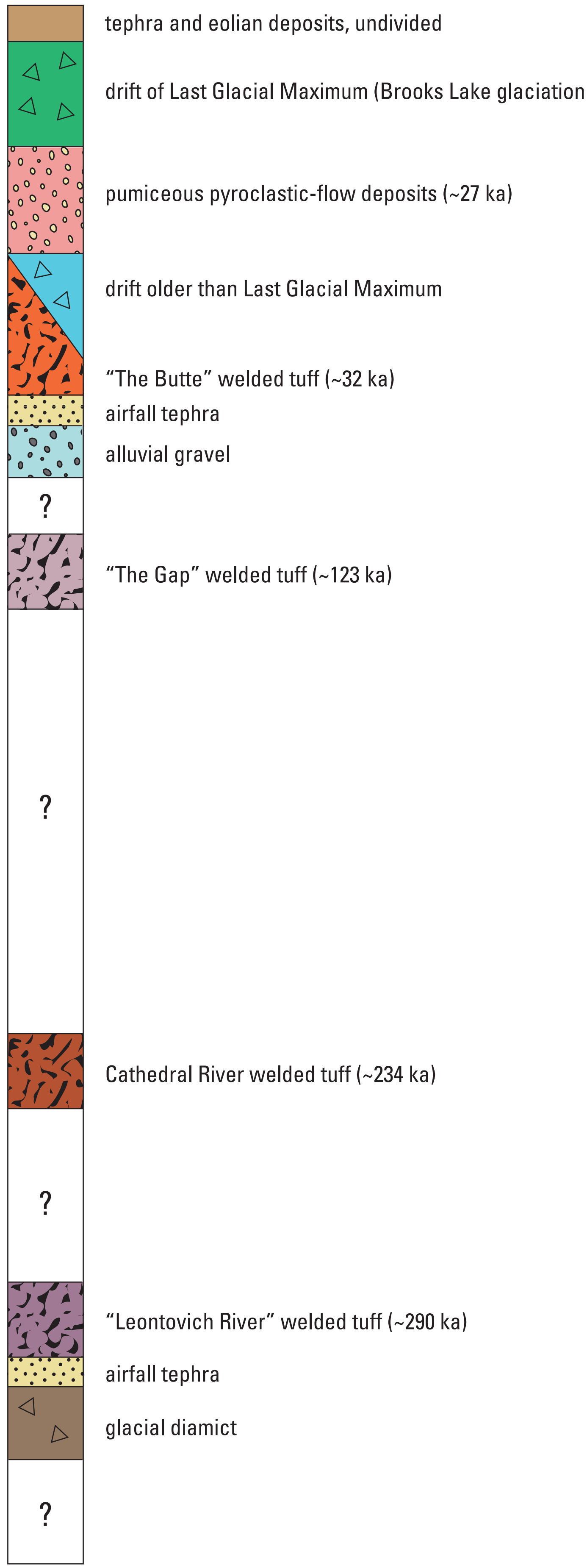


Figure 18. Schematic (not to scale) composite stratigraphic section, showing field relations common among various pyroclastic-flow deposits, airfall-tephra deposits, and glacial deposits in area of Emmons Lake volcanic center. Stratigraphy of queried sections is unknown. Abbreviation: ka, kilo-annum.

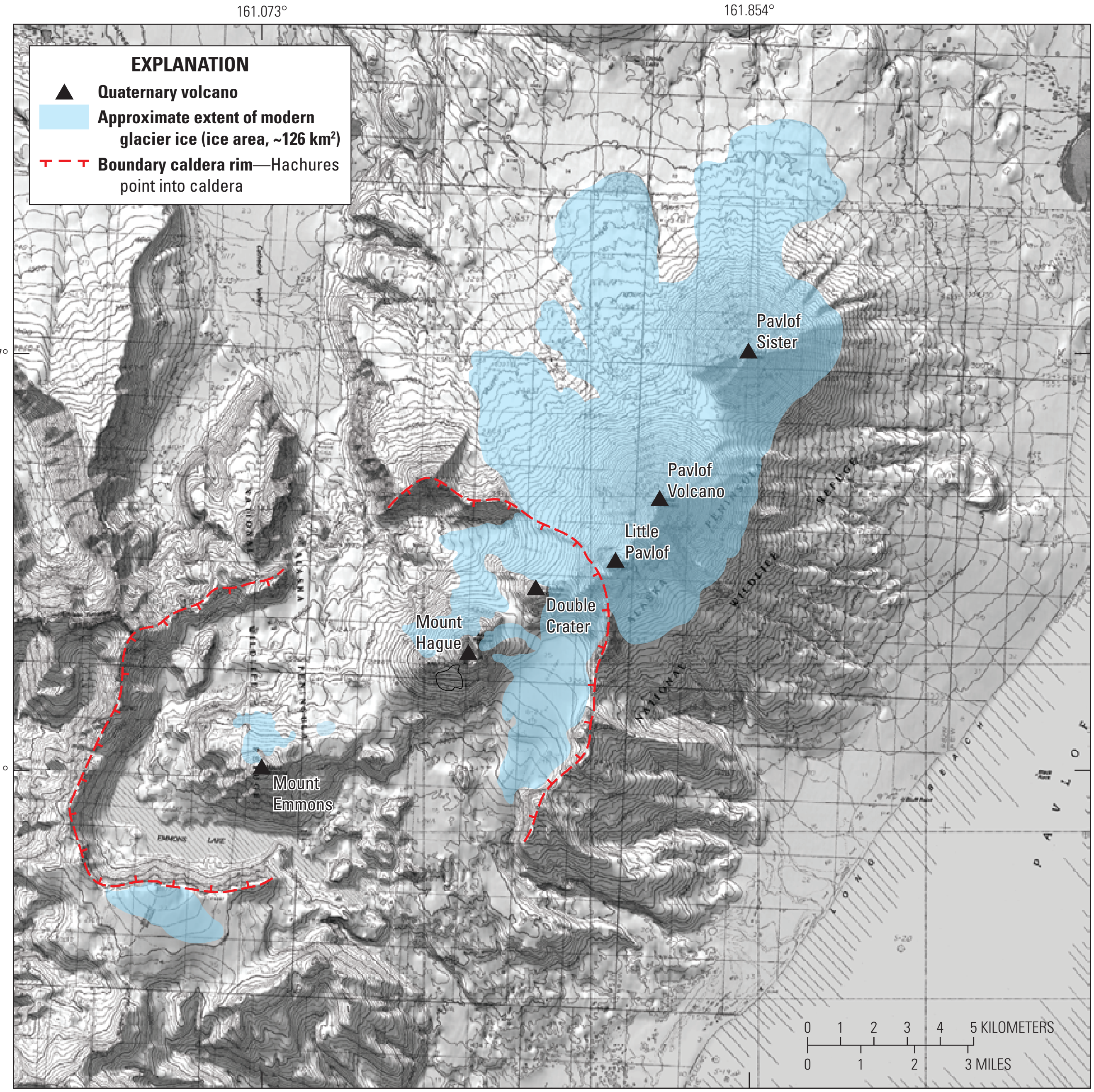


Figure 19. Shaded-relief map of Emmons Lake volcanic center (ELVC) and vicinity, showing extent of modern glacier ice (light-blue shading) in relation to Quaternary volcanoes (black triangles) and caldera boundaries (dashed, hachured red lines) at ELVC. Topographic base map from U.S. Geological Survey (USGS), Cold Bay B–1 and Port Moller B–6 (1983) 1:63,360-scale quadrangles. Shaded-relief base map from USGS 1/3-arc-second 1°×1° data. Abbreviation: km², square kilometer.

Introduction to the Description of Map Units

The area surrounding Emmons Lake includes a variety of volcanic cones, vents, and features, which formed during a long-lived period of energetic volcanism that spanned much of the late Quaternary. The area includes several large stratovolcanoes and at least three nested caldera structures, collectively referred to as the Emmons Lake volcanic center (ELVC). The elevation of the outermost caldera rim ranges from about 915 m southwest of Emmons Lake to 2,060 m at Little Pavlof volcano on the northeastern margin. The scarp above Emmons Lake exposes about 600 m of thick-bedded lava flows and volcaniclastic rocks that make up ancestral Mount Emmons. The caldera complex is breached on both its north and south sides by broad glacial valleys, and Holocene lava flows extend through these gaps. The north-side breach is about 3 km wide and contains the headwaters of the upper Cathedral River drainage. The breach on the south side, informally referred to as “The Gap,” is a 9-km-wide trough that includes an unnamed river that drains Emmons Lake. At least four geologically significant, silicic, welded rheomorphic tuffs (units cwt, bwt, hbwt, and gwt) have flowed through “The Gap” within the past 234 ka. Several of the welded tuffs show spectacular columnar jointing, particularly the Cathedral welded tuff (mapped as the rhyolite rheomorphic tuff, agglutinate, and breccia of upper Cathedral River drainage [unit cwt]) exposed at Dushkin Lagoon and in the upper Cathedral River drainage. The welded-tuff units are resistant to erosion, and, although these units have been repeatedly glaciated during the Pleistocene, many outcrops form prominent cliffs and mesas.

Glacier ice and various glacial deposits cover large parts of the floor of the EVLC, and a number of the eruptive units show evidence for interaction with glacier ice. Ice-contact lavas and hyaloclastite are common within the caldera. Pleistocene glaciers flowed through, over, and around parts of the ELVC, and most of the unconsolidated deposits peripheral to the volcanic center are glacial in origin.

Given the remote setting, terrain, and weather conditions, some volcanoes and features in the map area could not be sampled comprehensively. A few volcanoes, such as Little Pavlof, are nearly inaccessible, and few samples of eruptive products have been collected. In some cases, individual lava flows within the caldera could be traced to source vents, and relative ages could be determined; however, not all lava flows were sampled, and, thus, only a general idea of the composition of respective vents and volcanoes has been established.

Nearly all map units are newly defined, but they retain some similarity to the units described by Kennedy and Waldron (1955). For example, we no longer use the term Dushkin Basalt but instead have reinterpreted this unit as the various rheomorphic tuffs described herein. A number of lava flows and pyroclastic flows generated during historically recorded eruptions of Pavlof Volcano have been consolidated, as individual deposits are too small to be depicted at map scale. In total, 72 units (including areas of ice [i]) are depicted on the geologic map.

Most of the main rock units were sampled for whole-rock major- and trace-element analysis (table 2.1, in appendix 2). These analyses were completed at the Washington State University GeoAnalytical Laboratory, in Pullman, Wash. We use the normalized-SiO_2 contents (that is, oxides recalculated to sum to 100 percent, volatile free; LeBas and others, 1986) as the basis for rock classification in which basalt contains 47 to 52 percent SiO_2; basaltic andesite, 52 to 57 percent SiO_2; andesite, 57 to 63 percent SiO_2; dacite, 63 to 68 percent SiO_2; rhyodacite, 68 to 72 percent SiO_2; and rhyolite, more than 72 percent SiO_2.

Age estimates for the map units are based on stratigraphic position, degree of surface alteration and weathering, ^{14}C dating, and K-Ar and $^{40}Ar/^{39}Ar$ age determinations. Radiocarbon age determinations (table 3.1, in appendix 3) were made by Geochron Laboratories, in Cambridge, Mass. The three ^{14}C ages reported in table 3.1 (appendix 3) are from samples of soil organic matter associated with buried soils below lava flows of Pavlof Volcano, and they are maximum limiting ages for the lava flows. The $^{40}Ar/^{39}Ar$ age determinations (table 1.1, in appendix 1) were made in the U.S. Geological Survey (USGS) Laboratory in Menlo Park, Calif., by A.T. Calvert (USGS), following methods described in Calvert and Lanphere (2006).

Thin-section photomicrographs of representative samples of most major rock units, along with brief descriptions, are provided in figures 4.1 through 4.82 (in appendix 4); data for the thin-sections are also provided in table 4.1 (in appendix 4).

DESCRIPTION OF MAP UNITS

[Cinder cones on map are labeled with letters (for example, cone A is labeled “A”); letters in square brackets are placed at approximate location of cone. Abbreviations: %, percent; $^{40}Ar/^{39}Ar$, argon-argon; ^{14}C, carbon-14; ka, kilo-annum (or, thousand years ago); K-Ar, potassium-argon; km, kilometer; km^2, square kilometer; km^3, cubic kilometer; m, meter; m^3, cubic meter; mm, millimeter; yr B.P., years before present]

SURFICIAL DEPOSITS

UNCONSOLIDATED SEDIMENTARY AND VOLCANIC DEPOSITS

al **Alluvial deposits (Holocene)**—Chiefly water-deposited sand, silt, and gravel, with local cobbles and boulders. Deposits of modern streams, active floodplains, and lowermost hillslopes. May include outwash deposits, alluvial fan deposits, colluvium, and reworked laharic debris be **Beach and eolian deposits, undifferentiated (Holocene)**—Moderately well to well-sorted, fine to coarse sand, and minor amounts of fine gravel. Typically found in well-defined linear beach ridges and dunes along Bering Sea and North Pacific Ocean coasts

c **Colluvial and talus deposits, undifferentiated (Holocene)**—Chiefly poorly sorted silt, sand, gravel, and boulders, in wedge- or fan-shaped accumulations along bases of steep slopes. Consists mostly of reworked hillslope debris and may include variable amounts of rockfall talus, landslide debris, rock-glacier deposits, and other mass-wasting deposits. May include minor amounts of alluvium, glacial deposits, and coarse air-fall tephra

gf **Gelifluction deposits (Holocene and Pleistocene)**—Poorly sorted, relatively thin, lobate accumulations of angular rock rubble, sand, and silt. Deposits are common on low-angle, low-relief slopes but also extend to relatively high elevations on the north (Bering Sea) flank of Emmons Lake volcanic center. Forms nested lobes and surfaces; results from flow of water-saturated, active-layer hillslope debris, in areas underlain by seasonal ground ice or permafrost

tr **Talus and rockfall deposits, undifferentiated (Holocene)**—Poorly sorted accumulations of angular to subangular boulders and cobbles. Typically found at bases of steep rock slopes or within narrow channels and gullies in areas of steep terrain

ls **Landslide deposits (Holocene and Pleistocene)**—Poorly sorted, massive accumulations of silt, sand, gravel, and boulders. Associated with slump and block-glide deposits and large debris avalanches from volcanic bedrock. Also occasionally found in areas covered with moderate-relief glacial deposits

df **Debris-flow deposits (late Holocene)**—Poorly sorted, lobate-shaped accumulations of boulders, gravel, sand, and silt. Locally consists of remobilized accumulations of air-fall tephra. Commonly forms at bases of steep, debris-filled gullies and chutes

rwt **Reworked tephra and slopewash deposits, undifferentiated (late Holocene)**—Moderately well sorted, massive to stratified accumulations of tephra from Pavlof Volcano (pt) reworked by water and wind

ICE AND GLACIAL DEPOSITS

Quaternary glacial deposits in the map area are only generally subdivided on the basis of their location and degree of morphological preservation. In general, most of the fresh-appearing knob-and-kettle terrain in lobate- or spatulate-shaped end moraines is assigned to the Brooks Lake glaciation (the drift of Brooks Lake glaciation [unit gbl]) of Detterman (1986), correlative with marine oxygen-isotope stage 2 (Railsback and others, 2015). None of the glacial deposits in the map area are directly dated. In the lowlands north of Pavlof Bay (fig. 17), glacial deposits of Brooks Lake glaciation are locally overlain by 1 to 2 m of eolian silt that contains numerous buried soils (typically weak Aj/Cox soils) and multiple, thin, dark, fine-grained tephra layers of generally unknown sources but likely from Pavlof Volcano. These deposits are thought to be entirely of Holocene age. An older drift unit (the older glacial drift [unit gdu]) that lies beyond the moraines of Brooks Lake glaciation in the Pavlof Bay lowland (northeastern part of the map area) may be correlative with the Mak Hill glaciation, which is generally documented as the penultimate drift unit on the Alaska Peninsula (Muller, 1953; Detterman, 1986). Mak Hill drift in the Pavlof Bay lowland is overlain by pumice-bearing pyroclastic deposits (the rhyolite pyroclastic-flow deposits [unit pfd]) that erupted about 27 ka during the last known caldera-forming eruption of Emmons Lake volcanic center (Mangan and others, 2003) and, thus, records an ice advance of considerable extent that predates this eruption. Correlation of glacial deposits of Mak Hill glaciation in the map area was not attempted, but it is likely that the next drift unit (gdu) beyond moraines of Brooks Lake glaciation is associated with the Mak Hill ice advance. Although pumiceous pyroclasts (pfd) generated by the caldera-forming eruption about 27 ka are found in areas west-northwest of Emmons Lake volcanic center, other glacial deposits that are likely associated with the Mak Hill glaciation do not have a conspicuous cover of pumiceous material except for the deposits in the Pavlof Bay lowland (fig. 3).

i **Modern glacier ice (Holocene, modern)**—May include minor amounts of supraglacial drift, outwash deposits, and talus

gdh **Young glacial drift (Holocene, modern)**—Terminal, lateral, and ground moraines associated with Holocene and present-day (2021) glaciation. Typical deposits consist chiefly of poorly sorted, massive diamicton and rock rubble, in matrix of sand and silt. Moraines are commonly fronting or are just beyond termini of modern glaciers. Morphology is typically very fresh, and moraines are sharp crested and little modified. Vegetation cover ranges from none to scattered shrubs and discontinuous mats of moss and lichen within thin, discontinuous incipient soils. May include glaciofluvial outwash deposits gbl **Drift of Brooks Lake glaciation (late Pleistocene)**—Terminal, lateral, and ground moraines formed during Last Glacial Maximum. Includes local assemblages of nested end moraines mainly at heads of Cold Bay and Pavlof Bay and in lower Cathedral River valley (fig. 3). Deposits in these locations have characteristic knob-and-kettle topography and consist primarily of massive, unsorted, cobble-boulder diamict that has silty to sandy matrix. May include minor amounts of outwash and glaciolacustrine deposits. Moraines of Brooks Lake glaciation are vegetated and support nearly continuous cover of shrubs and subarctic tundra. Moraine crests are locally wind deflated or otherwise overlain by sequence, 1 to 2 m thick, of eolian deposits and tephra with multiple buried soils. Erratic boulders of various rock types derived from Emmons Lake volcanic center are present on most moraine crests

gblo **Outwash deposits of Brooks Lake glaciation (late Pleistocene)**—Moderately well sorted, stratified to massive accumulations of clast-supported sand, gravel, and scattered boulders. Forms glaciofluvial outwash terraces and outwash drainage channels associated with the drift of Brooks Lake glaciation (unit gbl)

gdu **Older glacial drift (Pleistocene)**—Glacial deposits that are more extensive and are morphologically more subdued than the drift of Brooks Lake glaciation (unit gbl). Hummocky kettle-kame morphology is largely absent, although isolated remnant kettle lakes are present. Consists mainly of drift of Mak Hill glaciation but also includes older drift units. Consists of poorly sorted, massive, cobble-boulder diamict overlain by 1 to 2 m of eolian silt that contains sparse layers of fine volcanic ash and buried soils. Typically supports muskeg tundra, grasses, and low shrubs

VOLCANIC ROCKS AND DEPOSITS

INTRACALDERA VOLCANIC ROCKS AND DEPOSITS

Cinder Cones

cc **Cinder cones (Holocene to late Pleistocene)**—At least 10 large, reddish cinder cones (labeled A–I and L) scattered across floor of caldera complex in Emmons Lake volcanic center (fig. 1). Two additional cinder cones (labeled J, K) are present on east flank of Pavlof Volcano. Composed of oxidized cinder, scoria, and agglutinate of basalt, basaltic andesite, and andesite composition. Cones are not dated directly but appear relatively fresh, are unvegetated, and likely range from Holocene to late Pleistocene age. Major phenocrysts in representative samples are mainly euhedral plagioclase (95−99 percent) 1 to 4 mm long and minor amounts of pyroxene as long as 1.5 mm

Lava Flows from Cinder Cones

Multiple, steep-fronted, blocky Holocene andesitic lava flows have erupted through breaches in six of the cinder cones (A, B, C, D, E, and F), and they form several lava fields inside the caldera complex that cover a total area of about 60 km^2 and have a total volume of at least 0.6 km^3. These lava flows are as much as 20 m thick and have steep flow fronts, well-developed marginal levees, and rough tops that are characterized by irregularly curved ridges (ogives). The Holocene lava flows have originated from six of the eight cinder cones within the caldera complex; most of them (about 75 percent) are from cones D and E, which are only 2 km apart near the base of the southwest flank of Mount Hague volcano.

Relative ages of individual flow units in a particular flow field can be determined by cross-cutting relations and stratigraphy; however, the age relations among the intracaldera lava fields are largely unknown. The amount of vegetation varies as a function of age and location. Some of the older, lower elevation lava flows, such as flows dlf1 and dlf3, are covered almost completely by lichen and shrubs.

Lava-flow fields range in elevation from 30 to 823 m, and they extend as much as 12 km from their source. The oldest lava flows from cone D extend the farthest, which suggests that the size of the magma source that feeds the intracaldera vents may be decreasing over time. Lava flows erupted from cone D flowed southeastward through “The Gap” to within a kilometer of the present-day (2021) coastline. The early lava flows from cone D that flowed toward the North Pacific Ocean may have partly blocked or slowed later flows, preventing them from following the same path and diverting them toward what is now Emmons Lake.

alf **Cone A lava flow (Holocene)**—Very fresh, blocky, dark-gray andesite (57% SiO_2) lava flow, erupted into Emmons Lake from breach in southwest wall of cone A. This flow and youngest lava flow from cone D (dlf5) are youngest lava flows within caldera complex. Covers about 3.2 km^2 and averages about 10 m in thickness. Major phenocrysts in one lava sample include about 90 percent plagioclase (1.7–2.2 mm long), 5 to 7 percent clinopyroxene (0.8–2.2 mm long), and 1 to 2 percent orthopyroxene (0.6–1 mm long)

blf **Cone B lava flow (Holocene)**—Minor lava-flow field associated with two small craters that make up cone B. Flows show relatively fresh appearing, blocky surface morphology and have patchy surface mantle of ash. Partly overlain by flow clf2 from cone C

Cone C lava flows (Holocene)—Blocky, ropey-surfaced ‘a‘ā lava flows from breached cone C. Divided into the following subunits:

clf2 **Cone C lava flow 2**—Lava flow that flowed northward and southward from cone C; overlies flow clf1

clf1 **Cone C lava flow 1**—Lava flow that flowed northward from cone C; underlies flow clf2

Cone D lava flows (Holocene)—Series of five overlapping, thick, blocky, dark-gray andesite (51–59% SiO_2) lava flows. Flows extend from cone D in about center of caldera complex, and they cover total area of about 45 km^2: to south, they extend to Emmons Lake, damming it at its east end; to southeast, they extend through “The Gap” almost to North Pacific Ocean. Individual lava flows have average thickness of about 10 m. Absolute age is unknown; however, flow dlf5 is youngest, covering 14 km^2, and flow dlf1 is oldest, on the basis of stratigraphy and differences in vegetation; flows dlf4 and dlf3 may be same flow. Youngest flow dlf5 originates from cone D; source of other cone D flows is obscured by flow dlf5 but is assumed to be cone D because of location and composition (table 2.1, in appendix 2). Major phenocrysts in one sample from flow dlf1 include 97 percent plagioclase (1.6–4.5 mm) and 3 percent clinopyroxene (1.4–2.8 mm); also includes trace amounts of orthopyroxene and olivine. Divided into the following subunits:

dlf5 **Cone D lava flow 5**

dlf4 **Cone D lava flow 4**

dlf3 **Cone D lava flow 3**

dlf2 **Cone D lava flow 2**

dlf1 **Cone D lava flow 1**

Cone E lava flows (Holocene)—Series of six partly overlapping, thick, blocky, dark-gray andesite (55.6% SiO_2) lava flows covering total area of about 7 km^2 in central part of caldera complex. Absolute age is unknown; flow elf1 is oldest flow of sequence, and elf6 is youngest. Divided into the following subunits:

elf6 **Cone E lava flow 6**

elf5 **Cone E lava flow 5**

elf4 **Cone E lava flow 4**

elf3 **Cone E lava flow 3**

elf2 **Cone E lava flow 2**

elf1 **Cone E lava flow 1**

flf **Cone F lava flow (Holocene)**—Small, blocky lava flow that extends from cone F on lower southwest flank of Mount Hague volcano. Covers about 0.4 km^2

glf **Cone G lava flow (Holocene)**—Thick, dark-gray, blocky basaltic andesite (53.6–54% SiO_2) lava flow, about 4 km long; extends out of northwestern part of caldera complex into headwaters of Cathedral River. Upper part near cone G is partly obscured by overlying glacial deposits of Holocene age. Compositionally similar to basaltic andesite lavas from Pavlof Volcano and is, thus, unlike other andesitic lava flows of Holocene age inside caldera complex. Major phenocrysts are 95 to 96 percent plagioclase (1.7–3.5 mm) and 2 to 4 percent clinopyroxene (1–4 mm), as well as sparse amphibole and olivine (1–2 mm)

Major Volcanic Vents and Associated Lava Flows

Volcanic rocks of Mount Hague (early Holocene? to late Pleistocene)—Lava flows of andesitic composition (57.5% SiO_2) on lower northwest flank of Mount Hague volcano. Lava flows show ice-erosional features associated with Holocene glacier expansion. Major phenocrysts in one sample from subunit hlf4 include 98 percent plagioclase (1.8–3 mm), 2 percent clinopyroxene (1–1.6 mm), and rare orthopyroxene (≤1.2 mm). Divided into the following subunits:

hlf4 **Volcanic rocks of Mount Hague, subunit 4**

hlf3 **Volcanic rocks of Mount Hague, subunit 3**

hlf2 **Volcanic rocks of Mount Hague, subunit 2**

hlf1 **Volcanic rocks of Mount Hague, subunit 1** hv **Volcanic rocks and pyroclastic deposits of Mount Hague (early Holocene? to late Pleistocene)**—Undifferentiated andesite to dacite (53.2–64.4% SiO_2) lava flows, volcanic breccia, and cinder-rich scoria deposits associated with Mount Hague volcano. Major phenocrysts include 98 percent plagioclase (1.6−3 mm) and 1 to 2 percent clinopyroxene (0.9−2.6 mm); also includes minor amounts of orthopyroxene and opaque minerals

dv **Volcanic rocks and pyroclastic deposits of Double Crater (early Holocene? to late Pleistocene)**—Andesite to dacite (56.1–65% SiO_2) lava flows and cinder-rich scoria deposits of Double Crater volcano. Major phenocrysts in one sample are 99 percent plagioclase (1.4−2.4 mm) and 1 percent orthopyroxene (0.9−1.4 mm); also includes rare clinopyroxene

ev **Volcanic rocks of Mount Emmons (late Pleistocene)**—Primarily massive andesite to dacite (55.2–63.6% SiO_2) lava flows containing prominent vertical to horizontal columnar joints and subordinate cinder-rich scoria deposits. Lava flows emanate from vents on or near summit of Mount Emmons volcano. Major phenocrysts include 90 to 97 percent plagioclase (1−5 mm), 1 to 5 percent pyroxene (0.8−2.3 mm), and <1 percent olivine (0.4−0.8 mm). $^{40}Ar/^{39}Ar$ ages: basal flow, 17.1±0.9 and 18±0.8 ka

lfu **Lava flows and pyroclastic deposits, undifferentiated with respect to source volcano (Pleistocene)**—Andesite lava flows, volcanic breccias, and cinder cones within central to southern part of caldera complex. Typically found as outliers (kipukas) surrounded by Holocene lava flows. Lava surfaces have glacial striations and local accumulations of drift and are, therefore, likely to be Pleistocene age. Major phenocrysts in one sample are 90 percent plagioclase (1.6−2.2 mm) and 10 percent clinopyroxene (0.7−1.2 mm)

Lava flows on south caldera rim (Pleistocene)—Andesitic lava flows confined to southern part of caldera rim. Columnar-jointed, thick, massive, and modified by glacial erosion. Flows olf4, olf3, and olf1 cover older caldera rim remnant south of Emmons Lake. Source volcano for these flows was likely large volcano (younger than ancestral Mount Emmons volcano) located in general area of Emmons Lake that was largely destroyed by later caldera-forming eruption between 99 and 126 ka. Major phenocrysts include 95 to 97 percent plagioclase (1.2−5 mm), 2 to 5 percent clinopyroxene (0.4−2.8 mm), and 1 to 2 percent orthopyroxene (0.6−2.2 mm), as well as rare olivine (0.5−1.1 mm). $^{40}Ar/^{39}Ar$ ages: flow olf4, 128.5±4.3 ka; flow olf1, 131.6±1.0, 136.7±1.3, and 197.0±21.5 ka. Divided into the following subunits:

olf4 **Lava flow 4 on south caldera rim**

olf3 **Lava flow 3 on south caldera rim**

olf2 **Lava flow 2 on south caldera rim**

olf1 **Lava flow 1 on south caldera rim**

CALDERA-RELATED ROCKS AND DEPOSITS

pfd **Rhyolite pyroclastic-flow deposits (late Pleistocene)**—Pumiceous pyroclastic-flow deposits produced by most recent caldera-forming eruption, dated locally at about 27 ka and by correlation with the Dawson tephra of Naeser and others (1982) (see Froese and others, 2002; Mangan and others, 2003; Davies and others, 2016). Composed of cream-colored, subrounded rhyolite pumice (69–72% SiO_2); includes pumice pyroclasts as much as 1 m long. Lithic clasts are sparse but, where present, are as much as 3 cm long. Phenocrysts are sparse and consist mainly of 98 to 99 percent plagioclase (0.4−2.4 mm) and scattered (1−2 percent) pyroxene (0.3−1 mm). Glassy, fibrous groundmass common. Typically matrix supported, nonwelded, and massive to thinly bedded; maximum primary thickness as much as 25 m. Locally contains as many as eight flow units. Reworked by glaciers, which has resulted in secondary thicknesses of as much as 100 m on east flank of caldera complex. Interbedded with fluvial and glacial deposits, as well as with Pavlof Volcano lava flows. Widespread and found in all areas around caldera complex, extending to distances of more than 60 km from center of caldera complex. Emplacement age may be as old as 29 ka, on the basis of correlation with the Dawson tephra of Naeser and others (1982) (Davies and others, 2016)

bwt **Dacite rheomorphic tuff and agglutinate of “The Butte,” undivided (late Pleistocene)**—Medium-dark-gray, intensely welded, columnar-jointed, lavalike dacite rheomorphic tuff and agglutinate exposed as flat-topped butte in center of “The Gap” on southeast flank of caldera complex. Major phenocrysts in one sample consist of 98 percent plagioclase (2.6−3.5 mm) and 1 to 2 percent clinopyroxene (0.9−1.4 mm), as well as rare amphibole and olivine (0.5−0.6 mm). $^{40}Ar/^{39}Ar$ age, 30.5±4.2 ka. Locally divided into the following subunit:

hbwt **Subglacial or subaqueous phase**—Consists of altered, tan-colored domes, pyroclastic material, and hyaloclastite, near southeast end of Emmons Lake

ida **Dacite to andesite lava domes, flows, coulees, and welded tuff (Pleistocene)**—Chiefly thick, black, glassy dacite to andesite (60–64% SiO_2) domes, flows, and coulees that have contorted, vertical to horizontal columnar jointing, indicative of glacier-ice contact during emplacement. Low-relief domes form prominent flat-topped, mesalike features near southeast end of Emmons Lake. Includes outcrop of rheomorphic rhyodacite welded tuff located in "The Gap" on southeast flank of caldera complex. Inside caldera complex, overlain by lava flows from Mount Emmons volcano. Major phenocrysts include 93 to 99 percent plagioclase (1−4 mm), 1 to 5 percent clinopyroxene (0.7−2.2 mm), and 1 to 3 percent orthopyroxene (0.6−2.4 mm), as well as rare amphibole (0.6−1.3 mm). $^{40}Ar/^{39}Ar$ ages, 98.6±6.6 and 99.2±3.2 ka

gwt **Rhyodacite rheomorphic tuff, agglutinate, and ignimbrite of "The Gap" (late Pleistocene)**—Medium-dark-gray, intensely welded, columnar-jointed, lavalike rhyodacite rheomorphic tuff, agglutinate, and ignimbrite. Exposed only along east wall of caldera complex, just northeast of "The Gap." Locally underlain by discontinuous, 2- to 3-m-thick deposits of light-colored, pumiceous rhyolite air-fall tephra (see fig. 7*C*). Major phenocrysts include 94 to 100 percent plagioclase (0.8−3.5 mm), 1 to 3 percent clinopyroxene (1−2 mm), and 1 to 3 percent orthopyroxene (0.9−1.4 mm), as well as rare amphibole (0.9−1.2 mm). $^{40}Ar/^{39}Ar$ age, 123.1±5.1 ka

cwt **Rhyolite rheomorphic tuff, agglutinate, and breccia of upper Cathedral River drainage (middle Pleistocene)**—Medium-dark-gray, intensely welded, lavalike rhyolite welded tuff, rheomorphic tuff, agglutinate, and caldera-collapse lithic breccia. Breccias are primarily in lower part of sequence. Many outcrops show prominent columnar jointing, have well-developed eutaxitic texture, and contain dense, black masses of obsidianlike glass that contains abundant lithic clasts. Major phenocrysts include 70 to 99 percent plagioclase (0.8−4 mm), 1 to 30 percent clinopyroxene (0.4−2.5 mm), and 1 to 2 percent orthopyroxene (0.8−4 mm), as well as rare amphibole (0.5−2.4 mm); olivine was present in only one sample (of 17). Exposed chiefly as prominent cliff-forming rocks in upper Cathedral River drainages (see fig. 7*D*) on north flank of caldera complex and in single, long exposure along north side of Dushkin Lagoon on southernmost flank of caldera complex. As much as 200 m thick where ponded near caldera rim on north flank of caldera complex. $^{40}Ar/^{39}Ar$ ages, 237±6.1 and 238±5.1 ka. K-Ar age, 187.2±21.4 ka

lwt **Rhyolite welded tuff of "Leontovich River," undivided (middle Pleistocene)**—Chiefly light– to medium–dark-blueish-gray, fine-grained, intensely welded rhyolitic tuff. Typical outcrops along unnamed river, known locally as "Leontovich River," consist of massive, slabby, thick-bedded deposits as much as 15 m thick. Exposed chiefly in lowlands 25 to 35 km northeast of caldera complex where tuff forms prominent cliff-forming, mesa-like body that crops out over 25 km^2 area in "Leontovich River" drainage. Locally overlies 2-m-thick, white, fine-grained rhyolitic air-fall tephra. Major phenocrysts include 95 to 98 percent plagioclase (1−2.7 mm), 1 to 2 percent orthopyroxene (0.5−1 mm), and 1 to 2 percent clinopyroxene (0.5−1.4 mm), but clinopyroxene is absent in some samples. Groundmass has distinctive flow banding and, in places, brown opaque glass. $^{40}Ar/^{39}Ar$ ages, 295±5.1 and 299±7.1 ka. K-Ar age, 290.9±6.1 ka. Locally divided into the following subunit:

lwto **"Otter Den" tuff subunit**—Partly welded tuff, distinguished by flattened pumice and fiamme, locally exposed low on flanks of precaldera Emmons Lake edifice, primarily on north side of caldera complex

VOLCANIC ROCKS AND DEPOSITS OUTSIDE CALDERA COMPLEX

Pavlof Volcano

Only the most recent lava flows from the 2013, 2014, and 2016 eruptions of Pavlof Volcano are mapped in detail. Older historically recorded lava flows are largely obscured by tephra, lahar deposits, and pyroclastic deposits. Historically recorded eruptions have occurred from a summit vent that has intermittently migrated between the north and southeast sides of the cone, resulting in lava flows, pyroclastic flows, and lahar deposits that extend toward either the Bering Sea (northwest side) or the North Pacific Ocean (southeast side). Typical Pavlof Volcano eruptions are Strombolian to Vulcanian in character; lava fountaining is common. Collapse of hot debris from the unstable crater lip area has resulted in clastogenic lava flows, pyroclastic flows, and surge deposits. Abundant debris-covered glacier ice on the volcano is a source of water for lahars, which typically form when hot granular-mass flows sweep down the flanks of the volcano and interact dynamically with ice and snow (Waythomas, 2015; Waythomas and others, 2017).

sa **Spatter, agglutinate, cinders, and ash of Pavlof Volcano summit (late Holocene)**—Irregular accumulations of spatter and coarse ash at summit of Pavlof Volcano, formed during periods of lava fountaining and explosive eruptions

vc **Inferred volcanic conduit (late Holocene)**—Shown in cross section only

ppf **Pyroclastic-flow deposits of 2016 eruption of Pavlof Volcano (late Holocene)**—Thin, granular, scoriaceous pyroclastic-flow deposits on flanks of Pavlof Volcano, emplaced during March 2016 eruption

pvl **Lahar deposits of historically recorded eruptions of Pavlof Volcano (late Holocene)**—Dark-gray to black, poorly sorted to moderately well sorted, clast-supported accumulations of boulders, gravel, sand, and silt. Forms valley-filling deposits in drainages of “Leontovich,” upper Caribou, and upper Cathedral Rivers and coalescing fans of laharic debris on south flank of Pavlof Volcano

plf14 **Basaltic andesite lava flow of 2014 eruptions of Pavlof Volcano (late Holocene)**—Dark-gray to reddish-brown, rubbly, clastogenic basaltic andesite (53% SiO_2) lava flow, emplaced during eruptions of Pavlof Volcano in May–June and November 2014. Total volume of lava erupted during 2014 eruptions is about 12×10^6 m^3 (Waythomas, 2015; Waythomas and others, 2017)

plf13 **Basaltic andesite lava flow of 2013 eruption of Pavlof Volcano (late Holocene)**—Dark-gray to reddish-brown, rubbly, clastogenic basaltic andesite (53% SiO_2) lava flow, emplaced during eruption of Pavlof Volcano in 2013. Total volume of lava erupted during 2013 eruption is about 1.5×10^6 m^3 (Waythomas and others, 2014)

pt **Tephra deposits of historically recorded eruptions of Pavlof Volcano (late Holocene)**—Dark-gray to black, fall-sorted, surface-mantling accumulations of coarse, scoriaceous air-fall tephra. Major phenocrysts in two samples include 98 to 99 percent plagioclase (1.5–2.4 mm) and minor amounts of pyroxene, olivine, and amphibole. Commonly reworked by wind, water, or both

plfh **Clastogenic lava flows of historically recorded eruptions of Pavlof Volcano (late Holocene)**—Dark-brown to reddish-brown, rubbly lava-flow remnants on upper north flank of Pavlof Volcano. Largely obscured by cover of tephra, pyroclastic debris, and lahar deposits. Major phenocrysts include 90 to 99 percent plagioclase (1.6–3 mm) and 1 to 10 percent olivine (0.4–0.6 mm), as well as minor amounts of pyroxene (0.4–0.7 mm). Radiocarbon ages on soil organic matter immediately below two lava flows are 3,500 to 4,500 ^{14}C yr B.P. (table 3.1, in appendix 3)

plh **Basalt to andesite lava flows of Pavlof Volcano (Holocene)**—Thick-bedded (>10 m), massive, blocky to rubbly, commonly clastogenic basaltic andesite (51.3–56.2% SiO_2) lava flows. Major phenocrysts include 90 to 99 percent plagioclase (0.5–2.6 mm) and 1 to 20 percent olivine (0.5–1.3 mm), as well as sparse (1–2 percent) pyroxene (0.4–1.7 mm)

plp **Andesite lava flows of Pavlof Volcano (Pleistocene)**—Thick-bedded, columnar-jointed andesite lava flows on southeast flank of Pavlof Volcano and in prominent tuya northeast of Pavlof Volcano. Major phenocrysts include 90 to 99 percent plagioclase (0.5–2 mm), 1 to 5 percent olivine (0.3–1 mm), and 1 percent pyroxene (0.6–2.7 mm). Largely mantled by younger lava flows, pyroclastic debris, and tephra, as well as glacial deposits of Brooks Lake glaciation. $^{40}Ar/^{39}Ar$ ages, 28.2±8.5 and 28.6±12.3 ka

Pavlof Sister

pslf **Basaltic andesite lava flows, breccia, and scoria of Pavlof Sister (Holocene to late Pleistocene)**—Lava flows interbedded with deposits of coarse volcanic breccia and cindery scoria. Lava flows are thick bedded (>10 m), massive, and blocky; some are clastogenic. Lava flows are chiefly porphyritic basaltic andesite (52.7–54.2% SiO_2). Major phenocrysts include 90 to 98 percent plagioclase (1.2–5 mm), 1 to 3 percent orthopyroxene (0.4–1.4 mm), 1 to 3 percent clinopyroxene (0.7–2 mm), and 1 percent olivine (0.3–1.3 mm). Edifice has relatively youthful appearance; it shows no evidence of being glaciated during late Pleistocene and probably developed after glaciers retreated from area, sometime after about 18 ka. Much of volcano is mantled by extensive cover of tephra from Pavlof Volcano (unit pt). No historically recorded eruptions have occurred

Little Pavlof

lplf **Basalt of Little Pavlof (Pleistocene)**—Basalt (51.3% SiO_2) lava flows interbedded with deposits of coarse volcanic breccia and cinder-rich scoria. Locally hydrothermally altered. Largely covered by glacier ice

Precaldera Volcanic Rocks

occ **Basaltic andesite cinder cones (Pleistocene)**—Dispersed field of subdued, reddish, highly oxidized basaltic andesite cinder-cone craters, located on distal west flank of Emmons Lake volcanic center

cbl **Andesite of ancestral Mount Emmons (middle to early Pleistocene)**—Predominantly basaltic andesite lava flows and subordinate interbedded volcaniclastic rocks that include volcanic breccias, scoria, pyroclastic deposits, conglomerates, and agglomerates. Major phenocrysts include 70 to 99 percent plagioclase (1.2–4.4 mm), 1 to 10 percent orthopyroxene (0.5–3.5 mm), 1 to 20 percent clinopyroxene (0.8–3.5 mm), and 1 to 2 percent olivine (0.5–2.5 mm). Massive and thick bedded to chaotic and poorly sorted; hundreds of meters thick. Cut by numerous near-vertical andesitic dikes. $^{40}Ar/^{39}Ar$ ages, 397±7.4 and 793.5±5.8 ka (basal lava flow) to 895.8±5.6 ka (distal lava flow)

cbv **Andesitic volcaniclastic rocks of ancestral Mount Emmons (middle to early Pleistocene)**—Predominantly massive and thick-bedded basaltic andesite volcaniclastic rocks, including volcanic breccia, pyroclastic rocks, conglomerates, and agglomerates and subordinate interbedded lava flows; hundreds of meters thick. Locally interbedded with rocks of the andesite of ancestral Mount Emmons (unit cbl) and cut by many near-vertical andesitic dikes

Other Volcanic Rocks and Deposits

erlf **Andesite of east caldera rim (middle Pleistocene)**—Massive, glaciated andesite lava flows truncated by east rim of caldera complex. May include some rocks of the andesite of ancestral Mount Emmons (unit cbl) and may be correlative in part to the andesite of Volcano Bay area (unit vblf). $^{40}Ar/^{39}Ar$ age, 149.8±3.8 ka

vblf **Andesite of Volcano Bay area (middle? Pleistocene)**—Massive, medium- to dark-gray andesite lava flows. May be locally truncated by ancestral caldera rim south of Emmons Lake. Age of unit is uncertain, but it is older than flow olf1, and it locally overlies, and is therefore younger than, the andesite of ancestral Mount Emmons (unit cbl)

ulf **Basalt and basaltic andesite lava flows (Pleistocene)**—Chiefly olivine-bearing basalt and basaltic andesite lava flows, in isolated outcrops at Arch Point, Bluff Point, Black Point, and along western shoreline of Pavlof Bay on North Pacific Ocean coast (fig. 2); some outcrops too small to show on map. Fresh, unaltered basaltic andesite lava (54.3% SiO_2) at Arch Point shows columnar jointing and numerous arches in coastal outcrops; possibly of ice-contact origin. Lenticular outcrop pattern and dip of fresh lava flows at Arch Point suggest correlation of these flows with the andesite of ancestral Mount Emmons (unit cbl) of Emmons Lake volcanic center. Major phenocrysts in one sample are 99 percent plagioclase (1–2 mm) and 1 percent pyroxene (0.5–2.1 mm). Source vents for other lava flows assigned to this unit are unknown, and individual outcrops may not be related

tmd **Hypabyssal dacite of Trader Mountain (early Pleistocene)**—Medium-gray, porphyritic dacite. Locally altered and frost shattered. K-Ar age, 980±50 ka (Wilson and others, 1995)

BASEMENT ROCKS

Ti **Hypabyssal quartz diorite (late Tertiary)**—Small stocks and plugs of fine-grained, hypabyssal quartz diorite. Probably of Pliocene to late Miocene age (Wilson and others, 1997)

Tvs **Volcanic and sedimentary rocks, undifferentiated (late Tertiary)**—Chiefly grayish-greenish purple, nonmarine volcanogenic sandstone, siltstone, and conglomerate, interbedded with tuff and volcanic breccia. Locally silicified and seriticized. Probably of Miocene to late Oligocene age (Wilson and others, 1997)

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Appendix 1. Argon Geochronology

Argon geochronology (ages and data) for selected volcanic rocks in the Emmons Lake volcanic center, Alaska, are provided in table 1.1.

Table 1.1. Argon geochronology (ages and data) for samples from the Emmons Lake volcanic center, Alaska.

[Latitude (lat) and longitude (long) values are in North American Datum of 1927 (NAD 27), Universal Transverse Mercator (UTM) zone 4. See Description of Map Units for map-unit descriptions. All argon-argon ($^{40}Ar/^{39}Ar$) and potassium-argon (K-Ar) ages are in kilo-annum (ka [thousand years ago]); ages in bold are preferred ages. Methods: $^{40}Ar/^{39}Ar$ incremental heating and argon-40–initial argon-36 atmospheric ($^{40}Ar/^{36}Ar_i$) ages; all ages calculated using 28.3436-mega-annum (Ma [million years ago]) U.S. Geological Survey (USGS) standard TCR-2 sanidine (equivalent to the Fish Canyon sanidine, at 28.0985 Ma; Fleck and others, 2019). Laboratories (Lab): 1, USGS, Menlo Park, Calif., $^{40}Ar/^{39}Ar$ laboratory; 2, University of Alaska Fairbanks, Alaska, $^{40}Ar/^{39}Ar$ laboratory (Drake and others, 2001); 3, USGS, Menlo Park, Calif, K-Ar laboratory (M.A. Lanphere, USGS, written commun., 1976). Other abbreviations: σ, sigma (standard deviation); ESE, east-southeast; MSWD, mean square of weighted deviates; ° N., degrees north; na, not available; NW, northwest; S, south; W, west; ° W., degrees west]

Map unit	Sample no.	Lat (° N.)	Long (° W.)	Description	Method	Material
bwt	99S13M1	55.30447	161.92486	Rheomorphic tuff	$^{40}Ar/^{39}Ar$	Dacite
cbl	03S72M1	55.54425	161.80231	Ancestral cone-building lava flow	$^{40}Ar/^{39}Ar$	Andesite
cbl	05ELAC04	55.49454	162.12573	Emmons cone building along Cathedral River	$^{40}Ar/^{39}Ar$	Andesite
cbv	05ELAC012	55.40412	162.12413	NW caldera wall; on map, colluvium (c) overlies cbv	$^{40}Ar/^{39}Ar$	Andesite
cwt	99S4M1	na	na	Cathedral welded tuff	$^{40}Ar/^{39}Ar$	na
cwt	99S6M2	na	na	Cathedral welded tuff	$^{40}Ar/^{39}Ar$	na
erlf	05ELAC32	55.35412	161.89929	Emmons cone building S of Little Pavlof volcano	$^{40}Ar/^{39}Ar$	Andesite
ev	05ELAC02	55.33133	162.06172	Mount Emmons plateau lava flow, ESE of Mount Emmons	$^{40}Ar/^{39}Ar$	Andesite
ev	05ELAC14	55.34705	162.09895	Mount Emmons plateau lava flow, W of Mount Emmons	$^{40}Ar/^{39}Ar$	Andesite
gwt	00S19M1B	55.32595	161.93776	Rheomorphic tuff	$^{40}Ar/^{39}Ar$	Dacite
gwt	00S19M1B	na	na	“The Gap” welded tuff	$^{40}Ar/^{39}Ar$	Dacite
ida	99S15M1	55.36372	162.11158	Subglacial dome or lava flow	$^{40}Ar/^{39}Ar$	Dacite
ida	00S28M3	55.28657	161.96099	Subglacial dome or lava flow	$^{40}Ar/^{39}Ar$	Dacite
lwt	99S9M3	55.61309	162.07	Welded tuff	$^{40}Ar/^{39}Ar$	Rhyolite
lwt	74AMm-9	55.61309	162.07	“Leontovich River” welded tuff	K-Ar	Dacite
lwto	00S31F1	na	na	“Otter Den” tuff	$^{40}Ar/^{39}Ar$	na
olf1	05ELAC21	55.31058	162.0745	Wall S of Emmons Lake	$^{40}Ar/^{39}Ar$	Andesite
olf1	05ELAC22	55.30512	162.07589	Wall S of Emmons Lake	$^{40}Ar/^{39}Ar$	Andesite
olf1	05NYEL032	55.31517	162.12282	Base of wall S of Emmons Lake	$^{40}Ar/^{39}Ar$	Andesite
olf4	03S88T1	55.29644	162.04997	Patio flow (drapes Volcano Bay caldera)	$^{40}Ar/^{39}Ar$	Andesite
plp	02S48M1	55.3961	161.85929	Pavlof Volcano lava flow; on map, ice (i) overlies plp	$^{40}Ar/^{39}Ar$	Andesite
plp	02S54M1	55.4001	161.80694	Older Pavlof Volcano lava flow; on map, glacial drift (gbl) overlies plp	$^{40}Ar/^{39}Ar$	Andesite
vblf	05ELAC38	55.28616	162.19267	Emmons cone building to W on wrist of “Mitten”	$^{40}Ar/^{39}Ar$	Andesite
vblf	74AMm-13B	55.23674	161.98034	Lava flow	K-Ar	Andesite
na	99S3T2	na	na	Fiamme welded lag breccia	$^{40}Ar/^{39}Ar$	na

Total gas age (ka)	Plateau age (ka) (±1σ)	Percentage (%) ^{39}Ar [steps]	MSWD	Isochron age (ka) (±1σ)	Percentage (%) ^{39}Ar [steps]	MSWD	$^{40}Ar/^{36}Ar_i$	Lab
40.7±3.1	**30.5±4.2**	51 [5 of 15]	0.25	18.7±38.7	100 [15 of 15]	10.06	307.6±13.1	1
921.6±5.1	**895.8±5.6**	47 [5 of 13]	0.11	898.9±5.6	47 [5 of 13]	0.07	295.8±3.6	1
840.2±3.1	**793.5±5.8**	38 [6 of 13]	0.4	797.7±9.7	38 [6 of 13]	0.49	297.8±2.2	1
370.3±8.1	**397.0±7.4**	73 [5 of 11]	0.35	418.1±65.7	73 [5 of 11]	0.45	295.6±14	1
na	na	na	na	237.0±6.1	na	na	na	2
na	na	na	na	238.0±5.1	na	na	na	2
140.4±4.1	**149.8±3.8**	92 [8 of 11]	0.88	149.8±10.4	92 [8 of 11]	1.05	298.6±5.4	1
15.3±1.0	**17.1±0.9**	95 [9 of 11]	1.25	19.6±2.5	95 [9 of 11]	1.18	295.2±6.9	1
16.3±1.0	**18.0±0.8**	90 [8 of 12]	1.23	14.4±2.9	90 [8 of 12]	1.18	303.3±8.4	1
133.3±1.0	**125.2±1.2**	88 [8 of 11]	0.68	127.6±2.1	88 [8 of 11]	0.55	291.9±8.3	1
na	na	na	na	123.1±5.1	na	na	na	2
na	na	na	na	100.7±7.1	na	na	na	2
na	na	na	na	100.7±3.1	na	na	na	2
na	na	na	na	299.0±7.1	na	na	na	2
290.9±6.1	na	na	na	na	na	na	na	3
na	na	na	na	295.0±5.1	na	na	na	2
136.3±1.0	**136.7±1.3**	82 [8 of 12]	2.56	143.1±6.8	82 [8 of 12]	2.86	293.5±10.9	1
131.2±1.0	**131.6±1.0**	90 [8 of 12]	2.32	133.7±5.0	90 [8 of 12]	2.75	296.1±11.3	1
265.5±6.1	219.4±7.5	49 [5 of 18]	1.35	**197.0±21.5**	100 [18 of 18]	3.97	302.3±2.8	1
128.2±5.1	**128.5±4.3**	100 [10 of 10]	0.34	125.6±11.1	100 [10 of 10]	0.36	299.6±5.3	1
37.3±11.2	20.9±8.3	53 [5 of 11]	1.04	**28.6±12.3**	100 [11 of 11]	1.73	294.0±2.2	1
29.5±10.2	**28.2±8.5**	100 [11 of 11]	0.52	35.4±13.7	100 [11 of 11]	0.45	296.9±3.4	1
224.8±1.0	**218.1±1.5**	67 [7 of 12]	1.54	223.0±4.0	67 [7 of 12]	1.38	293.1±8.6	1
187.2±21.4	na	na	na	na	na	na	na	3
na	na	na	na	424.2±9.2	na	na	na	2

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Appendix 2. Whole-Rock Compositions of Volcanic Rocks and Deposits

Whole-rock-composition data for selected volcanic rocks and deposits in the Emmons Lake volcanic center, Alaska, are provided in a data release (Waythomas and others, 2025) associated with this report. In the data release, the data are included in an Excel table entitled, “Table 2.1. Whole-rock compositions of volcanic rocks and deposits in Emmons Lake volcanic center in Alaska.xlsx.” Data are from Mangan and others (2009).

Table 2.1. Whole-rock compositions of volcanic rocks and deposits in Emmons Lake volcanic center in Alaska.

[Table is included in data release (Waythomas and others, 2025); table title included here for continuity]

References Cited in Appendix 2

Mangan, M., Miller, T., Waythomas, C., Trusdell, F., Calvert, A., and Layer, P., 2009, Diverse lavas from closely spaced volcanoes drawing from a common parent—Emmons Lake Volcanic Center, Eastern Aleutian Arc: Earth and Planetary Science Letters, v. 287, nos. 3–4, p. 363–372, https://doi.org/10.1016/j.epsl.2009.08.018.

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Appendix 3. Radiocarbon Ages

Radiocarbon-age data for selected volcanic rocks and deposits in the Emmons Lake volcanic center, Alaska, are provided in table 3.1.

Table 3.1. Radiocarbon ages of volcanic rocks and deposits in the Emmons Lake volcanic center, Alaska.

[Latitude (lat) and longitude (long) values are in North American Datum of 1927 (NAD 27), Universal Transverse Mercator (UTM) zone 4. Other abbreviations: σ, sigma (standard deviation); ^{14}C, carbon-14; ° N., degrees north; no., number; ° W., degrees west; yr B.P., years before present]

Sample no.	Laboratory no.	Lat (° N.)	Long (° W.)	^{14}C age (yr B.P.)	± (yr B.P.)	Calibrated 2σ age range (yr B.P.)	Relative area under probability distribution	Material
02S50F1C	GX-29848	55.38	161.79	3,470	70	3,568–3,911	1.0	Soil organic matter
02S50F2C	GX-29850	55.38	161.79	4,330	70	4,810–5,070	0.892	Soil organic matter
02S47F3C	GX-29849	55.37	161.80	4,560	130	4,870–5,484	0.955	Soil organic matter

Appendix 4. Thin-Section Photographs, Descriptions, and Associated Data

Thin-section data for selected volcanic rocks and deposits in the Emmons Lake volcanic center, Alaska, are provided in a data release associated with this report (Waythomas, 2025; see table entitled “Table 4.1. Thin-section data for volcanic rocks and deposits in the Emmons Lake volcanic center.xlsx”). Photographs and brief descriptions of the thin sections are provided in figures 4.1 through 4.82 below.

Table 4.1. Thin-section data for volcanic rocks and deposit in the Emmons Lake volcanic center.

[Table is included in data release (Waythomas, 2025); table title included here for continuity]

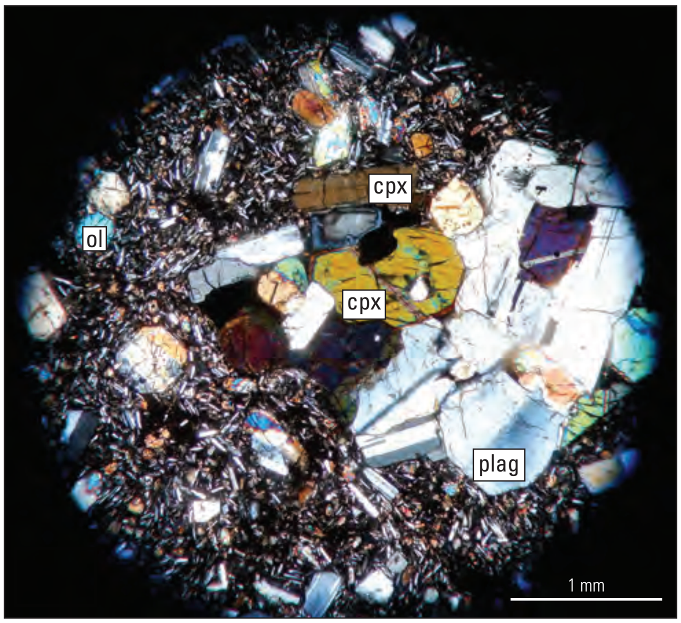

Figure 4.1. Thin-section photograph 1143 (thin-section no. 03S69M1) of sample of cone-building lava flow (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; ol, olivine; plag, plagioclase.

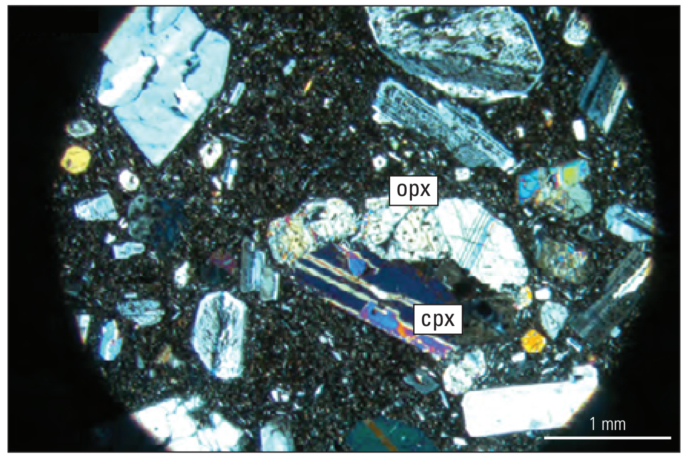

Figure 4.2. Thin-section photograph 05S104M1-1 of sample of cone-building lava flow (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; opx, orthopyroxene.

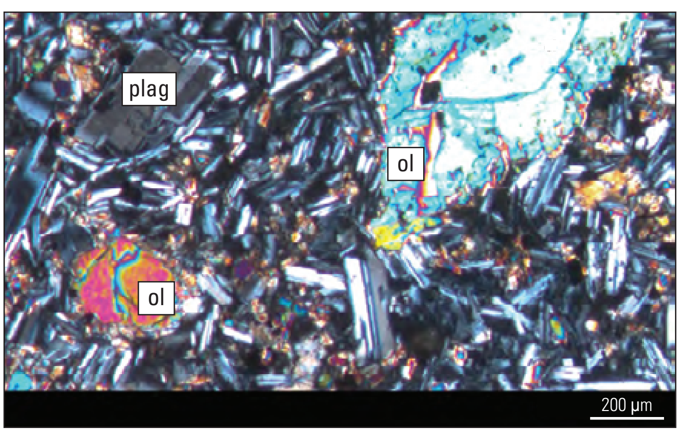

Figure 4.3. Thin-section photograph 05NYEL05-1 of sample of cone-building lava flow (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: µm, micrometer; ol, olivine; plag, plagioclase.

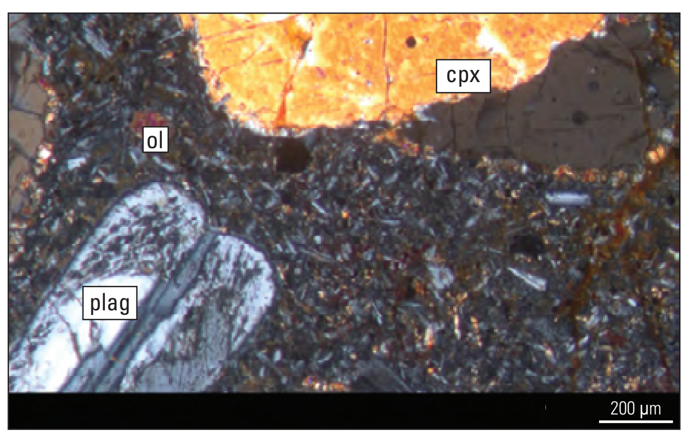

Figure 4.4. Thin-section photograph 99S14M1-1 of sample of cone-building lava flow (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

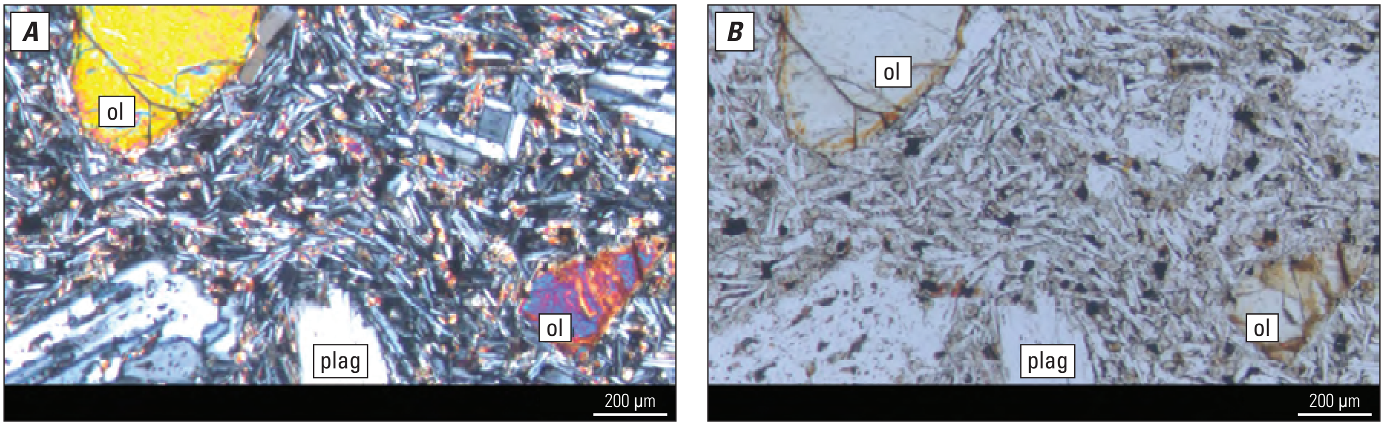

Figure 4.5. Thin-section photographs of sample of cone-building lava flow (unit cbl), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S57M1-1, in cross-polarized light. *B*, Photograph 02S57M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; ol, olivine; plag, plagioclase.

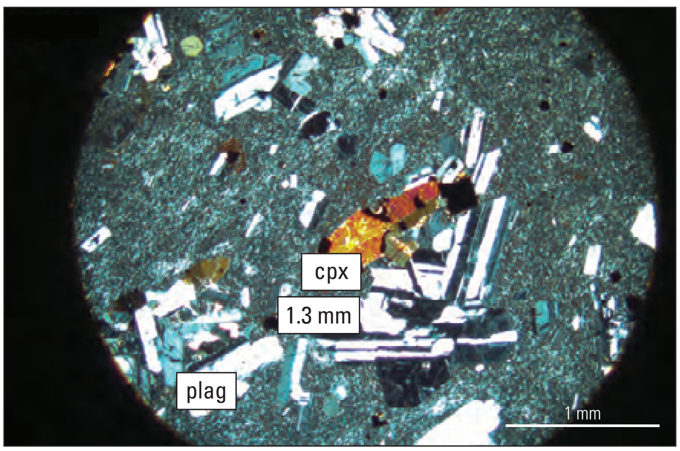

Figure 4.6. Thin-section photograph 05S97M3-1 of sample of scoria clast from cinder cone near Double Crater volcano (unit cc), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Length (1.3 millimeter [mm]) of clinopyroxene (cpx) phenocryst labeled near center of photograph. Other abbreviation: plag, plagioclase.

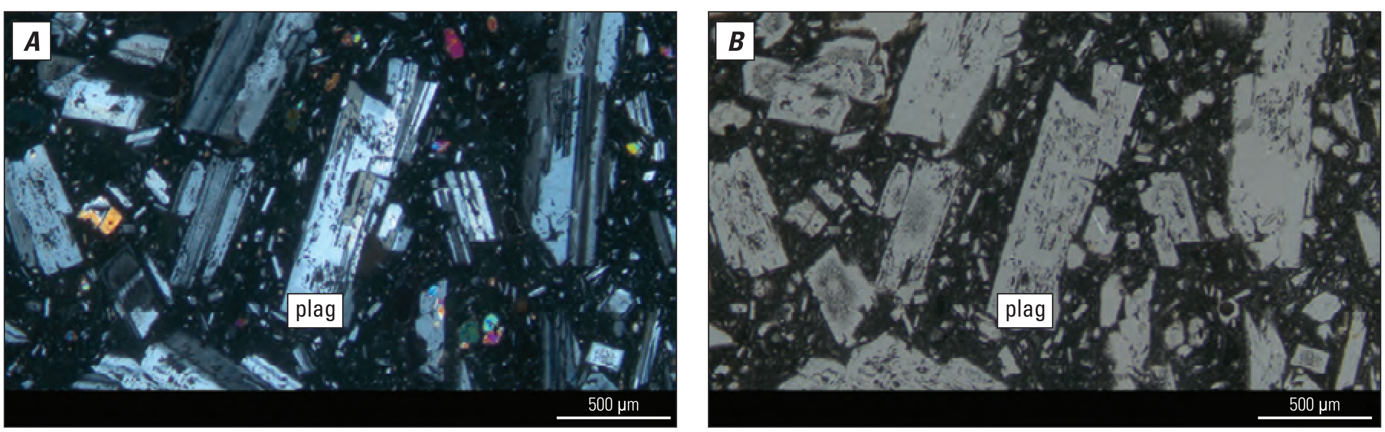

Figure 4.7. Thin-section photographs of sample of scoria clast from cone K (unit cc), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S75M1-1, in cross-polarized light. *B*, Photograph 03S75M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; plag, plagioclase.

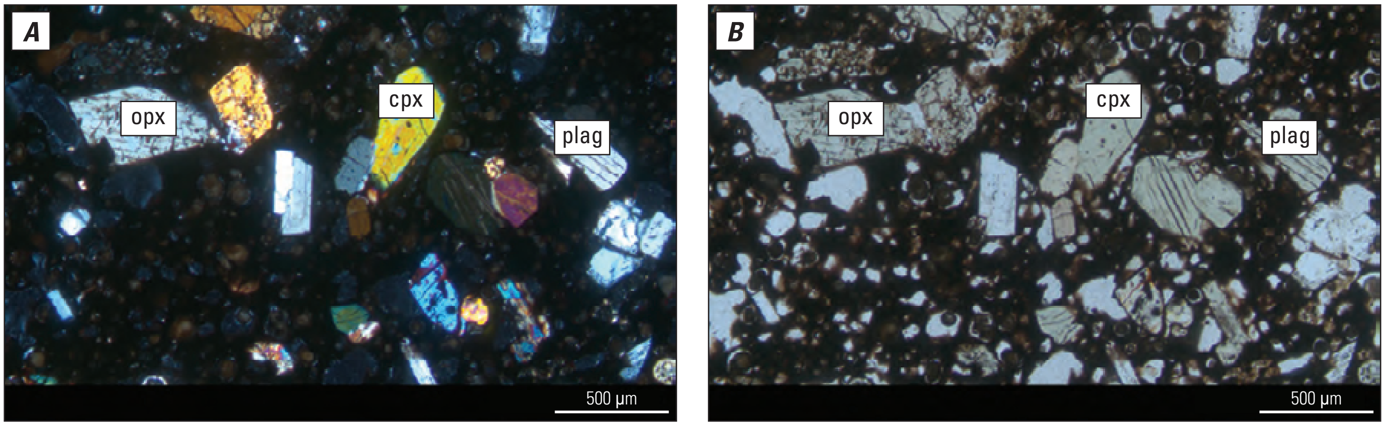

Figure 4.8. Thin-section photographs of sample of scoria clast from cinder cone (unit cc), within caldera complex in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S64M1-1, in cross-polarized light. *B*, Photograph 03S64M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

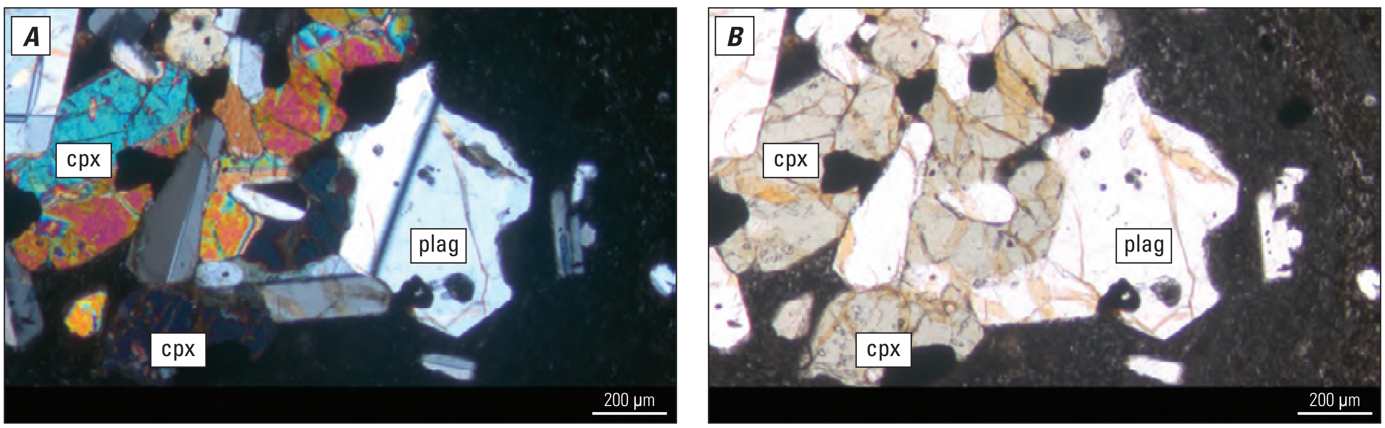

Figure 4.9. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S33M1-1, in cross-polarized light. *B*, Photograph 01S33M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

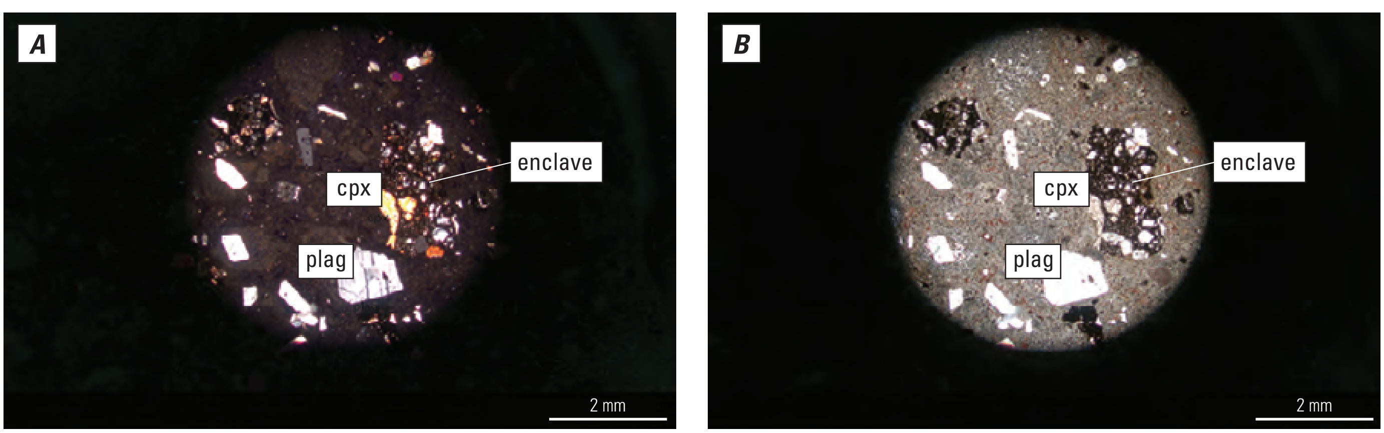

Figure 4.10. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S39F1, in cross-polarized light. *B*, Photograph 01S39F1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

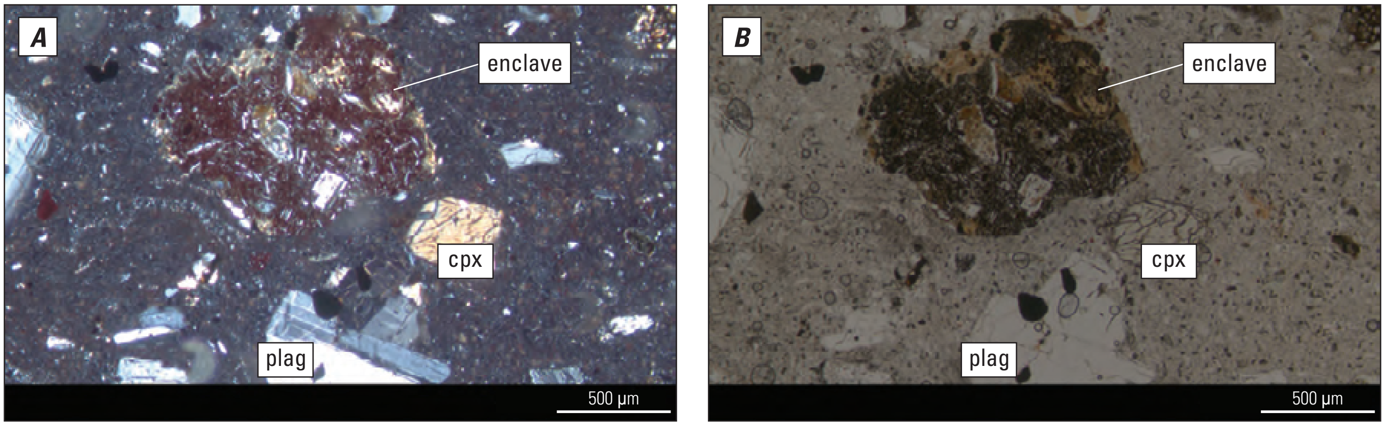

Figure 4.11. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S9M2-1, in cross-polarized light. *B*, Photograph 99S9M2-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

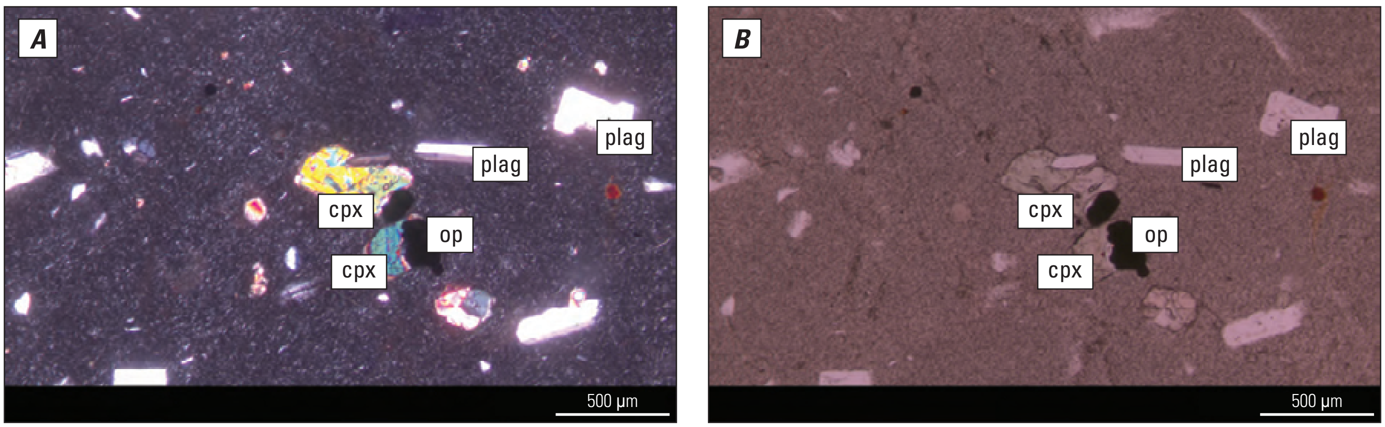

Figure 4.12. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 00S24F4-1, in cross-polarized light; same sample as figure 4.13 but closer view. *B*, Photograph 00S24F4-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; op, opaque mineral; plag, plagioclase.

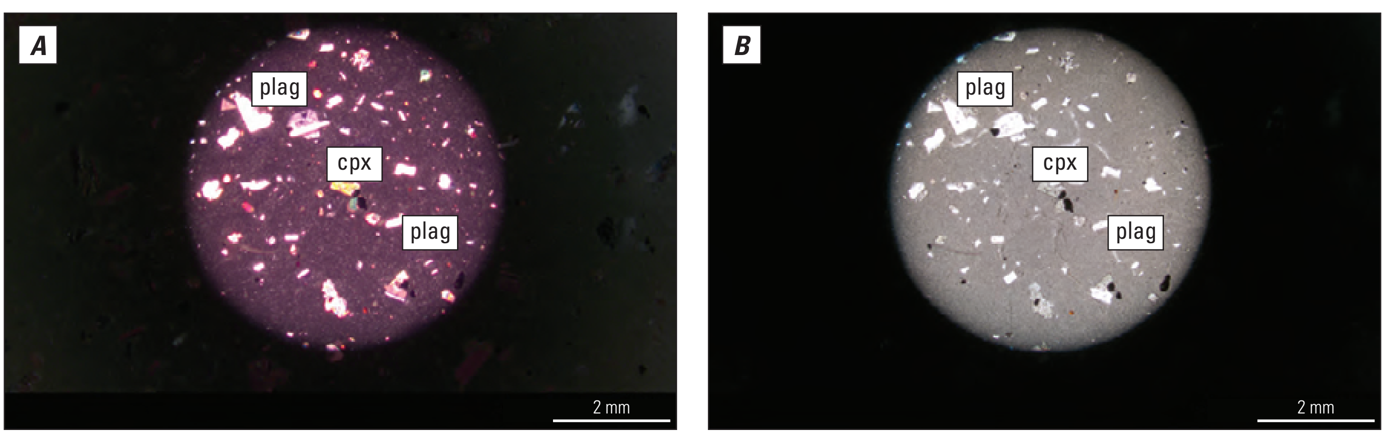

Figure 4.13. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 00S24F4-3, in cross-polarized light; same sample as figure 4.12 but wider view. *B*, Photograph 00S24F4-4, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

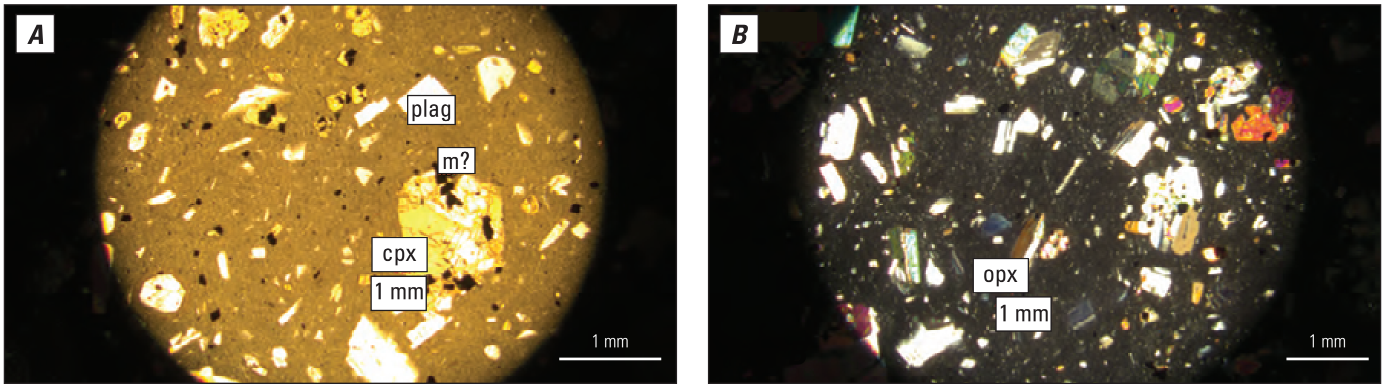

Figure 4.14. Two thin-section photographs of same sample (but different views) of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S15M1-1, in plane-polarized light. Length (1 millimeter [mm]) of clinopyroxene (cpx) phenocryst labeled in center-right part of photograph. *B*, Photograph 99S15M1-2, in cross-polarized light. Length (~1 mm) of orthopyroxene (opx) phenocryst labeled in lower center part of photograph. Other abbreviations: m?, magnetite(?); plag, plagioclase.

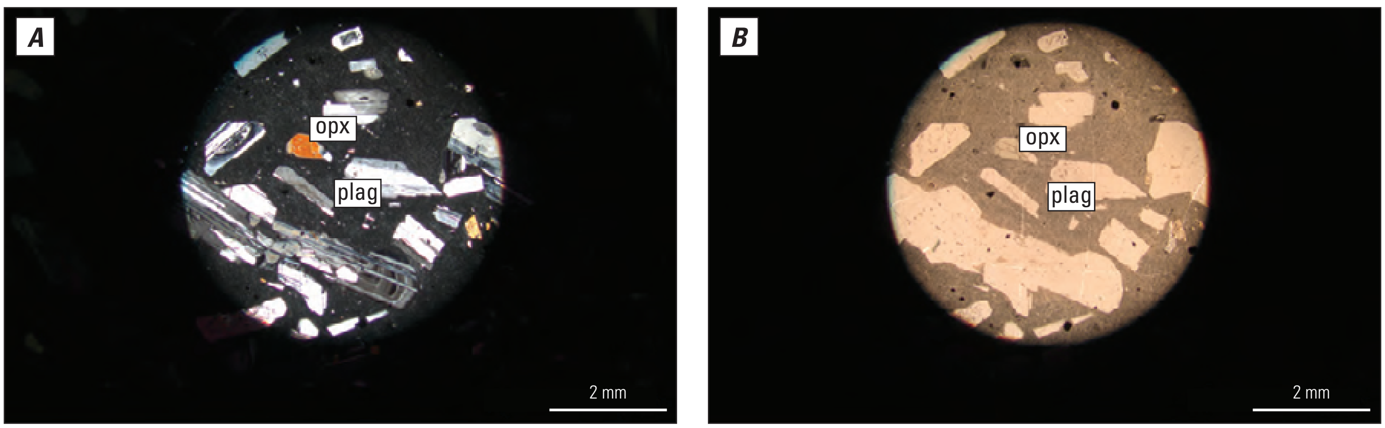

Figure 4.15. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S13M1-1, in cross-polarized light. *B*, Photograph 99S13M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

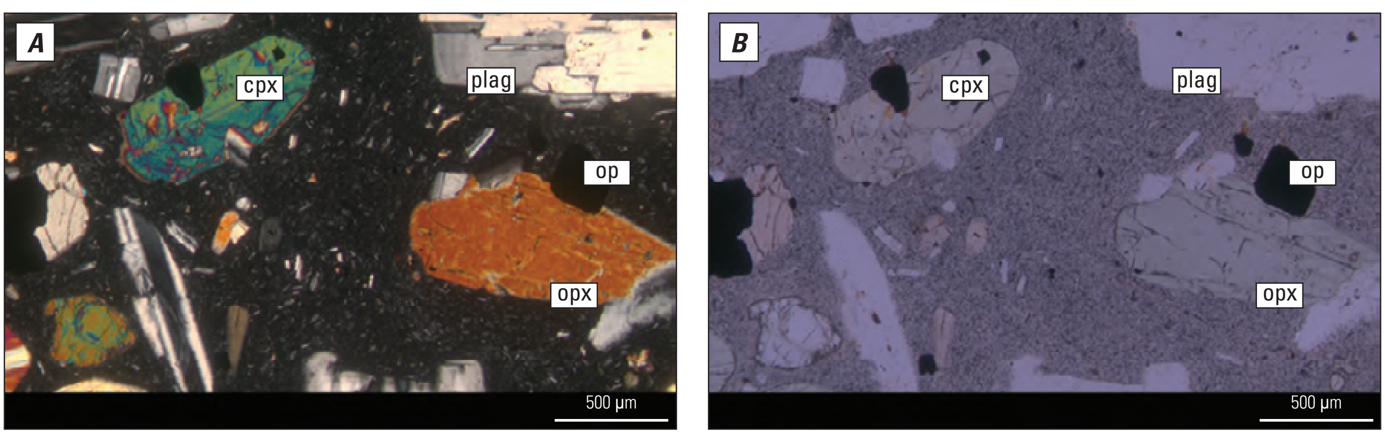

Figure 4.16. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S12M1-1, in cross-polarized light. *B*, Photograph 99S12M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; op, opaque mineral; opx, orthopyroxene; plag, plagioclase.

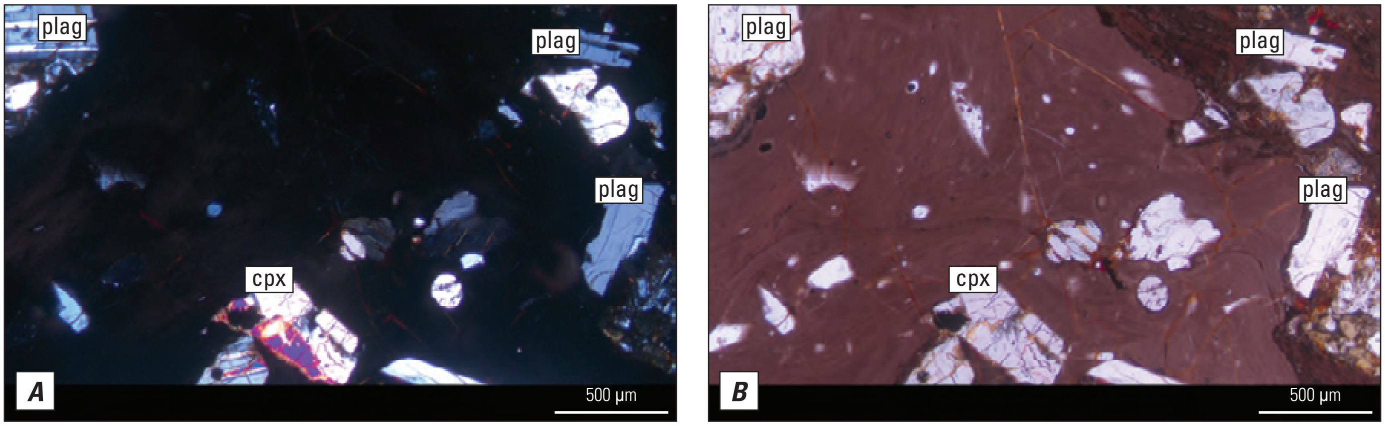

Figure 4.17. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S11M1B-1, in cross-polarized light. *B*, Photograph 99S11M1B-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

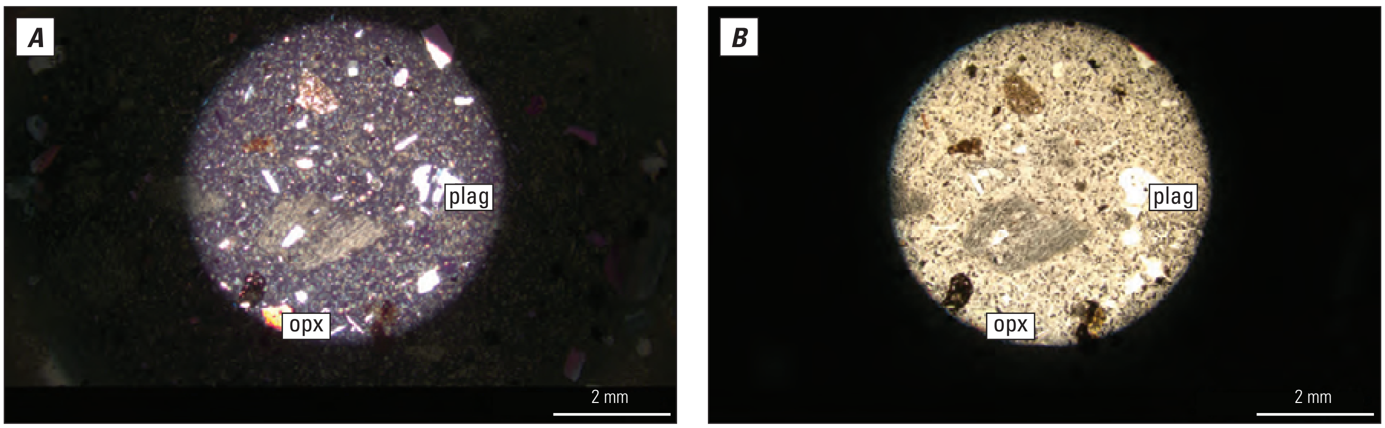

Figure 4.18. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S9M1-1, in cross-polarized light. *B*, Photograph 99S9M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

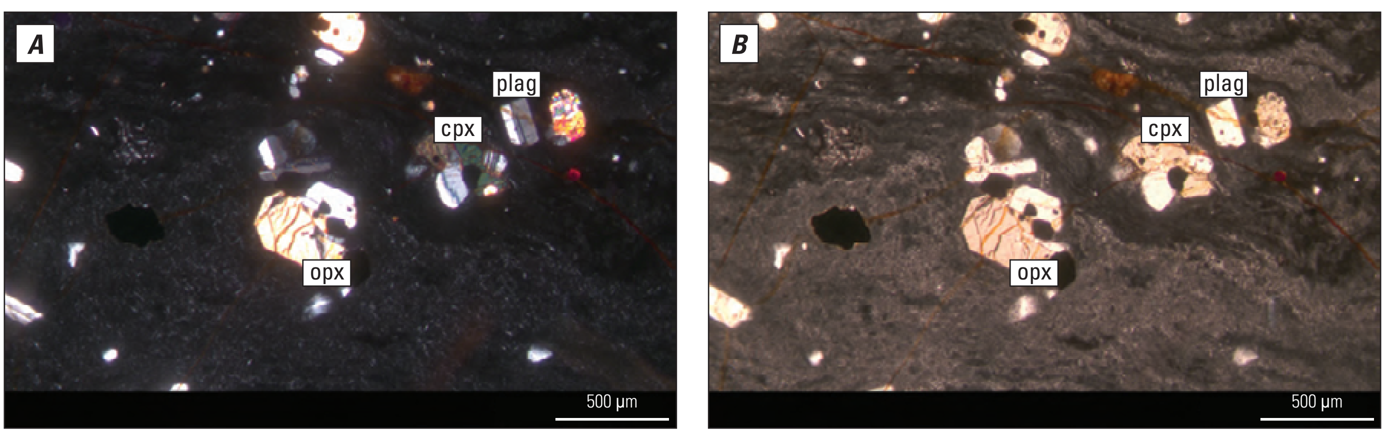

Figure 4.19. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S8M2-1, in cross-polarized light. *B*, Photograph 99S8M2-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

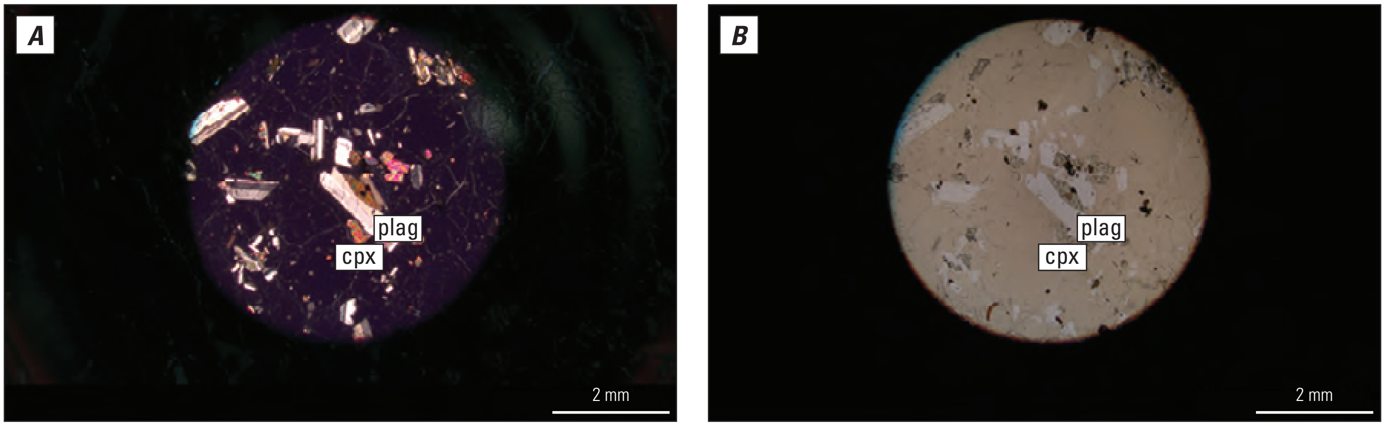

Figure 4.20. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S7M1E-1, in cross-polarized light. *B*, Photograph 99S7M1E-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

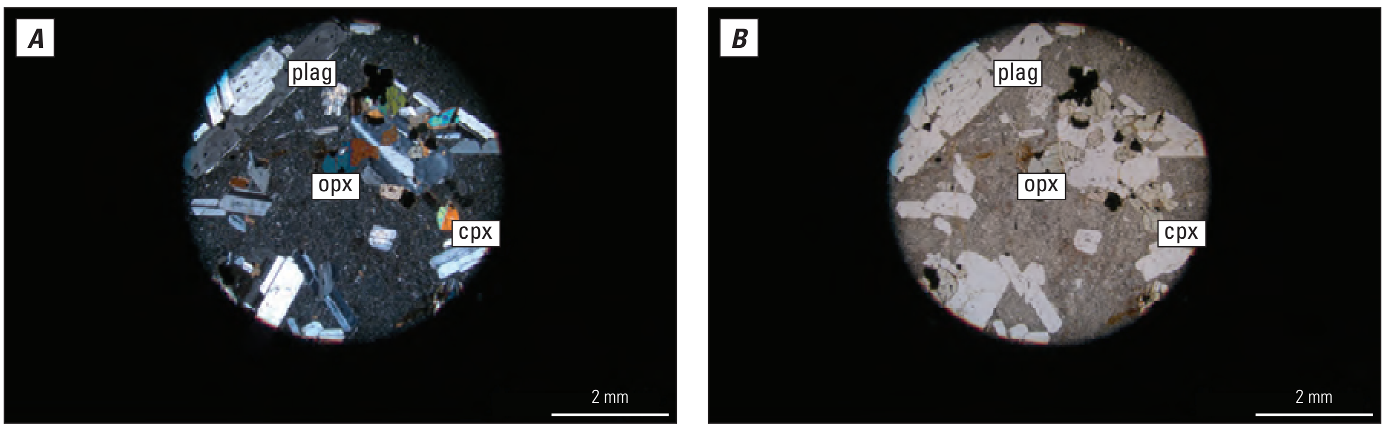

Figure 4.21. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S6M2-1, in cross-polarized light. *B*, Photograph 99S6M2-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; opx, orthopyroxene; plag, plagioclase.

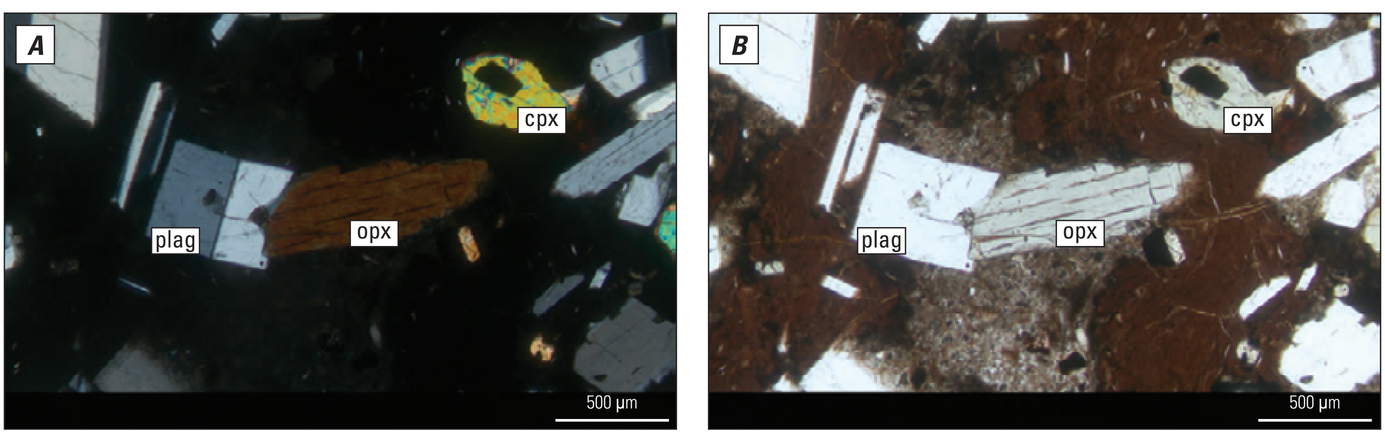

Figure 4.22. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S5M3-1, in cross-polarized light. *B*, Photograph 99S5M3-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

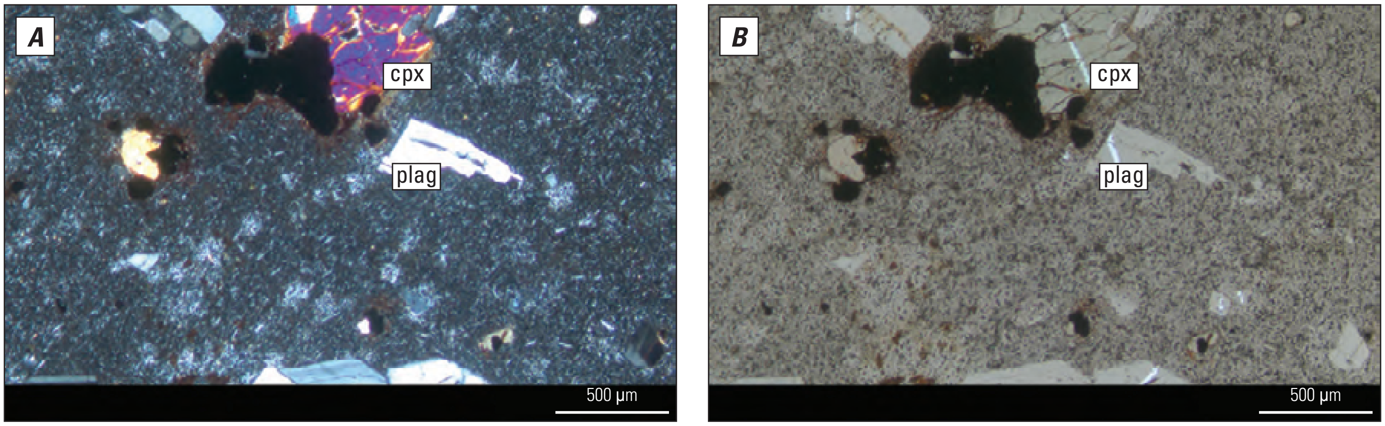

Figure 4.23. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S4M1-1, in cross-polarized light. *B*, Photograph 99S4M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

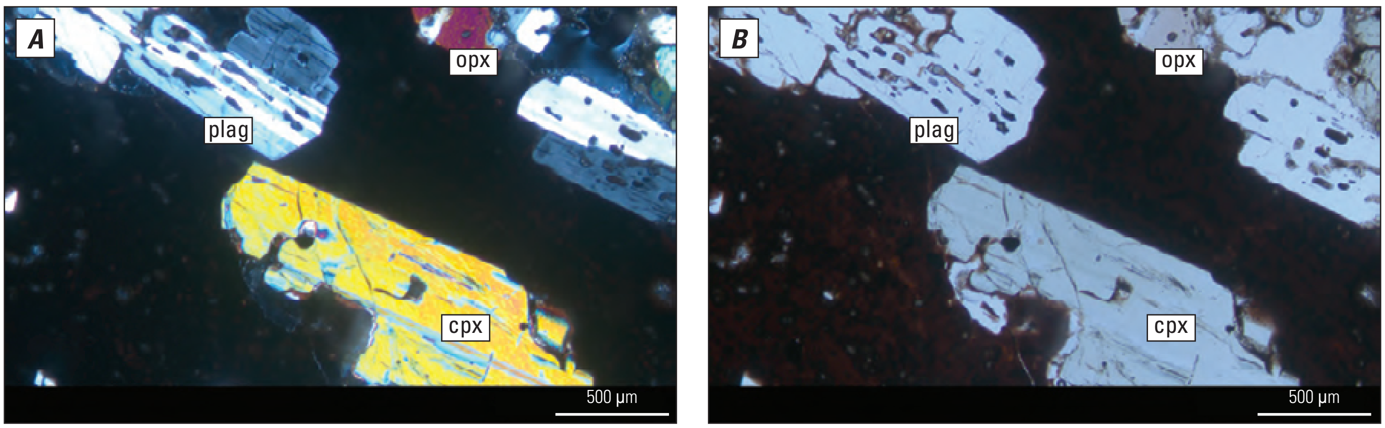

Figure 4.24. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S3T2-1, in cross-polarized light. *B*, Photograph 99S3T2-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

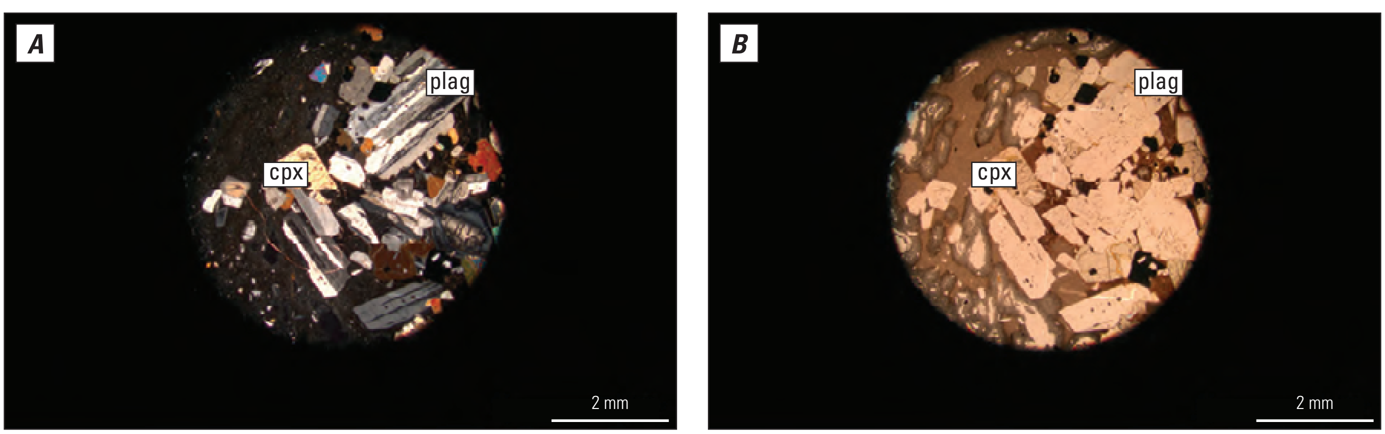

Figure 4.25. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S32F1-1, in cross-polarized light. *B*, Photograph 01S32F1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

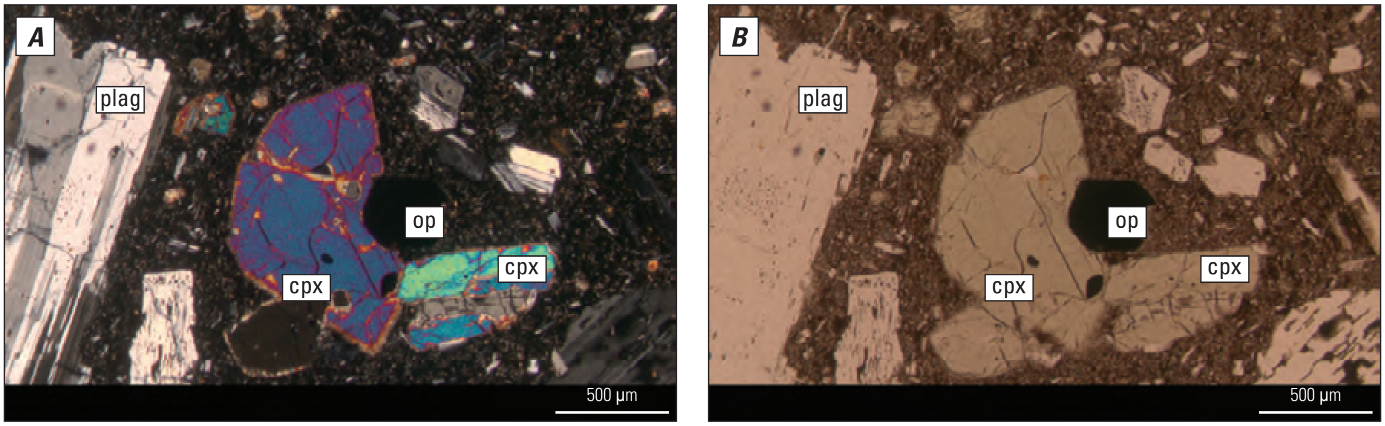

Figure 4.26. Thin-section photographs of sample of Cathedral welded tuff (unit cwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S21M3-1, in cross-polarized light. *B*, Photograph 05S21M3-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; op, opaque mineral; plag, plagioclase.

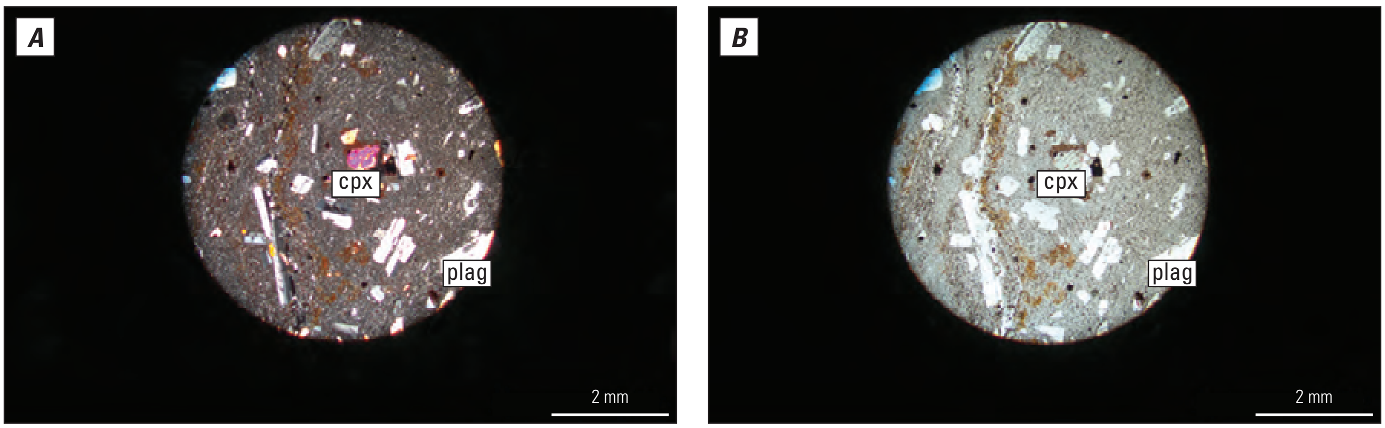

Figure 4.27. Thin-section photographs of sample of lava flow from Double Crater volcano (unit dv), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S97M1-1, in cross-polarized light. *B*, Photograph 05S97M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

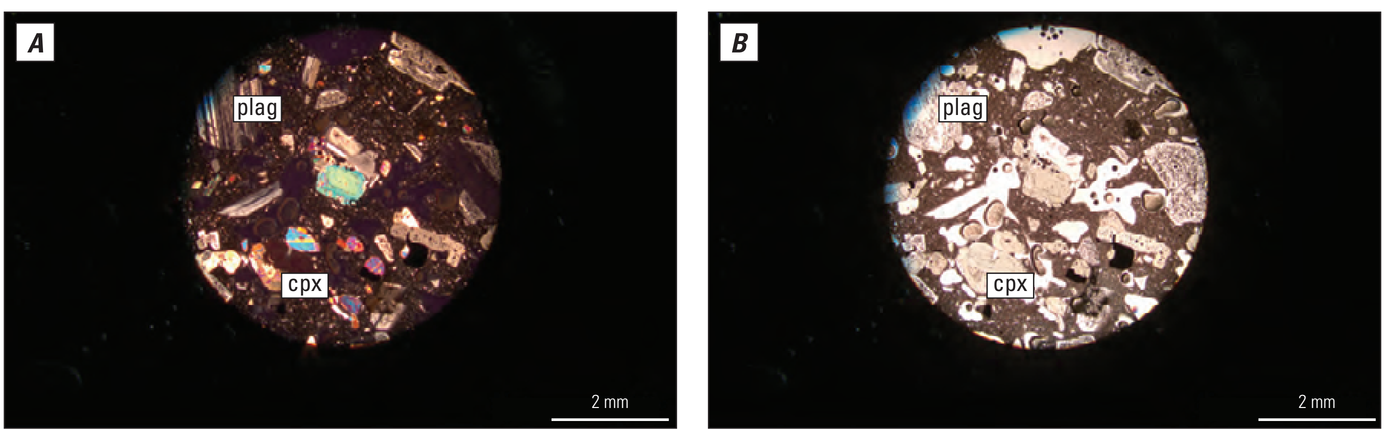

Figure 4.28. Thin-section photographs of sample of lava flow from Mount Emmons volcano (unit ev), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05NYEL01-1, in cross-polarized light. *B*, Photograph 05NYEL01-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

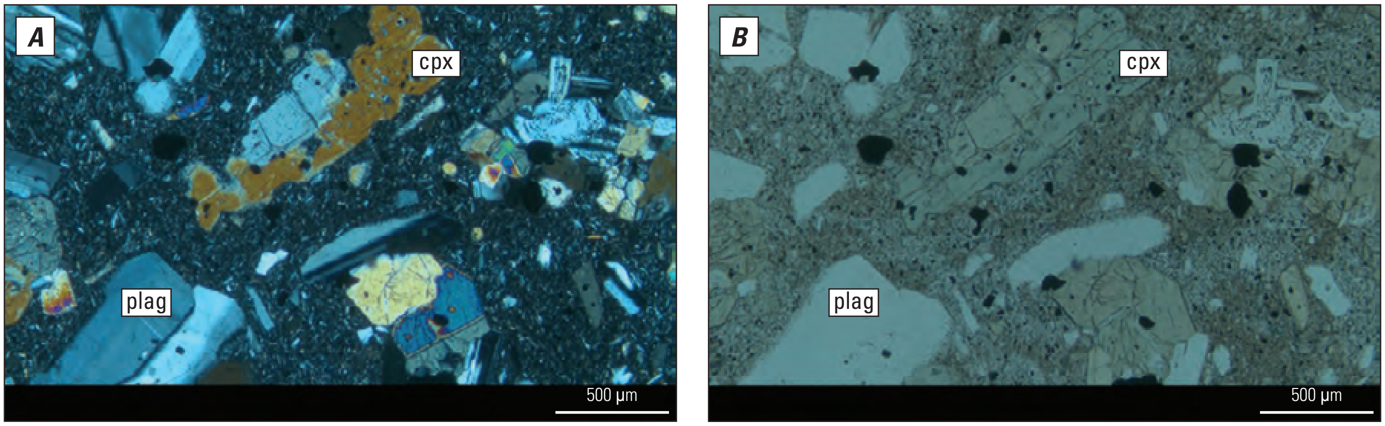

Figure 4.29. Thin-section photographs of sample of lava flow from Mount Emmons volcano (unit ev), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05ELAC001-1, in cross-polarized light. *B*, Photograph 05ELAC001-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

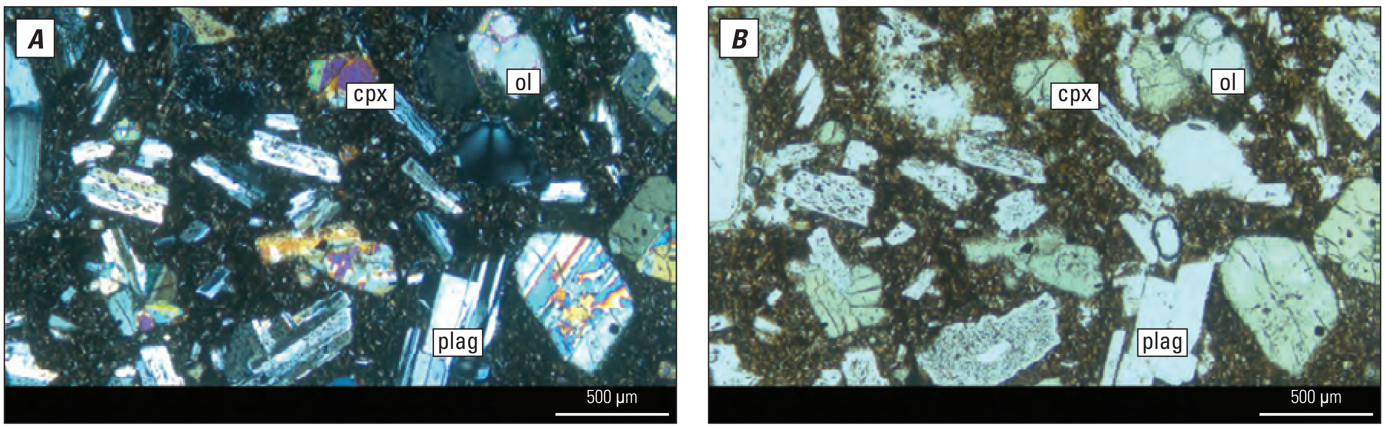

Figure 4.30. Thin-section photographs of sample of lava flow from Mount Emmons volcano (unit ev), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S86M1-1, in cross-polarized light. *B*, Photograph 03S86M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

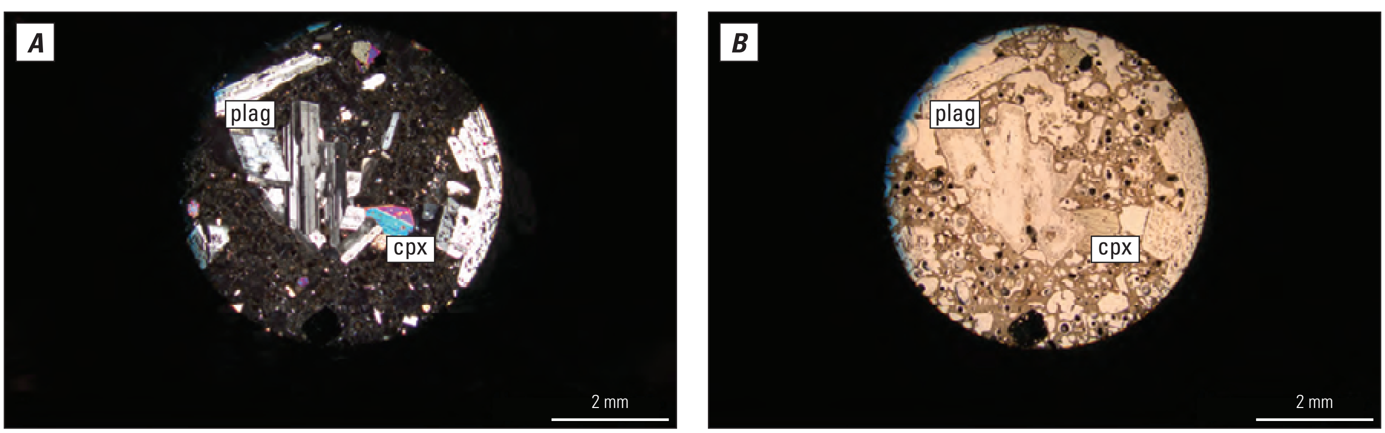

Figure 4.31. Thin-section photographs of sample of scoria from cone G (unit cc), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S98M1-1, in cross-polarized light. *B*, Photograph 05S98M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

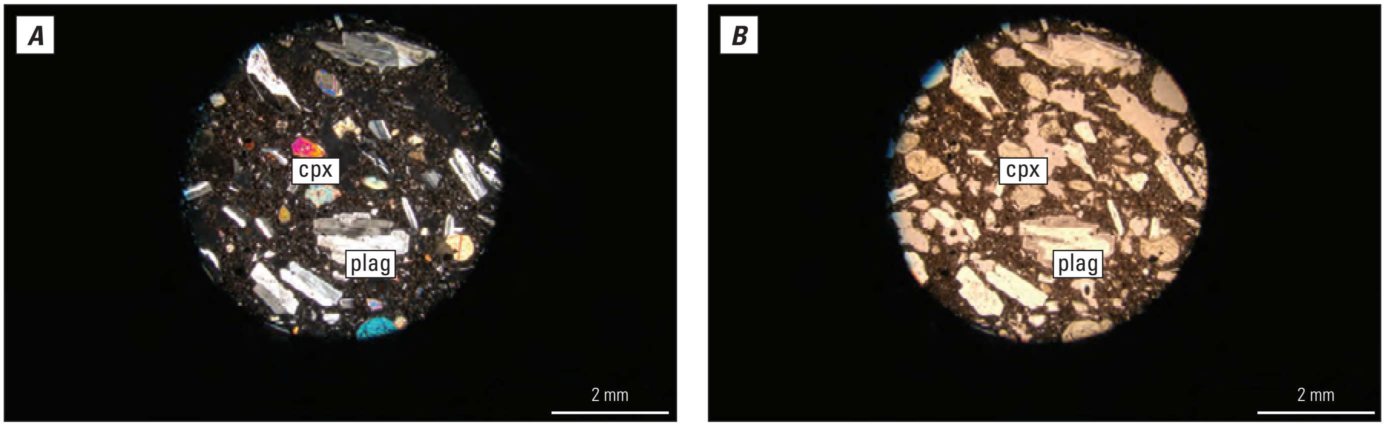

Figure 4.32. Thin-section photographs of sample of cone G lava flow (unit glf), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S63M1-1, in cross-polarized light. *B*, Photograph 03S63M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

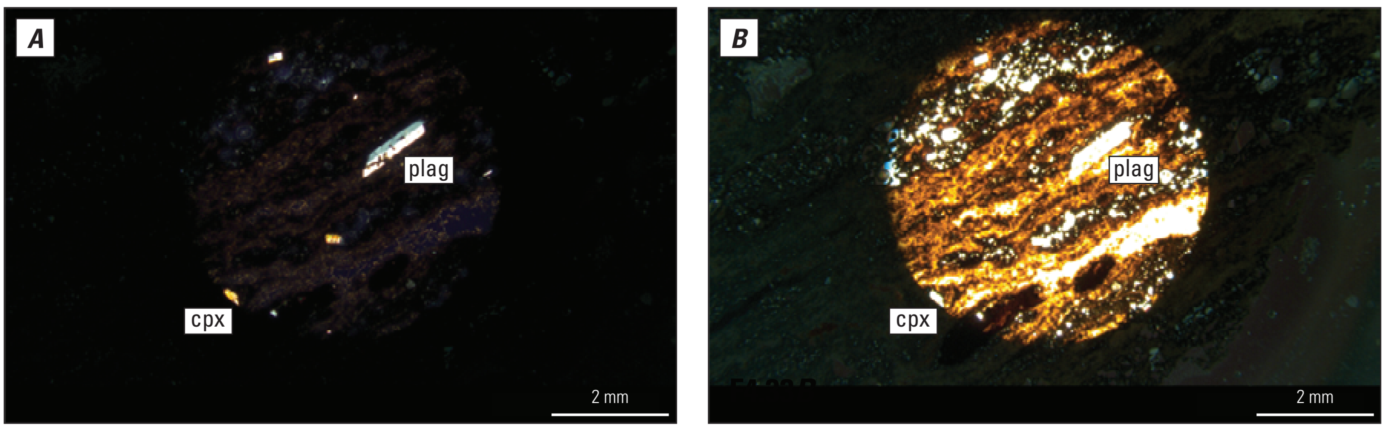

Figure 4.33. Thin-section photographs of sample of "The Gap" welded tuff (unit gwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S107M1-1, in cross-polarized light. *B*, Photograph 05S107M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

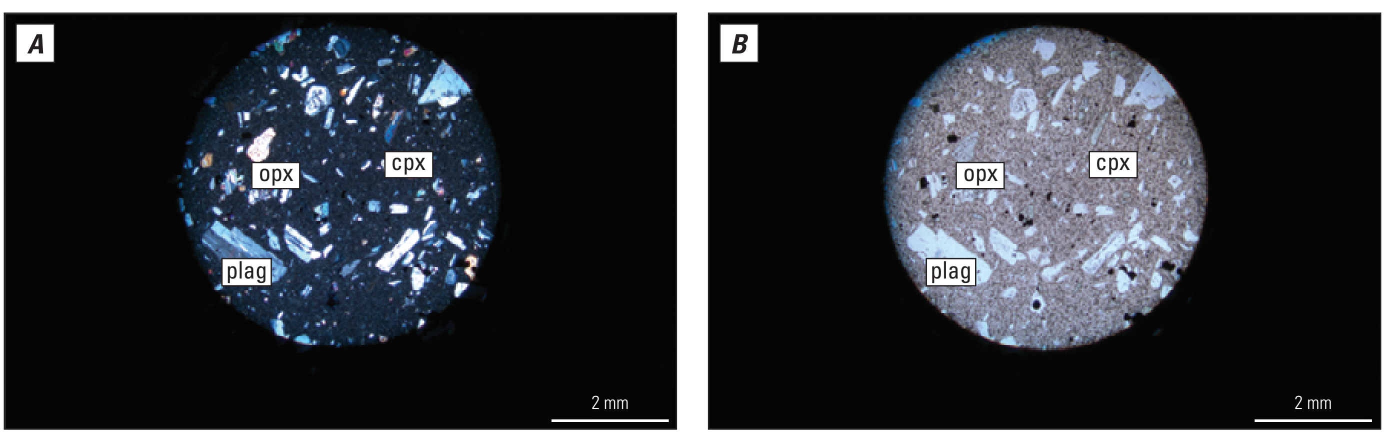

Figure 4.34. Thin-section photographs of sample of "The Gap" welded tuff (unit gwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S107M3-1, in cross-polarized light. *B*, Photograph 05S107M3-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; opx, orthopyroxene; plag, plagioclase.

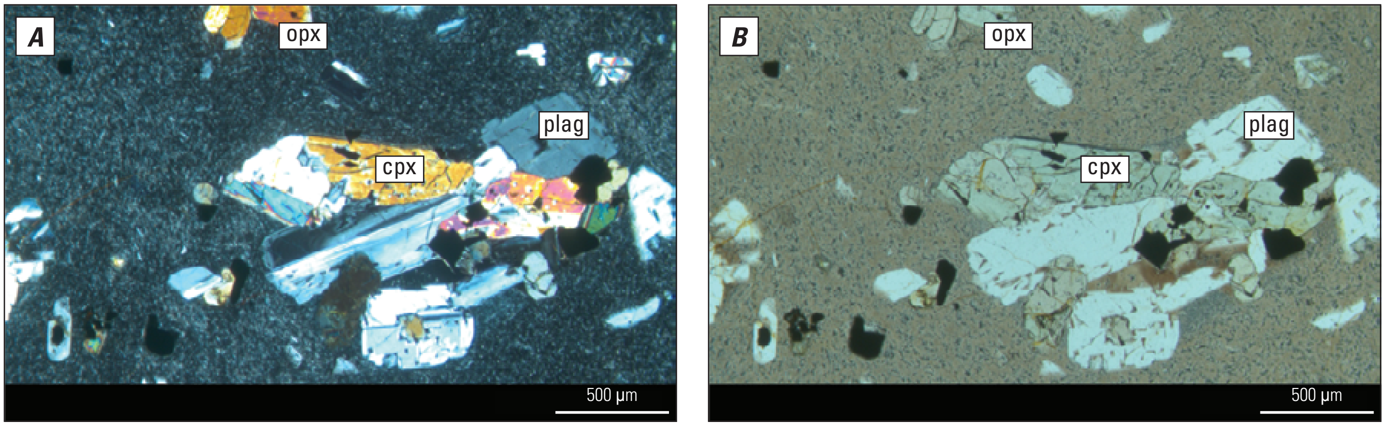

Figure 4.35. Thin-section photographs of sample of "The Gap" welded tuff (unit gwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S123M1-1, in cross-polarized light. *B*, Photograph 05S123M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

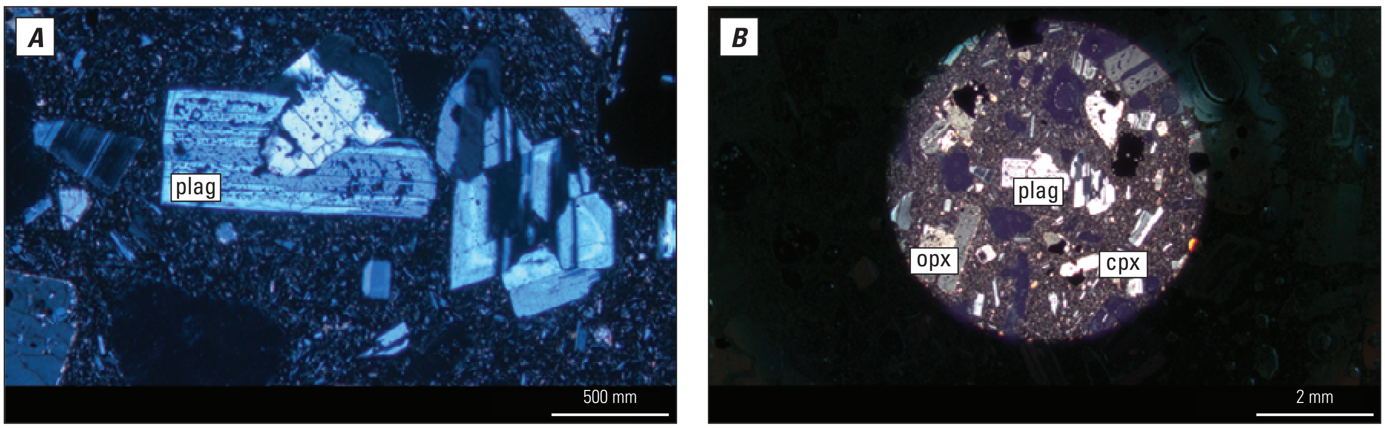

Figure 4.36. Thin-section photographs of sample of cone D lava flow (unit dlf5), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S102M2-1, in cross-polarized light. *B*, Photograph 05S102M2-2, same sample as *A* but wider view and in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; mm, millimeter; opx, orthopyroxene; plag, plagioclase.

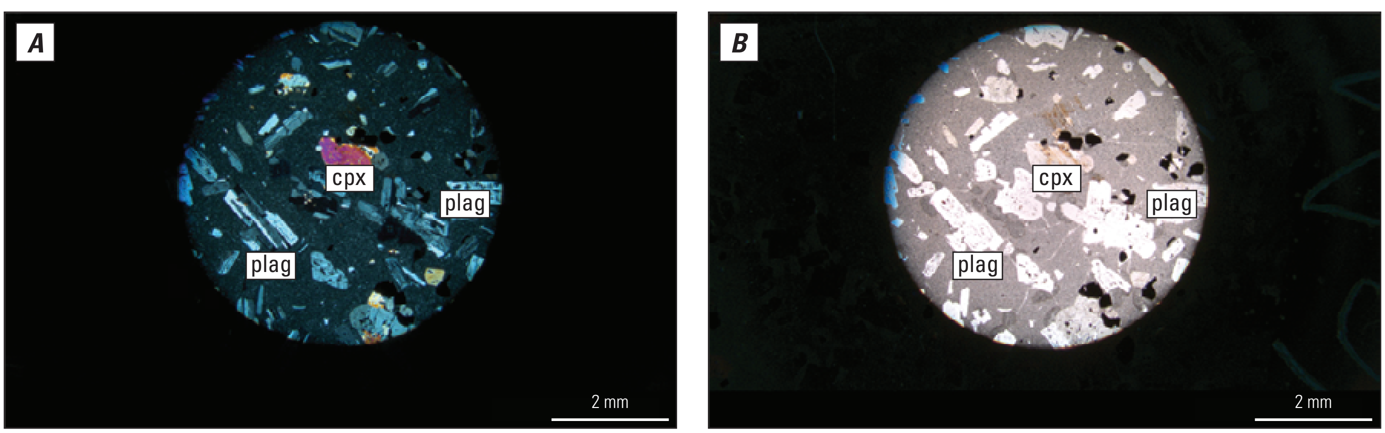

Figure 4.37. Thin-section photographs of sample of lava flow from Mount Hague volcano (unit hv), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S96M1-1, in cross-polarized light. *B*, Photograph 05S96M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

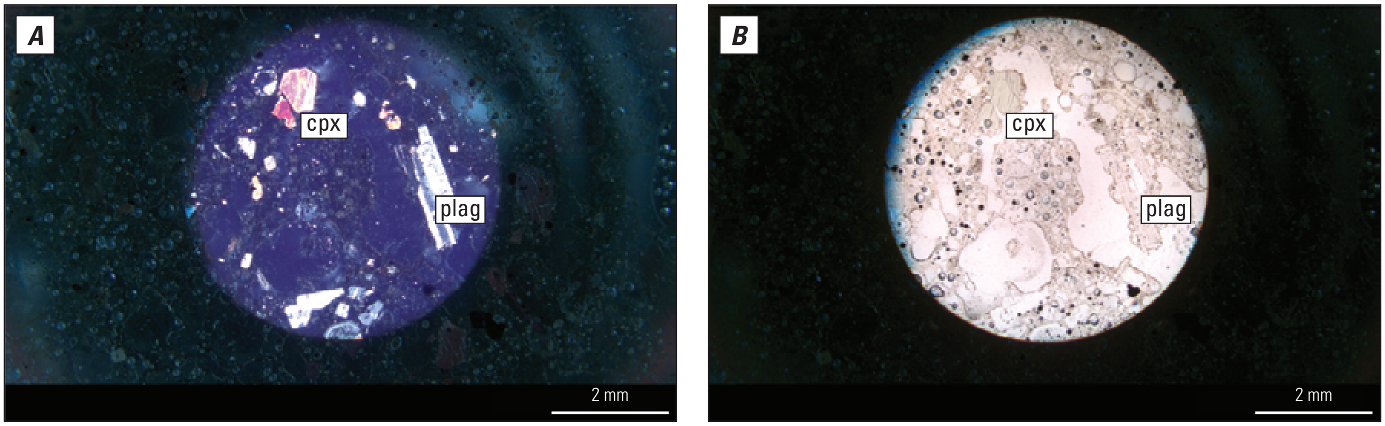

Figure 4.38. Thin-section photographs of sample of lava flow from Mount Hague volcano (unit hv), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S132M1A-1, in cross-polarized light. *B*, Photograph 05S132M1A-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

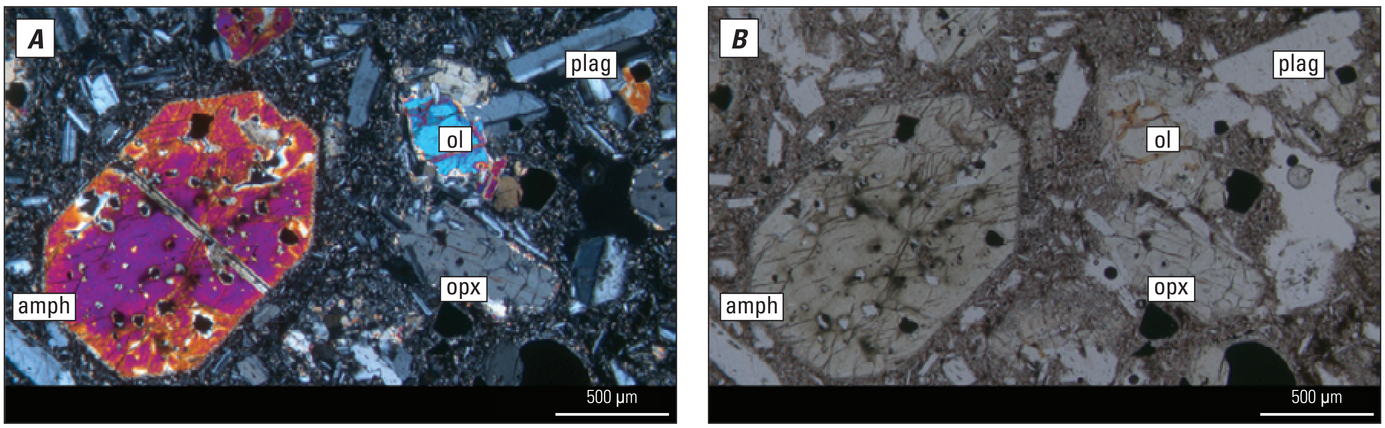

Figure 4.39. Thin-section photographs of sample of intracaldera dome (unit ida), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S121M1-1, in cross-polarized light. *B*, Photograph 05S121M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; amph, amphibole; ol, olivine; opx, orthopyroxene; plag, plagioclase.

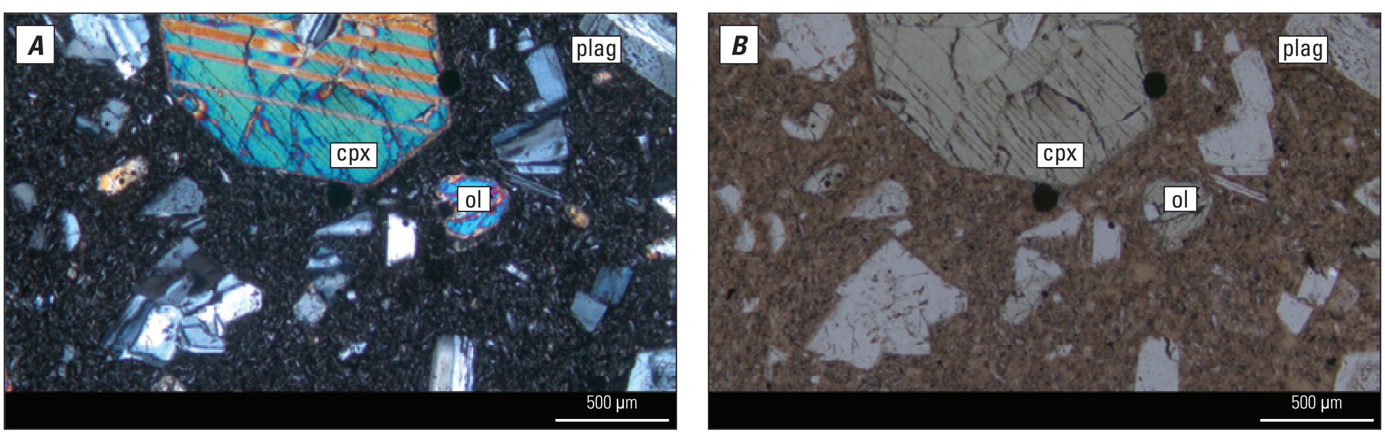

Figure 4.40. Thin-section photographs of sample of intracaldera dome (unit ida), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S119M1-1, in cross-polarized light. *B*, Photograph 05S119M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

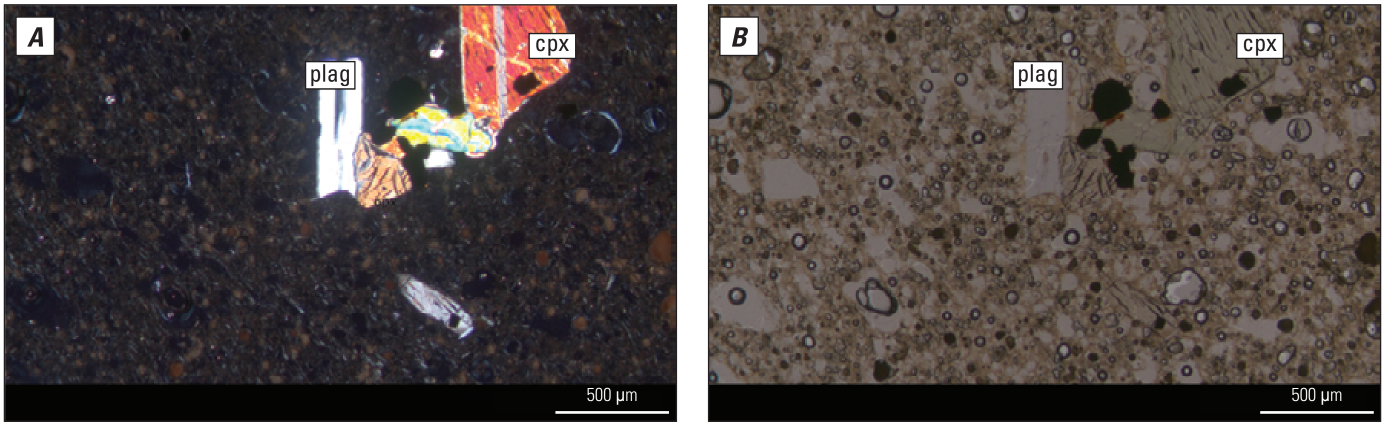

Figure 4.41. Thin-section photographs of sample of intracaldera dome (unit ida), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S87T1-1, in cross-polarized light. *B*, Photograph 03S87T1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

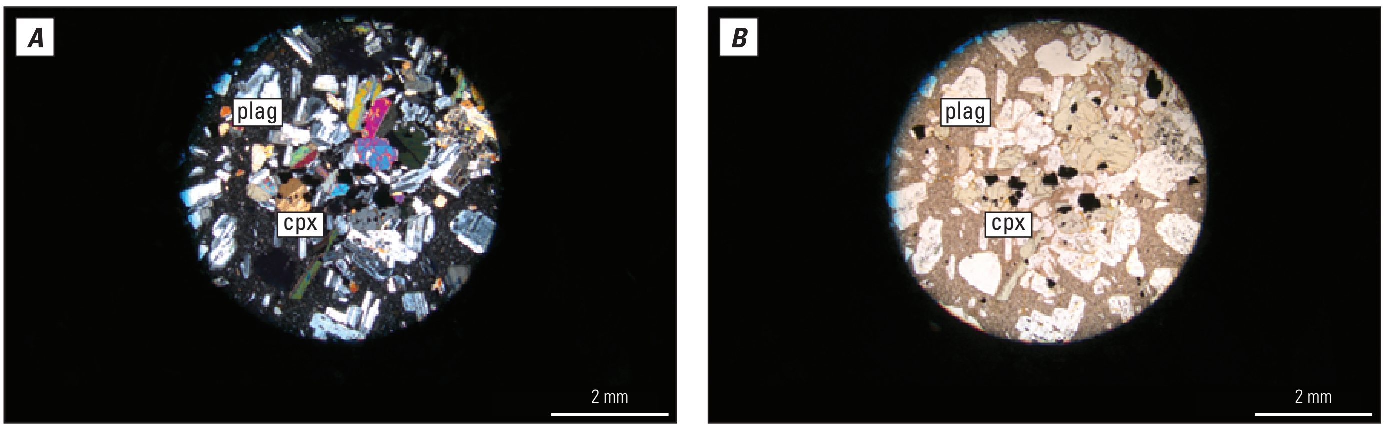

Figure 4.42. Thin-section photographs of sample of intracaldera dome (unit ida), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S25M1-1, in cross-polarized light. *B*, Photograph 05S25M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

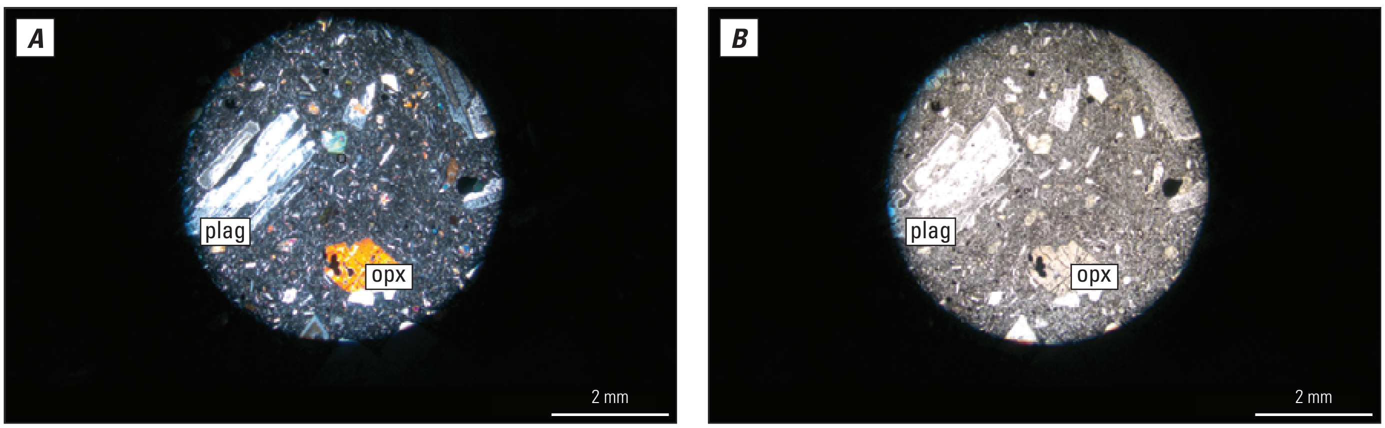

Figure 4.43. Thin-section photographs of sample of intracaldera dome (unit ida), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S68M1-1, in cross-polarized light. *B*, Photograph 03S68M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

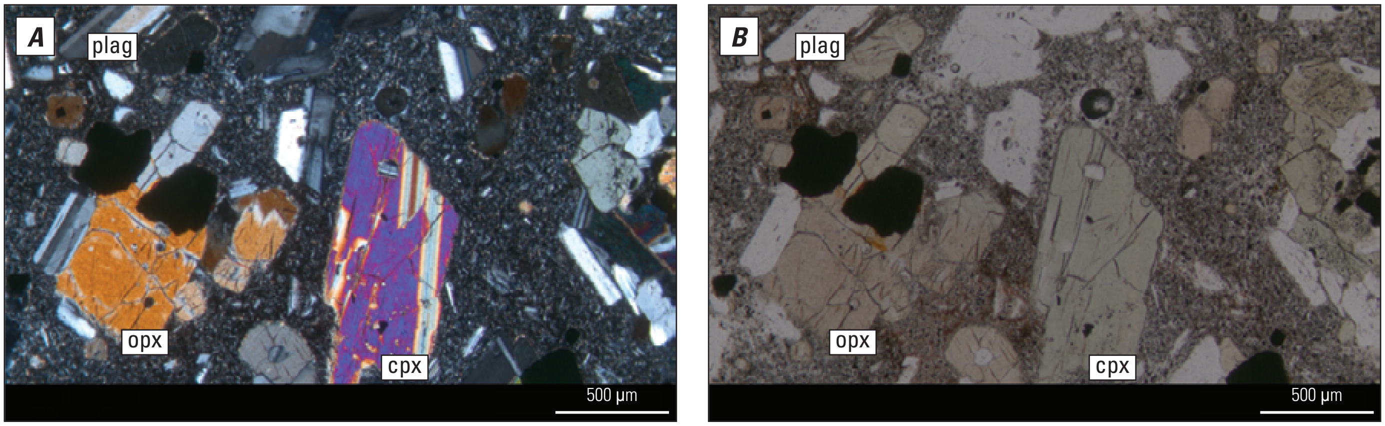

Figure 4.44. Thin-section photographs of sample of undifferentiated lava flow (unit lfu), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S120T1-1, in cross-polarized light. *B*, Photograph 05S120T1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene; plag, plagioclase.

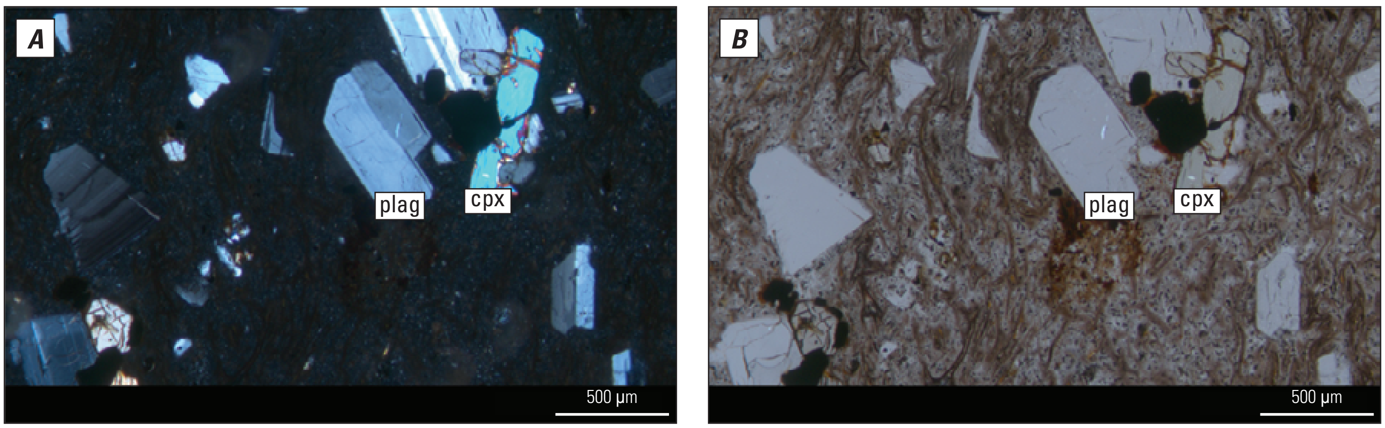

Figure 4.45. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 00S31F1-1, in cross-polarized light. *B*, Photograph 00S31F1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

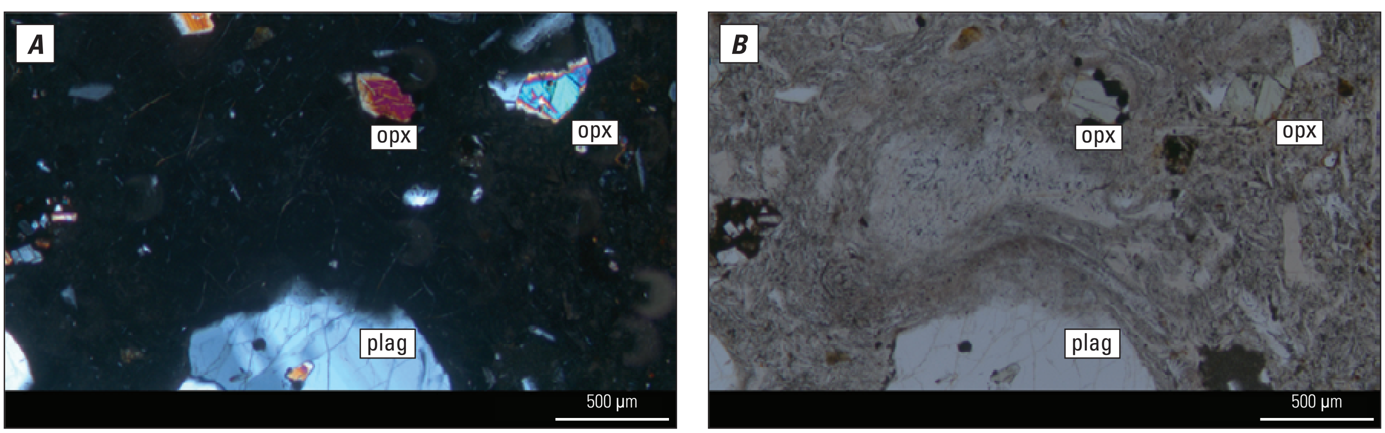

Figure 4.46. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 00S30F1-1, in cross-polarized light. *B*, Photograph 00S30F1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; opx, orthopyroxene; plag, plagioclase.

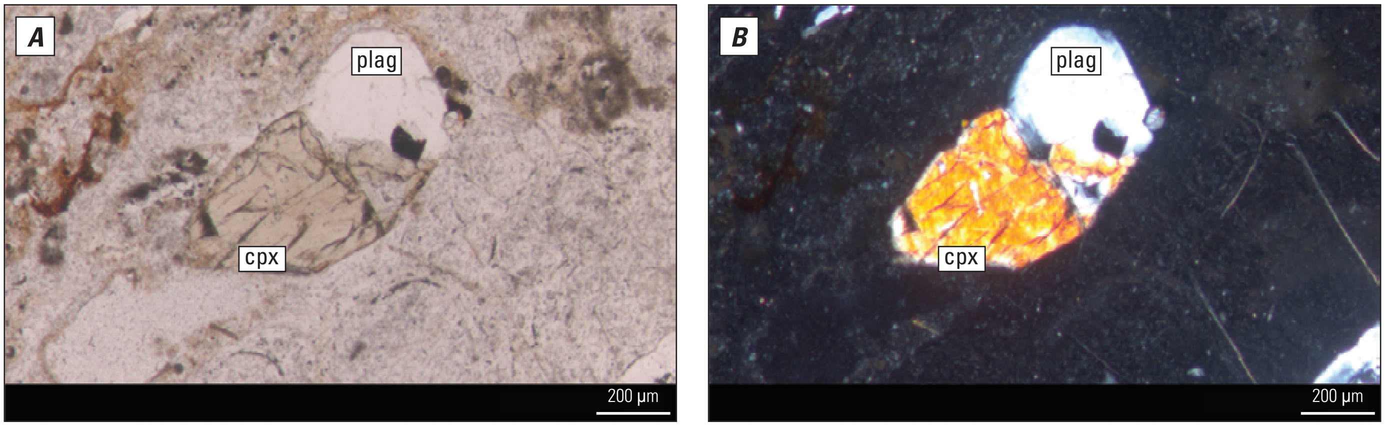

Figure 4.47. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S36M1A-1, in plane-polarized light; same sample as figure 4.48 but closer view. *B*, Photograph 01S36M1A-2, same view as *A* but in cross-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

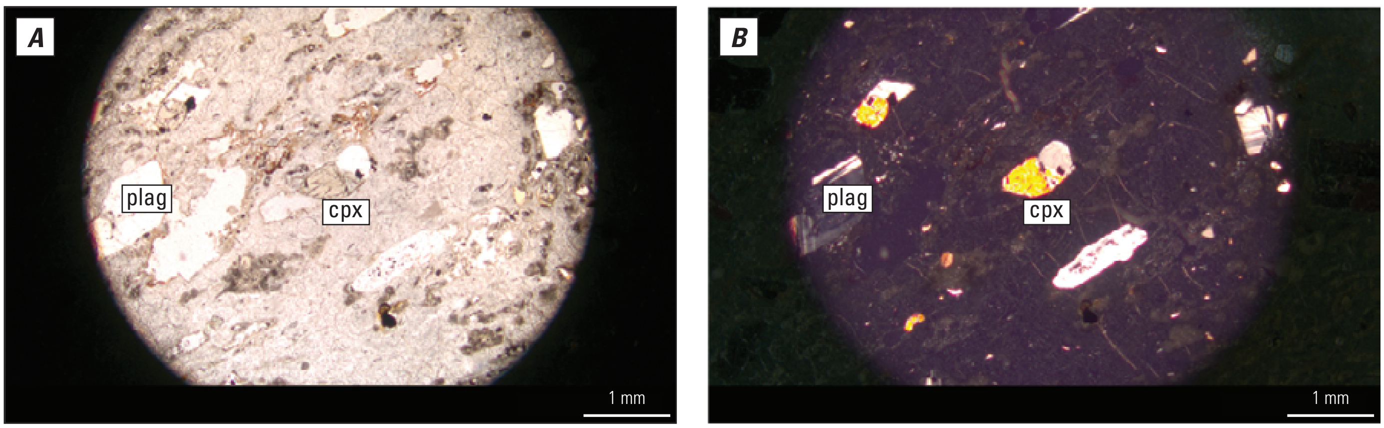

Figure 4.48. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S36M1A-3, in plane-polarized light; same sample as figure 4.47 but wider view. *B*, Photograph 01S36M1A-4, same view as *A* but in cross-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

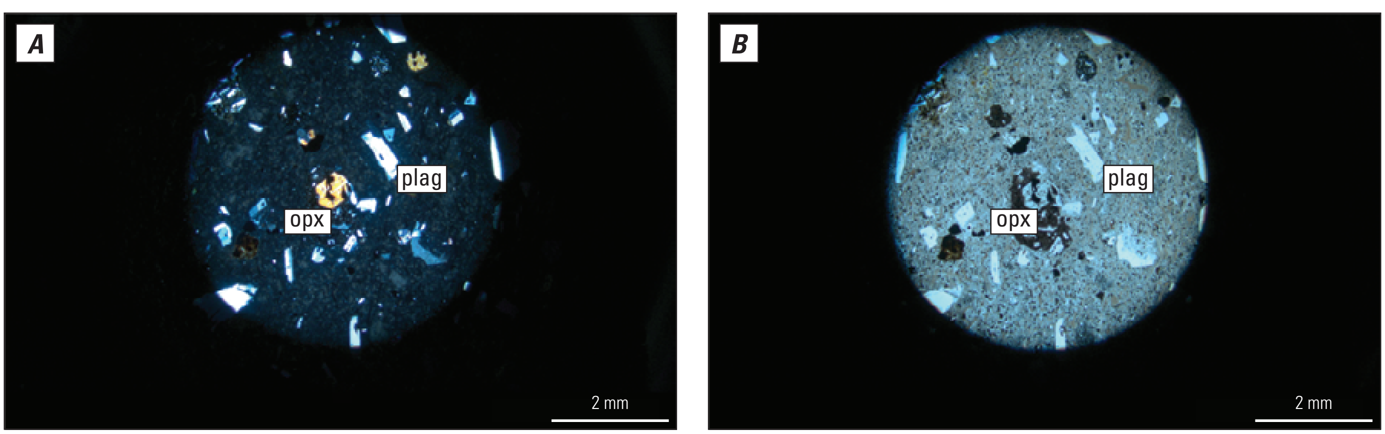

Figure 4.49. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S40F1-1, in cross-polarized light. *B*, Photograph 01S40F1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

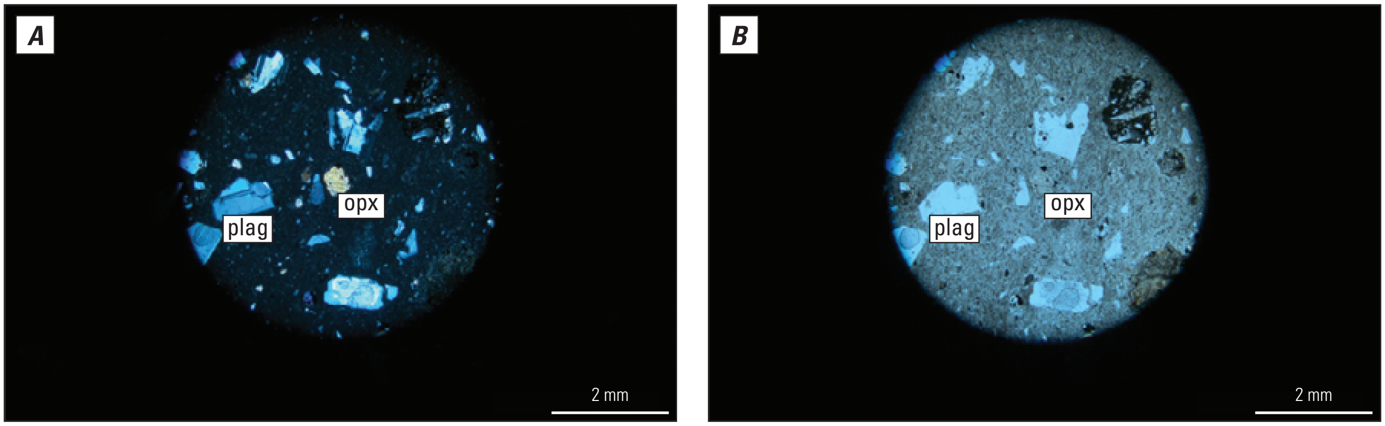

Figure 4.50. Thin-section photographs of sample of "Leontovich River" welded tuff (unit lwt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S2M1-1, in cross-polarized light. *B*, Photograph 99S2M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

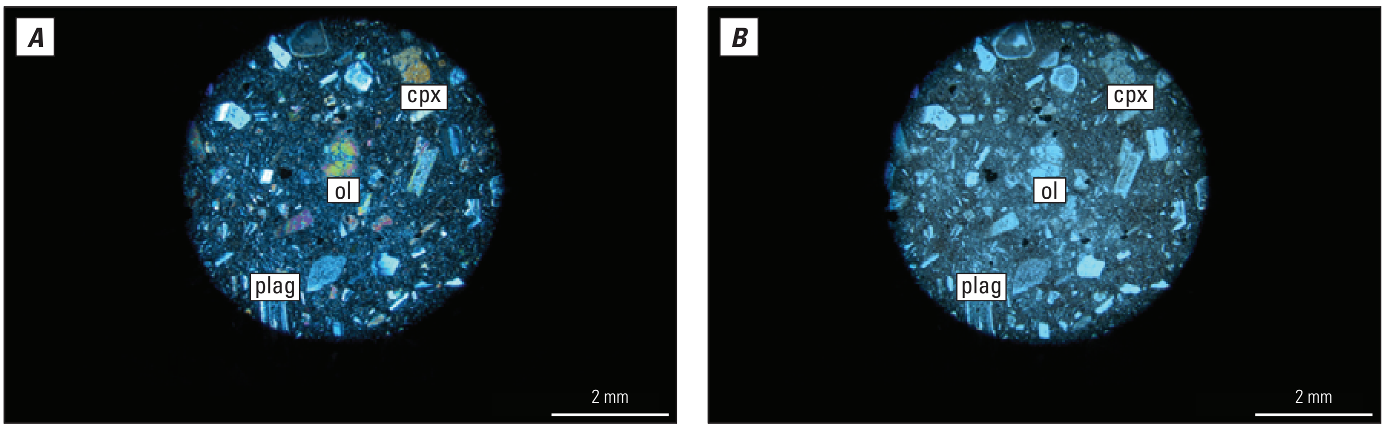

Figure 4.51. Thin-section photographs of sample of lava flow on south caldera rim (unit olf4), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S88T1-1, in cross-polarized light. *B*, Photograph 03S88T1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; ol, olivine; plag, plagioclase.

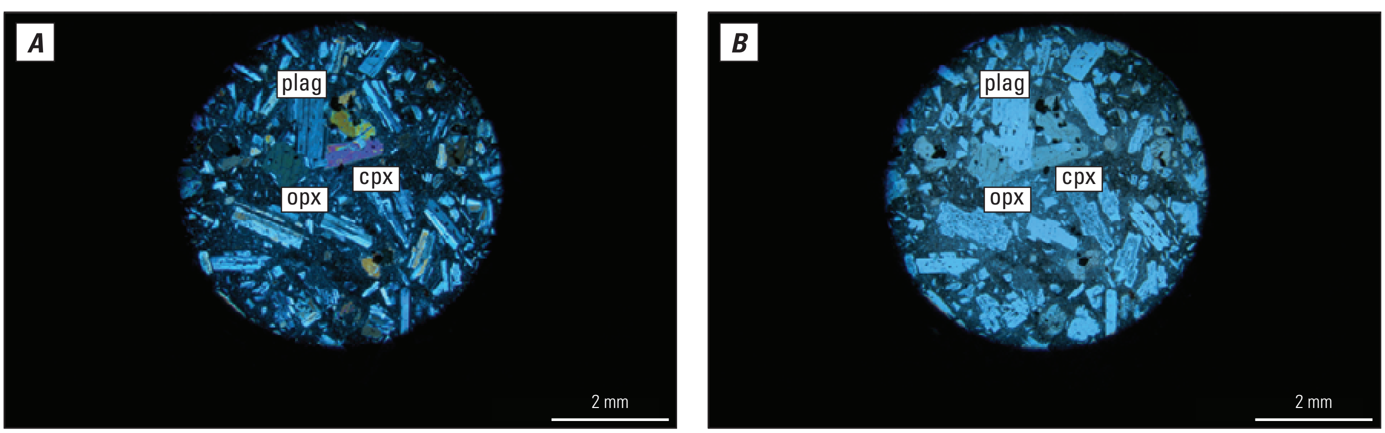

Figure 4.52. Thin-section photographs of sample of lava flow on south caldera rim (unit olf4), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S84M2-1, in cross-polarized light. *B*, Photograph 03S84M2-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; opx, orthopyroxene; plag, plagioclase.

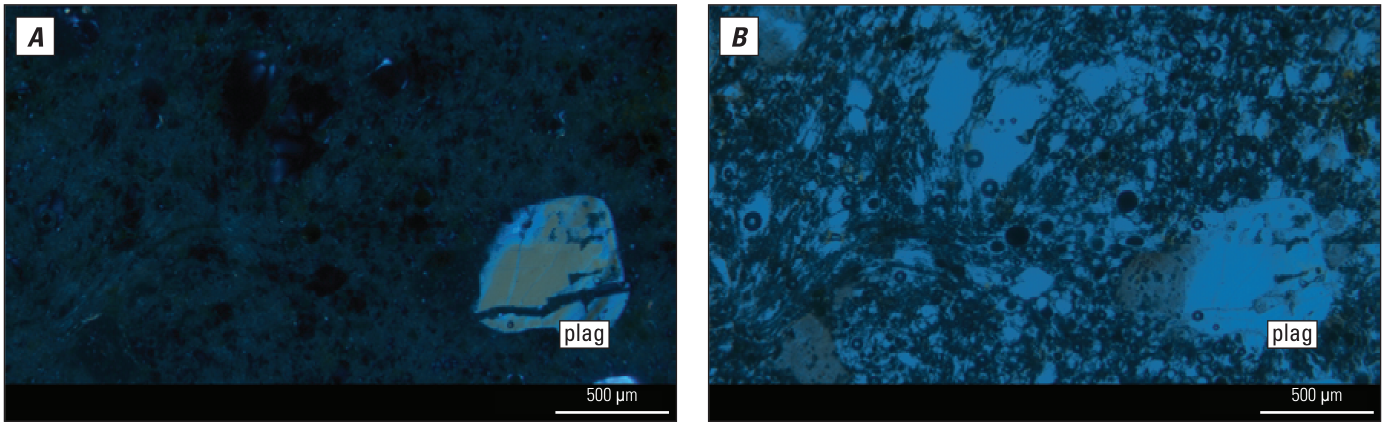

Figure 4.53. Thin-section photographs of sample of pumiceous pyroclastic-flow deposit (unit pfd), in Emmons Lake volcanic center, Alaska. *A*, Photograph 00S16M1P-1, in cross-polarized light. *B*, Photograph 00S16M1P-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; plag, plagioclase.

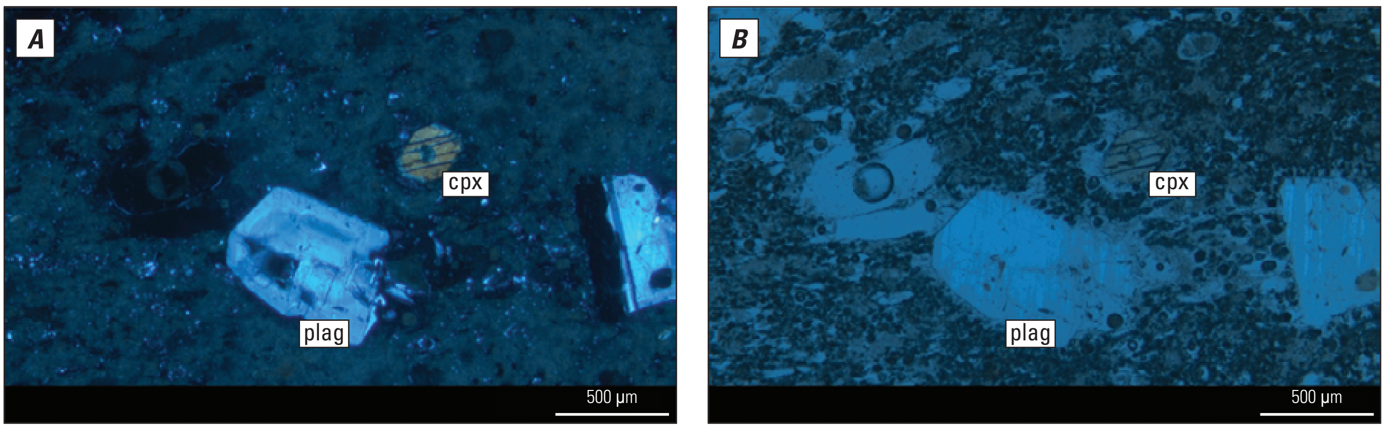

Figure 4.54. Thin-section photographs of sample of pumiceous pyroclastic-flow deposit (unit pfd), in Emmons Lake volcanic center, Alaska. *A*, Photograph 99S1M1-1, in cross-polarized light. *B*, Photograph 99S1M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; plag, plagioclase.

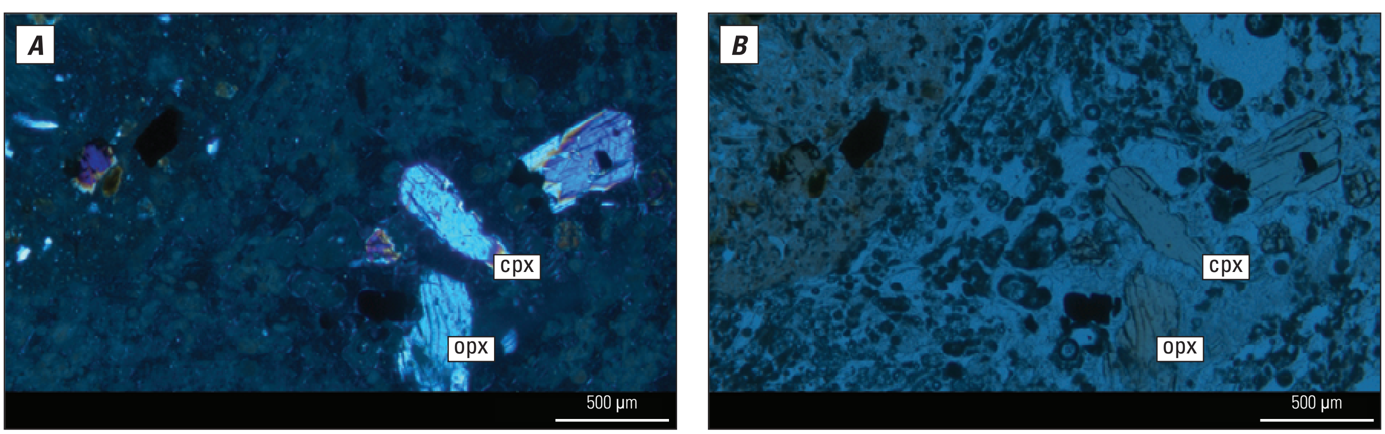

Figure 4.55. Thin-section photographs of sample of pumiceous pyroclastic-flow deposit (unit pfd), in Emmons Lake volcanic center, Alaska. *A*, Photograph 01S37M1-1, in cross-polarized light. *B*, Photograph 01S37M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; opx, orthopyroxene.

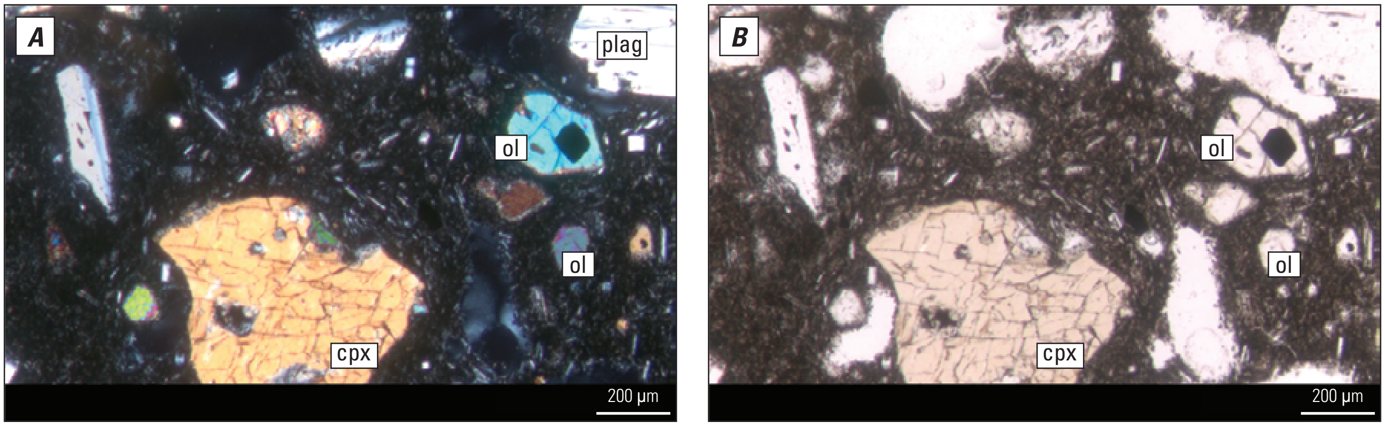

Figure 4.56. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S56M2-1, in cross-polarized light. *B*, Photograph 02S56M2-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

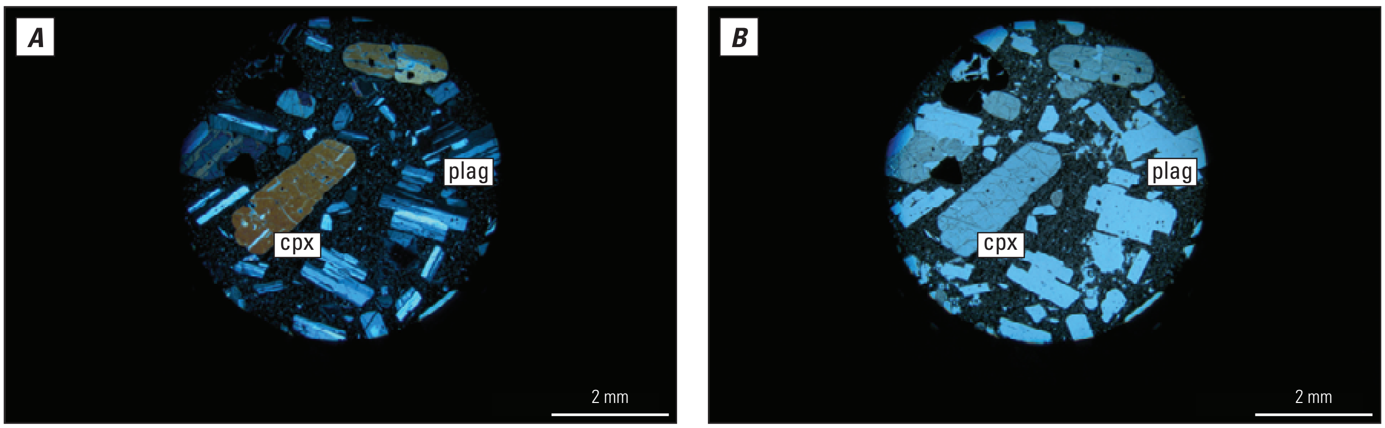

Figure 4.57. Thin-section photographs of sample of lava flow on south caldera rim (unit olf1), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05NYEL02-1, in cross-polarized light. *B*, Photograph 05NYEL02-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

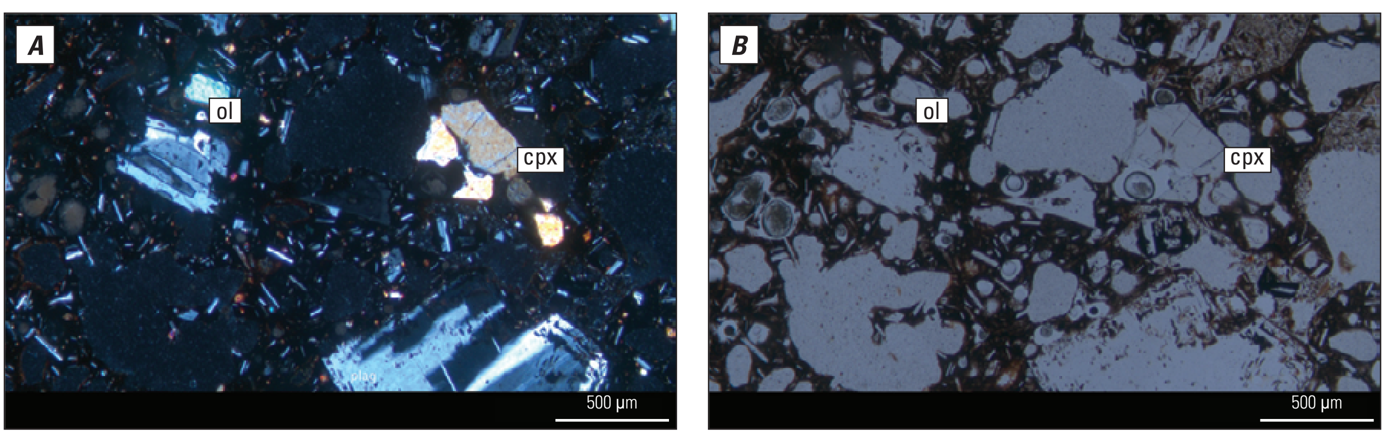

Figure 4.58. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plfh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S46M3-1, in cross-polarized light. *B*, Photograph 02S46M3-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine.

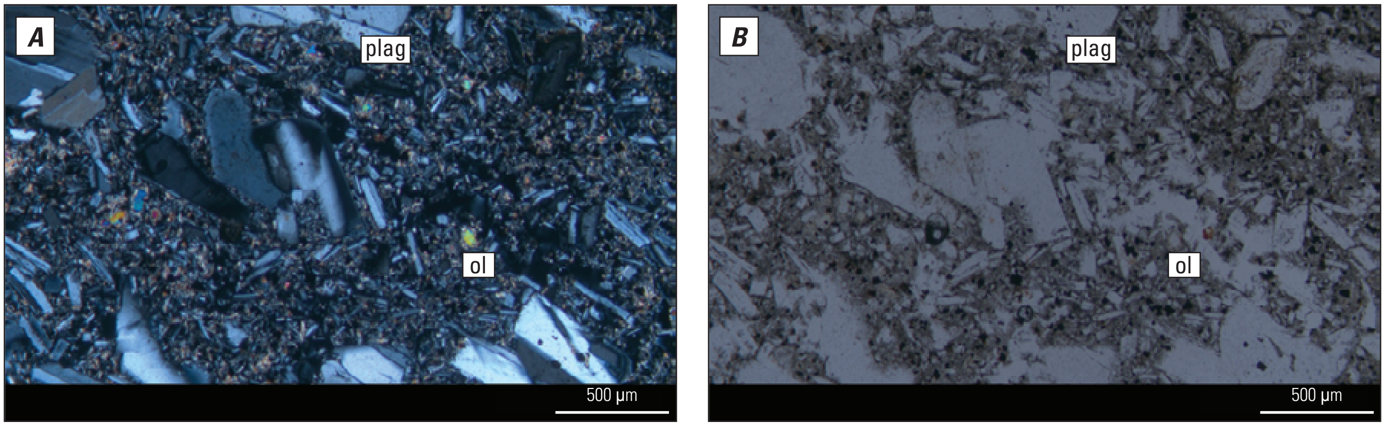

Figure 4.59. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S109M1-1, in cross-polarized light. *B*, Photograph 05S109M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; ol, olivine; plag, plagioclase.

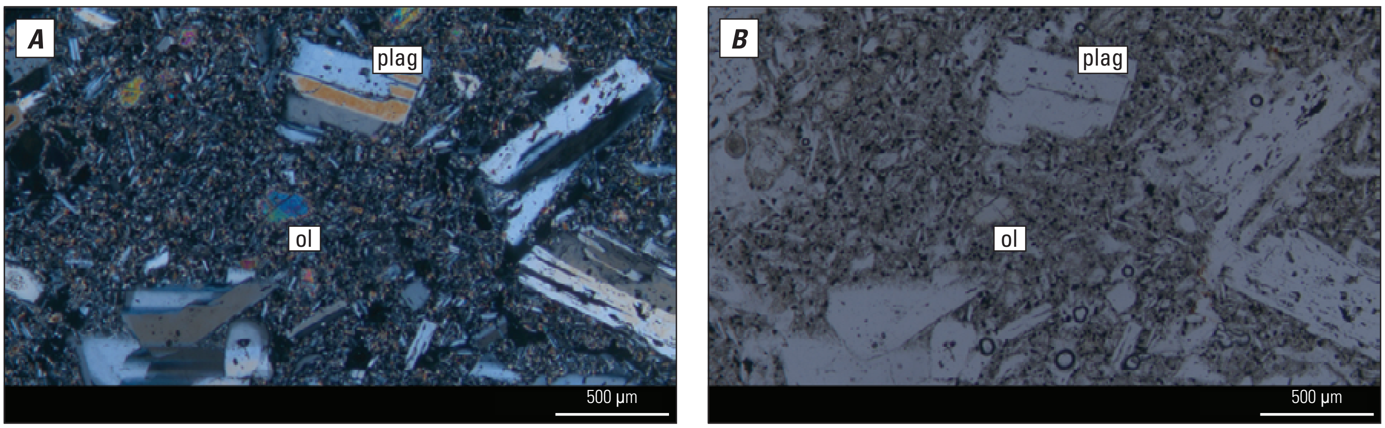

Figure 4.60. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S61M1-1, in cross-polarized light. *B*, Photograph 02S61M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; ol, olivine; plag, plagioclase.

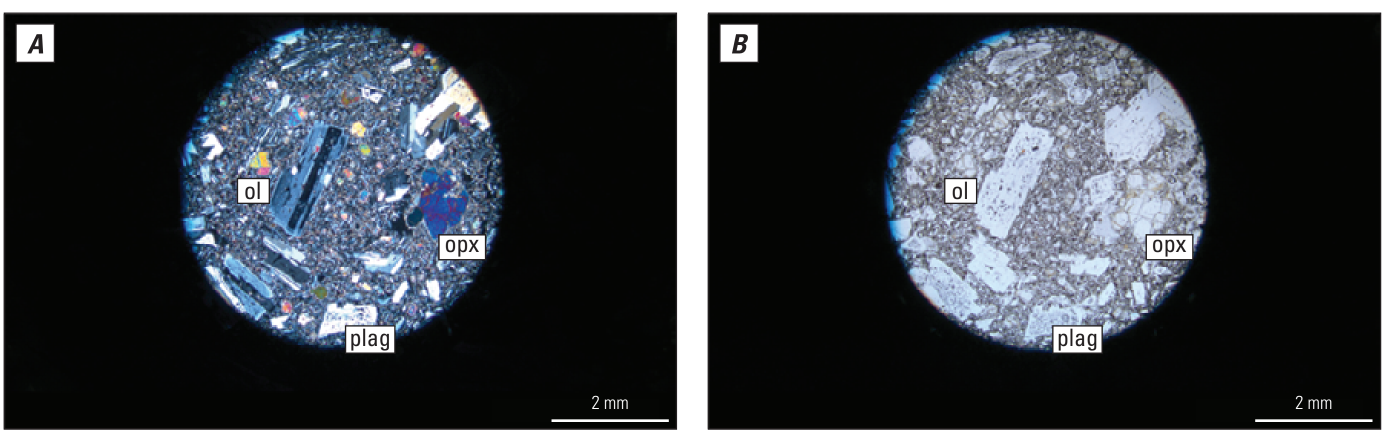

Figure 4.61. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S52F1-1, in cross-polarized light. *B*, Photograph 02S52F1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; ol, olivine; opx, orthopyroxene; plag, plagioclase.

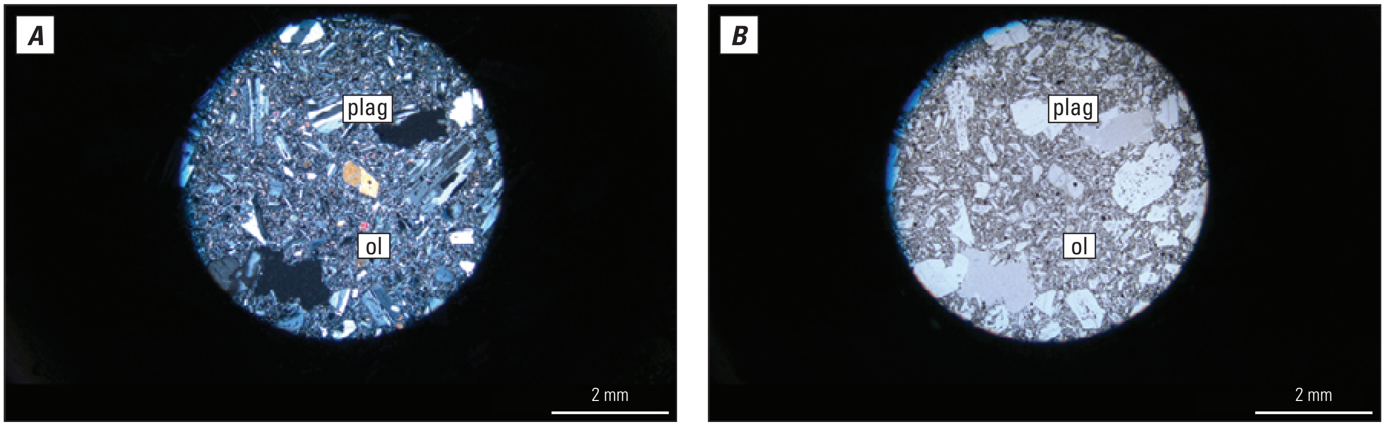

Figure 4.62. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S50F1A-1, in cross-polarized light. *B*, Photograph 02S50F1A-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; ol, olivine; plag, plagioclase.

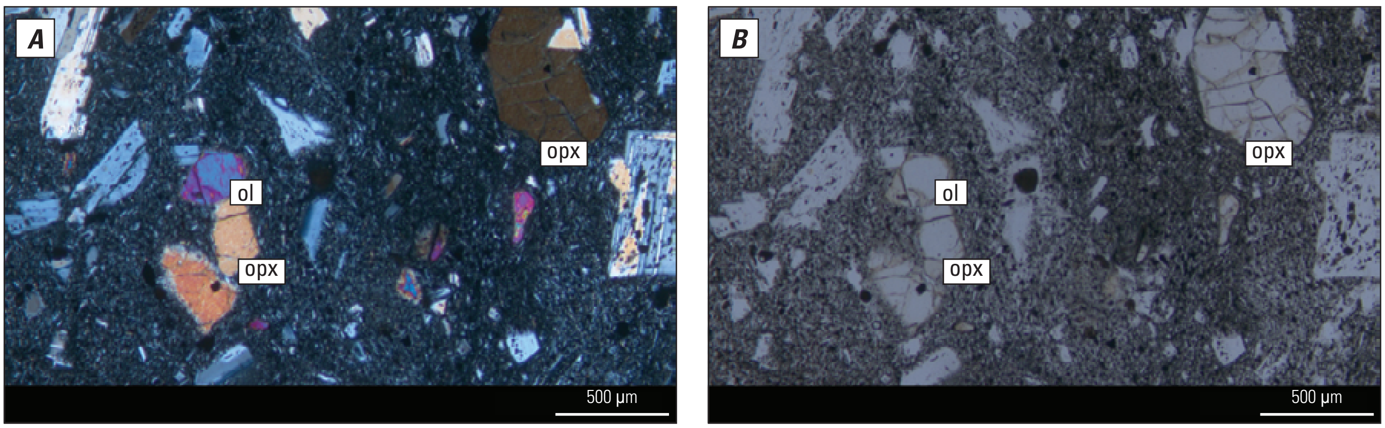

Figure 4.63. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S76M1-1, in cross-polarized light. *B*, Photograph 03S76M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; ol, olivine; opx, orthopyroxene.

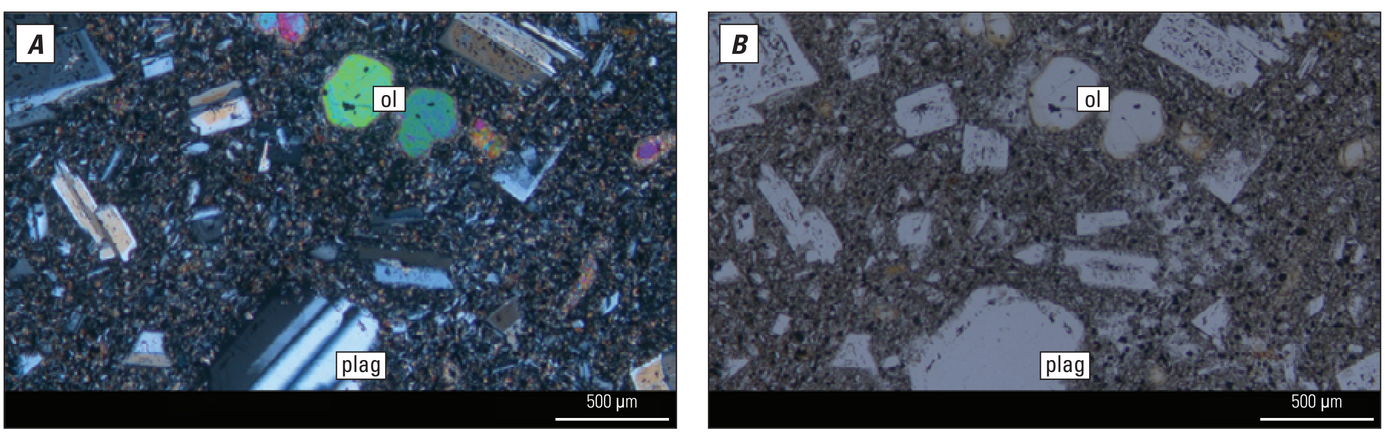

Figure 4.64. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S53M1-1, in cross-polarized light. *B*, Photograph 02S53M1-2, same view as *A* but in plane-polarized light. Abbreviations: µm, micrometer; ol, olivine; plag, plagioclase.

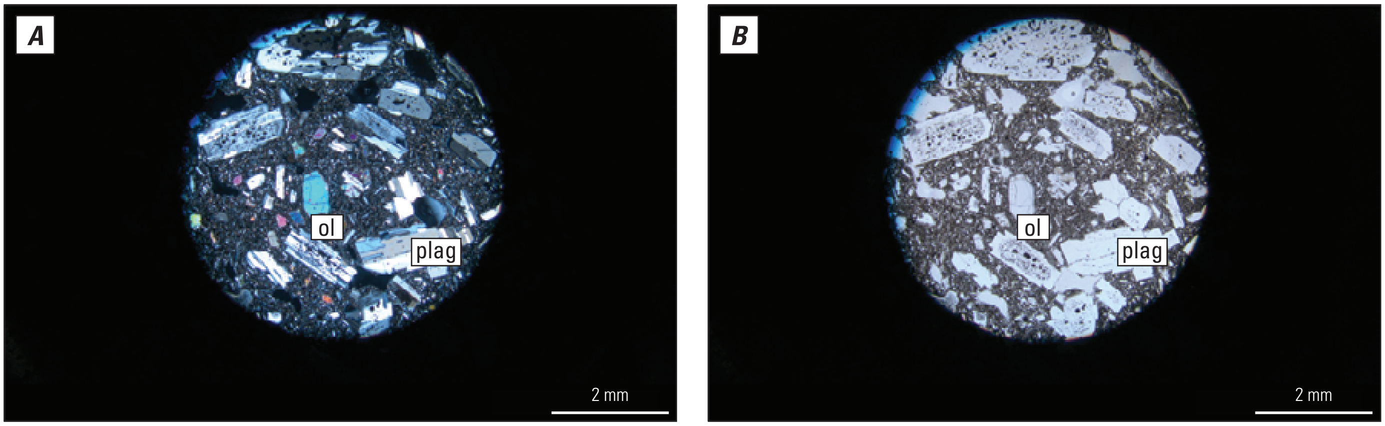

Figure 4.65. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S51F1-1, in cross-polarized light. *B*, Photograph 02S51F1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; ol, olivine; plag, plagioclase.

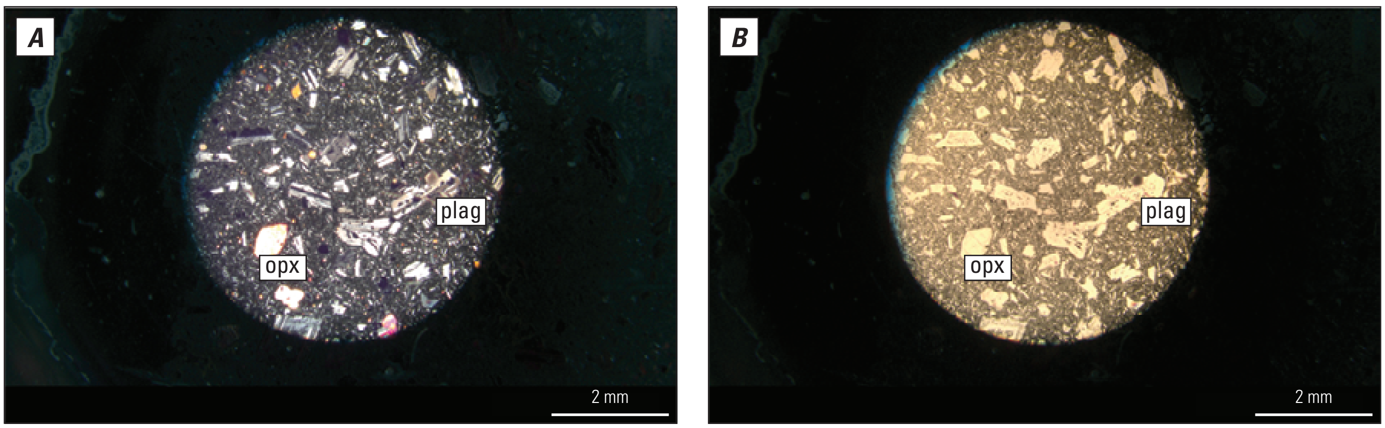

Figure 4.66. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S74M1-1, in cross-polarized light. *B*, Photograph 03S74M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

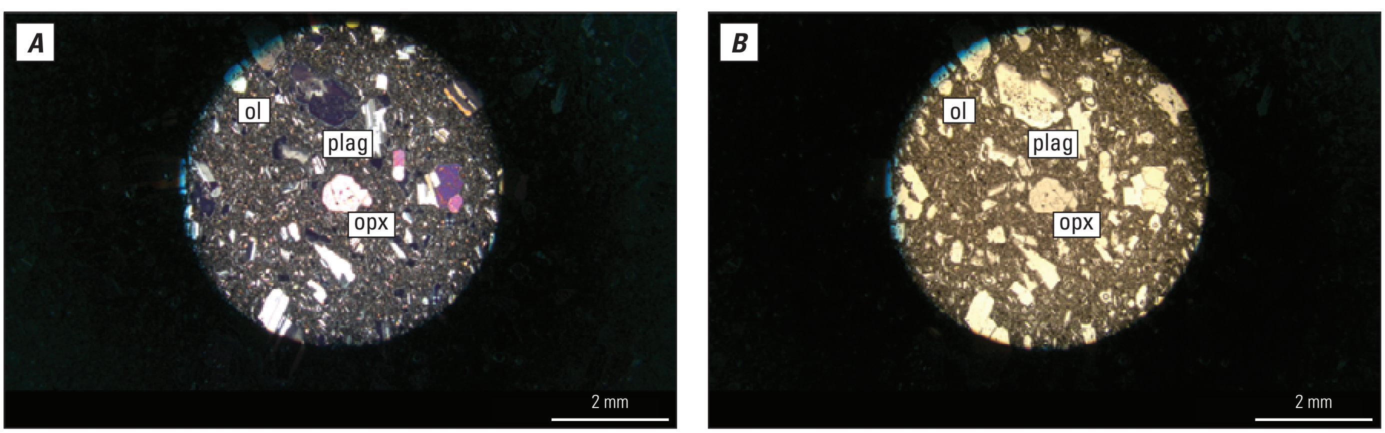

Figure 4.67. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plh), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S60M1-1, in cross-polarized light. *B*, Photograph 02S60M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; ol, olivine; opx, orthopyroxene; plag, plagioclase.

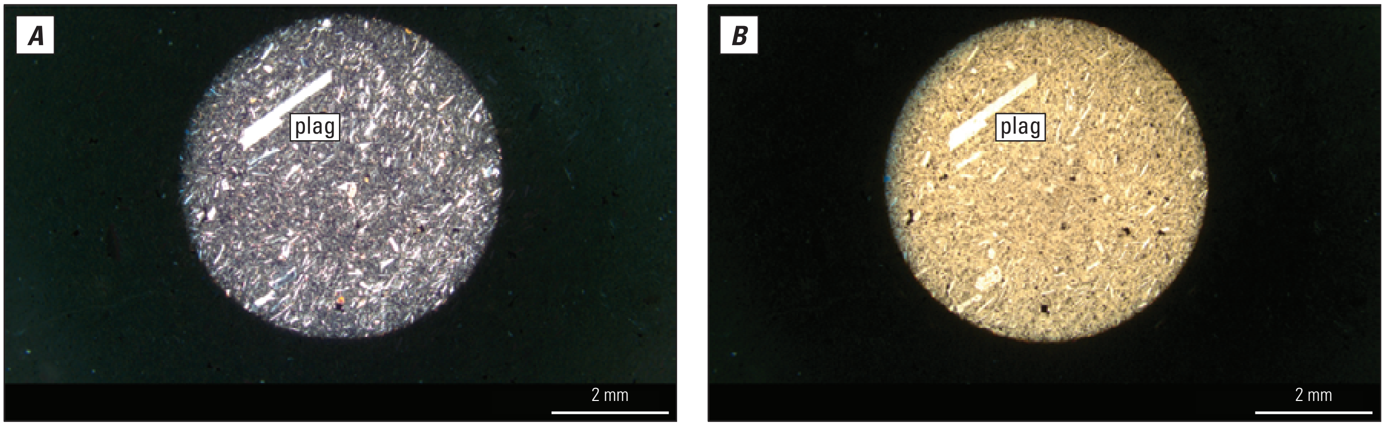

Figure 4.68. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plp), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S112T1-1, in cross-polarized light. *B*, Photograph 05S112T1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; plag, plagioclase.

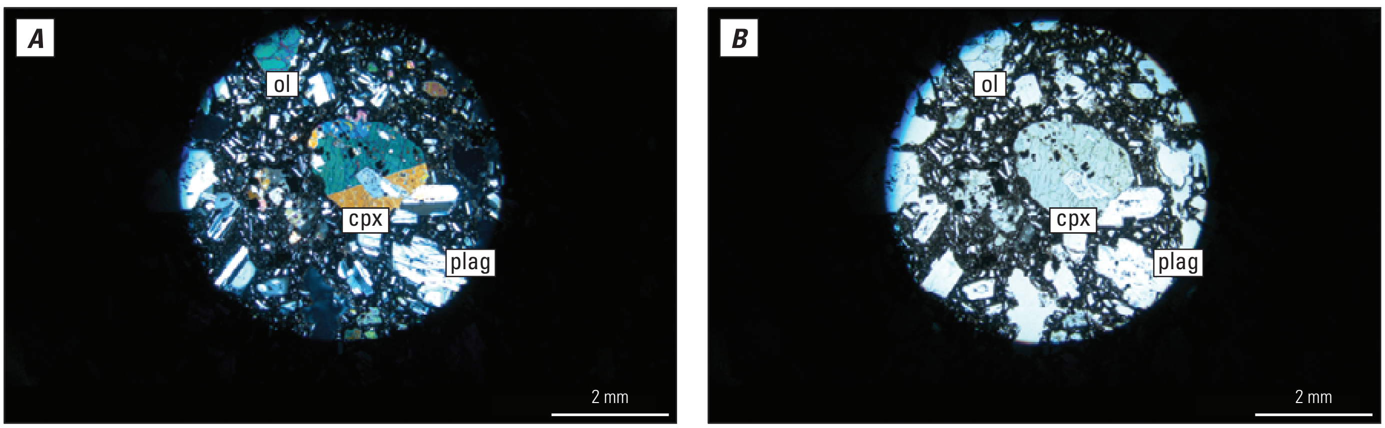

Figure 4.69. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plp), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S59M2-1, in cross-polarized light. *B*, Photograph 02S59M2-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; ol, olivine; plag, plagioclase.

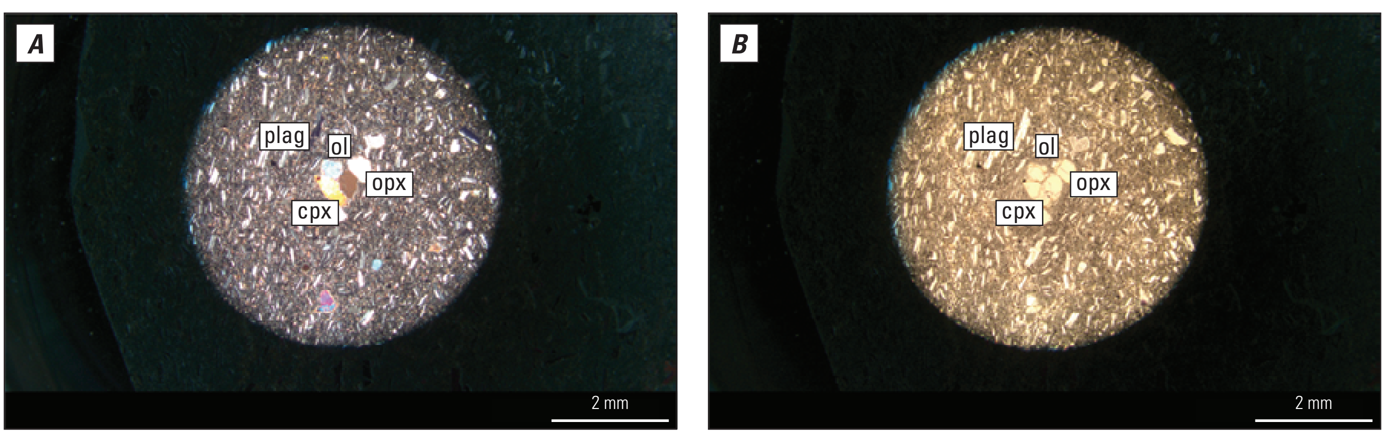

Figure 4.70. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plp), in Emmons Lake volcanic center, Alaska. *A*, Photograph 02S54M1-1, in cross-polarized light. *B*, Photograph 02S54M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; ol, olivine; opx, orthopyroxene; plag, plagioclase.

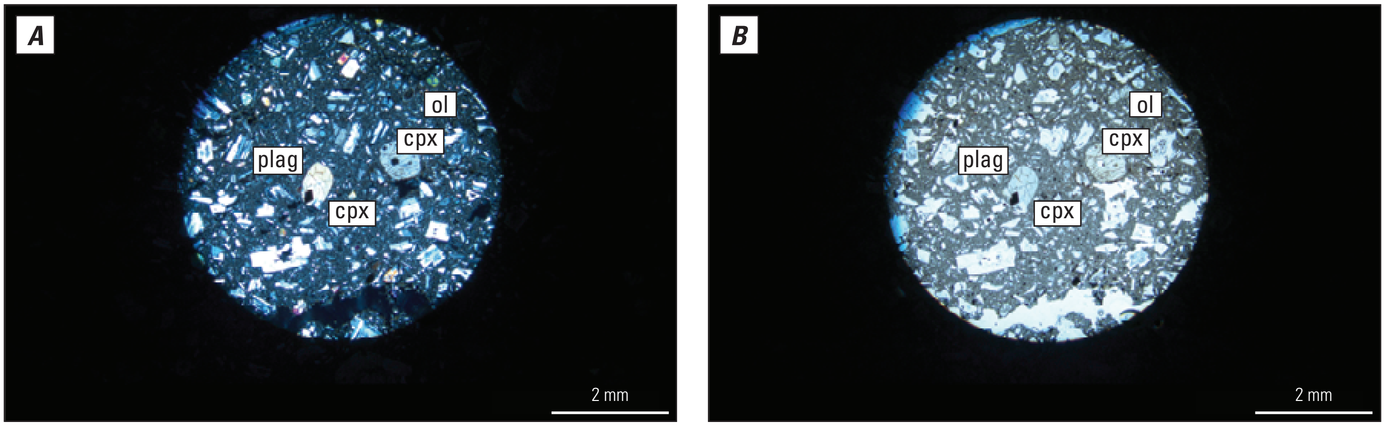

Figure 4.71. Thin-section photographs of sample of lava flow from Pavlof Volcano (unit plp), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S118T1-1, in cross-polarized light. *B*, Photograph 05S118T1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; ol, olivine; plag, plagioclase.

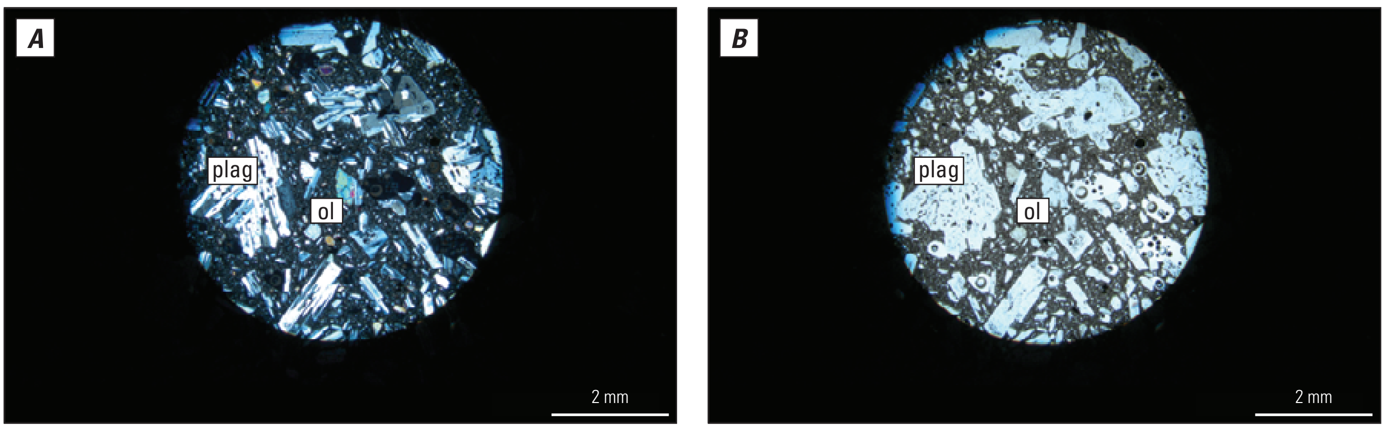

Figure 4.72. Thin-section photographs of sample of lava flow from Pavlof Sister volcano (unit pslf), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S115M1-1, in cross-polarized light. *B*, Photograph 05S115M1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; ol, olivine; plag, plagioclase.

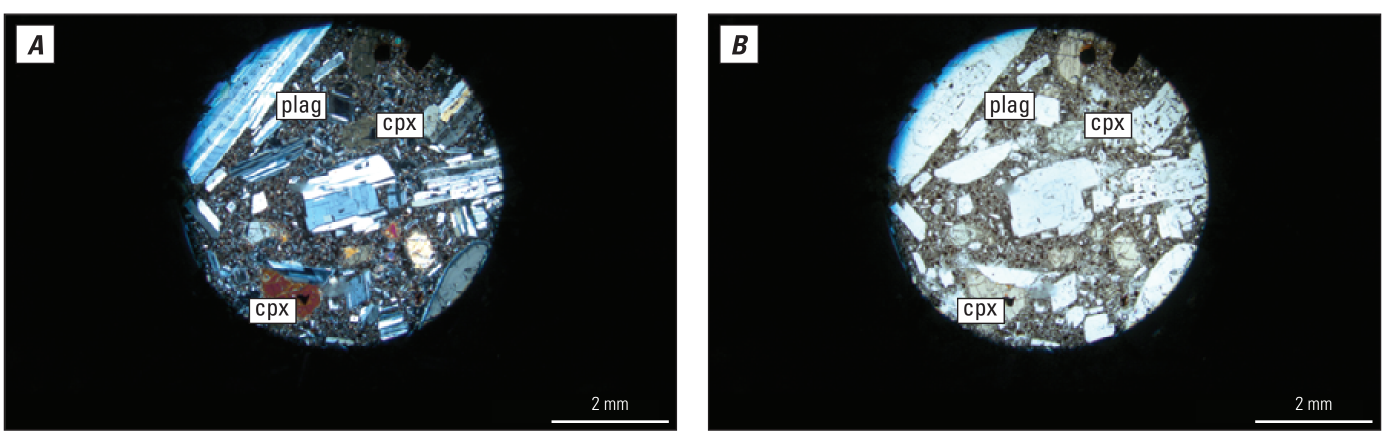

Figure 4.73. Thin-section photographs of sample of lava flow from Pavlof Sister volcano (unit pslf), in Emmons Lake volcanic center, Alaska. *A*, Photograph 03S72M1-1, in cross-polarized light. *B*, Photograph 03S72M1-2, same view as *A* but in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

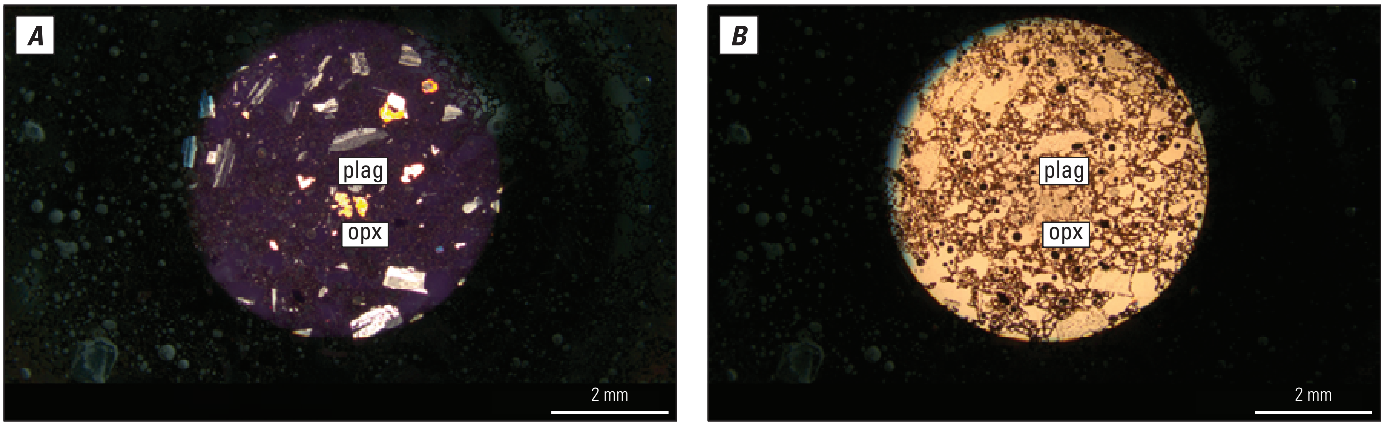

Figure 4.74. Thin-section photographs of sample of scoria bomb from Pavlof Volcano (unit pt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S125M2-1, in cross-polarized light. *B*, Photograph 05S125M2-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

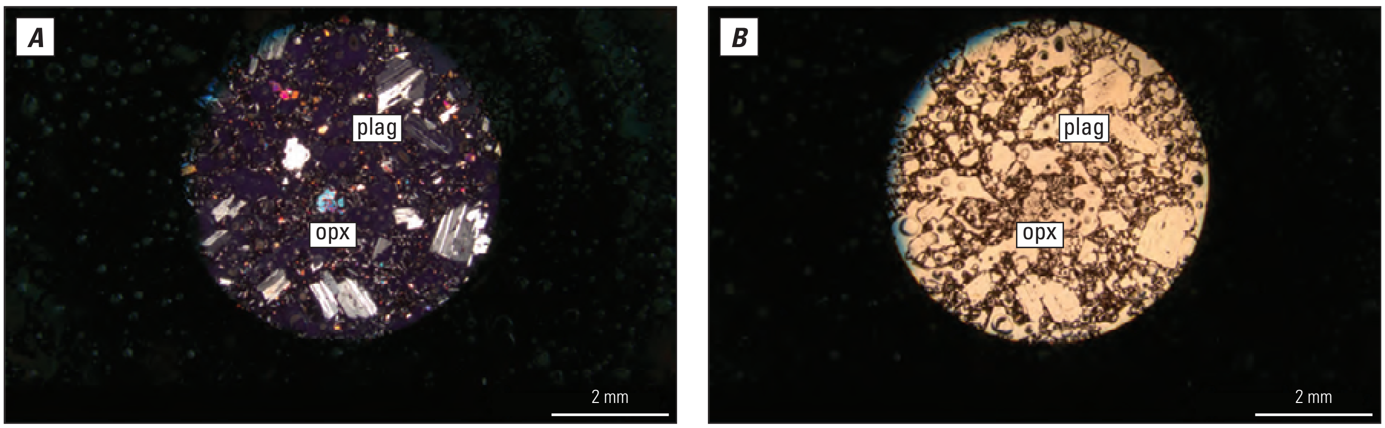

Figure 4.75. Thin-section photographs of sample of scoria bomb from Pavlof Volcano (unit pt), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S94M5-1, in cross-polarized light. *B*, Photograph 05S94M5-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

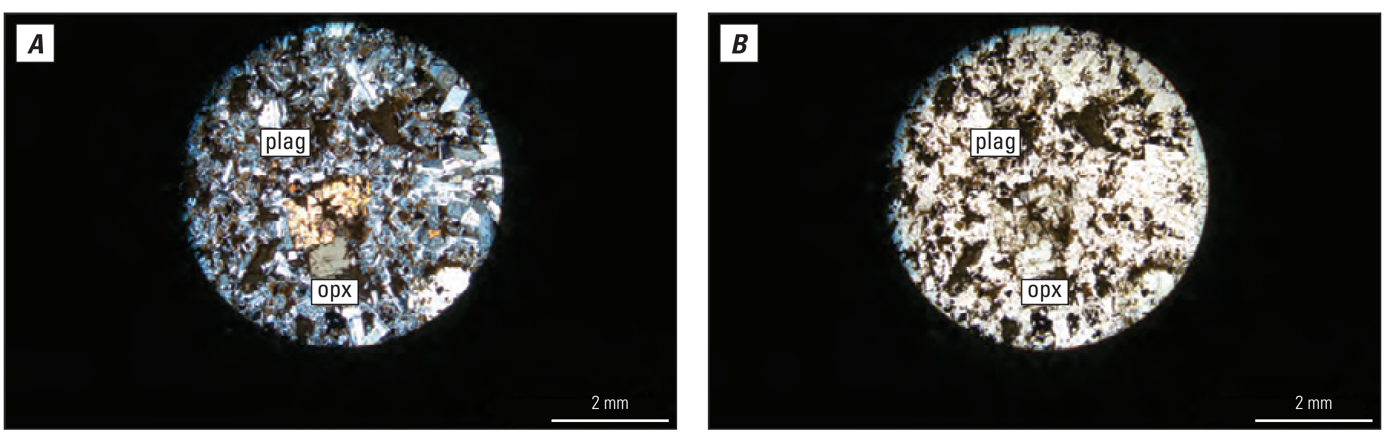

Figure 4.76. Thin-section photographs of sample of lava flow (unit ulf), in Emmons Lake volcanic center, Alaska. *A*, Photograph 05S111T1-1, in cross-polarized light. *B*, Photograph 05S111T1-2, same view as *A* but in plane-polarized light. Abbreviations: mm, millimeter; opx, orthopyroxene; plag, plagioclase.

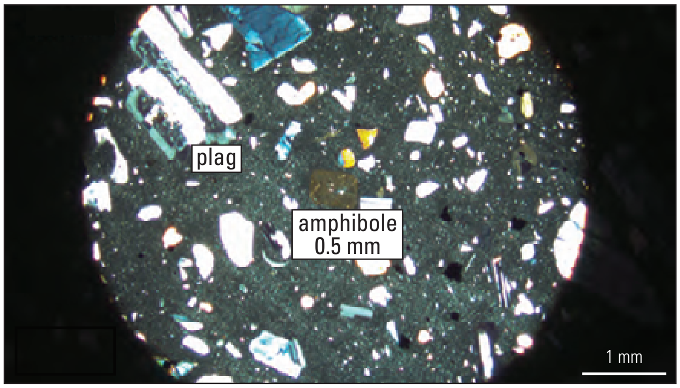

Figure 4.77. Thin-section photograph 05S130M1-1 of sample of tuff and agglutinate of "The Butte" (unit bwt), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Length (0.5 millimeter [mm]) of amphibole phenocryst labeled in center of photograph. Other abbreviation: plag, plagioclase.

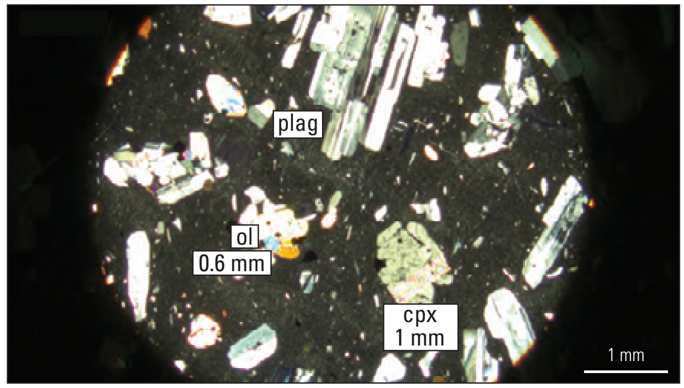

Figure 4.78. Thin-section photograph 05S130M1-2 of sample of tuff and agglutinate of "The Butte" (unit bwt), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Lengths of olivine (ol; 0.6 millimeter [mm]) and clinopyroxene (cpx; 1 mm) phenocrysts labeled in lower center of photograph. Other abbreviation: plag, plagioclase.

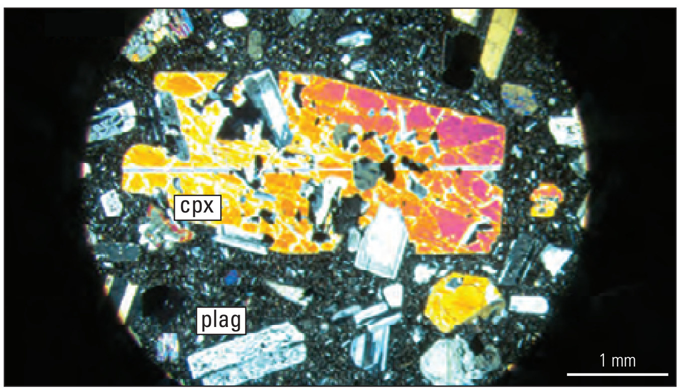

Figure 4.79. Thin-section photograph 05S104M1-2 of sample of lava flow from ancestral Mount Emmons (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

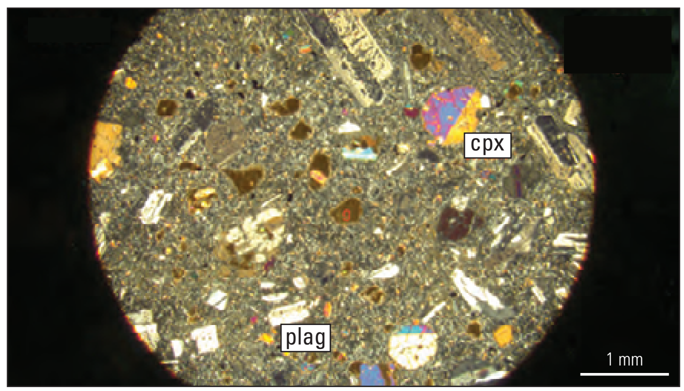

Figure 4.80. Thin-section photograph 05NYEL13-1 of sample of lava flow from ancestral Mount Emmons (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

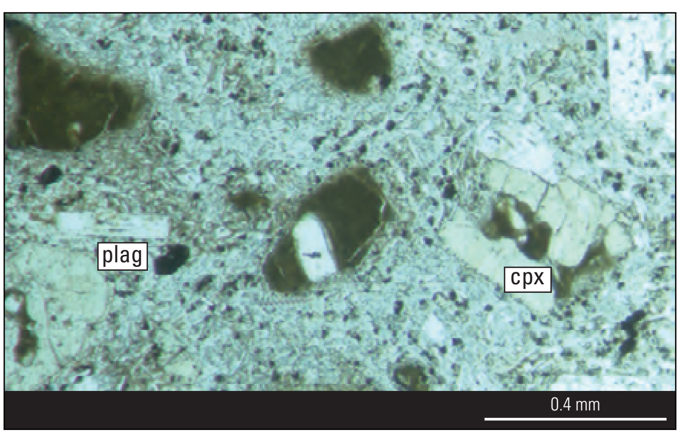

Figure 4.81. Thin-section photograph 05NYEL13-2 of sample of lava flow from ancestral Mount Emmons (unit cbl), in Emmons Lake volcanic center, Alaska, in plane-polarized light. Abbreviations: cpx, clinopyroxene; mm, millimeter; plag, plagioclase.

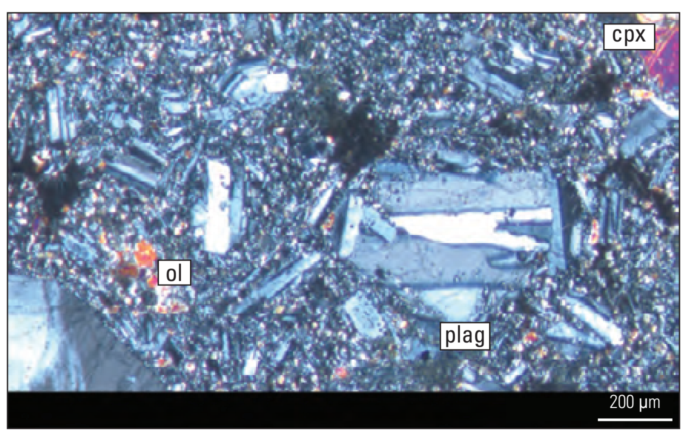

Figure 4.82. Thin-section photograph 05ELAC06-1 of sample of lava flow from ancestral Mount Emmons (unit cbl), in Emmons Lake volcanic center, Alaska, in cross-polarized light. Abbreviations: µm, micrometer; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

References Cited in Appendix 4

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