Geologic Studies in Alaska by the
U.S. Geological Survey, 1998
U.S. Geological Survey Professional Paper 1615

Mount Mageik: A Compound Stratovolcano in Katmai National Park

By Wes Hildreth, Judy Fierstein, Marvin A. Lanphere, *and* David F. Siems

Beautifully sky blue, [his eyes] peered at you from seemingly all angles
at once as he cocked his head first on one side, then on the other.
He gave spontaneous evidence of being the character dog of the trip.
That is why I named him Mageik, after the great volcano that, with Katrnai,
guards the entrance to the former Valley of Ten Thousand Smokes.

Bernard R. Hubbard
Mush You Malemutes (1932)

Abstract

Mount Mageik is an ice-clad 2,165-m andesite-dacite stratovolcano in the Katmai volcanic cluster at the head of the Valley of Ten Thousand Smokes. New K-Ar ages indicate that the volcano is as old as 93±8 ka. It has a present-day volume of 20 km^3 but an eruptive volume of about 30 km^3, implying a long-term average volumetric eruption rate of about 0.33 km^3 per 1,000 years. Mount Mageik consists of four overlapping edifices, each with its own central summit vent, lava-flow apron, and independent eruptive history. Three of them have small fragmental summit cones with ice-filled craters, but the fourth and highest is topped by a dacite dome. Lava flows predominate on each edifice; many flows have levees and ice-contact features, and many thicken downslope into piedmont lava lobes 50–200 m thick. Active lifetimes of two (or three) of the component edifices may have been brief, like that of their morphological and compositional analog just across Katmai Pass, the Southwest (New) Trident edifice of 1953–74. The North Summit edifice of Mageik may have been constructed very late in the Pleistocene and the East Summit edifice (along with nearby Mount Martin) largely or entirely in the Holocene. Substantial Holocene debris avalanches have broken loose from three sites on the south side of Mount Mageik, the youngest during the Novarupta fallout of 6 June 1912. The oldest one was especially mobile, being rich in hydrothermal clay, and is preserved for 16 km downvalley, probably having run out to the sea. Mageik's fumarolically active crater, which now contains a hot acid lake, was never a magmatic vent but was reamed by phreatic explosions through the edge of the dacite summit dome. There is no credible evidence of historical eruptions of Mount Mageik, but the historically persistent fumarolic plumes of Mageik and Martin have animated many spurious eruption reports. Lavas and ejecta of all four component edifices of Mageik are plagioclase-rich, pyroxene-dacites and andesites (57–68 weight percent SiO_2) that form a calcic, medium-K, typically low-Ti arc suite. The Southwest Summit edifice is larger, longer lived, and compositionally more complex than its companions. Compared to other centers in the Katmai cluster, products of Mount Mageik are readily distinguishable chemically from those of Mount Griggs, Falling Mountain, Mount Cerberus, and all prehistoric components of the Trident group, but some are similar to the products of Mount Martin, Southwest Trident, and Novarupta. The crater lake, vigorous superheated fumaroles, persistent seismicity, steep ice blanket, and numerous Holocene dacites warrant monitoring Mount Mageik as a potential source of explosive eruptions and derivative debris flows.

Introduction

Mount Mageik is a 2,165-m-high andesite-dacite compound stratovolcano adjacent to Katmai Pass at the head of the Valley of Ten Thousand Smokes (fig. 1). Consisting of a tightly bunched group of four overlapping cones (fig. 2), Mageik rivals Mount Katmai as the broadest (80 km^2) and most productive (30 km^3) edifice in the Katmai volcanic cluster (Hildreth, 1987). All within 15 km of Mount Mageik, the Katmai cluster includes Alagogshak, Martin, Katmai, and Griggs volcanoes, four discrete cones of Trident volcano, several peripheral lava domes, and the flank vent called Novarupta that produced the great eruption of 1912 (Griggs, 1922; Fierstein and Hildreth, 1992).

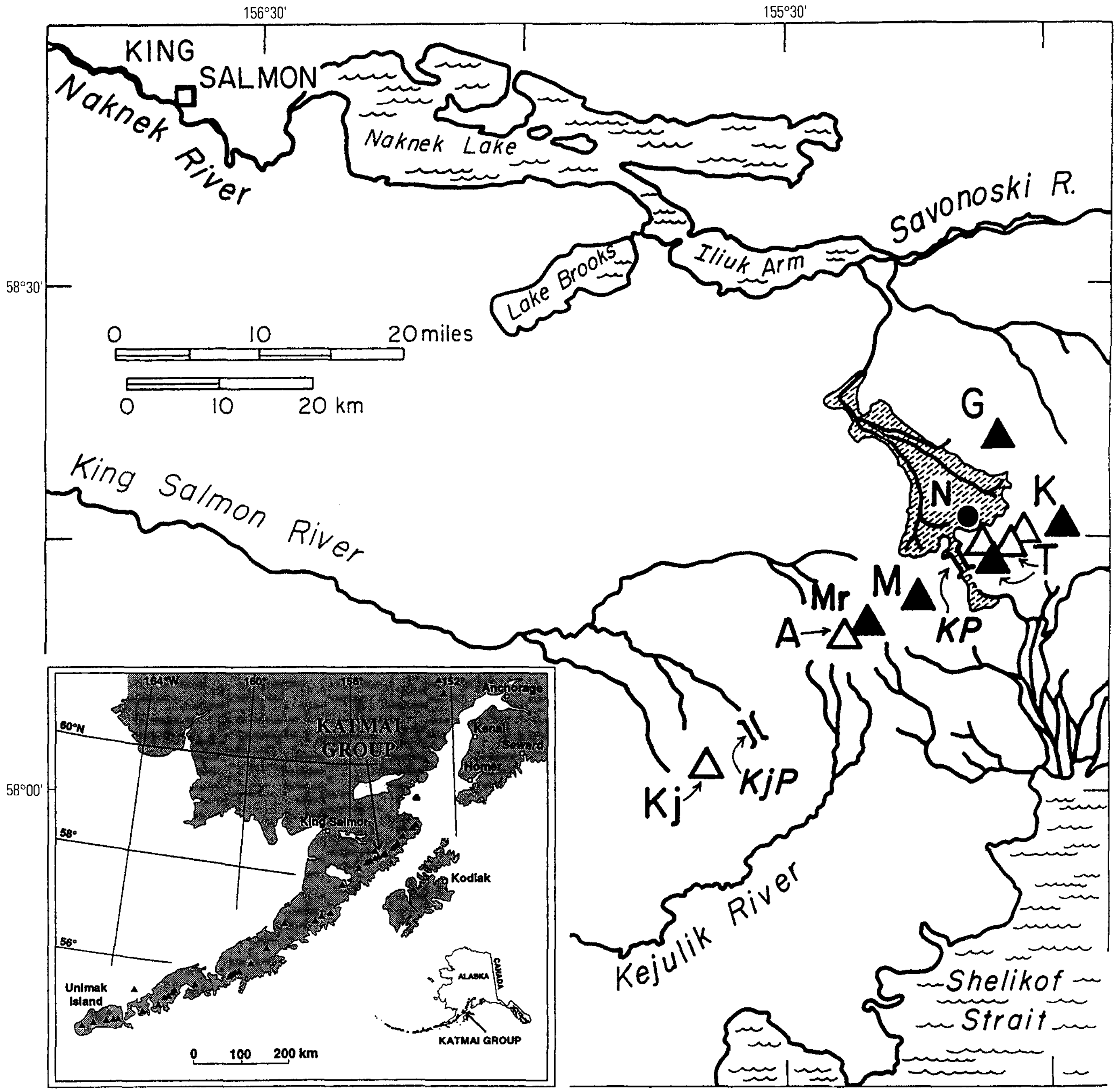

Figure 1. Map showing part of the volcanic chain along the Alaska Peninsula, southeast of the town of King Salmon. Solid triangles indicate cones active during the Holocene; open triangles indicate Pleistocene cones long extinct. The Katmai volcanic cluster includes Alagogshak (A), Martin (Mr), Mageik (M), Griggs (G), Trident (T; three extinct cones and one recently active cone), and Mount Katmai (K). Farther southwest is Kejulik (Kj) volcano. Solid circle (N) indicates Novarupta, site of the great explosive eruption of 1912, when ignimbrite (shaded valley fill) was emplaced in the Valley of Ten Thousand Smokes (Fierstein and Hildreth, 1992). Low points along the volcanic axis, which here forms the Alaska Peninsula drainage divide, include Katmai Pass (KP) and Kejulik Pass (KjP).

The four crowded cones of Mount Mageik epitomize the remarkable proximity of so many volcanic centers in this district, a clustering quite unusual for the Alaska Peninsula–Aleutian Arc.

The Mageik complex is superimposed upon a ruggedly glaciated ridge of subhorizontal siltstone and sandstone of the Jurassic Naknek Formation (Riehle and others, 1993; Detterman and others, 1996) that forms the Alaska Peninsula drainage divide in this area (fig. 1). Because Mageik and many other centers along the axial volcanic chain in the Katmai district straddle the basement divide, their eruptive products can flow either southeastward down the Pacific slope toward Shelikof Strait or northwestward toward Bristol Bay and the Naknek Lake system.

Mageik is a native Alaskan name pronounced *muh-GEEK*. The Mageik edifice was recognized as a young volcano by J.E. Spurr, who led a U.S. Geological Survey (USGS) party across Katmai Pass in October 1898, and part of the volcano was sketched on the reconnaissance topographic map of his route (Spurr, 1900). Spurr did not, however, mention any name for

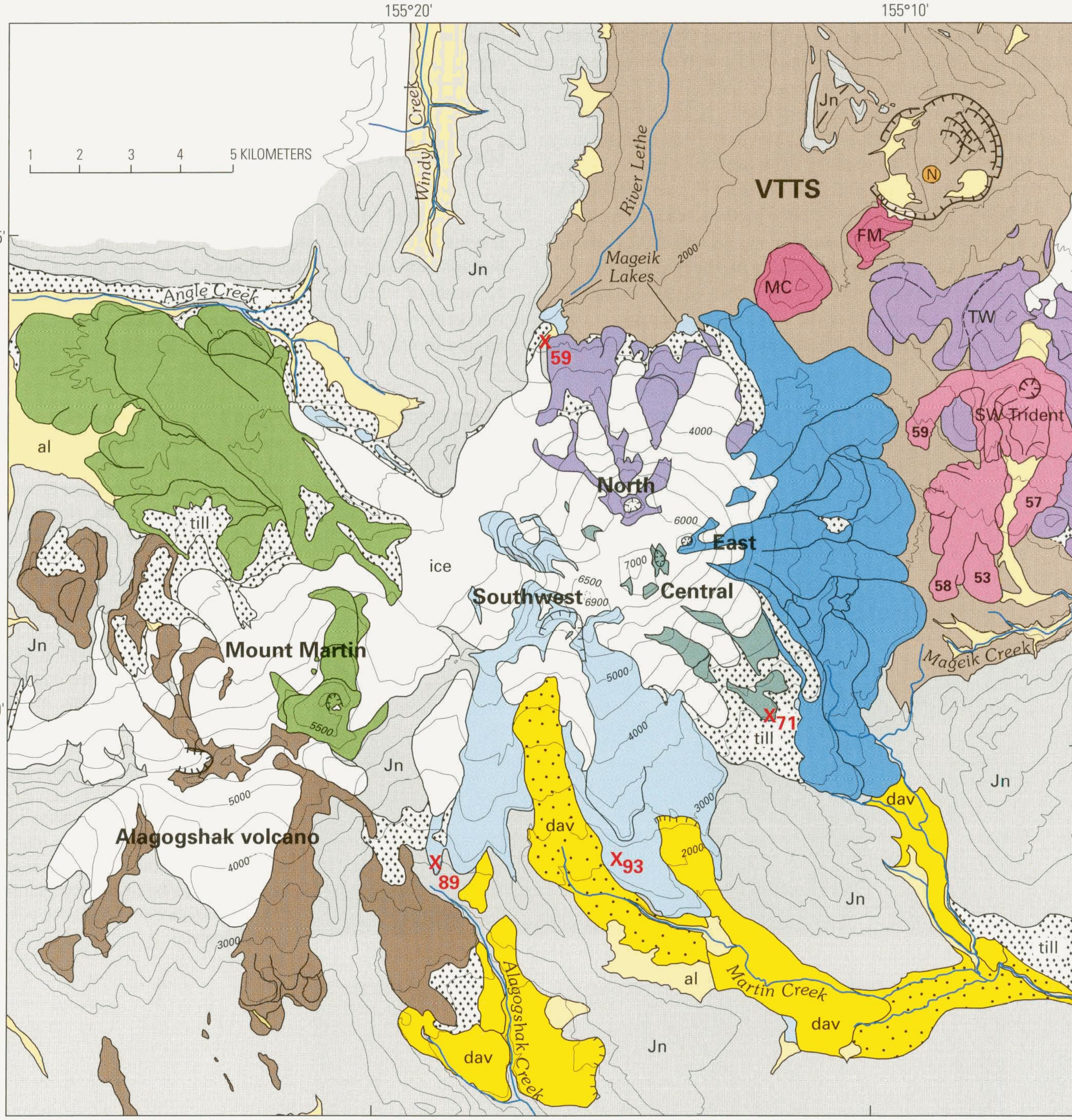

Figure 2. Simplified geologic map of Mount Mageik and its immediate surroundings. Eruptive products of Alagogshak volcano, Mount Martin, and Southwest Trident are indicated in brown, green, and magenta, respectively, and the four discrete centers of Mount Mageik in shades of blue. Year of emplacement of successive lava flows (1953–59) from Southwest Trident are indicated: 53, 57, 58, 59. Also identified at the head of the Valley of Ten Thousand Smokes (VTTS) are the 1912 rhyolite dome, Novarupta (N), and late Pleistocene dacite domes, Falling Mountain (FM) and Mount Cerberus (MC). Purple pattern (TW) shows part of glaciated prehistoric components of the Trident group. Pale tan pattern in VTTS and Mageik Creek is 1912 ignimbrite. Bright yellow pattern (dav) includes debris avalanches and landslides. Pale yellow (al) is alluvium, much of it reworked 1912 ejecta. Glacial ice is white, coarse stipple is till, and gray regional basement (Jn) is Jurassic Naknek Formation (plus scattered surficial deposits and minor Tertiary intrusive rocks, not shown separately). Craters atop volcanic cones, backfilled 1912 vent depression around Novarupta, and scarps of debris-avalanche headwalls are indicated by hachures. Locations of samples dated by K-Ar method (table 2) are indicated by red X, accompanied by age (in ka). Topographic base simplified from USGS 1:63,360 quadrangles Mt. Katmai A-4, A-5, B-4, B-5. Elevations in feet; contour interval 500 ft (1 m = 3.28 ft).

the volcano, even though he was accompanied by ten local porters. The name first(?) appears on a National Geographic Society map published in 1913 (Martin, 1913), well before the first Griggs expedition to the area (Griggs, 1922).

Although Mount Mageik is not known to have erupted historically, its near-summit fumaroles have been continuously active for at least the last century. The fumarolic crater was first visited in 1923 by C. Yori and C.N. Fenner (Fenner, 1930). Our own fieldwork, which began in 1976, included extensive sampliig on foot in 1979 of the northern and eastern flanks and of the fumarolic crater, and it concluded with mapping and sampling by helicopter each summer from 1996 to 1998 as part of a volcano-hazards assessment of the whole Katmai cluster. Owing to its present-day fumarolic and seismic activity, its extensive ice cover, and its numerous dacitic eruptions in the Holocene, we consider Mount Mageik to be a hazardous volcano capable of englacial lava flows, explosive ejection of far-flung tephra, and generation of far-reaching debris flows.

Ice-Mantled Compound Edifice

Each of Mageik's four ice-mantled summits (figs. 2, 3) is a discrete eruptive center, and each is the source of numerous andesite and dacite lava flows (57–68 percent SiO_2; table 1), many of which are 50–200 m thick distally. Three of the four centers are of late Pleistocene age, but the East Summit is largely or entirely a Holocene center. Ice-filled craters atop

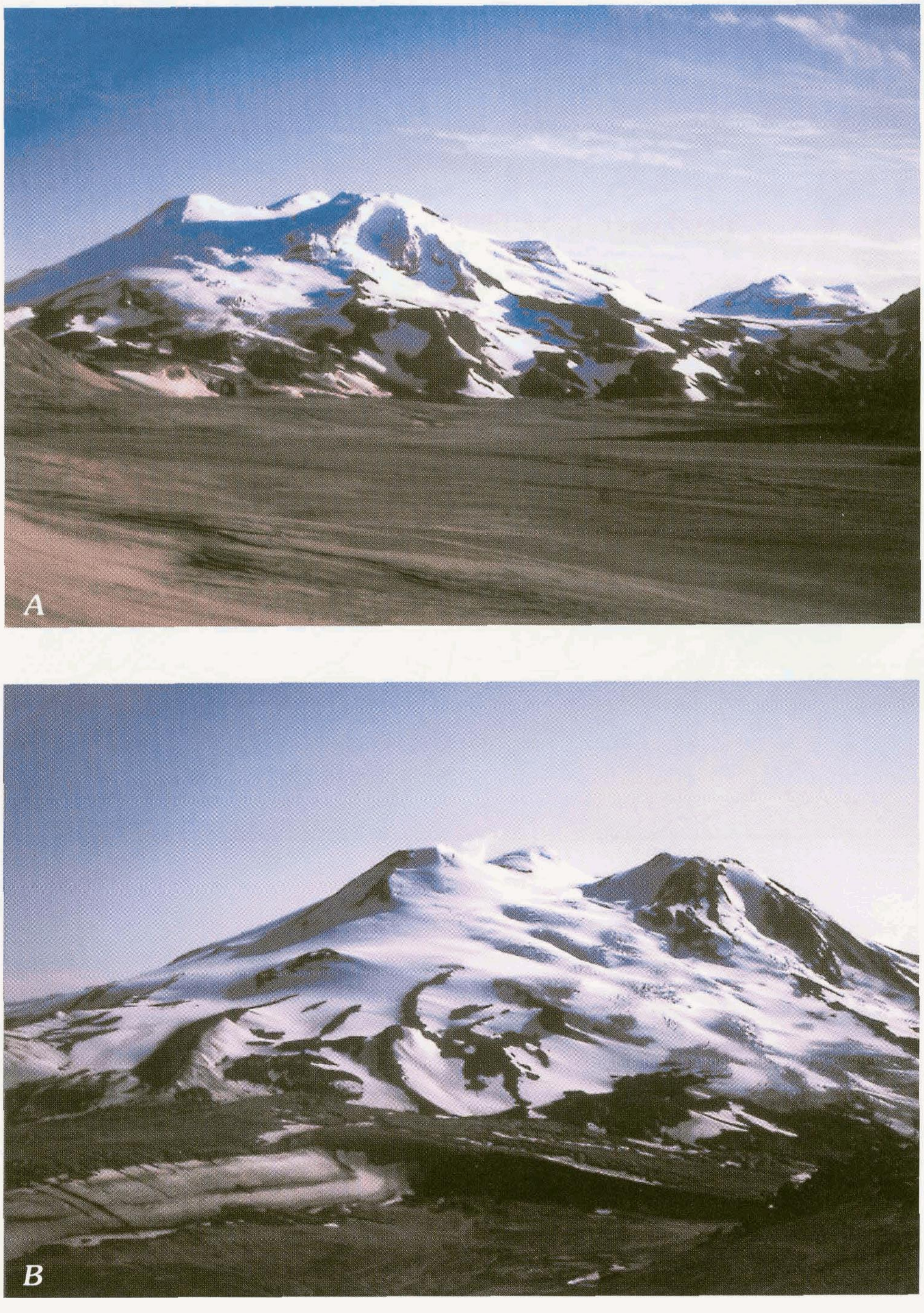

Figure 3. Ice-clad Mount Mageik as viewed southwestward from *A,* the Valley of Ten Thousand Smokes and *B,* the summit of Falling Mountain. East Summit is on left skyline in both panels. North Summit to its right is topped by an ice-filled crater, from which a blocky corrugated dacite lava flow extends 1 km northeast, toward the camera. Central Summit, highest point on the mountain at just over 7,100 ft (2,165 m), rises on background skyline with fumarolically active crater below it to its left. Southwest Summit is hidden. In *A,* Mount Martin rises on the right skyline, 7 km southwest of Mageik's North Summit. At base of Mageik, North Summit lavas end in glacially eroded buttresses that stand precipitously above the valley-filling 1912 ignimbrite. In *B,* fumarolic plume rises from the phreatic crater, and levees of northeast-flowing bifurcating lava (mapped in fig. 2) emerges from the glacier below the East Summit.

Table 1. Chemical analyses of eruptive products, Mount Mageik.

[The 10 major oxides (reported in weight percent) are normalized to H_20-free totals of 99.6 weight percent (allowing 0.4 weight percent for trace oxides and hallogens); determinations by wavelength-dispersive XRF in USGS laboratory at Lakewood, Colorado; D.F. Siems, analyst. Rb, Sr, and Zr (in parts per million) determined by energy-dispersive XRF by D.F. Siems. Precision and accuracy are discussed by Bacon and Druitt (1988). FeO* is total iron calculated as FeO. "Original total" is the volatile-free sum of the 10 oxides, as analyzed, before normalization, with total iron calculated as Fe_2O_3. LOI=weight loss on ignition at 900°C]

	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Original total	Rb	Sr	Zr
							Central Summit								
K-193	60.8	0.74	16.5	6.60	0.13	3.28	6.52	3.61	1.34	0.07	–	98.80	28	308	132
K-2118	63.1	0.66	15.9	5.87	0.11	2.81	5.69	3.50	1.77	0.14	0.30	99.04	41	234	144
K-2143	64.9	0.64	15.6	5.38	0.11	2.36	4.97	3.56	1.98	0.14	0.24	99.00	42	221	160
K-2144	57.8	0.80	17.2	8.03	015	3.85	7.20	3.29	1.15	0.16	-	99.46	22	287	113
K-2268	60.1	0.73	16.7	6.82	0.14	3.48	6.61	3.55	132	0.15	0.22	98.73	23	259	131
K-2271	64.1	0.69	16.0	5.36	0.11	2.45	5.34	3.74	1.60	0.16	0.35	98.82	31	250	149
K-2427	62.9	0.66	16.2	5.97	0.12	2.76	5.84	3.41	168	0.15	0.01	98.98	36	246	143
K-2429	66.0	0.62	15.1	5.09	0.10	2.24	4.68	3.44	2.14	0.14	0.09	99.04	46	202	173
							East Summit								
K-167	63.8	0.66	15.9	5.49	0.11	2.45	5.46	3.75	1.74	0.17	0.20	98.80	37	250	153
K-178	63.4	0.71	15.8	6.08	0.12	2.54	5.55	3.71	1.65	0.09	-	98.70	37	262	154
K-196	62.3	0.69	16.8	5.87	0.13	2.65	5.52	3.92	1.60	0.07	-	98.33	37	262	152
K-197A	63.1	0.69	15.9	5.90	0.12	2.82	5.45	3.87	1.68	0.08	-	99.43	39	246	155
K-197-B	63.9	0.67	15.9	5.59	0.12	2.52	5.33	3.73	7	0.16	0.16	99.20	33	244	156
K-218	60.1	0.67	16.5	6.74	0.13	3.71	7.10	3.39	1.26	0.06	-	99.29	28	269	125
K-2151	61.5	0.71	16.3	6.40	0.13	3.27	6.13	3.57	145	0.16	0.36	99.06	27	247	131
K-2152	63.0	0.70	16.2	5.64	0.12	2.70	5.53	3.92	1.59	0.18	0.00	99.26	33	288	157
K-2160	61.6	0.71	16.3	6.40	0.13	3.17	6.16	3.58	i45	0.16	0.26	98.83	29	252	131
K-2272	62.7	0.68	16.0	6.03	0.08	3.37	5.84	3.31	1.48	0.16	2.86	95.97	27	234	146
K-2273	64.1	0.75	15.1	6.04	0.12	2.90	5.13	3.71	1.55	0.15	1.05	97.61	29	257	146
K-2493A	62.0	0.69	16.2	6.11	0.12	3.05	6.13	3.49	1.59	0.22	0.63	98.26	34	253	155
K-2548	60.0	0.74	17.0	6.83	0.13	303	6.61	3.52	1.49	023	0.24	99.06	34	299	140
K-2425	63.5	0.69	16.0	5.67	0.12	2.58	5.50	3.67	1.68	0.17	0.19	98.85	35	240	153
K-2426	63.5	0.68	15.8	5.96	0.12	2.76	5.46	3.52	1.70	0.15	0.34	98.64	35	238	155
K-2430	62.4	0.69	16.2	6.09	0.12	2.93	5.91	3.54	1.57	0.16	0.03	99.42	33	242	142
K-2431	60.6	0.73	16.5	6.75	0.14	3.41	6.51	3.44	1.35	0.15	–	99.48	27	259	131
K-2432	62.0	0.73	16.2	6.04	0.13	3.10	5.96	3.74	1.48	0.17	-	99.29	29	291	140
K-2434	63.0	0.71	15.9	6.00	0.12	2.84	5.62	3.56	1.63	0.16	-	99.02	35	243	147
K-2435	62.6	0.70	16.2	6.01	0.12	2.79	5.78	3.61	159	0.17	0.14	98.83	34	249	138
K-2436	63.5	0.70	15.9	5.82	0.12	2.66	5.45	3.62	1.68	0.16	0.31	98.68	30	238	142
K-2438	63.9	0.68	15.8	5.68	0.12	2.60	5.38	3.61	174	0.15	0.13	97.95	40	242	154
							North Summit								
K-176	63.0	0.70	15.8	6.20	0.12	2.78	5.91	3.46	1.57	0.06	–	98.75	37	239	152
K-207	63.6	0.68	15.8	5.71	0.12	2.59	5.45	3.74	1.73	0.16	0.06	99.23	31	242	147
K-209	60.5	0.65	16.6	6.55	0.13	3.47	7.07	3.57	1.06	0.05	–	99.36	20	269	114
K-210	63.0	0.68	16.1	6.04	0.12	2.70	5.91	3.41	1.48	0.12	0.13	99.43	30	249	141
K-211	62.8	0.68	15.8	6.25	0.12	2.56	6.10	3.75	1.48	0.06	–	98.89	35	251	136
K-212	62.3	0.65	16.7	5.85	0.11	2.53	6.45	3.54	1.42	0.12	0.50	98.53	32	249	144
K-213	63.4	0.65	16.2	5.66	0.10	2.42	6.03	3.41	155	0.12	0.11	98.80	36	238	145
K-215	61.7	0.69	16.2	6.39	0.13	3.14	6.39	3.47	1.45	0.07	–	98.50	33	257	137
K-222	60.6	0.73	16.6	6.81	0.13	3.33	6.62	3.53	1 17	0.12	–	98.63	24	272	119
K-223	60.6	0.75	16.2	6.96	0.14	3.49	6.62	3.57	1.23	0.08	–	99.75	25	271	122
K-223-A	60.6	0.74	16.6	6.67	0.13	3.33	6.55	3.53	1.24	0.17	0.68	98.83	21	266	115
K-2092	62.7	0.65	16.0	5.91	0.12	3.03	5.95	3.47	1.64	0.16	0.28	98.81	38	264	149
K-2265	62.8	0.67	15.9	5.96	0.12	300	5.86	3.47	1.67	0.15	0.27	98.80	32	247	142
K-2267	60.6	0.74	16.6	6.73	0.13	3.31	6.54	3.56	124	0.17	–	98.74	22	268	122
K-2269	63.5	0.68	16.8	5.65	0.09	2.54	5.27	3.31	1.66	0.14	1.91	97.22	35	222	152
K-2437	61.5	0.71	16.5	6.19	0.13	2.99	6.13	3.59	1.42	0.17	0.10	99.17	27	269	128
K-2475	62.0	0.70	16.3	6.26	0.12	3.02	6.10	3.13	1.49	0.15	–	98.73	29	251	132
K-2481	64.2	0.68	15.6	5.62	0.12	2.59	5.32	3.53	1.83	0.15	0.09	98.66	44	237	167
							Southwest Summit								
K-2052	65.1	0.61	16.1	5.01	0.13	2.12	4.49	4.26	1.65	0.19	0.56	98.66	27	249	131
K-2056	57.7	0.80	16.5	7.55	0.14	4.35	7.74	3.18	1.43	0.19	0.94	98.51	29	284	125
K-2091	62 0	0.70	16.2	6.40	0.12	3 03	5.67	3.41	1.84	0.17	0.28	98.87	46	258	162
K-2113	634	0.68	16.1	5.90	0.12	2.48	5.M	3.54	2.13	0.19	0.80	98.37	46	257	179
K-2114	61.4	0.78	16.4	6.74	0.13	2.99	5.76	3.47	1.78	0.18	0.60	98.42	37	271	156
K-2116	59.2	0.73	16.3	7.05	0.13	4.03	7.19	3.20	1.57	0.19	0.16	98.91	35	304	139
K-2117	58.9	0.73	16.2	7.13	0.14	4.11	7.37	3.23	1.55	0.19	0.38	99.33	35	306	141
K-2126	65.1	0.57	15.9	5.19	0.12	2.26	4.73	3.69	1.90	0.16	0.34	98.65	34	245	128
K-2127	65.1	0.57	15.8	5.26	0.12	2.33	4.70	3.72	1.91	0.16	0.58	99.07	39	246	132
K-2128	63.9	0.67	16.0	5.71	0.12	242	4.89	3.52	2.23	0.18	0.41	98.80	55	249	182
K-2129	61.4	0.86	16.1	6.92	0.12	292	5.57	3.36	2.08	0.20	1.00	98.03	45	247	190
K-2130	61.9	0.75	16.3	6.47	0.13	2.85	5.68	3.52	1.88	0.18	0.10	99.04	47	271	162
K-2131	63.4	0.70	16.0	5.86	0.12	2.53	5.25	3.57	2.03	0.17	0.15	98.95	49	265	174
K-2131-A	56.3	0.92	17.7	8.46	0.15	403	7.30	3.25	1.28	0.19	0.40	98.60	25	321	116
K-2132	67.9	0.51	15.8	3.98	0.08	1.53	3.74	3.82	2.17	0.15	1.18	98.33	43	236	143
K-2133	65.5	0.58	15.8	4.81	0.13	2.11	4.63	4.07	1.77	0.17	1.10	98.21	35	241	131
K-2136	60.4	0.80	16.6	7.09	0.14	323	6.01	3.47	1.67	0.20	0.18	99.03	38	293	149
K-2171	65.5	0.63	15.4	5.21	0.10	2.20	4.79	3.59	2.11	0.14	0.74'	98.32	47	206	165
K-2171-A	62.6	0.66	16.1	6.13	0.12	2.86	5.92	3.46	1.64	0.16	0.25	99.01	37	239	138
K-2264	62.4	0.73	16.0	6.28	0.12	2.78	5.70	3.55	1.85	0.15	0.24	98.76	46	263	160
K-2270	57.4	0.71	17.4	7.29	0.14	4.29	8.27	3.00	0.93	0.16	0.84	98.70	17	287	100

the North and East Summits are usually obscured by snow, but an ice-free 350-m-wide phreatic crater that lies between the East and Central Summits contains an acid lake and several jet-like superheated fumaroles. About 30 percent of the present-day surface of Mageik is covered by glacial ice, including about 80 percent of the four-summit region, where rock outcrops are limited to scattered windows through the ice, most of them very steep.

Southwest Summit

The Southwest Summit vent supplied the products that make up the southwestern half of the volcano (fig. 2). Although it is the stratigraphically oldest and most ice-ravaged of the four components, it remains the most voluminous, providing about half the mass of present-day Mount Mageik. Most products of the Southwest Summit (57–68 percent SiO_2) are compositionally distinguishable from those of the other three in being generally richer in K_2O (table 1). Basal lava flows in two areas yield K-Ar ages close to 90 ka, which thus apparently dates the initiation of volcanic activity at Mount Mageik (table 2). For convenient discussion, we treat the many lava flows of the Southwest Summit edifice as four spatially distinct groups:

(1) The SSE. planeze is a stack of at least seven andesite and dacite lava flows having an exposed maximum total thickness of at least 350 m. There is no simple compositional progression, as the most silicic lava known to have erupted from Mount Mageik is in the middle of the stack. As dips lessen downslope from 25° or 30° proximally to about 10" distally, most of the flows thicken; the two thickest (62 percent and 65 percent SiO_2) each reach about 150 m at their eroded distal termini.

(2) A stack of about eight andesite and dacite lava flows (61–64 percent SiO_2), each 30-100 m thick, makes up the south-trending ridge separating the headwaters of Alagogshak and Martin Creeks. The maximum exposed thickness of the south-dipping stack is 275 m on the cliffs facing Martin Creek.

(3) Remnants of a single andesite flow line the north edge of the glacial trough that runs northwestward toward Angle Creek where its distal extremity is 150 m thick. One of the least silicic lavas (57.7 percent SiO_2) sampled at Mount Mageik, the flow was no doubt far more extensive prior to glacial erosion. In common with the southerly stacks of lavas just described, this flow probably extended down-canyon several kilometers beyond its present limit; all three glacially truncated termini today lie about 6 km from the Southwest Summit vent.

(4) The great northwest buttress, its 600-m cliffs surrounded by ice (figs. 2, 4), exposes a set of andesite-dacite lava flows (62–65.5 percent SiO_2) that dip gently away from the Southwest Summit; several are as thick as 100 m and one exceeds 200 m (fig. 4).

The Southwest Summit itself (2,105 m; 6,900 ft) is an ice-covered mound 1 km wide that rises 180 m above the saddle to its east. The only exposure is on the sheer south face where coarse ejecta suggest the edge of a fragmental cone (rather than a dome) concealed by the icecap. At the east end of this face, a stubby andesite lava flow that issues from the cone emerges from beneath the icecap and extends steeply down the ESE. spur for some 500 m. At 57.4 percent SiO_2, this is the

Table 2. Whole-rock potassium-argon ages and analytical data.

[Analysts: Potassium by D.F. Siems; Argon by F.S. McFarland and J.Y. Saburomaru (Menlo Park, California). Constants: λ =0.581 x 10^{-10} y^{-1}; λ_b=4.962 × 10^{-10} y^{-1}; $^{40}K/K$=1.167 × 10^{-4} mol/mol]

Sample number	Location (see fig. 2)	Wt % SiO_2	Wt % K_2O	Radiogenic ^{40}Ar 10^{-13}mol/g	Radiogenic ^{40}Ar %	Calculated age
K-2130	Martin Creek, West Fork; NE. wall, 2300-ft rim. Basal lava flow.	61.9	2.009±0.007	2.681	9.5	93±8 ka
K-2136	Alagogshak Creek, 2800-ft nose in headwaters. Basal lava flow.	60.4	1.830f0.005	2.356	10.8	89±8 ka
K-2144	Upper bowl of North Fork, Martin Creek; 2600-ft rim of thick basal lava flow, 4 km SE. of Mageik's Central Summit.	57.8	1.250±0.001	1.282	5.4	71f I1 ka
K-2267A	NW. base Mount Mageik, 300 m S. of W. Mageik Lake. Basal lava flow.	60.6	1.344±0.001	1.138	6.6	59±11 ka

Figure 4. Northwest buttress of Mount Mageik. View toward NNE with Valley of Ten Thousand Smokes in distant background. Stack of andesite-dacite lava flows from Southwest Summit vent is 600 m thick. Top flow is 100 m thick and third flow from top thickens downslope to more than 200 m. Note 10° dips, vertical noncolumnar jointing, thick massive zones, thinness of darker (glassier) flow-breccia zones intercalated, and relative conformity of upper part of the stack. Thinner flows at base of buttress and in wall at right are likewise from the Southwest Summit vent.

most mafic lava sampled anywhere on Mount Mageik (table 1). The icecap that mantles the Southwest Summit is too thick to reveal whether it fills a small crater atop the cone, but a slight depression in the ice suggests that. A major cirque headwall just southwest of the cone provides the largest exposure of severely hydrothermally altered rock on Mount Mageik. This is the source of a clay-rich debris-avalanche deposit that covers the floor of Martin Creek for more than 16 km downstream (fig. 2).

Central Summit

The Central Summit is a 1-km-wide ice-clad knob that rises 180–250 m above the adjacent saddles that separate it from the other summits. At an elevation of more than 2,165 m (7,100 ft), it forms the highest point on the volcano. The steep north and west faces of the knob are sheer ice, but the east face was exposed by explosive excavation of the fumarolically active crater at its eastern base. The ice-mantled southern slope is gentler but smooth, providing no hint of a depression that might conceal an ice-filled crater, and low on the slope are two small exposures of blocky dacite lava (64 percent SiO_2) that could be exogenous lobes of a lava dome. The 100-m-high western wall of the crater appears to be one massive lava, consistent with the Central Summit being a lava dome, although (slightly altered) blocks from that wall yield 61-63 percent SiO_2, similar but not identical to the blocky lava on the south slope. Lava flows radiating away from the Central Summit vent are exposed 1–1.5 km to the northwest as windows of andesite (60 percent SiO_2) through the ice and as far as 4 km down the southeast slope (fig. 2) as a set of glaciated benches and cleavers (58–66 percent SiO_2). Even ignoring the ice cover, products of the Central Summit are estimated to make up only about 15 percent of the surface area of Mount Mageik (fig. 2). Their volumetric proportion is likely to be larger owing to partial concealment by products of the younger North and East Summit vents.

The age relationship between the Central and Southwest Summit edifices, both ubiquitously glaciated, is equivocal as their contacts are everywhere obscured by ice. The Central Summit is nonetheless inferred to be the younger of the pair on the basis of (a) the more advanced hydrothermal alteration of parts of the Southwest Summit edifice, (b) the apparent structural underpinning of Central Summit lavas on the southeast slope by those of the Southwest Summit, (c) the northeastward-younging trend among the three companion edifices, and (d) the compositional distinctiveness of the higher K products of the Southwest Summit relative to those of the three (younger) edifices. The basal lava flow of the stack dipping southeast from the Central Summit gave a K-Ar age of 71±11 ka, clearly younger than the approximately 90-ka basal lavas of the Southwest Summit (table 2).

North Summit

The North Summit (2,012 m; 6,600 ft) rises only 100 m above the saddle to its south (fig. 5) but has long steep slopes in all other directions (figs. 2, 3). Although its eruptive products (60.5–64 percent SiO_2) are glacially modified everywhere, erosion is more severe lower on the edifice. An ice-filled crater 300 m wide is still well formed, and the surface of a 1-km-long proximal dacitic lava flow high on the northeast slope (fig. 3) remains blocky and scoriaceous. Exposures along the crater rim are intensely altered solfatarically, but products elsewhere are fresh and generally at least partly glassy. As the North Summit vent is high on the northern slope of the older edifice (figs. 2, 3), all of its 10–12 exposed lavas flowed approximately northward. Most of the flows are 25–75 m thick medially where dipping 20°–30°, but several thicken substantially downslope where they encountered lesser gradients and in some cases were probably impounded by thick glacial ice. Glacially eroded termini of andesite-dacite lava flows 100–200 m thick at the northern base of Mount Mageik (figs. 2, 3) today support precipitous waterfalls and some of the most spectacular scenery in the district.

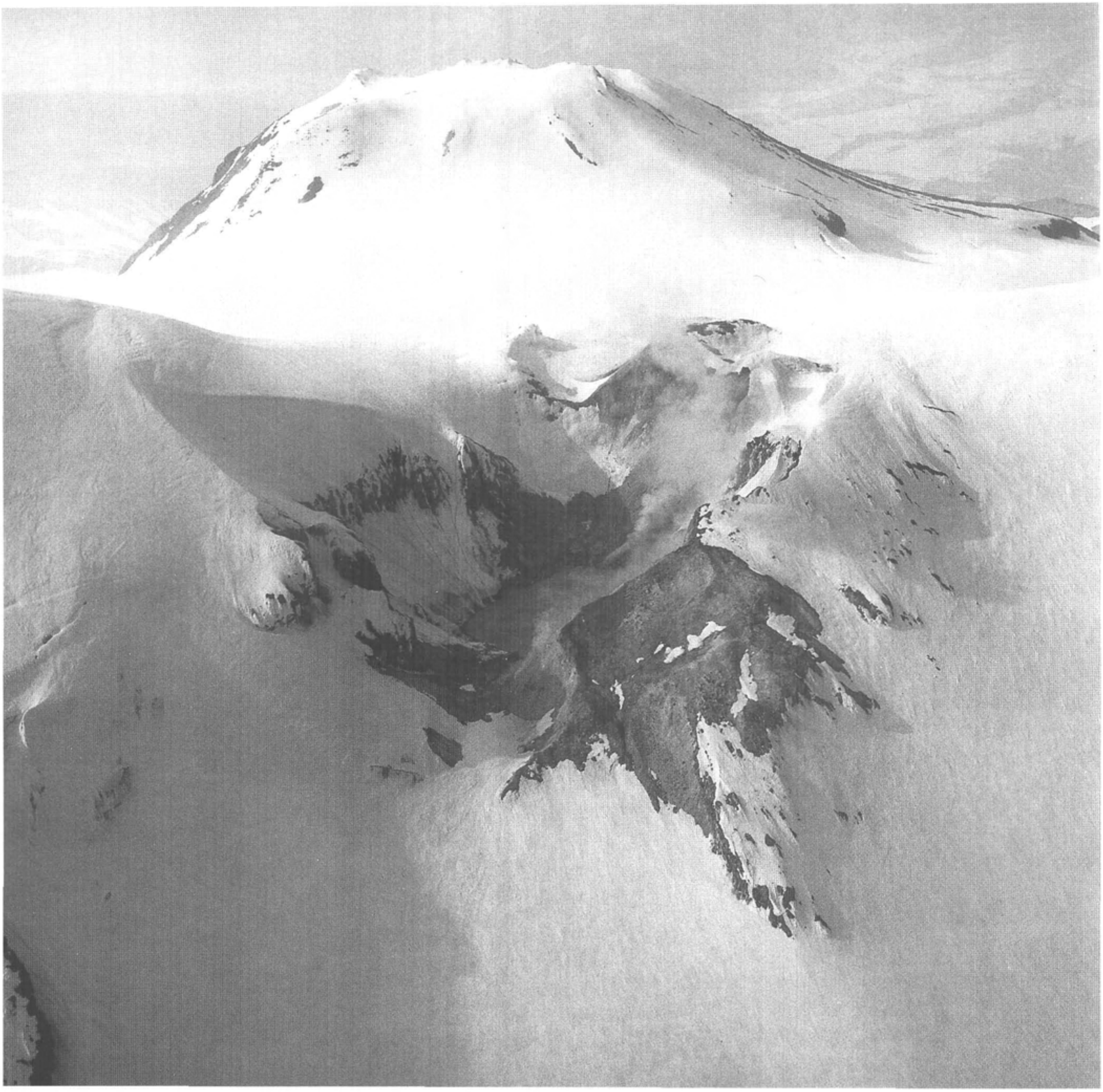

Figure 5. Aerial view northwestward of fumarolically active crater and North Summit of Mount Mageik. Rock walls and talus around crater are dacite of Central Summit, which lies partly out of field of view to left. Veneer of scattered dacite blocks mantles outer slope at lower right. Crater contains fumarole groups visible to south and northeast of its 125-m-wide acid lake. North Summit is 1 km beyond the crater and rises 50 m higher than the crater rim. Just discernible atop snow-draped North Summit is the flat surface of its own ice-filled crater and part of its (solfatarically altered) northwest rim. National Park Service photograph by W.S. Keller, summer 1969.

Despite the ubiquitous (and ongoing) glacial erosion, the North Summit edifice is thought to be young—late Pleistocene certainly and perhaps also in part early Holocene. Its northwesternmost basal lava flow, a fresh andesite that rests on Jurassic basement about 300 m south of West Mageik Lake, yields a K-Ar age of 59±11 ka (table 2).

East Summit

The East Summit (2,012 m; 6,600 ft), was also built against the preexisting edifice, so (in common with the North Summit) its summit rim rises barely 50 m above the adjacent saddle and its lava flows were constrained to spread downslope very asymmetrically—in this case into the easterly sector (figs. 2, 3). About a dozen lava flows (60–64 percent SiO_2) descend toward Katmai Pass and Mageik Creek, forming a series of leveed tongues, stairstep benches, and sprawling piedmont lava lobes, each 50–150 m thick distally. From the vent at an elevation of more than 2,010 m, two of the flows extend 6 km to termini as low as 300–350 m in Martin Creek. One of the youngest flows bifurcates to the northeast (fig. 3), one of its lobes banking against the Mount Cerberus dacite dome and the other halting at

Katmai Pass against the toe of an andesite lava flow from West Trident volcano (fig. 2). The East Summit vent is marked by an ice-filled crater about 250 m wide. Its rim is strewn with coarse scoriae and dense glassy blocks of phreatomagmatic ejecta, and exposed there locally are the blocky to rubbly surfaces of thin lava-flow veneers (64 percent SiO_2) that largely drained away downslope. In contrast to the North Summit rim, no fumarolically altered exposures were seen around the crater rim of the East Summit, although altered fragmental strata do crop out high on the east face.

The East Summit edifice appears to be entirely Holocene in age. Although all of its lava flows are being eroded proximally by active glaciers, none of the lower benches, lobes, and leveed lava tongues are glacially scoured. The many flows (fig. 2) nonetheless exhibit considerable variation in relative retention of primary surface roughness, aeolian silt accumulation, incipient soil development, and gully incision, suggesting that the dozen or so Holocene lavas represent not a single episode but at least three eruptive episodes substantially separated in time. A thick cover of pumiceous 1912 fallout on low-relief parts of these flows makes any such relative age assessments hard to quantify.

Similarity to Southwest (New) Trident Cone of 1953–74

Each of the four summits is a discrete eruptive center, each the source of numerous lava flows from a simple fixed vent, expressed either as a plug dome or a cratered fragmental cone. We infer that each had a discrete conduit system independent of those of its companions, at least at shallow levels, and that each of the four centers underwent separate independent periods of activity. The morphological, structural, and compositional similarity of all four Mageik centers to an edifice just across Katmai Pass that was built from scratch starting in 1953 is striking and instructive.

Beginning in February 1953, a new andesite-dacite edifice (figs. 2, 6) was built at the southwest margin of the Trident volcanic group (Snyder, 1954; Ray, 1967). Although referred to informally as "New Trident," we recommend calling it Southwest Trident, in anticipation of the day it ceases to be Trident's youngest component. During two decades of sporadic explosive activity (largely vulcanian), a new 3-km^2 fragmental cone was constructed of block-and-ash deposits, scoria, agglutinate, and intercalated lava flows to an elevation of about 1,515 m (GPS measurement by M. Coombs, 1997) on the site of a former fumarole at about 1,174 m on the glacially eroded southwest flank of Trident I (the central and highest cone of the Trident group). Although relief on its south slope exceeds 700 m, the new cone therefore has a central thickness of only 340 m and a volume of about 0.3 km^3. At successive stages of cone construction, four blocky leveed lava flows effused from its central vent in 1953, 1957, 1958, and during the winter of 1959–60 (fig. 6). Each lava flow is 30–70 m thick and 2.5–4.5 km long, and altogether they add about 0.35 km^3 to the eruptive volume. The cone's summit is today marked by a shallow crater, 350 m wide, that was the site of several small interim plugs, which were emplaced after the final lava flow and were repeatedly destroyed by intermittent explosive activity (1960–74). Black ash clouds rose 6–9 km several times between 1953 and 1968 and perhaps to 12 km once or twice; undated ballistic blocks are strewn as far as 3 km from the vent. A single layer of coarse ash, typically 5–17 cm thick, is preserved at a few protected sites as far as 7 km northeast. Liberal estimates of total fallout yield less than 0.05 km^3, giving a total eruptive volume of about 0.7 km^3. Most of the fallout and at least half the total volume of lava and proximal ejecta were emplaced within the first four months, before June 1953 (Snyder, 1954). Minor ejections of tephra, some involving plug blowout, took place from 1963 to 1974, but volumetrically significant eruptions were over by 1963. Numerous fumaroles, superheated and sulfurous in the 1960's but near- or sub-boiling today, persist on upper parts of the cone (fig. 6).

The width of the crater, the size of the fragmental cone, and the intercalation within the cone itself of the proximal parts of effusive lava flows with the progressively accumulating pyroclastic debris are similar to the equivalent features on Mageik. The blocky leveed lava flows of 1953–60 are morphologically and texturally similar to the young coulees from the East Summit of Mageik, and many of the steep rubbly flow-fronts are of similar height. Their magmas were similar as well, as the lavas and scoria blocks erupted from 1953 to 1963 are olivine-poor two-pyroxene andesite and dacite (57–65 percent SiO_2; Hildreth and Fierstein, 2000), many of which are hard to distinguish (fig. 7) from the comparable products of East Mageik (60–64 percent SiO_2) If the cone and lavas of 1953–74 had vented on the opposite side of Katmai Pass, they would no doubt have been regarded as a fifth component of Mount Mageik.

The volume of Southwest Trident is an order of magnitude smaller than those of the East and Southwest components of Mageik but not drastically smaller than volumes of the North and Central Mageik centers (fig. 2). Could any of these have been constructed in 20 years? We have found little evidence for severe erosional unconformities within any of the four Mageik edifices (e.g., fig. 4), despite the prevalence of glacial ice. We may never know how long their eruptive lifetimes lasted, but, whether 20 years, 200, or 2,000, it seems likely that each component cone of Mount Mageik grew fairly rapidly.

Fumarolically Active Crater

Mageik's fuming crater is about 100 m deep, 450 m long, and 280–400 m wide at the rim (fig. 5). It penetrates the margin of the Central Summit dome (fig. 2) and is clearly separated by a gentle 300-m-wide saddle from the East Summit. Elongate north-south, the crater's eastern and western walls are precipitous, but notches at both ends permit access. Its talus-mantled lower walls funnel down to an ovoid lake about 125 m wide that occupies much of the crater floor. Fumarolic discharge through the lake keeps the water yellow-green, acid (pH=1–2), as hot as 72°C, and in a continual state of roiling agitation. The resulting waves pile up a fringe of yellow sulfurous frothy spindrift along the shoreline. Several fumaroles, some quite vigorous, emerge from the talus south and northeast of the lake as well as beneath it. Some are superheated; the hottest one measured in 1979 was 172°C. According to recent work by R.B. Symonds (Cascades Volcano Observatory, oral commun., 1998), the Mageik fumaroles are predominantly steam but are rich in CO_2 and H_2S

Figure 6. Southwest (New) Trident edifice constructed **1953–74.** ***A,*** View westward over coarsely fragmental cone, showing 350-m-wide crater and, just outside the rim, pale collar zone marked by solfataric alteration and weak fumaroles. East and North Summit cones of snow-covered Mount Mageik, 8 km farther west, are structurally, morphologically, and compositionally similar, but their craters are now filled by ice. Levees of Holocene lava flows from the East Summit can be seen emerging from the icecap at midslope and descending into clouds drifting through Katmai Pass, which separates Trident from Mageik (fig. 2). Atop Mageik, small puffs of fumarolic vapor on skyline rise from open phreatic crater hidden between East Summit and Central (true) Summit behind it. ***B,*** View northeastward of Southwest Trident across upper Mageik Creek from big southeastern piedmont lava lobe of Mount Mageik (fig. 2). Dark fragmental cone has 700 m relief on this (downslope) side. In foreground, blocky andesite-dacite lava flows of 1953 and 1958 have flow-fronts 50–70 m high and rest on thin white ignimbrite of 1912, which in turn overlies gray glacial deposits. At far left near Katmai Pass is dark andesite lava flow of 1959–60, and at far right center (with snowpatches) is leveed lava flow of 1957. On skyline beyond 1953–74 cone are glaciated edifices of the Trident group: West Trident at left, Trident I at right, and a bit of East Trident in distance at extreme right.

and have C- and He-isotope ratios typical of magmatic gases from arc volcanoes. Depending on wind and condensation conditions, their combined plume is commonly visible from afar, but it rarely rises as high as 1 km above the crater rim and is never as large as the fumarolic plume from nearby Mount Martin. Though the rim is surrounded by glacial ice (fig. 5), the thermal flux keeps the crater largely ice-free. Even fresh snow quickly acquires from the fumaroles a yellow dusting of sulfur sublimate.

When the crater was first visited by Fenner and Yori on 4 August 1923 (Fenner, 1930), its configuration was essentially the same as today (fig. 8), except that instead of the present 125-m-wide lake there were two shallow muddy pools (10 m and 15–20 m wide) that were made to boil and fountain by the fumarolic discharge through them. Fenner noted the unstable rockfall talus, the angularity of the talus blocks, the sublimates of sulfur on rocks and snow, the strong sulfurous fumes, and the fumarolic roar like "a great waterfall."

Fenner also noted loose blocks of lava and finer debris on the glacier near the crater's southeast rim, attributing them to relatively recent ejection. We have likewise found such blocks scattered as far as the East Summit, about 600 m northeast of the crater and at least 50 m higher than the saddle between them. Lithologically, the blocks resemble the rock making up the walls of the crater, which was excavated explosively through a dome (or single thick lava flow) of massive pyroxene-plagioclase dacite (63–64 percent SiO_2). Part of the Central Summit, the crater-wall dacite is heavily jointed, irregularly oxidized, and incipiently acid-altered along fractures. That such alteration is only moderate, rather than advanced and pervasive

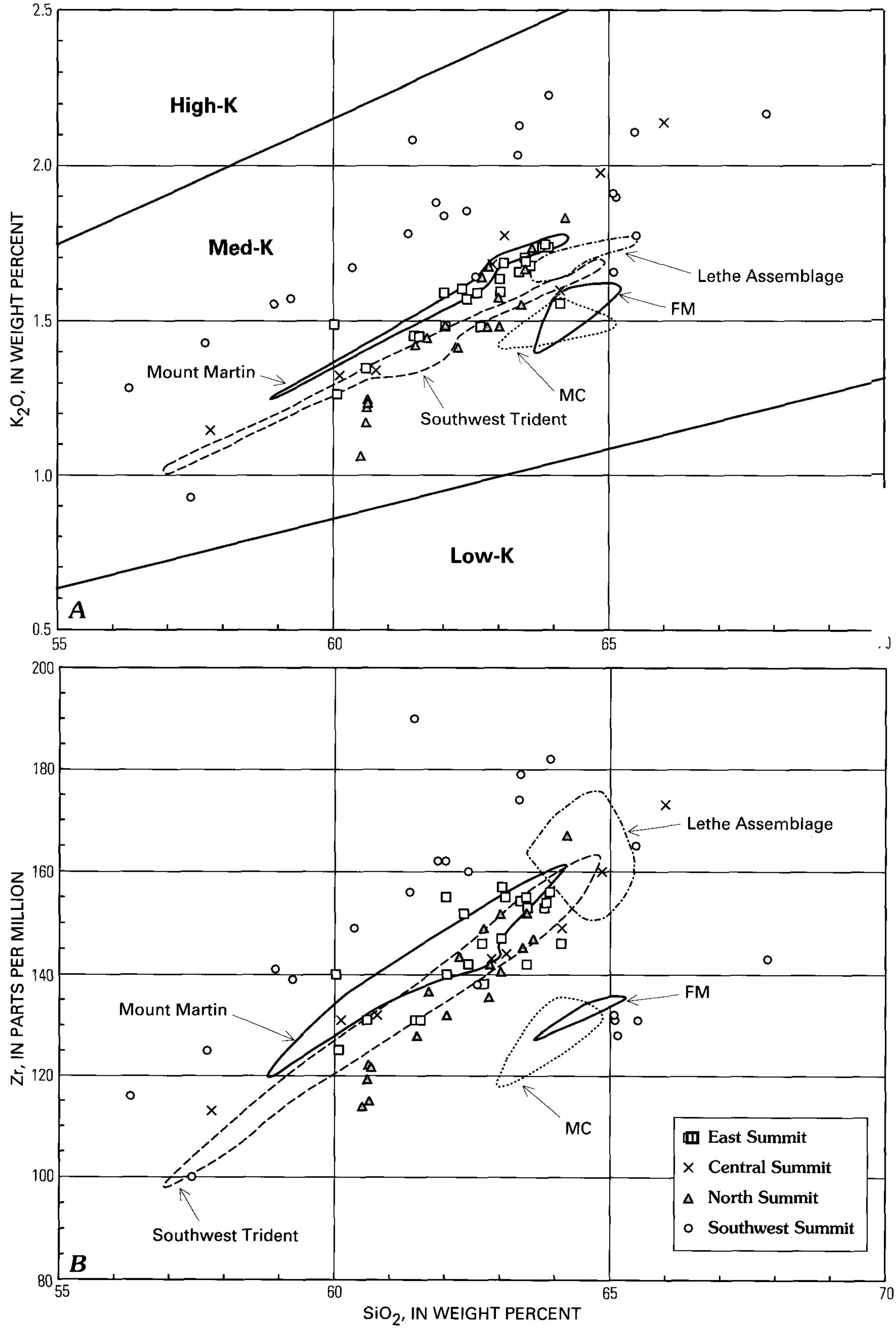

Figure 7. Whole-rock compositional data for the four centers making up Mount Mageik, as identified in inset. The conventional division in arc suites between andesite and dacite at 63 percent SiO_2 is, as usual, an arbitrary tick on a continuum. In addition to Mageik data, fields outlining the compositional ranges determined for our suites of samples from nearby Mount Martin (n=13) and Southwest (New) Trident (n=15) are shown for comparison, along with fields for 11 pumice blocks from the Lethe Assemblage and 4 samples each from the Falling Mountain (FM) and Mount Cerberus (MC) domes (fig. 2). A, K_2O vs. SiO_2. B, Zr vs. SiO_2. Data from Hildreth and others (1999); Hildreth and Fierstein (2000); and table 1, this report.

Figure 8. Fumarolically active crater of Mount Mageik in 1923 and 1979. *A*, View north along crater floor toward north notch. by C. Yori on 4 August 1923. Talus blocks and craterwalls are massive dacite of Central Summit. Hidden by talus are two shallow muddy ponds described by Fenner (1930). *B*, View south from just below north notch, by W. Hildreth 10 July 1979. Much of crater floor is occupied by 125-m-wide hot acid lake, which remained much the same when we last saw it on 28 July 1997. Fumarole groups are vigorously active in talus south and northeast of the lake as well as beneath it. Note that pumice, scoriae, agglutinate, and other juvenile ejecta are lacking in both views.

as on the North Summit rim and on cirque headwalls adjacent to the Southwest Summit, suggests that the crater is of fairly recent origin. The lack of any juvenile ejecta indicates that the crater-forming event was phreatic, and the absence of a constructional ejecta ring around the crater suggests that vigorous phreatic explosions dispersed about 0.01 km^3 of shattered dacite blocks as a thin but extensive sheet across the summit glaciers. The fumarolically active crater is therefore not a magmatic vent in the sense that each of the four summits is.

Holocene Activity

Unglaciated lava flows indicate that the East Summit of Mount Mageik has erupted several times since the shrinkage of the regionally extensive glaciers (Riehle and Detterman, 1993) that marked the Pleistocene-Holocene transition. All unequivocally unglaciated eruptive products of Mageik have issued from the East Summit vent, which appears to be of Holocene age in its entirety. It appears unlikely that the North Summit, second youngest of the four centers, has been active in the Holocene, but the evidence does not necessarily exclude minor lingering activity there in the early Holocene. All lava flows from the North Summit are laterally glaciated (fig. 3), and their distal flow surfaces are everywhere ice-scoured. Nonetheless, preservation of crags and ridges of friable acid-altered ejecta around the crater rim (fig. 5) and of primary surface morphology on a stubby proximal lava flow (fig. 3) raises some doubts about overinterpreting the age significance of glacial erosion on a volcano sustaining active glaciers. The small proximal lobe might be early Holocene.

Unglaciated lavas from the East Summit vent (figs. 2, 3, 6) include at least 10 discrete vent-derived flows and an additional eight flow lobes that may or may not have budded or branched from the others. All are blocky flows of plagioclase-rich two-pyroxene andesite or dacite (60–64 percent SiO_2), most of them leveed and corrugated, with steep flow-fronts and margins that are typically 50–150 m high. Below the Neoglacial ice limit, the lava flows are unglaciated, but small differences in surface degradation and aeolian silt accumulation suggest at least three independent episodes of Holocene emplacement. There could well have been 10 or more such eruptive episodes but, on the other hand, the 1953–60 activity at nearby Trident demonstrated that four discrete lava flows could be emplaced in 7 years. The two northernmost lava flows from the East Summit center are younger than a locally widespread fall deposit that is bracketed by ^{14}C ages elsewhere to be about 4,000 years old. The southeasternmost lava flow from the East Summit is overlain by this tephra as well as by another regional ash that fell about 5,500 ^{14}C years ago.

A glassy nonwelded lithic pyroclastic-flow deposit, as thick as 2.5 m, is locally exposed atop the 2,400-ft rim of the broad piedmont lava lobe 4 km east of the East Summit (fig. 2). In a dark-gray matrix of coarse andesitic ash, black juvenile lapilli are massive, poorly vesicular, glassy silicic andesite (62 percent SiO_2; table 1, sample K-2493A). This is the only Holocene pyroclastic-flow deposit identified at Mount Mageik, and it evidently erupted from the East Summit vent. The deposit is variously overlain by 1912 fallout directly, by 10–25 cm of pre-1912 aeolian silt, or locally by 10–50 cm of clayey, orange-brown, diamict, rich in rounded clasts of fresh and hydrothermally altered andesite that probably avalanched from the brow of the East Summit.

Correlation of postglacial ashfall layers intercalated with peat, incipient soils, and ubiquitous aeolian silt mantling the lowlands around the Katmai cluster is an ongoing project that will be published separately. At least eight tephras age-bracketed between 500 and 8,500 ^{14}C years B.P. are locally derived from centers in the Katmai cluster. All represent explosive ejecta that are dacitic or andesitic in bulk composition. A few probably issued from Mageik's East Summit, and at least one tephra is compositionally similar to the Holocene dacite lava flows (fig. 2) of Mount Martin.

Spurious Eruption Reports

Mount Mageik's conspicuous fumarolic plume, like that of adjacent Mount Martin (fig. 3), has animated many spurious eruption reports. Not a single one of the 20th century tephra eruptions of Mageik listed in "Volcanoes of the World (Simkin and Siebert, 1994) seems plausible. Configuration of the crater has not changed since it was first photographed in 1923 (fig. 8); there are no juvenile ejecta in the crater or around its rim (except a scattering of 1912 pumice lapilli); and the only late Holocene fall deposits on or near the lower flanks of Mageik are the Novarupta pumice falls of 1912 and the black Trident ash of 1953–74.

In particular, Jaggar (1927) repeated a fisherman's story reported in Seattle and Tacoma newspapers—in August 1927 "we noticed a gigantic puff at the top of Mageik" and that soon "it began to rain pumice stone" on their boat in Shelikof Strait "50 miles off the Alaska Peninsula." Although fumarolic "puffs" are common, there is no evidence of a post-1912 Plinian pumice-fall deposit anywhere between Mount Mageik and Shelikof Strait (fig. 1). The report also mentioned fine white ash falling on the decks. Fine white ashfall is still produced occasionally today during spells of dry summer weather when windstorms loft ash from the barren surface of the Valley of Ten Thousand Smokes to altitudes of many kilometers.

The supposed eruption of Mount Mageik listed for 1936 appears to be based wholly on a romantic travel book (Hutchison, 1937) that mentions a brief call by the S.S. *Starr* at Halibut Bay on the southwest corner of Kodiak Island, 95 km south of Mageik. Although the writer did not land, the captain "brought back some interesting specimens of pumice stone with which the waters of the harbour were sprinkled as well as the shore. It had been vomited from the crater of the giant Mageik... on the 4th and 5th of July, a week previous to our visit." Commerce, tourism, and patriotism, like literature, commonly assert their artistic license. The floating pumice was, of course, that of 1912, which lines the beaches of Shelikof Strait to this day. On a trip to Katmai Bay in 1934, Hubbard (1935, p. 208) had witnessed the 1912 pumice floating in Shelikof Strait "in irregular lines many miles long," remobilized from the shorelines by storms and tides. Along with the fumarolic plumes, the far-flung Plinian pumice of 1912 will probably continue to inspire imaginative eruption reports well into the 21st century, as it has during much of the 20th.

Debris Avalanches from Mount Mageik

Holocene debris avalanches from three different sites on the south slopes of Mount Mageik devastated the forks of Martin Creek (fig. 2). The oldest and largest broke loose from the strongly acid-altered southwest face of the Southwest Summit and flowed down the west fork for at least 16 km. It no doubt further spread out onto the floodplain of Katmai River (fig. 1) but has since been stripped there. Orange-brown, yellow, white, and clay-rich like its headwall source rocks, this unit was far more mobile than the other two. At least 70 m thick proximally (where partly reworked by Neoglacial ice), the deposit is marked medially by an abundance of subdued hummocks 5–15 m high, but distally it spread into a low-relief sheet 5–10 m thick. Being 0.8 to 1.4 km wide along its entire length, the deposit today covers at least 15 km^2. If it averages 50 m thick proximally, 15 m medially, and 5 m distally, its volume is about 0.35 km^3. Although no datable organic material was found, the unglaciated deposit fills a glacial valley and is certainly Holocene, most likely early Holocene judging from the subdued morphology of its hummocky surface.

The smallest of the three debris-avalanche deposits came down the east fork of Martin Creek, covers an area of about 2.7 km^2, and is 15–25 m thick distally at the junction of the forks (fig. 2). Intermediate in age relative to the other two, it consists almost entirely of fresh andesite (massive to scoriaceous and apparently monolithologic), contains abundant angular blocks as large as 5 m, and supports hummocks 5–15 m high. Hummocky to its terminus, it ends abruptly where it meets the older avalanche deposit (fig. 2). We estimate its volume to be about 0.025 km^3, but its source and proximal path are covered by Holocene lava flows from the East Summit (fig. 2). Analysis of a large distal block yields 60.0 percent SiO_2 and 1.49 percent K_2O (table 1; sample K-2548), consistent with derivation from East Summit lavas but not unequivocal (fig. 7). Local reddening of the gritty matrix suggests (but does not prove) hot avalanching such as commonly takes place during extrusion of a viscous lava on a steep slope. Based on tephra layers as old as 5,500 ^{14}C years B.P. that are intercalated within 70–110 cm of aeolian silt that overlies the avalanche deposit, we estimate its emplacement age to be middle Holocene.

The youngest of the three was emplaced in Martin Creek on 6 June 1912 during the eruption at Novarupta, presumably triggered by the seismicity accompanying caldera collapse at Mount Katmai (Hildreth, 1991). The deposit is overlain by most of the 1912 fallout but not by the earliest layers (Fierstein and Hildreth, 1992). Described in detail by Griggs (1920, 1922), who called it "the Mageik Landslide", the 1912 avalanche deposit extends 6 km southeast of its headwall and overruns the medial part of the more subdued larger deposit (fig. 2). Consisting predominantly of angular blocks of fresh dacite, it broke loose from a steep face glacially carved into a stack of dacite lava flows that make up the southeast planeze of the Southwest Summit edifice, leaving behind a 120-m-high scarp with a rim at the 3,000-ft level . The deposit has millions of angular blocks larger than 1 m (mostly dacite, plus sparse basement sandstone), contains dacite slabs as long as 20 m, and supports hummocks as high as 20 m. It locally left superelevated trimlines and ponded drainages along its abrupt margins. About 800 m wide proximally, the deposit spreads out to 1.5 km medially and covers about 6 km^2. Griggs (1920) estimated its area as more than 10 km^2, but this included parts of the subjacent older deposit. Although thickness (5–30 m) is hard to average, the volume is probably in the range 0.05–0.1 km^3.

Much smaller avalanches of altered debris from the steep east face of the East Summit have probably been common, but deposits are obscured by ice, snow, and 1912 fallout. The most obvious sources on Mount Mageik (fig. 2) for future avalanches are the altered headwall of the west fork of Martin Creek, the northwest face of the ridge west of that headwall, lava-flow dipslopes of the northwest buttress, and the steep fragmental cones of the East and North Summits.

Geochronology

K-Ar ages were measured for whole-rock samples of andesitic lava flows that rest on Jurassic basement rocks at the bottom of the Mageik volcanic pile in four different drainages (fig. 2; table 2). Two erupted at the Southwest Summit, one at the Central Summit, and one at the North Summit. Sample selection criteria and analytical methods were described by Hildreth and Lanphere (1994). Seeking high-precision age determinations of late Pleistocene rocks, we employed the multiple-collector mass spectrometer (Stacey and others, 1981) at the U.S. Geological Survey in Menlo Park.

In uppermost Alagogshak Creek at the southwestern limit of Mageik lavas, the basal lava flow of the stack of Southwest Summit lavas that forms the south-trending ridge separating Martin and Alagogshak Creeks yields an age of 89±8 ka. An analytically indistinguishable age of 93f8 ka was determined for the basal lava flow along the eastern wall of Martin Creek at the bottom of the stack of flows that forms the main planeze dipping SSE. away from the Southwest Summit vent. Farther northeast, in a glaciated bowl at the head of the north fork of Martin Creek, the basal lava flow from the Central Summit yields an age of 71±11 ka, confirming our stratigraphic inference that the Central Summit pile postdates the Southwest Summit. A thick lava flow from the North Summit vent forms a 150-m cliff that commands West Mageik Lake and rests on Jurassic strata a few hundred meters south of the lake. Stratigraphically one of the oldest products of the North Summit edifice, this lava yielded an age of 59±11 ka. No attempt was made to date by K-Ar any lavas from the East Summit edifice, which is entirely postglacial.

Eruptive Volumes

Mount Mageik has suffered glacial erosion throughout its existence, the present climate being globally the mildest during its approximately 90-k.y. lifetime. The rapid glacial erosion promoted by Pleistocene expansions of glacial ice that recurrently blanketed much of the Alaska Peninsula (Riehle and Detterman, 1993) makes it difficult to estimate the volumes actually erupted.

At 2,165 m, the true summit today rises 1,500 m above the adjacent Valley of Ten Thousand Smokes and 1,300–1,600 m above the southerly base of the volcano. On the west, however, the ridge of Jurassic basement rocks that forms the saddle between Mageik and Martin is as high as 1,555 m, only 610 m lower than the summit. Nonetheless, northeastward beneath Mount Mageik this basement ridge diminishes sharply in elevation, failing to crop out at 800-m-high Katmai Pass, 1,365 m lower than the summit. Katmai Pass and the adjacent area now beneath the East Mageik edifice were the lowest local crossing of the Alaska Peninsula rangecrest long before construction of the Mageik edifice.

Taking into account the constraints provided by the basement elevations, the modem topography, and the (poorly exposed) overlapping relationships among Mageik's four component edifices, we estimate their present-day volumes as follows: Southwest Summit 9–10 km^3, Central Summit 4 km^3, North Summit 1.5 km^3, and East Summit 5 km^3, yielding a total of about 20 km^3. Attempting to reconstruct (pre-erosion) eruptive volumes of each edifice, we tenuously estimate that more than 40 percent of the Southwest Summit has been removed by erosion, more than 30 percent of the Central Summit, at least 20 percent of the North Summit, and 5–10 percent of the East Summit. Such estimates neglect any intracanyon lavas that might have flowed far from the edifice. Using these rough estimates, then, we calculate original edifice volumes of 15–17, 6, 2, and 5.5 km^3, respectively, yielding a total of about 30 km^3 erupted. The late Pleistocene Lethe Assemblage (discussed below) along with a possibly correlative regional ashfall (Reger and others, 1996), if from Mageik, could add an additional 1 km^3 or more to the total. No other potentially Mageik-derived tephra layer identified in the region is likely to add more than 0.1 km^3. For a 90-k.y. lifetime, an eruptive volume of 30 km^3 yields an average eruption rate of 0.33 km^3 per 1,000 years. This lies in the range typical of long-term average rates for well-studied arc stratovolcanoes (0.1–1 km^3/k.y.) but far below the rates of peak episodes (>5 km^3/k.y.) (Hildreth and Lanphere, 1994). Such large volumetric eruption rates may well have characterized activity at Mount Mageik during construction of each of its component edifices.

Mount Martin

A few kilometers southwest of Mageik (figs. 1–3), Mount Martin consists of a small fragmental cone and a staircase of 10 overlapping coulees of blocky dacite, each 75–100 m thick, that descends northwestward for 10 km. Although its summit exceeds 1,860 m in elevation, the 2-km-wide cone itself has local relief of only 500 m, owing to its construction upon a high ridge of Jurassic basement rocks. The extremely asymmetrical distribution of lava flows with respect to the summit vent (fig. 2) resembles those of Southwest Trident and the North and East Summits of Mageik. Of the 7-km^3 present-day volume we estimate for Mount Martin, the cone represents only 5 percent and the 31-km^2 lava-flow field about 95 percent. Scoriaceous and massive glassy (phreatomagmatically ejected) blocks of the cone are andesitic (58.5–61 percent SiO_2), whereas the sequence of coulees is largely dacitic (62.5–64.2 percent SiO_2). A widespread fallout deposit is compositionally similar to the coulees. Despite a cone-encircling collar of active glaciers, erosion of the cone and coulees is almost insignificant, indicating that Mount Martin is a Holocene volcano in its entirety. Glaciated lavas adjacent to its west flank are chemically and stratigraphically distinguished as flows from Alagogshak volcano (Hildreth and others, 1999). The cone of Mount Martin is marked by a persistent steam plume derived from as many as 20 fumaroles that are precipitating sulfur in the talus northwest of a shallow lake on the floor of its 300-m-wide crater. Like the plume of Mount Mageik, the larger plume of Mount Martin is the basis of many spurious eruption reports. A USGS overfight in 1998 detected significant concentrations of CO_2 and SO_2 in the Martin plume (M. Doukas, Cascades Volcano Observatory, oral commun., 1999).

Composition Of Eruptive Products

Many separate lava flows and a few near-vent scoria bombs were collected on Mount Mageik, and about 69 samples were analysed by X-ray fluorescence spectroscopy. Results are given in table 1 and illustrated in figure 7. Virtually all samples are plagioclase-rich two-pyroxene andesites and dacites, all of which also carry Fe-Ti oxides. Sparse olivine occurs in some of the most mafic rocks, and rare amphibole is present in one or two of the most silicic. Glass-bearing blebs and clots of plagioclase-pyroxene microdiorite are present in many of the samples, but, in contrast to neighboring Trident volcano, ordinary 1- to 10-cm mafic magmatic inclusions are relatively uncommon in Mageik lavas.

All 69 samples plot in the medium-K field of figure 7, and all fall in the calcalkaline field on a conventional FeO*/MgO vs. SiO_2 diagram (not shown). Alkali-lime intersections at 63–64 percent SiO_2 define calcic suites (Peacock, 1931) for all components of Mount Mageik, as previously also determined for Novarupta (Hildreth, 1983) and for nearby Martin and Alagogshak volcanoes (Hildreth and others, 1999). SiO_2 ranges from 57.4 to 67.9 percent, the entire range being represented in products of the Southwest Summit alone (fig. 7). The lone mafic magmatic inclusion analysed gave 56.3 percent SiO_2. The range in SiO_2 is comparable to those of suites from Trident, Martin, and Alagogshak but much more restricted than those of Novarupta and Mount Katmai (Hildreth, 1987; Hildreth and others, 1999; Hildreth and Fierstein, 2000). Mageik products form a typical low-Ti arc suite, containing only 0.51–0.86 percent TiO_2; the mafic inclusion has 0.92 percent. Contents of Al_2O_3 are ordinary for arc suites, ranging from 15.1 to 17.4 percent; the mafic inclusion has 17.7 percent. Relatively primitive material has not erupted here, all samples having less than 4.4 percent MgO. The lone Sr-isotope determination for a Mageik lava, a Holocene dacite from the East Summit, yielded a $^{87}Sr/^{86}Sr$ ratio of 0.70366, at the upper end of the range (0.70335–0.70366) of relatively sparse data for nonrhyolitic products of the Katmai cluster (Hildreth, 1987).

Figure 7 illustrates the limited compositional ranges of the younger centers compared to that of the larger and longer lived Southwest Summit edifice. The North Summit (60.5–64.2 percent SiO_2) and East Summit (60.0–64.1 percent SiO_2) have the shortest arrays, whereas the Central Summit array (57.8–66.0 percent SiO_2) is similar to those of Mount Martin (58.9–64.2 percent SiO_2) and Southwest Trident (56.9–64.8 percent SiO_2). The contrast between the scattered arrays of all four Mageik centers and the narrowly linear trends for Holocene Mount Martin and 1953–74 Southwest Trident suggests more complex magmatic histories, and thus implicitly longer eruptive histories, for the Mageik centers.

Compositionally most complex is the Southwest Summit suite, which extends in SiO_2 from 56.3 to 67.9 percent and, for example, among its dacites alone, from 1.65 to 2.23 percent K_2O and from 128 to 182 ppm Zr (fig. 7). The least potassic sample (0.93 percent K_2O) is from the highest exposure on the Southwest Summit, a lava ledge at the southeast edge of the summit-mantling icecap at the 6,700-ft level; it is thus likely to be among the youngest products erupted from the Southwest

Summit vent. The five low-Zr dacites that plot apart from other Mageik samples on the Zr-SiO_2 panel of figure 7 are all lavas from the stack of flows at the 2,500- to 3,300-ft level of the southeast planeze, directly downslope from the Southwest Summit (fig. 2); they apparently reflect enhanced effects of zircon fractionation from the magmas or greater retention of zircon in the residues of melts that contributed to the magmas. The stratigraphically oldest lava flows of the Southwest Summit edifice erupted at about 90 ka (table 2), but we have no evidence to estimate the age of its youngest activity. Its wider and more severe hydrothermal alteration, its deeper glacial incision, its larger eruptive volume, and its greater compositional heterogeneity all point to an eruptive lifetime much longer than those of its companion edifices. The magma system beneath the Southwest Summit probably produced quasi-independent batches that evolved and erupted in several episodes over an interval that might well have exceeded 20 k.y.

The Falling Mountain (FM) and Mount Cerberus (MC) fields (fig. 7) for the two big dacite lava domes at Katmai Pass (fig. 2) are representative of the compositionally allied products of pre-Holocene components of Trident volcano, which are generally deficient in K_2O and Zr relative to eruptive products of Mount Mageik and the rest of the Katmai cluster (Hildreth and Fierstein, 2000), including Novarupta, Mount Katmai, and Southwest (New) Trident itself. The dacite domes are thus unrelated to the Mageik (and Novarupta) plumbing systems. Although they are similar in age to the Southwest Summit edifice (Hildreth and Fierstein, 2000), the domes are unequivocally older than the nearby North and East Summit edifices of Mount Mageik.

Lethe Assemblage

Extensive remnants of a late Pleistocene deposit rich in dacite pumice are exposed along the walls of lower Windy Creek and River Lethe (fig. 2) in the Valley of Ten Thousand Smokes, about 15 km northwest of Mount Mageik. The pumice is compositionally similar (though not identical) to younger Mageik lavas (fig. 7) as well as to a few of the younger eruptive units from Mount Katmai (Hildreth and Fierstein, 2000). First described by Pinney and Beget (1991), the deposit consists of fines-poor sandy debris flows rich in rounded dacite pumice clasts (as large as 40 cm) interstratified with massive emplacement units of coarse (phenocryst) sand, evidently transported by hyperconcentrated streamflow. At least 10 pumiceous debris-flow units, 0.1 to 4 m thick, have gradational contacts with (and a coarse sandy matrix continuous with) the interstratified beds of massive sand, which are as thick as 10 m! The sand beds consist predominantly of plagioclase and pyroxene crystals (like those in the pumice); they display ubiquitous water-escape (dish) structures and carry sparse dispersed lithics (mostly picked up during flowage) and abundant dispersed granules and small lapilli of dacite pumice. For the whole assemblage, the greatest thickness observed is 25–30 m on the walls of the river gorges where there is no basal exposure. Although many of the pumice-rich flow units are lenticular, there is no significant unconformity or intercalation of normal fluvial gravel within the assemblage. All the flow units thus appear to have been deposited rapidly in response to a single eruptive event.

The assemblage is widely overlain by several meters of till, and, wherever its base is exposed, it also rests directly upon till. A few of the debris flows spilled northwestward across a low marshy divide into upper Margot Creek, leaving behind a (now wind-deflated) veneer of dacite pumice clasts atop hilly till deposits bordering the marsh. Most of the assemblage, however, appears to have ponded in a shallow 3-km^2 paleodepression that may have held a shallow periglacial lake. What else could have trapped and rapidly dumped 30 m of poorly sorted fast-moving debris? As no equivalent ignimbrite is recognized anywhere in the district, we envisage an eruption scenario wherein a sub-Plinian pumice shower was rapidly remobilized by snowmelt into slurries that poured off the glaciated source edifice and down an ice-filled paleovalley during a nonmaximal glacial stage when valley glaciers were extensive but parts of the surrounding lowlands were ice-free. As documented for the Novarupta dacite fall deposits of 1912 (Fierstein and Hildreth, 1992), much of the primary medial fallout of the phenocryst-rich dacite would have been crystal ash, accounting for the volumetric dominance of the sand facies. In addition to segregation during flow, either pulsatory eruption or repeated remobilization of coarse proximal pumice from slopes of the ice-clad volcano would account for the recurrent intercalation of pumiceous debris flows throughout the thick deposit of massive sand.

The present-day valleys leading from Mount Mageik and Mount Katmai to the Lethe Assemblage provide no additional exposures of such deposits, as virtually all likely areas are covered by the 1912 ignimbrite (fig. 2). Likewise, we have searched for but not found remnants of any correlative deposits south of the volcanic axis, so the physical evidence linking the deposit to Mount Mageik is tenuous. The phenocryst assemblage in the pumice (plagioclase, hypersthene, augite, and Fe-Ti oxides), though the same as in the Mageik lavas, is so commonplace that it is not diagnostic. Figure 7, however, illlustrates that the dacite pumice in the Lethe Assemblage is compositionally close to the evolved end of the range identified for the products of Mageik's East and North Summits. Figure 7 shows furthermore that the Lethe pumice is distinguishable from eruptive products of Mount Martin and from the late Pleistocene lava domes, Mount Cerberus and Falling Mountain, at the head of the Valley of Ten Thousand Smokes (fig. 2). The 1953–74 products of Southwest Trident are only slightly less potassic than the Lethe pumice, but all prehistoric products of the Trident volcanic group are similar to the domes in being significantly less potassic and much poorer in Zr (fig. 7). Agglutinated dacite fall units high on Mount Katmai (Hildreth and Fierstein, 2000) represent the only potential alternative to a Mageik source recognized in the Katmai cluster. The field and compositional evidence now in hand weigh slightly in favor of Mount Katmai rather than Mount Mageik as the source of the Lethe pumice, but the choice remains unresolved.

An ashfall layer widespread in late Pleistocene deposits on the Kenai Peninsula 260–380 km northeast of the Katmai cluster has been correlated with the Lethe Assemblage by Reger and others (1996) on the basis of microprobe determinations of glass compositions. From stratigraphic relationships in the Kenai Lowland, they inferred an age for the tephra slightly younger than 16,000 ^{14}C years B.P. For the Lethe Assemblage itself, we have obtained an older limiting age of 18,980±90 ^{14}C years B.P. for a rip-up clast of silty soil enclosed in the massive sand deposit near Windy Creek. Pinney and Beget (1991) published an upper limiting age of 12,640±100 ^{14}C years B.P. for "organic silt" nearby, which they inferred from their interpretation of the local glacial deposits to be younger than the Lethe Assemblage. If Reger and others (1996) are correct in their correlation, the far-flung eruption was certainly Plinian, even though no equivalent proximal pumice-fall deposit is known to have survived in the Mageik-Katmai region.

Evidence for Present-Day Magma Storage

Gravity and seismic data that identify a low-density low-velocity region centered near Kstmai Pass are summarized by Ward and others (1991). A southeasterly gravity traverse that crossed the volcanic axis by way of Katmai Pass showed cross-axial width of the anomalous region to be about 15 km, but the data are insufficient to know how far it extends along the axis. Of the several seismic stations in the Katmai array, only the one in Katmai Pass (central to the gravity anomaly) consistently showed travel-time delays for deep local and regional earthquakes. The delays require great thickness for the low-velocity domain, which may well extend deeper than 20 km (Ward and others, 1991), thus involving most or all of the crust. Their seismic data also indicated significant attenuation of P- and S-waves, but they found no screening of S-waves (in contrast to seismic reconnaissance studies 25 years earlier; Matumoto, 1970). To explain the data, they invoked present-day crustal magma storage, favoring scattered small magma bodies rather than a large chamber. Recent and ongoing analysis by P-wave tomography has identified a moderately low-velocity anomaly (4.4 km/s), shallower than 3 km, beneath the same area in Katmai Pass (Jolly and others, 1998).

The pattern of seismicity recognized by Ward and others (1991) has persisted during the 1990's, as the Alaska Volcano Observatory continues to locate 40–130 earthquakes each month along and near the volcanic axis of the Katmai cluster. Most of the earthquakes located fall into four persistent clusters: (1) beneath the volcanic line from Mount Martin to Southwest Mageik; (2) beneath Katmai Pass and the northwest slope of the Trident group; (3) beneath Mount Katmai, especially its northern slopes; and (4) east of Mount Griggs (figs. 1, 2). Nearly all the earthquakes are smaller than magnitude 2.5, and only a few events have been in the range 3.0–4.5. Many are shallower than 5 krn, and nearly all are shallower than 10 km. The dense shallow seismicity seems inconsistent with present-day upper-crustal storage of voluminous magma and is more likely to reflect flow of gases and fluids, attendant volume changes, and hydraulic microfracturing in hydrothermal systems, along with slip-threshold reduction in geochemically weakened rocks. If magma bodies other than small distributed pods and dikes are now present in the evidently brittle top 10 km of the crust, they are more likely to underlie the gaps between the seismic clusters. In the area specifically addressed in the present paper, if shallow chambers exist at all, they would thus lie beneath the East Summit of Mageik (fig. 2) or between Trident and Mount Katmai (fig. 1). Beneath the seismic clusters themselves, however, any *large* magma chambers today are probably deeper than 10 km—i.e., below the brittle zone.

Vigorous fumaroles in the Katmai cluster are good evidence that magma stored somewhere below is actively degassing, though this provides little or no control on depths, distribution, volume, or degree of crystallization of such magma. Superheated fumaroles in the crater of Mount Mageik (fig. 8) and high on Mount Griggs are steam dominated but rich in CO_2, SO_2, and H_2S and have magmatic He-isotope ratios 7–8 times the atmospheric value (R.B. Symonds, oral commun., 1998). Boiling-temperature fumaroles on the southeast flank of Trident have similarly magmatic signatures and have discharged vigorously since before 1916 when first recorded (photo on p. 99 of Griggs, 1922). Though never yet sampled directly, many fumarolic jets in the crater of Mount Martin are precipitating abundant sulfur, are probably superheated, and combine to discharge the biggest and (olfactorily) H_2S-richest plume in the Katmai district. A 1998 USGS flight through the Martin plume detected strong concentrations of SO_2 and CO_2 (M. Doukas, oral commun., 1999). Atop the Southwest Trident cone (fig. 6), numerous fumaroles must have been superheated during the 1953–74 eruptive episode and were still depositing sulfur and remained at or above the boiling point in 1979, but they have since declined both thermally and in H_2S output.

The vigorous fumaroles of Martin, Mageik, Trident, and Griggs have apparently been continuously active with little change in style or configuration since they were first photographed in the period 1913–19 (Griggs, 1922), but not one of these volcanoes produced any ejecta in 1912 or has erupted at any time since. In contrast, the fumaroles at all three volcanic vents that did erupt in the 20th century (Southwest Trident, Novarupta, and Mount Katmai) have been in decline. Magma appears to be distributed widely and discretely beneath the Katmai cluster. Depletion or exhaustion of local magma bodies by eruption may have little impact on coexisting independent components of the crustal magma storage system that underlies the volcanic line.

Glacier Retreat

Although about 30 percent of the surface area of Mount Mageik is covered by ice, the ice volume has historically been shrinking substantially. Three north-flowing glaciers descend the north flank of Mount Mageik (figs. 2, 3). In 1912, two of them still terminated on what is now the floor of the Valley of Ten Thousand Smokes, where the 1912 ignimbrite banked against them (photo on p. 264 of Griggs, 1922). By 1951 (the year of our first set of aerial photographs), recession of their termini by 200 m and 400 m, respectively, had created the ignimbrite-surrounded depressions occupied by West and East Mageik Lakes (fig. 2). By 1987, the year of our latest aerial photographs, total post-1912 recession of the termini was 900 m for the western glacier and 700 m for the eastern. The terminus of the third glacier lying between them, just short of the valley floor in 1912, receded about 500 m between 1951 and 1987.

The terminus of the northwest-flowing Angle Creek glacier, fed from the icefield west of Mount Mageik, receded about 350 m between 1951 and 1987 and about 1.2 km from its Neoglacial (Little Ice Age?) maximum, which postdated emplacement of the adjacent dacite coulees from Mount Martin (fig. 2) at about 4 ka.

On the southeast flank of Mount Mageik, three southeast-flowing parallel glaciers (fig. 2) have all retreated substantially. The easternmost, which remarkably had advanced along the central trough of a Holocene lava flow, confined between its high levees, retreated 1.5 km between 1951 and 1987. During the same interval, the middle one retreated 450 m. By 1987, the western one had retreated about 1 km since 1951 and (judging by the distribution of till and 1912 fallout) about 1.7 km from its probable 1912 terminus. Termini of a few lesser glaciers that flow eastward toward Katmai Pass (fig. 2) have retreated 600–800 m since 1951 and 1.2–1.7 km from their Neoglacial (Little Ice Age?) maxima. Likewise, the terminus of the small axial glacier in upper Martin Creek, fed from the cirque below Mageik's Southwest Summit, has retreated 1.1 km since 1951.

Pronounced shrinkage of the glacial cover on steep parts of the Mageik edifice elevates the likelihood of failure of oversteepened glacial deposits, cliffy stacks of rubbly lava flows, and hydrothermally altered parts of the volcano. By lifting the deformable ice envelope sealing such unstable materials, the retreat of glaciers can actually increase the hazards of debris avalanches and derivative downstream debris flows.

The generality and magnitude of 20th century retreat of glaciers on Mount Mageik are noteworthy and probably reflect climatic controls on the ice budget. It is unlikely that the thermal budget of the volcano is a factor, as neither warm springs nor hot spots have been observed on Mageik, other than in the fumarolically active crater, which has undergone no major changes historically. Nor is the 1912 fallout likely to be a factor; it thinned across Mount Mageik from 50 cm at the northeast to about 5 cm at the southwest, and nearly all of it was removed from the glaciers within a few years. In contrast, only 4–11 km northeast of Mount Mageik, in the principal fallout sector downwind from Novarupta, the Knife Creek Glaciers received (and remain covered by) a thick blanket of 1912 fallout (Fierstein and Hildreth, 1992), yet the termini of three of the five Knife Creek Glaciers (Glaciers 1, 3, and 4 of Hildreth, 1987, 1991) actually advanced about 100 m between 1951 and 1987, edging out over the adjacent 1912 ignimbrite. The buff pumice mantle may actually retard glacial ablation.

Conclusions

The principal volcano hazards in this wilderness region are to aviation, fish and wildlife resources, and backcountry travellers. Because so much magma was withdrawn so recently from the Novarupta-Katmai storage system in 1912 and from beneath Trident in 1953–60, it may be that Mount Mageik and Mount Martin have become the local centers most likely to erupt next. Mageik's later history of erupting 0.5–5 km^3 batches of phenocryst-rich intermediate magma in discrete episodes, similar to that of Southwest Trident in 1953–74, suggests distributed crustal magma storage rather than a large zoned reservoir capable of caldera-forming eruption. The abundance of Holocene dacite nonetheless highlights the likelihood of explosive eruptions of intermediate magnitude. Phreatomagmatic or vulcanian ash clouds or even sub-Plinian to Plinian pumice eruptions are possible and could reach altitudes of 6–15 km (20,000 to 50,000 ft). The icecap, crater lakes, and year-round snow cover raise the likelihood of phreatic and phreatomagmatic eruptions and generation of debris flows that could have impacts on Shelikof Strait and the Naknek Lake system.

Acknowledgments

Michelle Coombs, Anita Grunder, Dave Johnston, and Dave Tucker helped with the fieldwork, Tracey Felger and Jan Cecil with map preparation, Forrest McFarland and James Saburomaru with K-Ar dating, and John Paskievitch with sometimes challenging field logistics. Janis Meldrum of the National Park Service provided prints of figures 5 and 8A. For encouraging this work, we are especially grateful to Terry Keith at the helm of the Alaska Volcano Observatory. Helpful review comments by Jake Lowenstern, Bob Symonds, Seth Moran, and Bea Ritchie improved the manuscript. Recalling our introductory epigraph, we note that blue-eyed Mageik made the first ascent of Shishaldin volcano and the first winter ascent of Mount Katmai (in both instances barefoot), providing an example of tenacity, endurance, doggedness, foolhardiness, and footwork motivational to this project.

References Cited

Bacon, C.R., and Druitt, T.H., 1988, Compositional evolution of the zoned calcalkaline magma chamber of Mount Mazama, Crater Lake, Oregon: Contributions to Mineralogy and Petrology, v. 98, p. 224–256.

Detterman, R.L., Case, J.E., Miller, J.W., Wilson, F.H., and Yount, M.E., 1996, Stratigraphic framework of the Alaska Peninsula: U.S. Geological Survey Bulletin 1969-A, 74 p.

Fenner, C.N., 1930, Mount Katmai and Mount Mageik: Zeitschrift für Vulkanologie, Band 13, p. 1–24.

Fierstein, J., and Hildreth, W., 1992, The Plinian eruptions of 1912 at Novarupta, Katmai National Park, Alaska: Bulletin of Volcanology, v. 54, p. 646–684.

Griggs, R.F., 1920, The great Mageik landslide: Ohio Journal of Science, v. 20, no. 8, p. 325–354.

Griggs, R.F., 1922, The Valley of Ten Thousand Smokes: Washington, D.C., National Geographic Society, 340 p.

Hildreth, W., 1983, The compositionally zoned eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska: Journal of Volcanology and Geothermal Research, v. 18, p. 1–56.

Hildreth, W., 1987, New perspectives on the eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska: Bulletin of Volcanology, v. 49, p. 680–693.

Hildreth, W., 1991, The timing of caldera collapse at Mount Katmai in response to magma withdrawal toward Novarupta: Geophysical Research Letters, v. 18, p. 1541–1544.

Hildreth, W., and Fierstein, J., in press, The Katmai volcanic cluster and the great eruption of 1912: Geological Society of America Bulletin.

Hildreth, W., Fierstein, J., Lanphere, M.A., and Siems, D.F., 1999, Alagogshak volcano: A Pleistocene andesite-dacite stratovolcano in Katmai National Park, *in* Kelley, K.D., ed., Geologic Studies in Alaska by the U.S. Geological Survey, 1997: U.S. Geological Survey Professional Paper 1614, p. 105–113.

Hildreth, W., and Lanphere, M.A., 1994, Potassium-argon geochronology of a basalt-andesite-dacite arc system: The Mount Adams volcanic field, Cascade Range of southern Washington: Geological Society of America Bulletin, v. 106, p. 1413–1429.

Hubbard, B.R., 1932, Mush you malemutes: New York, The America Press, 179 p.

Hubbard, B.R., 1935, Cradle of the storms: New York, Dodd, Mead & Co., 285 p.

Hutchison, I.W., 1937, Stepping stones from Alaska to Asia: London & Glasgow, Blackie & Son, 246 p.

Jaggar, T.A., 1927, Eruption of Mageik in Alaska: The Volcano Letter, no. 147, Hawaiian Volcano Observatory. [Implausible eruption report.]

Jolly, A.D., Moran, S.C., and McNutt, S.R., 1998, P-wave tomography at Katmai National Park, Alaska Peninsula, Alaska: Eos, Transactions American Geophysical Union, v. 79, no. 46, p. F621.

Martin, G.C., 1913, The recent eruption of Katmai volcano in Alaska: National Geographic Magazine, v. 24, p. 131–181.

Matumoto, T., 1970, Seismic body waves observed in the vicinity of Mount Katmai, Alaska, and evidence for the existence of molten chambers: Geological Society of America Bulletin, v. 82, p. 2905–2920.

Peacock, M.A., 1931, Classification of igneous rock series: Journal of Geology, v. 39, p. 54–67.

Pinney, D.S., and Beget, J.E., 1991, Late Pleistocene volcanic deposits near the Valley of Ten Thousand Smokes, Katmai National Park, Alaska, *in* Reger, R.D., ed., Short Notes on Alaskan Geology 1991: Alaska Division of Geological & Geophysical Surveys Professional Report 111, p. 45–53.

Ray, D.K., 1967, Geochemistry and petrology of the Mt. Trident andesites, Katmai National Monument, Alaska: University of Alaska, Fairbanks, Ph.D. thesis, 198 p.

Reger, R.D., Pinney, D.S., Burke, R.M., and Wiltse, M.A., 1996, Catalog and initial analyses of geologic data related to middle to late Quaternary deposits, Cook Inlet region, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigations 95-6, 188 p.

Riehle, J.R., and Detterman, R.L., 1993, Quaternary geologic map of the Mount Katmai quadrangle and adjacent parts of the Naknek and Afognak quadrangles, Alaska: U.S. Geological Survey Map I-2032, scale 1:250,000.

Riehle, J.R., Detterman, R.L., Yount, M.E., and Miller, J.W., 1993, Geologic map of the Mount Katmai quadrangle and adjacent parts of the Naknek and Afognak quadrangles, Alaska: U.S. Geological Survey Map I-2204, scale 1:250,000.

Simkin, T., and Siebert, L., 1994, Volcanoes of the World: Tucson [Arizona], Geoscience Press, 349 p.

Snyder, G.L., 1954, Eruption of Trident volcano, Katmai National Monument, Alaska: U.S. Geological Survey Circular 318, 7 p.

Spurr, J.E., 1900, A reconnaissance in southwestern Alaska in 1898, p. 31–264 *in* Twentieth Annual Report of the U.S. Geological Survey to the Secretary of the Interior, 1898–1899; Part VII, Explorations in Alaska in 1898: Washington, Government Printing Office, 1900.

Stacey, J.S., Sherrill, N.D., Dalrymple, G.B., Lanphere, M.A., and Carpenter, N.V., 1981, A five-collector system for the simultaneous measurement of argon isotope ratios in a static mass spectrometer: International Journal of Mass Spectrometry & Ion Physics, v. 39, p. 167–180.

Ward, P.L., Pitt, A.M., and Endo, E., 1991, Seismic evidence for magma in the vicinity of Mt. Katmai, Alaska: Geophysical Research Letters, v. 18, p. 1537–1540.

Reviewers: J.B. Lowenstern and R.B. Symonds