U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Geology of the Ugashik-Mount Peulik Volcanic Center, Alaska

Open-File Report 2004–1009

This report is preliminary and subject to revision as new data become available. It does not conform to U.S. Geological Survey editorial standards or with the North American Stratigraphic Code.

Cover photograph: Mount Peulik Volcano. View looking north from shore of Ugashik Lake. Alaska Volcano Observatory photo, 1979.

Geology of the Ugashik-Mount Peulik Volcanic Center, Alaska

By Thomas P. Miller

U.S. GEOLOGICAL SURVEY

Open-File Report 2004–1009

Alaska Volcano Observatory

Anchorage, Alaska

2004

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

Copies of this report can be obtained from either of the following sources:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225–0286
(Tel. 303-236-7477 or 800-USA-MAP)

U.S. Geological Survey
Earth Science Information Center
4230 University Drive
Anchorage, AK 99508
(Tel. 907-786-7011)

How to contact the Alaska Volcano Observatory:

U.S. Geological Survey
4200 University Drive
Anchorage, AK 99508
(Tel. 907-786-7497)
(Fax 907-786-7425)
(Internet: http://www.avo.alaska.edu)

CONTENTS

PLATES

FIGURES

TABLES

CONVERSION FACTORS and VERTICAL DATUM

Multiply	by	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
cubic kilometer (km^3)	0.2399	cubic mile
meter per second (m/s)	3.281	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second

In this report, temperature is reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the equation

$$°F = (1.8 \times °C) + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called “Sea-Level Datum of 1929”), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada. In the area of this report, datum is mean lower low water.

Geology of the Ugashik-Mount Peulik Volcanic Center, Alaska

By Thomas P. Miller

Abstract

The Ugashik-Mount Peulik volcanic center, 550 km southwest of Anchorage on the Alaska Peninsula, consists of the late Quaternary 5-km-wide Ugashik caldera and the stratovolcano Mount Peulik built on the north flank of Ugashik. The center has been the site of explosive volcanism including a caldera-forming eruption and post-caldera dome-destructive activity. Mount Peulik has been formed entirely in Holocene time and erupted in 1814 and 1845. A large lava dome occupies the summit crater, which is breached to the west. A smaller dome is perched high on the southeast flank of the cone. Pyroclastic-flow deposits form aprons below both domes. One or more sector-collapse events occurred early in the formation of Mount Peulik volcano resulting in a large area of debris-avalanche deposits on the volcano's northwest flank.

The Ugashik-Mount Peulik center is a calcalkaline suite of basalt, andesite, dacite, and rhyolite, ranging in SiO_2 content from 51 to 72 percent. The Ugashik-Mount Peulik magmas appear to be co-genetic in a broad sense and their compositional variation has probably resulted from a combination of fractional crystallization and magma-mixing.

The most likely scenario for a future eruption is that one or more of the summit domes on Mount Peulik are destroyed as new magma rises to the surface. Debris avalanches and pyroclastic flows may then move down the west and, less likely, east flanks of the volcano for distances of 10 km or more. A new lava dome or series of domes would be expected to form either during or within some few years after the explosive disruption of the previous dome. This cycle of dome disruption, pyroclastic flow generation, and new dome formation could be repeated several times in a single eruption.

The volcano poses little direct threat to human population as the area is sparsely populated. The most serious hazard is the effect of airborne volcanic ash on aircraft since Mount Peulik sits astride heavily traveled air routes connecting the U.S. and Europe to Asia. Activity of the type described could produce eruption columns to heights of 15 km and result in significant amounts of ash 250-300 km downwind.

INTRODUCTION

The Ugashik-Mount Peulik volcanic center is 8 km south of Becharof Lake, 550 km southwest of Anchorage on the Alaska Peninsula (fig. 1). The center includes two major late Quaternary volcanic landforms, the circular Ugashik caldera and the Mount Peulik stratovolcano on the north flank of Ugashik. Eruptive activity began at Ugashik in the late Pleistocene and has continued into historic time at Mount Peulik, where eruptions occurred in 1814 and 1845 (Miller and others, 1998).

The volcanoes are in a roadless part of the Alaska Peninsula National Wildlife Refuge that is mostly treeless although the lower flanks of the volcanic center are covered by willows, brush, and other low vegetation.

The center has been the site of many explosive eruptions, the largest of which was the caldera-forming event. At least three lava domes, one of which may be Holocene in age, subsequently grew in the caldera. The Holocene Mount Peulik edifice is breached on the west by a large horseshoe-shaped summit crater. A lava dome partly fills this summit crater, and extensive avalanche and pyroclastic-flow deposits extend outward from the west and northwest flanks of the cone. A smaller dome perched high on the southeast side of the cone has a small apron of pyroclastic-flow deposits beneath it.

Geologic Setting

The Ugashik-Mount Peulik volcanic center is in the eastern, continental-margin part of the 2600-km-long Aleutian volcanic arc. The center is about 320 km landward of the Aleutian trench (Plafker and others, 1994) that marks the subduction zone boundary between the Pacific and North American plates (fig. 1). Earthquake hypocenter plots indicate that the center lies 110 to 120 km above the top of the Benioff zone that dips 35° to 40° to the north-northwest (Kienle and others, 1980).

The Aleutian volcanic arc has been divided into segments formed by groups of regularly spaced volcanoes aligned along linear trends (Kay and others, 1982; Kienle and Swanson, 1983; Miller and Richter, 1994). The Ugashik-Mount Peulik center is at the

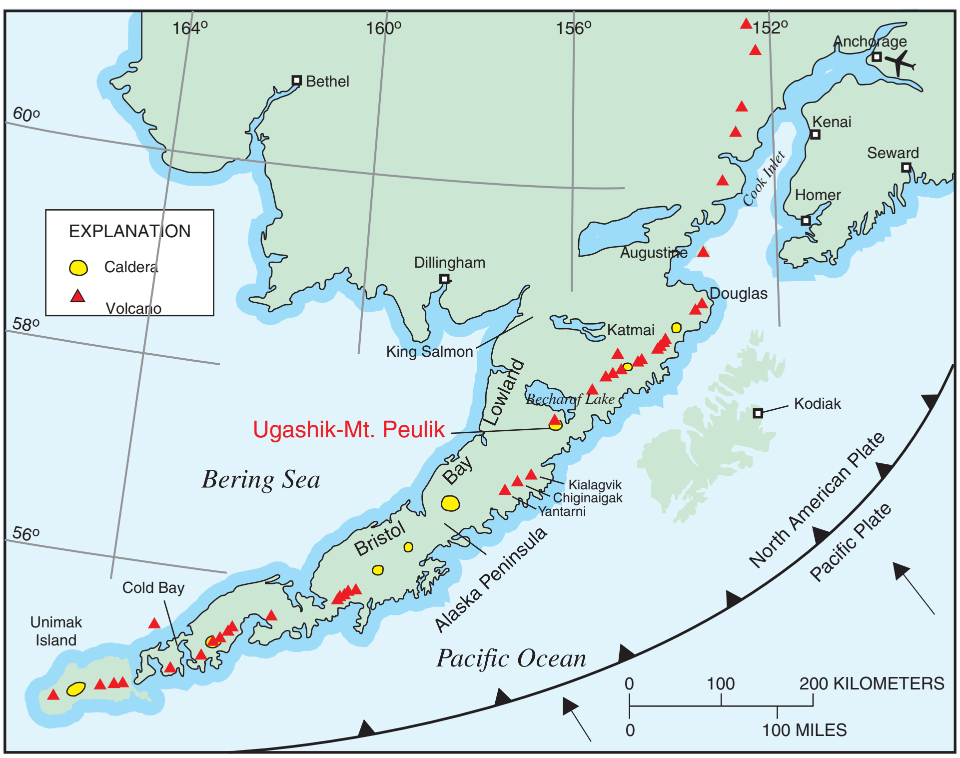

Figure 1. Location of the Ugashik-Peulik volcanic center, and other volcanoes and calderas in the eastern Aleutian arc. Also shown is the direction of movement between the Pacific and North American plates.

southwest end of a 200-km-long segment of 14 late Quaternary volcanoes (Miller and Richter, 1994) that extends through the Katmai region to Douglas volcano (fig. 1); 11 of the volcanoes are closely-spaced and lie within a 75 km length of the segment. The center is separated from Kejulik, the nearest volcano to the northeast, by about 60 km and from Kialagvik, the nearest volcano to the southwest by about 65 km (Miller and Richter, 1994). The volcanic front southwest of the Ugashik-Mount Peulik center, as defined by the closely-spaced (18 km separation) Kialagvik-Chiginigak-Yantarni volcanoes, is off-set about 25 km seaward from the Mount Peulik-Katmai-Douglas segment

The Ugashik-Mount Peulik center is built on the crest of a northeast-trending anticline (Detterman and others, 1987a), the westernmost of a series of broad open folds that lie west of the Wide Bay Anticline. Basement rocks beneath the center consist of marine and continental sedimentary rocks (chiefly sandstone) of the Upper Jurassic Naknek Formation, and siltstone, shale, and mudstone of the Upper Cretaceous Chignik Formation (Detterman and others, 1987a). The center is about 13 km east of the northeast-trending Bruin Bay Fault (plate 1), a major structure that juxtaposes Jurassic granitic rocks of the Alaska-Aleutian Range batholith against the upper Mesozoic sedimentary rocks. A dome complex, one of several small volcanic centers of late Quaternary age in the general area, crops out along the south shore of Becharof Lake near Gas Rocks and has yielded K-Ar ages ranging from 0.13 to 0.61 Ma (Detterman and others, 1987a).

Previous Work

The geology of the Ugashik-Mount Peulik area was little known before the 1980's. Capps (1923) visited the region in 1921 and published a reconnaissance geologic map that outlined part of the area underlain by Mount Peulik volcanic rocks. Capps noted that Mount Peulik was only slightly dissected by erosion and that its flows reached Becharof Lake. He also noted that Mount Peulik volcano was built on the north edge of an older crater (Ugashik) in which the Mesozoic Naknek Formation was exposed and that the volcano was on the northwest flank of an anticline. Smith and Baker (1924) visited the area a few years later, but added little to the knowledge of the volcanic center.

Detterman and others (1987a,b) published geologic maps of the area at a scale of 1:250,000, which show many of the geologic units discussed in this report.

Historical Activity

The name "Peulik" means "smoking mountain" in Aleut (Osgood, 1904) although historic eruptions at the Ugashik-Mount Peulik center are poorly documented. Miller and others (1998) list reports of "smoke" apparently from Mount Peulik observed from ships in the Pacific Ocean ten's of kilometers to the south and east of the volcano in 1814 and 1852. Because Mount Peulik is separated from other prominent active volcanic edifices in the region (fig. 1), these reports are credible and may represent the most recent eruptions at the center.

Fumaroles and hot springs are unknown at Mount Peulik and Ugashik. Waring (1917) mentioned hot springs on the southwest shore of Becharof Lake and gave their location near Gas Rocks (plate 1), an area that contains a group of CO_2-rich springs, some of which are above ambient temperature (Barnes and McCoy, 1979, Symonds and others, 1997).

The stream draining Ugashik caldera was called Hot Springs Creek at least as early as 1923 (Orth, 1967), but the origin of the name is unknown. Although the Ugashik C-1 1:63,360-scale topographic map shows numerous springs near this stream both inside and outside the caldera, no thermal springs have been found. Springs inside the caldera are at ambient temperature and occur at the base of intracaldera lava domes. The springs are dilute containing only slightly elevated amounts of SiO_2, Na, K, Cl, and HCO_3 (table 1 on plate 2). Their chemical and isotopic compositions suggest that the spring water is mainly of meteoric origin, but has reacted weakly with local rocks (T.E.C. Keith, written communication, 1994). Springs outside the caldera have not been sampled.

The most recent eruption in the area was in April 1977, when phreatomagmatic activity produced two small maars 12 km northwest of Mount Peulik (plate 1, Kienle and others, 1980: Self and others, 1980). Tephra from this eruption blankets a widespread area immediately south of the Gas Rocks (plate 1) with thicknesses up to 10 m at the maar craters. These maars, named the Ukinrek Maars, are located behind the volcanic front and erupted undersaturated alkaline

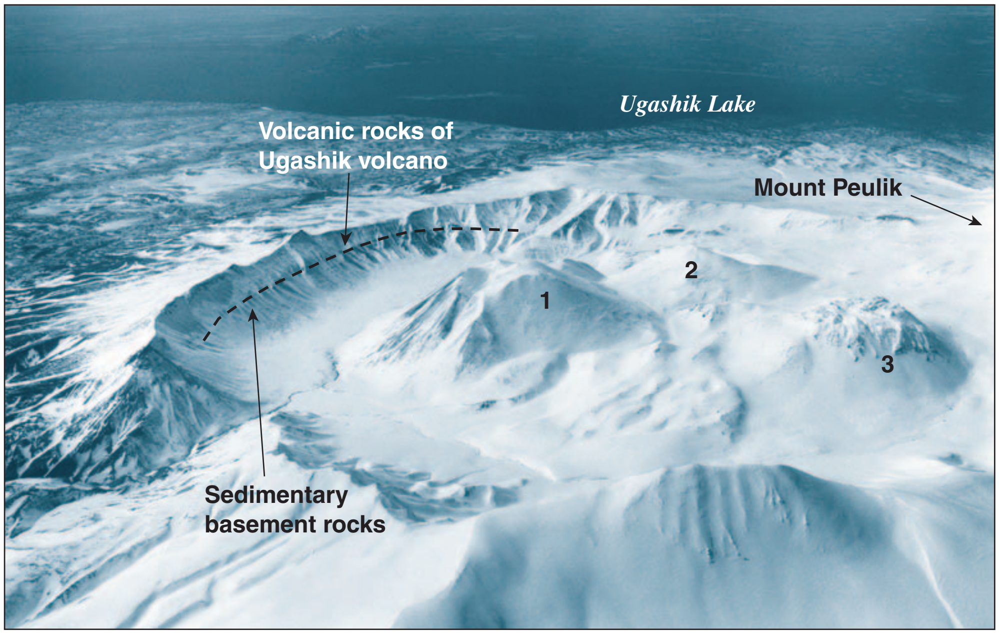

Figure 2. Five-km-wide Ugashik caldera and intracaldera lava domes (1, 2, 3). Oblique view looking west towards Ugashik Lake. Contact between basement rocks and Ugashik volcanic rocks visible in far caldera wall. Dome (3) on extreme right still has rugged carapace and may be Holocene in age. Mount Peulik is just out of view to the right of photo. Alaska Volcano Observatory photo, 1984.

basalt resembling back-arc magmas that Kienle and others (1980) believe is unrelated to Mount Peulik volcanism.

GEOLOGY OF THE UGASHIK CALDERA

Pre-Caldera Stage

Reconstructing the pre-caldera history of Ugashik caldera (fig. 2) is difficult given the scarce outcrops of pre-caldera Ugashik volcanic rocks. Most of the caldera wall consists of sandstone and siltstone from the Jurassic Naknek and Cretaceous Chignik Formations (unit KJnc, plate 1). A thin cover (~25 m) of hornblende-dacite and silicic andesite volcanic breccia (unit Qub, plate 1) overlain by 15 to 20 m of discontinuous dacitic lava flows (Quf, plate 1) remains on the south and west rim of the caldera. The eastern rim of the caldera is topped by silicic hornblende-andesite and dacite lava flows. A thick lava flow, or a series of lava flows, extends down the eastern flank of the volcano filling a pre-existing valley. Although some pre-caldera rocks have undoubtedly have been stripped by erosion or are covered by Mount Peulik eruptive products, the meager distribution and relatively small volume of these rocks suggest that the pre-caldera volcanic edifice was probably <10 km^3 in volume.

The pre-caldera volcanic rocks are mostly high-silica andesite that ranges from 59.1 to 62.6 percent SiO_2. These rocks are moderately phyric as phenocryst contents range from 25 to 35 percent by volume. Plagioclase constitutes about 70-80 percent of the phenocrysts; hornblende about 1-14 percent, orthopyroxene about 3-13 percent, and clinopyroxene about 1-6 percent. Biotite and olivine are present in trace amounts. Groundmass is glass and fine-grained glassy cryptocrystalline material.

The pre-caldera edifice may have been a dome complex rather than a stratovolcano. Breccia on the south and west rims resembles dome-margin crumble breccia common on flanks of domes. The predominance of hornblende over pyroxene, the occurrence of biotite in trace amounts, and the lack of basaltic and low-silica andesitic rocks are suggestive of dome-building, rather than cone-building magmas. Volcanic centers composed of a composite dome core and flanking breccias, flows, and pyroclastic deposits occur elsewhere in the Aleutian arc at Augustine

volcano in the Cook Inlet area (Swanson and Kienle, 1988) and at Dutton volcano near the tip of the Alaska Peninsula (Miller and others, 1999).

The only isotopically-dated volcanic rocks are dacite from the south rim of the caldera which yielded a single whole-rock K-Ar age determination of 171,000±22,000 yrs (table 2 on plate 2).

Caldera-Forming Stage

The volcanic complex at Ugashik experienced a catastrophic eruption in the late Pleistocene. Most of the pre-existing dome complex was destroyed or collapsed resulting in the formation of a small caldera about 5 km in diameter and with a volume of about 5 km^3. Given these dimensions, it is unlikely that the edifice itself was more than 5 km^3 in volume. The caldera-forming eruption, therefore, would have ejected about 5-10 km^3 (DRE) of material. The almost circular plan of the caldera lacking an explosion breach suggests that the caldera was formed by collapse; the lack of a scalloped margin indicates that the collapse was a single event.

An eruption of this volume should produce extensive pyroclastic deposits near the volcano as have similar late Quaternary caldera-forming eruptions elsewhere on the Alaska Peninsula (Miller and Smith, 1987). Such deposits apparently were removed by late Pleistocene glaciation and only reworked remnants are preserved. Light-colored pyroclastic-flow deposits (unit Qupf, plate 1) of probable syn-caldera age are exposed in the walls of the eastern Ukinrek maar (Kienle and others, 1980) overlain by several meters of 1977 Ukinrek tephra. The only available samples of the 20-m-thick pyroclastic deposits (collected in 1993 by Michael Ort) are slightly pumiceous crystal-rich hornblende-pyroxene dacite. This lithology and the proximity to Ugashik caldera suggests that the pyroclastic-flow deposits are from the caldera-forming eruption. Low vegetation-covered hills with similar morphology are nearby to the west (plate 1) and may also be underlain by pyroclastic-flow deposits.

The caldera must be younger than the 171,000±22,000 yr K-Ar age determined on pre-caldera volcanic rocks. Beach sands underneath a tuff cone 15 km west of the caldera on the south side of Becharof Lake and only 5 km northwest of the pyroclastic flow deposit in the Ukinrek maars (plate 1) contain abundant coarse white pumice lapilli and charcoal fragments. These charcoal fragments yielded ^{14}C ages of 31,960±1190 and 42,900±3,780 yr BP (Miller and Smith, 1987) which, because of their antiquity and age spread, are almost certainly minimum ages. If both the pumice and the charcoal are related to the caldera-forming eruption (and it is entirely possible that they have no relation to each other or to the caldera-forming eruption), then the eruption would have a minimum date of ~40,000 yr B.P.

Pumice and hornblende-dacite debris similar to that at the Ukinrek Maars and the intracaldera domes at Ugashik caldera is found in late Pleistocene to Holocene lake sediments in the lowlands south and north of the caldera (plate 1). Similar material was reported by Detterman and others (1987b) in glacial moraine of the Bering Sea lowland immediately west of Ugashik Lake. These glacial deposits were assigned by Detterman and others to the late Wisconsin (<25 ka) Brooks Lake glaciation suggesting that the Ugashik caldera formed >25,000 years ago. The lack of similar material in older moraine deposits (i.e, the Mak Hill glaciation) which were considered by Detterman and others to be of early Wisconsin age and >40,000 yr B.P. suggests that the caldera formed in early to late Wisconsin time, perhaps about 40,000 yr B.P.

Post-Caldera Stage

Post-caldera eruptions in Ugashik caldera formed a nested cluster of dacite-rhyolite domes (unit Qud, plate 1). Three large domes (I, II, III, plate 1) overlap several smaller mounds that are either smaller domes or debris from dome explosions. Dome material covers most of the caldera floor, leaving only a narrow moat separating domes from the caldera wall (unit Qmt, plate 1). A block lava flow from Mount Peulik partly covers the northwest side of the dome cluster. The largest dome, which is composite, is about 440 m high and 2 km wide.

Most of the domes have smooth surfaces that appear to have been glaciated, indicating that they are pre-Holocene in age. Dome I (plate 1), however, has a crackled, blocky carapace that almost certainly has not been glaciated and is interpreted to be Holocene in age.

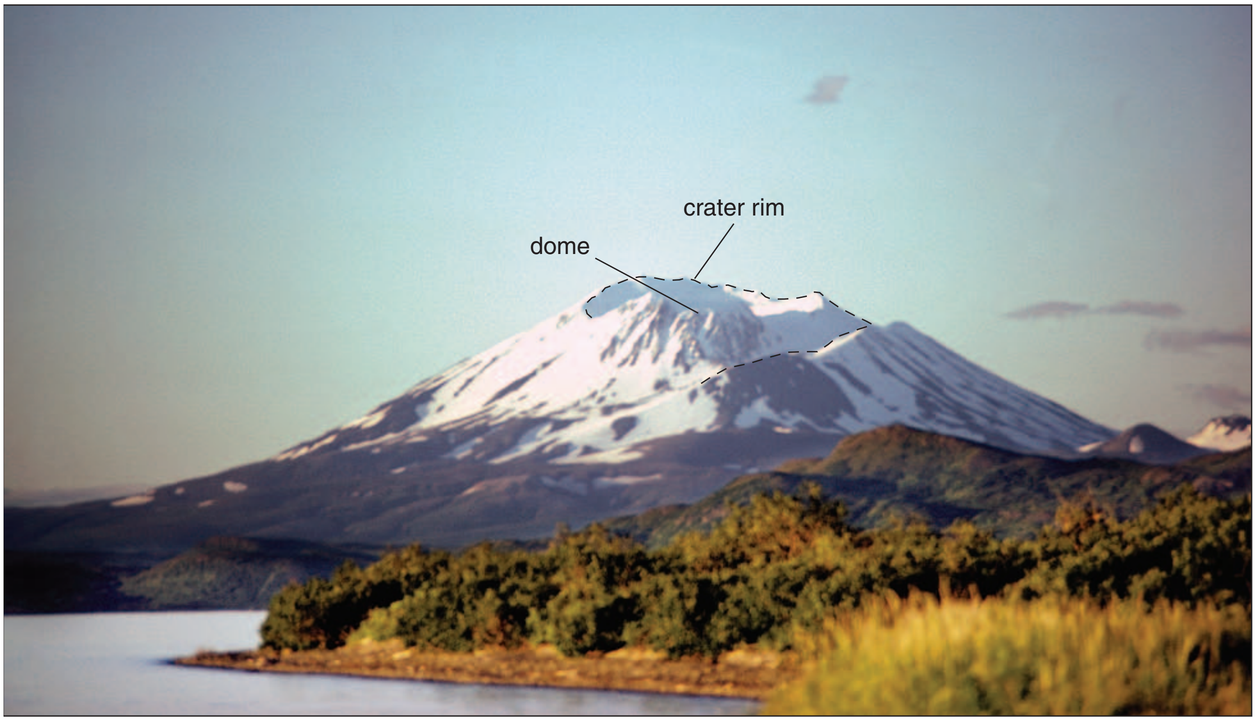

Figure 3. Mount Peulik volcano. View looking north from shore of Ugashik Lake. Summit crater and dome visible. Alaska Volcano Observatory photo, 1979.

Dome rocks are reddish-gray, dense, porphyritic to almost aphanitic dacite and rhyolite with SiO_2 contents ranging from 65 to 72 percent. The rocks are slightly to moderately phyric with about 10 to 30 percent phenocrysts of which 60 to 90 percent are plagioclase. Hornblende and orthopyroxene make up 6-10 and 1-2 percent of the phenocrysts, respectively, and biotite and more rarely quartz are in trace amounts.

Geology of Mount Peulik Volcano

Mount Peulik is a small stratovolcano that rises to an elevation of 1,474 m, has a height of 710-864 m, and a volume of about 5.6 km^3. It was constructed during at least 3 cone-building episodes involving both central (summit) and flank vents (fig. 3). Outlying flowage deposits account for <5 km^3. An amphitheater crater open to the west occupies the summit.

Numerical age data from Mount Peulik volcano are absent. The main edifice has not been glaciated, however, and the volcano is thus assumed to be entirely Holocene in age. The most recent major activity (and almost certainly the historic activity) was dome emplacement in or near the summit area, accompanied by pyroclastic flows. Overlapping block-lava flows that erupted from one or more vents on the northwest flank and from a vent high on the southeast flank have a fresh morphology indicative of recent eruptions, but are probably older than the pyroclastic-flow deposits.

The volcano was built on the northwest-sloping flank of a topographic and structural basement high at an elevation of about 760 m (plate 1). Cone-building rocks spread as far as 7 km to the north and northwest but, with the exception of one small flow, are confined to within 1.5 km of the vent to the south. As a result, the volcano is strongly asymmetrical below 760 m (the 2500-foot contour).

Multiple episodes of summit and flank collapse have occurred at Mount Peulik. The summit crater is breached to the west and a large pyroclastic-flow apron lies below the dome at the foot of the volcano. The present summit almost obliterates an older crater that opened to the north and northwest (plate 1). Extensive debris-avalanche deposits originating from Mount Peulik underlie an area of about 75 km^2 north and northwest of the cone.

Cone-Building Stage

"Old" Mount Peulik lavas

The low north-sloping plain between Mount Peulik volcano and Becharof Lake is underlain by a broad expanse of flat-lying lava flows (unit Qpoc, plate 1). These flows range from 5 to 10 m thick and form a well-vegetated surface that has little relief and is deeply incised by streams. The flows overlie lake sediments and gravels near Becharof Lake and are in turn overlain by the volcanic rocks forming the present Mount Peulik volcanic edifice. These flows are Holocene in age as they have not been glaciated. The distribution of the flows and their north-facing slope indicates that the source vents were in the Mount Peulik volcano area.

These flows, and a small plug-like satellite to the northwest of them (unit Qb, plate 1), represent the earliest outpouring of Mount Peulik magma. The flows are composed of dense, non-vesiculated, olivine-bearing, two-pyroxene porphyritic andesite and lesser amounts of porphyritic olivine basalt. Phenocrysts are plagioclase, clinopyroxene, orthopyroxene, and small amounts of olivine. The groundmass includes plagioclase microlites, pyroxene anhedra, and some altered glass, but lacks the fresh brown glass so common in the younger Mount Peulik cone-building volcanic rocks. These flows have generally <2 percent vesicles and are much less vesiculated than the younger Mount Peulik lavas that form the modern edifice. These older flows have a distinguishing compositional characteristic in that they typically contain small amounts of strongly altered hornblende and rounded quartz grains. The hornblende, commonly altered to metallic oxides, is as much as 5 percent of the phenocrysts and 1.5 percent of the modal volume of the rock. Quartz is persistent, but generally is present only in trace amounts.

The occurrence of disequilibrium assemblages of quartz (plus hornblende) and olivine in many "old" Mount Peulik andesites indicates magma mixing. However, the rounded nature of the quartz grains and the fresh appearance of the olivine suggest that the quartz could also be xenocrystic and the result of assimilation of basement rocks in the near surface. No xenoliths were noted.

Present edifice

The steep-sided Mount Peulik cone is only slightly incised, and the upper 800 m of the cone has a blocky rubble-strewn surface. Slope debris covers most outcrops, and the ratio of pyroclastic rocks to lava is unknown. The cone appears to consist chiefly of non-vegetated, non-glaciated two-pyroxene andesite and lesser amounts of olivine basalt block flows interbedded with subordinate pyroclastic deposits of similar composition (unit Qpc, plate 1). The flows are stubby and thick and traveled only short distances. The rocks are strongly phyric as modal phenocryst contents and weakly vesiculated (1-16 percent vesicles).

Plagioclase phenocrysts are ubiquitous in all rocks and are by far the most abundant phase ranging from 45 to 84 percent of total phenocryst volume. Normal and oscillatory zoning are common and the An content ranges from 50 to 75 percent. The phenocrysts are typically fresh, but commonly have a spongy cellular morphology consisting of brown glass inclusions oriented along crystallographic planes.

Orthopyroxene is the most abundant mafic phenocryst in the andesites, ranging in modal volume from 4 to 8 percent and comprising 9 to 24 percent of total phenocryst content. Orthopyroxene is absent in the olivine basalts. Clinopyroxene is also an abundant mafic phase with a modal range similar to orthopyroxene (4 to 8 percent for the whole rock and 7 to 23 percent for phenocryst content); clinopyroxene/orthopyroxene ratios range from 0.7 to 1.6. Clinopyroxene is common as the mafic phase in the groundmass of many andesites and is in trace to moderate (~4 percent) amounts in olivine basalt. The modal abundance of olivine ranges from about 4 percent in the olivine basalt (where it forms about 10 percent of the total phenocryst volume and is associated with minor amounts of clinopyroxene) to trace amounts in most andesites. The olivine is fresh, unzoned, and generally surrounded by thin jackets of fine interlocking pyroxene and plagioclase crystals. These phenocrysts are in a hyalopilitic groundmass of generally clear brown glass containing plagioclase microlites, Fe-Ti oxides, and clinopyroxene anhedra.

These cone-building rocks are similar in mineralogy and chemical composition to "old" Mount Peulik flows, but lack the altered hornblende and rounded quartz. These later cone-building flows may have gained access to the surface through a conduit

“armored” by the “old” Mount Peulik flows and less susceptible to assimilation of near-surface rocks.

The youngest flows (unit Qpyf, plate 1) of the present edifice are from flank eruptions, mostly from the base of the northwest and north flanks of the cone at elevations of 610 m, but including one young flow high on the southeast flank at 1020 m; overlapping flows and slope debris conceal the actual vents. Flows from this unit on the northwest flank overlie and are younger than adjacent debris-avalanche deposits. These flows have steep flow-fronts, blocky irregular surfaces, and crescent-shaped wave-like ridges that probably resulted from irregular outflow. They are up to 2100 m long by 300 m wide at their flow fronts. Their mineralogy and chemistry is identical to the cone-building flows (unit Qpc, plate 1) that form most of the present edifice xenoliths were noted.

Debris Avalanche Deposits

Hummocky terrain, characterized by low conical hills and closed depressions, many of which are lake-filled, underlies an area of about 75 km^2 northwest of the base of Mount Peulik volcano (unit Qpda, plate 1). Such terrain is typical (figs. 4, 5) of debris-avalanche

Figure 4. Debris-avalanche deposit on northwest flank of Mount Peulik volcano. Mounds and closed depressions (including ponds) are separated by flat, vegetation covered areas. Helicopter in center of photo for scale. Alaska Volcano Observatory photo, 1985.

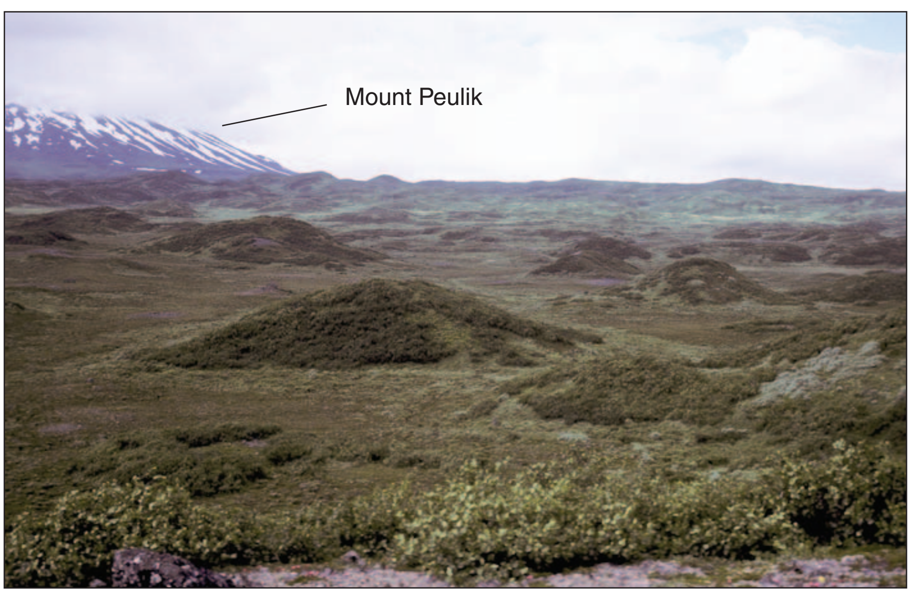

Figure 5. Close-up view (looking south) of typical topography of hummocky debris-avalanche deposits with cone shaped mounds about 50 m in diameter. Mount Peulik in the upper left corner of the photograph. Alaska Volcano Observatory photo, 1979.

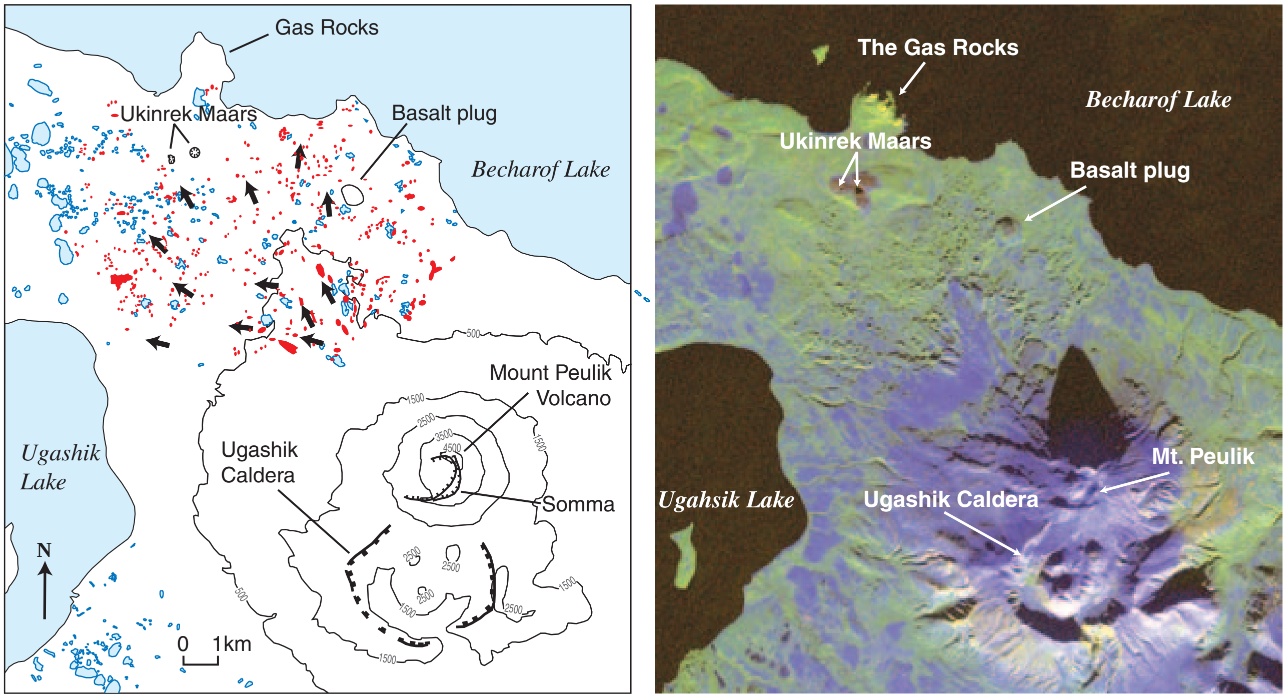

Figure 6. A) General distribution of debris-avalanche deposits relative to Mount Peulik volcano. Larger mounds (as taken from 1:63,360-scale topographic map with 50-foot contours; see text) shown in solid red. Arrows indicate direction of flow as suggested by longitudinal ridges. B) Landsat Enhanced Thematic Mapping (ETM) false color composite satellite image, acquired on October 31, 1999. In this band combination (ETM bands 754), snow-covered ground is represented in shades of blue, vegetation in green to yellow, and water and shadows in black.

deposits that flank volcanoes worldwide (Siebert, 1984, Ui and others, 1986). Smith and Baker (1924) noted this hummocky ground, but believed it to be moraines.

The low conical hills or mounds range from a few meters to over 30 m in height and from 50 to a 100 m in diameter. Ridges up to 500 m in length are also common. The 75-km^2 area is a minimum figure for the deposits as they are overlain by younger pyroclastic-flow deposits along their southern margin. Also, the debris avalanches almost certainly went into Becharof Lake (plate 1). The debris avalanche may have originally covered at least 85 km^2.

About 450 mounds are denoted by closed contours (50-foot contour interval) within the deposit boundaries on the 1:63,360-scale Ugashik D-2 topographic map of the area (fig. 6). About 360 lakes and ponds with an average diameter >30 m are also shown. Because only the largest mounds and depressions will show on a map of this scale and contour interval, these sums are only a fraction of the total number of such features. Estimates of about 40 mounds per km^2 were made from aerial photographs in some of the hummocky terrain but the total number of such mounds may be on the order of 2,000 to 3,000. This density estimate compares reasonably well to the 3648 avalanche mounds (mostly under 30 m high) over 175 km^2 at Galunggung volcano in Indonesia, but is significantly greater than the 2,000 hills counted over 650 km^2 at Raung volcano (Siebert, 1984).

The mounds decrease in volume and height from east to west across the deposit and in number and size toward the distal part of the deposit. Clusters of mounds are common and are locally separated by flat areas that are assumed to be underlain by lahars and reworked material similar to debris-avalanche deposits elsewhere (Ui, 1983).

The conical mounds, though well-vegetated with brush and sedges, appear to be cored by a poorly sorted mixture of andesite and porphyritic dacite volcanic debris, most of which is lithic material derived from Mount Peulik. Many of the andesite clasts (>50 percent) contain small amounts of altered hornblende and persistent round quartz grains, a characteristic of

Figure 7. Large andesite and dome boulders on surface of debris-avalanche deposit mound. Boulders at some mounds are up to 5 m in diameter. Alaska Volcano Observatory photo, 1979.

Figure 8. Unsorted matrix of debris-avalanche mound. Clast in center of photo shows jigsaw fracture indicating clast was hot when emplaced.

“old” Mount Peulik lava flows. Included in the deposits are clasts of slightly to moderately vesiculated lava dome material, some of which have breadcrust surfaces indicative of a hot juvenile origin.

Boulders, some up to 5 m across, dot the surface of many mounds (fig. 7) and appear to be present in a clast-supported matrix of coarse sand-to-cobble size material (fig. 8). Clasts at one mound may consist entirely of andesite and scoria, while clasts at adjoining mounds consist of dacitic dome debris or a mixture of the two materials. This difference in dominant lithology may result from the incomplete mixing of heterogeneous source debris typical of many volcanic debris avalanches (Siebert, 1984).

Coherent “megablocks” composed of parts of the volcanic cone up to tens and even hundreds of meters across that occur in debris avalanches at some volcanoes (e.g., Mount St. Helens, Voight and others, 1981) have not been identified at Mount Peulik. This apparent absence could be the result of poor exposures given the heavy vegetation, but it may also indicate a large explosive component to the eruption.

A difference in surface morphology of the debris-avalanche deposits in the south-central part of the avalanche field (unit Qpda, plate 1) suggests more than one period of debris avalanche deposition. In this 5-km^2 area, hummocks are fewer and longitudinal ridges more common. The debris in these particular deposits is similar to that elsewhere in the avalanche field and the deposits are assumed to have a debris-avalanche origin, possibly including a pyroclastic-flow component.

The debris-avalanche deposits are 5 to 15 km from Mount Peulik and at elevations mostly between 150 and 10 m (500 to 34 feet, plate 1). The maximum distance travelled (L) has been plotted as a function of vertical drop (H) for many volcanic debris-avalanche deposits by Ui (1983) and Siebert (1984). The H/L ratio of 0.10 for the Mount Peulik deposits compares closely to the median H/L ratio of 0.11 calculated by Siebert (1984) for over 60 deposits worldwide.

The debris avalanches must have formed by a major slope failure of the Mount Peulik volcanic edifice. The occurrence in the debris-avalanche deposits of vesiculated breadcrusted dome debris that appears to have cooled in place suggests that the failure included an explosive magmatic component, a feature commonly associated with slope failures and debris avalanches at many volcanoes (Mount St. Helens, Bezymianny, Sheveluch; see Siebert, 1984). Directed blast deposits as described by Hoblitt and others (1981) at Mount St. Helens have not been found at Mount Peulik. Brown pumice lapilli found scattered over the tops of many of the debris-avalanche deposit mounds probably came from later eruptions since similar material overlies surfaces away from the deposits (in the quadrant northeast of the volcano, for example).

The fan-like distribution of the avalanche deposits and associated longitudinal ridges point back to Mount Peulik volcano. The present summit crater, however, opens to the west, not to the northwest and it would be impossible for the debris-avalanche deposits northwest of the volcano to have originated from the present summit area. A remnant scarp, or somma, on the south and east sides of the summit (plate 1) is part of an older summit crater that is truncated by the present crater. This older crater, which appears to have been larger than the present crater, opened to the northwest and may record the result of a massive slope failure and explosive eruption that produced the debris avalanches.

The age of these debris-avalanche deposits is poorly constrained. The abundance of “old” Mount Peulik andesite debris in the deposits is evidence that the avalanching occurred before extrusion of the younger cone-building flows (unit Qpyf, plate 1) which are ponded against the older debris-avalanche deposits.

Support for such a hypothesis is contained in the composition of the dome material from the avalanche deposits, the present summit lava dome and its pyroclastic-flow deposits, and the pyroclastic deposits associated with the dome exposed high on the east flank of Mount Peulik (plate 1). All four of these units have similar major element compositions, being composed of dacite and rhyodacite ranging from 65 to 69 percent SiO_2 (table 3 on plate 2). Inspection of trace element contents, however, reveals significant differences between some of the units. In figure 9, Ba, Zr, Sr, and Rb are plotted against SiO_2 for all the rock units from the Ugashik-Mount Peulik volcanic center. The present summit dome and the east dome have distinct differences in Ba, Zr, and Sr contents. The trace element content of dome material from the pyroclastic-flow deposits at the foot of the present dome shows the expected strong correlation with the summit dome. Ba, Zr, and Sr contents of dome material from the debris-avalanche deposits, however, have a closer

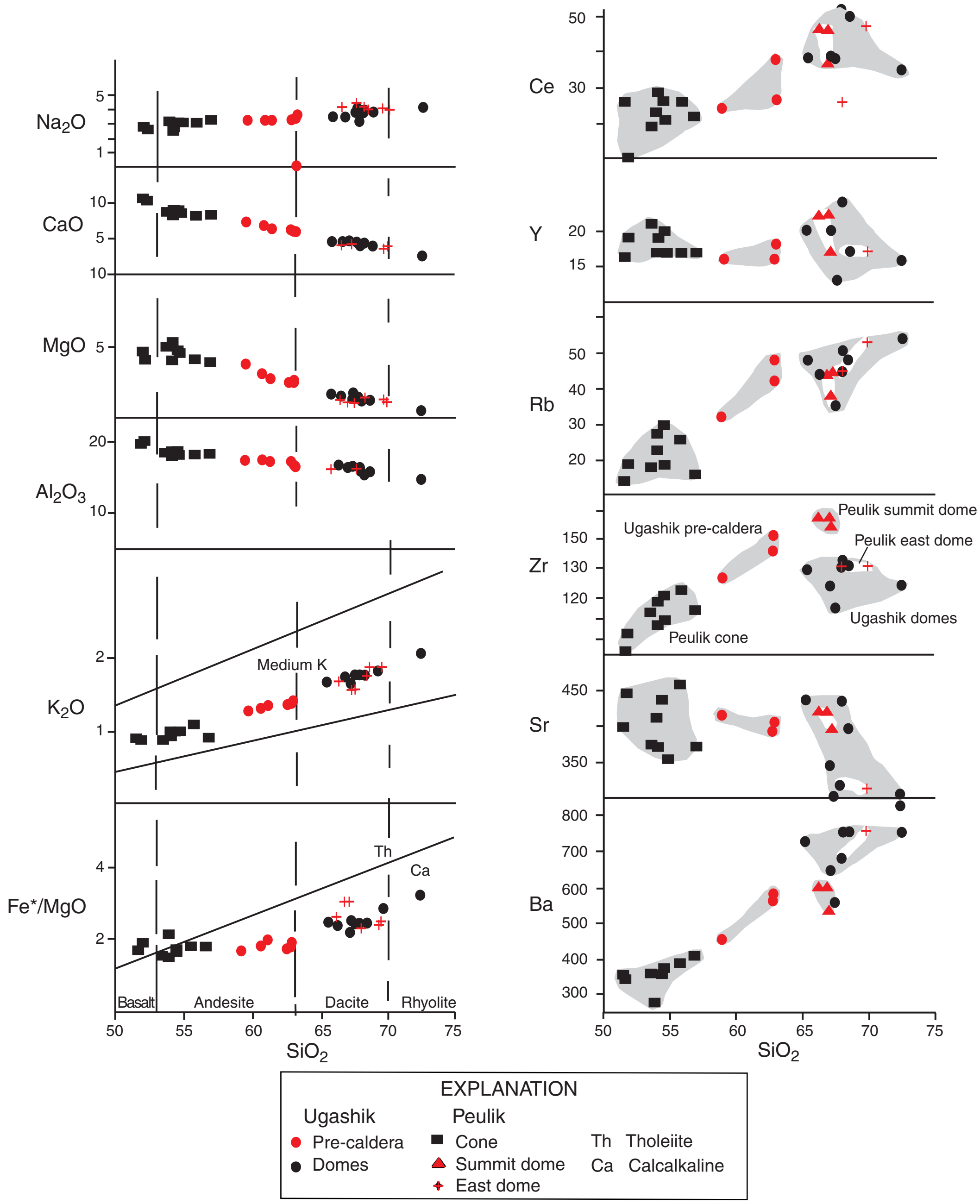

Figure 9. SiO_2 variation diagrams for rocks from Ugashik-Mount Peulik volcanic center. Vertical discrimination lines from Peccerillo and Tayler (1976).

correlation to the east dome than to the present dome. The trace-element chemistry suggests that the dome material in the debris avalanches was not derived from the present summit dome or its immediate predecessors.

A volume estimate for the debris-avalanche deposits is difficult to determine because of poor exposures and uncertainties about the average thickness, particularly in regard to how much, if any, deposit underlies the closed depressions. If an average density of 40 mounds per km^2 is assumed and each conical mound has an average diameter of 50 m and a height of 30 m, a volume of 0.07 km^3 is obtained for the 85 km^2 area of the deposit. An average unexposed basal thickness of 1 meter may be reasonable for the

deposit area that adds 0.085 km^3 for a total of 0.16 km^3 for the entire deposit.

Another approach to determine the volume is to assume that the ancestral horseshoe-shaped crater that formed after the slope failure is similar in volume to the present crater. This seems to be a reasonable minimum assumption given the extent of the somma high on Mount Peulik. The present crater minus the current dome has a volume of about 0.12 km^3; 0.08 km^3 (maximum) could be added if the pre-failure cone is assumed to have extended above the altitude of the present crater rim resulting in a total volume of about 0.2 km^3 (DRE) for the missing material. The volumes estimated by these two techniques, although crude, are similar. The initial debris-avalanche deposits, therefore, probably had a bulk volume of about 0.2-0.4 km^3.

Summit Domes

Two lava domes occur near the summit of Mount Peulik. The larger of the two (unit Qpds, plate 1) forms a steep-sided bulbous pile inside the summit crater, has a summit elevation of 1340 m (4395 feet), a width of about 400 m, and an estimated volume of about 10 x 106m^3. A much smaller dome (<150 m wide) about a kilometer away high on the southeast flank of the cone (1220 m [4000 feet], unit Qpde, plate 1) has an estimated volume of about 1 x 10^6 m^3. The summit crater dome and its flowage deposit (Qpba, plate 1) consist of porphyritic hornblende-pyroxene-biotite dacite (66-67 percent SiO_2). Phenocrysts make up only about 20 percent of the rock and consist chiefly of plagioclase (~80 percent by modal volume), hornblende (6-7 percent), orthopyroxene (~ 1 percent), and trace amounts of brown-red biotite, Fe-Ti oxides, and quartz. The hornblende phenocrysts are rounded and composed of dark-brown to yellow oxyhornblende. They commonly have either opaque rims suggesting resorption or are completely altered to opaques. The groundmass consists of only slightly vesiculated fine glass and cryptocrystalline felsic material.

The east dome has been sampled only from its associated pyroclastic-flow deposit and appears to consist of hornblende dacite (~69 percent SiO_2) with 30-40 percent phenocrysts. About 80 percent of phenocrysts are plagioclase, with about 15 percent hornblende and trace amounts of biotite, orthopyroxene, and even more rarely, quartz in a moderately vesiculated groundmass of clear glass. The hornblende phenocrysts are fresh, unaltered, green to brown euhedra.

The two Mount Peulik domes have similar mineralogy although the summit dome and associated pyroclastic-flow deposits, as well as the debris-avalanche deposits, are dark brown to yellow oxyhornblende. The phenocrysts are rounded and have opaque rims suggesting resorption; in some cases, the phenocrysts are completely altered to opaques. Hornblendes in the east dome, in contrast to the summit dome, are fresh, unaltered, green to brown euhedra.

Both domes are unglaciated and retain their blocky carapaces. The east dome appears to be older than the summit dome; indeed, it may be exposed in the summit crater wall. The relative lack of vegetation on the pyroclastic-flow deposits derived from the east dome, however, and the fact that these deposits overlie very fresh lobate basaltic flows means that the east dome is very young.

These two domes are the youngest materials mapped at the Ugashik-Mount Peulik volcanic center since their associated pyroclastic-flow deposits mantle all other map units. In addition, dome pumice rests on the ground surface in all quadrants around the volcano.

Pyroclastic-Flow Deposits

An apron of block-and-ash flow deposits (unit Qpba, plate 1) covers the lowland west of Mount Peulik immediately down slope from the mouth of the breached horseshoe-shaped crater (fig. 10). The deposits reach almost to Ugashik Lake 11 km to the west. These are typical block-and-ash deposits in that they are unsorted, massive, and contain large (1-2 m) blocks of dome debris in an ash matrix (fig. 11). About 80 percent of the clasts are hornblende dacite porphyry and pumice similar to that seen in the summit dome; the remaining 20 percent consist of andesite from the cone. The abundance of pumice, breadcrust surfaces, and prismatic cooling joints indicates that many dacite clasts were hot when emplaced. The base is not exposed, and the unit has a maximum exposed thickness of 15 m. The deposits commonly are reversely graded and have flat to gently undulating, terrace-like, vegetated surfaces. Material at the distal end at Ugashik Lake appears to have been reworked.

Figure 10. Vegetated, flat-topped block-and-ash flow deposit on west side of Mount Peulik volcano. Ugashik Lake in background. Alaska Volcano Observatory photo, 1974.

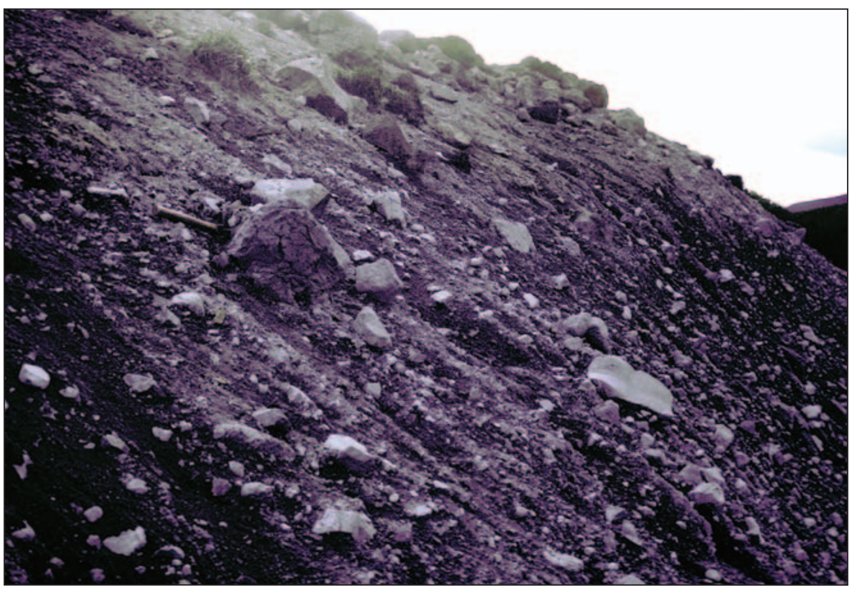

Figure 11. Unsorted, poorly consolidated block- and ash-flow deposit on west side of Mount Peulik volcano. Large breadcrust bombs in fine-to-coarse, ash-rich matrix; largest boulder about 1 meter across. Alaska Volcano Observatory photo, 1982.

A smaller block-and-ash flow deposit lies below the east dome and extends about 1.7 km to the east (plate 1). This deposit overlies a young basalt flow and has a well-developed levee on its north flank.

COMPOSITION

Major-element chemical analyses of representative rock samples (table 3 on plate 2) from the Ugashik-Mount Peulik volcanic center reveal a wide compositional spectrum for the center that ranges from basalt (51.7 percent SiO_2) to rhyolite (72.1 percent SiO_2). SiO_2 variation diagrams define a medium-K calc-alkaline series as characterized by Gill (1981) and Miyashiro (1974) similar to most volcanic centers in the eastern third (700 km) of the Aleutian volcanic arc (Miller and Richter, 1994). Rocks that are genetically related should define linear trends with incompatible elements such as K_2O increasing progressively with SiO_2. Representative samples from the Ugashik-Mount Peulik volcanic center do show linear trends indicating a co-magmatic suite. K_2O and Na_2O, for example, plot-

ted against SiO_2 have good positive linear trends and MgO, CaO, Al_2O_3, and TiO_2 show tight negative trends.

Examining the composition of the volcanoes separately reveals a more complicated magmatic history than one of simple differentiation from a mafic parent to a silicic end member. The SiO_2 variation plots for the individual volcanoes are overlapping trends with compositional gaps. The Ugashik pre-caldera flows and breccia, the oldest known erupted material from the Ugashik-Mount Peulik center, were moderately silicic (59.1 to 62.6 percent SiO_2, nos. 1-6, table 3 on plate 2). Ugashik post-caldera rocks range from 62.1-72.1 percent SiO_2 (nos. 7-15, table 3 on plate 2) and show a compositional gap between 62.6 and 66.1 percent SiO_2.

After the emplacement of the post-caldera Ugashik domes, magmas at the center reverted to a mafic (i.e., basaltic) stage (no. 16, table 3 on plate 2). Cone-building Mount Peulik rocks have a narrower compositional range from 51.9 to 56.7 percent SiO_2 (nos. 16-24, table 3 on plate 2) as opposed to Ugashik rocks. Interspersed with these cone-building episodes were silicic dome-building eruptions. At least two cycles of mafic to silicic magma emplacement have thus occurred at Mount Peulik. A compositional gap of about 10 percent SiO_2 exists in each case between the dome and cone-building rocks.

Trace-element chemistry also suggests a complicated magmatic history (fig. 9). Rb generally increases with SiO_2 as does Ba, although not in a linear mode; the summit dome is off-trend. Zr increases with SiO_2 for the Mount Peulik cone-building rocks and summit dome, but less so for the east dome which shows a plot distinct from the summit dome; Zr generally decreases with increasing SiO_2 for Ugashik rocks. Sr also shows substantial variation, but, again, distinct differences are apparent between the summit and east domes. Y varies little with SiO_2, although Ce increases; Ni and Cr decrease.

Ugashik dome rocks show considerable internal variation in incompatible trace elements vs. SiO_2 (fig. 9). The summit and east domes of Mount Peulik differ in trace- element composition, but have tight plots; the east dome generally plots close to or within the Ugashik dome field. These differences in incompatible trace-element contents suggest the summit and east domes represent similar but distinct batches of magma. The broad scatter in trace- element plots for the Ugashik dome complex implies that a similar situation may be true for the individual domes of the complex.

A shallow silicic magma chamber and one or more deeper mafic magma chambers co-existed beneath the volcano during much of Mount Peulik's history. At times, these magmas may have partially mixed, but more likely, they generally erupted separately and in slightly different locales.

The cyclic eruption of mafic and silicic magmas separated by significant composition gaps implies that their relationship is not the result of simple fractional crystallization from a mafic parent to a silicic differentiate. Furthermore, the "old" Mount Peulik cone-building lava flows (unit Qpoc, plate 1) contain evidence of assimilation, a process that may also be reflected in subtle but distinct differences in trace-element composition. Clear-cut compositional evidence of mixing between magmas is lacking as are such indicators as banded pumice, although the near-contemporaneity of mafic and silicic magma eruptions enhances the likelihood of this happening. I conclude that the magmas erupted at the Ugashik-Mount Peulik center formed through a combination of assimilation and fractional crystallization of magmas that resided in small, short-lived, near-surface chambers.

SUMMARY OF ERUPTIVE HISTORY

The Ugashik-Mount Peulik volcanic center has a complicated and explosive eruptive history. Activity at the site began in late Pleistocene time (~171,000 yr B.P.) as dacitic and silicic andesite dome-building resulted in a complex perhaps similar to that seen today at Augustine or Dutton volcanoes in Alaska (Miller and others,1998).

In late Wisconsin time (perhaps about 40,000 yr B.P.), a Plinian eruption resulted in the ejection of 5-10 km^3 DRE of material, destruction of the edifice (probably through collapse), and the formation of a 5-km-diameter caldera. Still in late Pleistocene time to perhaps early Holocene time, several large, broad-

shouldered dacite and rhyolite domes were extruded inside the caldera.

In Holocene time, eruptive activity has shifted a few kilometers to the north and reverted to more mafic compositions of basalt and andesite resulting in the formation of an ancestral Mount Peulik stratovolcano that was probably similar in size to the present edifice. Early in its formation, the cone then experienced one or more episodes of sector collapse and dome destruction.

These events formed a horseshoe-shaped crater open to the northwest, a remnant of which remains as the large somma just south of the present horseshoe-shaped crater (and truncated by it). The dimensions of this old crater are uncertain, but the length and degree of curvature of the somma indicates that it was probably larger than the present crater.

A large debris avalanche was generated that underlies a 75 km^2 area northwest of the volcano. Given the runout distance of the debris avalanche and the somma remnant, the pre-collapse edifice probably had attained a height similar to that of the present cone. Since the volcanic edifice was built high on a northwest-sloping topographic high, the direction of slope failure (northwest) was probably determined by gravitational stresses. The abundant dome material in these deposits suggests that lava domes occupied the upper part of the structure during or before these collapse events.

The nature of eruptive activity then reverted to cone-building resulting in the present edifice. After the cone reached its present height, short, stubby lava flows were extruded from sites on the lower flanks of the cone.

The most recent activity has been the emplacement of the present summit domes. Predecessors to these domes collapsed or were blown out in one or more episodes resulting in the present 1- to 2-km-wide horseshoe-shaped crater and an associated apron of pyroclastic-flow deposits. During this time, a small dome was also emplaced outside the summit crater high on the southeast flank of the cone. This dome also has experienced one or more episodes of destruction and pyroclastic flow formation.

Lu and others (2003), using satellite-based interferometric synthetic aperture radar imagining techniques, suggested that a presumed magma body located at a depth of 6.6 km beneath Peulik volcano inflated 0.051 km^3 between October 1996 and September 1997. Although Peulik is currently in repose, such unrest along with historic activity strongly indicates future eruptive activity can be expected.

HAZARDS

The Ugashik-Mount Peulik center has undergone explosive volcanism, including caldera formation and repeated dome growth and destruction. Mount Peulik and its flanks have been the sites of most, if not all, of the eruptions at the Ugashik-Mount Peulik volcanic center for the past 10,000 years, including those reported in 1814 and 1852. The location of Mount Peulik volcano on the slope of a topographic high has exerted an influence on past eruptions and will continue to do so in the future.

The most likely scenario for a future eruption is for the present summit dome(s) to be partly or wholly destroyed as new magma rises to the surface. Debris avalanches and pyroclastic flows containing both juvenile and present dome material might then flow down the west and, perhaps also, east flanks of the volcano for distances of 10 km or more. Such flows could enter Ugashik Lake at sufficient velocity to generate one or more large waves.

A new lava dome might form during, or some years after, the disruption of the previous dome. A cycle of dome disruption, pyroclastic flow generation, and new dome formation might be repeated several times during a single eruption. The 1989-90 eruption of Redoubt volcano in the Cook Inlet region of Alaska, for example, resulted in the emplacement and the subsequent destruction of 13 domes over a 4-month-period (Miller, 1994).

The inhabited area nearest the volcano is Pilot Point (fig. 1), about 65 km west-southwest of the center; other nearby populated areas are Egegik 80 km to the northeast, and King Salmon 100 km to the north. None of these villages had more than 500 residents in 2000. Sport fisherman, hunters, and hikers visit the volcano area, particularly during the non-winter months, and could be at risk from volcanic eruptions described above as could recreational boaters on Ugashik Lake. Ugashik and Becharof Lakes are large natural hatcheries and rearing areas for the commercially valuable red salmon. Entry of large volumes of pyroclastic flows into these lakes could adversely

affect the survival rates of salmon eggs, fry, and smolt present.

Perhaps the most serious potential hazard is the effect of airborne volcanic ash on nearby communities and particularly to aircraft. A dome-forming eruption could be expected to produce one or more eruption columns to heights of 12-15 km. Significant amounts of ash could easily drift 250-300 km downwind, as did ash from the 1989-90 eruptions of Redoubt volcano (Scott and McGimsey, 1994) and the 1992 eruption of Spurr volcano (Neal and others, 1995), in the Cook Inlet area of Alaska. Such an ash fall can have significant impacts on commerce and societal activities in the fall-out zone (Tuck and Huskey, 1994) which could include not only the nearby communities, but also the much larger city of Kodiak 240 km directly downwind from the volcano (fig. 1).

Mount Peulik volcano lies astride the heavily traveled North Pacific air routes connecting the U.S. and Europe to Asia. The hazard posed by volcanic ash to jet aircraft has been increasing rapidly over the past decade as aircraft with larger, hotter-burning jet engines encounter and melt volcanic ash, sometimes hundreds of kilometers downwind from the eruption volcano (Miller and Casadevall, 2000). Thus, eruptions that eject ash into air routes pose a serious hazard to jet aircraft.

A possible but less likely eruptive scenario is for a flank eruption of block lava flows either on the northwest or southeast sides of the volcano. Such flows would be highly viscous and unlikely to flow more than a few kilometers. Associated eruption columns would not be expected to reach altitudes of more than 5 km and would likely be short-lived, thus not posing an important hazard to high-flying aircraft or distant communities.

Typically, the longer the interval between eruptions, the more voluminous and energetic is the next eruption. As of 2000, Mount Peulik has been dormant for at least 146 years, a period of quiescence hardly unknown for an active volcano. This period of dormancy is significantly longer, however, than the few ten's of years between eruptions at the geologically similar Augustine and Redoubt volcanoes in nearby Cook Inlet (Miller and others, 1998). The most recent eruptions from these volcanoes in 1986 and 1989-90 had serious economic consequences (Tuck and Huskey, 1994).

CONCLUSIONS

The Ugashik-Mount Peulik volcanic center began with dome emplacement followed by collapse and caldera formation (including subsequent dome emplacement). After a slight northward shift in the focus of eruptive activity, a stratovolcano was rapidly constructed through central vent and flank eruptions ending in the emplacement of dacite and rhyodacite summit domes. This stratovolcano has undergone major sector collapse on one or more occasions resulting in the formation of large debris avalanches and their associated deposits. Reconstruction of the cone was extensive and rapid enough so as to cover much of the horseshoe-shaped amphitheater crater(s) formed as a result of collapse(s).

The occurrence of roughly contemporaneous silicic lava domes in or near the summit and mafic basaltic andesite lava flows on the flanks indicates that both a shallow silicic magma chamber(s) and deeper mafic magma chamber(s) co-exist, or have recently co-existed, beneath Mount Peulik. Magmas from the Ugashik-Mount Peulik center are calc-alkaline ranging from basalt to rhyolite. The compositional changes are not simply the result of differentiation from mafic to silicic magmas in a single magma chamber. The center as a whole appears to have gone through at least 3 cycles of mafic to silicic magmatism. The Ugashik-Mount Peulik magmas are co-genetic in a broad sense and appear to result from a combination of fractional crystallization, magma-mixing, and assimilation.

Given the compositional and eruptive characteristics of recent volcanic activity at Mount Peulik, future eruptions will likely include explosive activity similar to that of the recent past. Such eruptions pose little direct threat to the sparsely populated countryside, but could put air traffic at considerable risk.

ACKNOWLEDGEMENTS

Robert L. Smith, Martha E. Yount, and Robert L. Detterman provided valuable assistance in the field. Brent Dalrymple and Marvin A. Lanphere supplied the K-Ar age determination on the Ugashik pre-caldera rocks. Chris Nye, Wendell Duffield and Christopher Waythomas gave helpful reviews.

REFERENCES CITED

Barnes, Ivan, and McCoy, G.A., 1979, Possible role of mantle-derived CO2 in causing two "phreatic" explosions in Alaska: Geology, v. 7, p. 434-435.

Capps, S.R., 1923, The Cold Bay District: U.S. Geological Survey Bulletin 739, p. 77-116.

Detterman, R.L., Case, J.E., Wilson, F.H., and Yount, M.E., 1987a, Geologic map of the Ugashik, Bristol Bay, and western part of Karluk quadrangles, Alaska: U.S. Geological Survey Miscellaneous Geological Investigation Series, Map I-1685, 1:250,000-scale.

Detterman, R.L., Wilson, F.H., Yount, M.E., and Miller, T.P., 1987b, Quaternary geologic map of the Ugashik, Bristol Bay, and western part of Karluk quadrangles, Alaska: U.S. Geological Survey Misccellaneous Investigations Series Map I-1801, 1:250,000-scale.

Gill, J.B., 1981, Orogenic Andesites and Plate Tectonics: Springer-Verlag, New York, 390 p.

Hoblitt, R.P., Miller, C.D., and Vallance, J.W., 1981, Origin and stratigraphy of the deposit produced by the May 18 directed blast; *in* Lipman, P.W. and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington, U.S. Geological Survey Professional Paper 1250, p. 401-420.

Kay, S. Mahlburg, Kay, R.W., and Citron, G.P., 1982, Tectonic controls on tholeiitic and calc-alkaline magmatism in the Aleutian Arc: Journal of Geophysical Research, v. 87, n. B5, p. 4051-4072.

Kienle, J., Kyle, P.R., Self, S., Motyka, R.J., and Lorenz, V., 1980, Ukinrek Maars, Alaska, I. April 1977 eruption sequence, petrology and tectonic setting: Journal of Volcanology and Geothermal Research, V. 7, p. 11-37.

Kienle, J., and Swanson, S.E., 1983, Volcanism in the eastern Aleutian arc: late Quaternary and Holocene centers, tectonic setting and petrology: Journal of Volcanology and Geothermal Research, v. 17, p. 393-432.

Lu, Zhong, Wicks, Jr., Charles, Dzurisin, Daniel, Power, John, Thatcher, Wayne, and Masterlark, Timothy, 2003, Interferometric synthetic aperture radar studies of Alaska volcanoes: Earth Observation Magazine, v. 12, n. 3, p. 8-19.

Miller, T.P., 1994, Dome growth and destruction during the 1989-90 eruption of Redoubt volcano, *in* Miller, T.P., and Chouet, B.A., eds., The 1989-90 eruption of Redoubt volcano, Alaska: Journal of Volcanology and Geothermal Research, v. 62, n. 1-4, p. 197-212.

Miller, T.P., and Richter, D.H., 1994, Quaternary volcanism in the Alaska Peninsula and Wrangell Mountains, Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North American, v. G-1, p. 759-779.

Miller, T.P., and Smith, R.L., 1987, Late Quaternary caldera-forming eruptions in the eastern Aleutian arc, Alaska: Geology, v. 15, p. 434-438.

Miller, T.P., McGimsey, R.G., Richter, D.H., Riehle, J.R., Nye, C.J., Yount, M.E., and Dumoulin, J.A., 1998, Catalog of historically active volcanoes of Alaska: U.S. Geological Survey Open-File Report 98-252, 103 p.

Miller, T.P., Chertkoff, D.G., Eichelberger, J.C., and Coombs, M.L., 1999, Mount Dutton volcano, Alaska: Aleutian arc analog to Unzen volcano, Japan: Journal of Volcanology and Geothermal Resources, v. 89, nos. 1-4, p. 275-302.

Miller, T.P., and Casadevall, T.J., 2000, Volcanic ash hazards to aviation, *in* Haraldur Sigurdsson, ed., Encyclopedia of Volcanoes, Academic Press, New York, p. 915-930.

Miyashiro, A., 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321-355.

Neal, C.A., McGimsey, R.G., Gardner, C.A., Harbin, M.L., Nye, C.J., 1995, Tephra-fall deposits from the 1992 eruptions of Crater Peak, Spurr Volcano, Alaska: Preliminary report on distribution, stratigraphy, and composition, *in* Keith, T.E.C., ed., The 1992 eruptions of Mount Spurr volcano, U.S. Geological Survey Bulletin 2139, p. 65-80.

Orth, D.J., 1967, Dictionary of Alaska Place Names: U.S. Geological Survey Professional Paper 567, 1084 p.

Osgood, W.H., 1904, A biological reconnaissance of the base of the Alaska Peninsula: North American Fauna, No. 24, Division of Biological Survey, 86 p.

Peccerillo, Angelo, and Taylor, S.R., 1976, Geochemistry of Eocene calcalkaline rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology, v. 58, p. 63-81.

Plafker, G., Gilpin, L.M., and Lahr, J.C., 1994, Neotectonic map of Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1.

Scott, W.E., and McGimsey, R.G., 1994, Character, mass, distribution, and origin of tephar-fall deposits of the 1989-1990 eruption of Redoubt volcano, southcentral Alaska, *in* Miller, T.P., and Chouet, B.A., eds., The 1989-1990 eruptions of Redoubt Volcano, Alaska: Journal of Volcanology and Geothermal Research, v. 62, p. 251-272.

Self, Stephen, Kienle, Juergen, and Huot, Jean-Paul, 1980, Ukinrek Maars, Alaska, II. Deposits and formation of the 1977 craters: Journal of Volcanology and Geothermal Research, v. 7, p. 39-65.

Siebert, L., 1984, Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruptions: Journal of Volcanology and Geothermal Research, v. 22, p. 163-197.

Smith, W.R., and Baker, A.A., 1924, The Cold Bay-Chignik district: U.S. Geological Survey Bulletin 755, p. 151-258.

Swanson, S.E., and Kienle, J., 1988, The 1986 eruption of Mount St. Augustine: Field test of a hazard evaluation: Journal of Geophysical Research, v. 93, p. 4500-4520.

Symonds, R.B., Ritchie, B.E., McGimsey, R.G., Ort, M.H., Poreda, R.J., Evans, W.C., and Janik, C.J., 1997, Investigations of gas seeps and springs in the vicinity of Gas Rocks, Alaska: U.S. Geological Survey Open-File Report 97-127, 27 p.

Tuck, B.H., and Huskey, L., 1994, Economic disruptions by Redoubt Volcano: Assessment methodology and anecdotal empirical evidence, *in* Casadevall, T.J., ed., Volcanic ash and aviation safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety: U.S. Geological Survey Bulletin 2047, p. 137-140.

Ui, T., Yamamoto, H., and Suzuki-Kamata, 1986, Characterization of debris avalanche deposits in Japan, *in*, I.Kushiro, ed., M. Sakuyama and H.Fukuyama Memorial Volume, Journal of Volcanology and Geothermal Research, V. 29, p. 231-244.

Voight, B., Glicken, H., Janda, R.J., and Douglas, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in*, Lipman, P.W.,and Mullineaux, D.R., eds., The 1980 Eruptions of Mount St. Helens, Washington, U.S. Geological Survey Professional Paper 1250, p. 347-378.

Waring, G.A., 1917, Mineral springs of Alaska: U.S. Geological Survey Water-Supply Paper 418, 112 p.

Wilson, F.W., and Shew, N., 1992, Map and tables showing geochronology and whole-rock geochemistry of selected samples, Ugashik and part of Karluk quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF 1539-E, 33 p.

Miller—GEOLOGY OF THE UGASHIK-MOUNT PEULIK VOLCANIC CENTER, ALASKA—U.S. Geological Survey Open-File Report 2004–1009