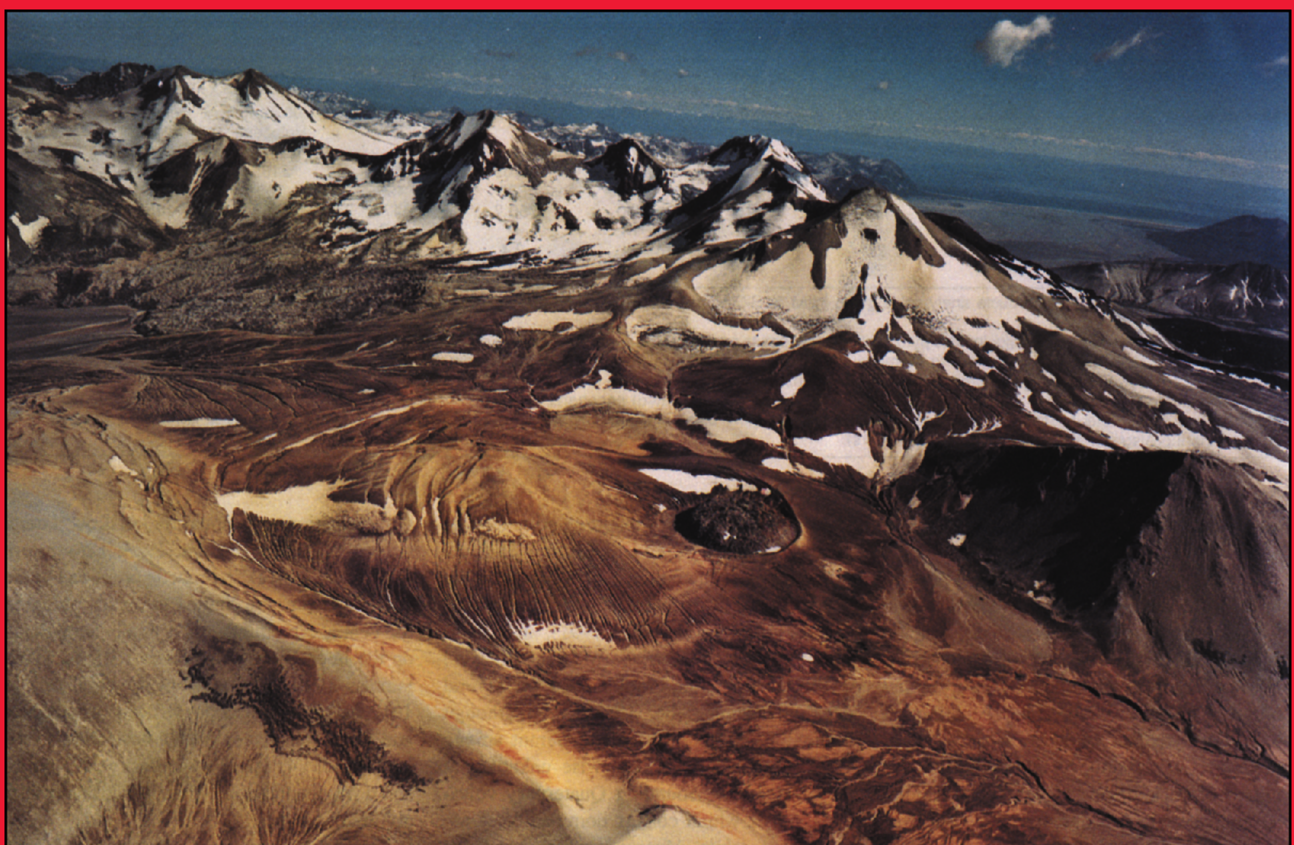
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

# Preliminary Volcano-Hazard Assessment for the Katmai Volcanic Cluster, Alaska

Open-File Report 00–489



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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.

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*The Alaska Volcano Observatory (AVO) was established in 1988 to monitor dangerous volcanoes, issue eruption alerts, assess volcano hazards, and conduct volcano research in Alaska. The cooperating agencies of AVO are the U.S. Geological Survey (USGS), the University of Alaska Fairbanks Geophysical Institute (UAFGI), and the Alaska Division of Geological and Geophysical Surveys (ADGGS). AVO also plays a key role in notification and tracking eruptions on the Kamchatka Peninsula of the Russian Far East as part of a formal working relationship with the Kamchatkan Volcanic Eruptions Response Team.*

*Cover photograph:* Aerial view southeastward over Novarupta toward Trident Volcano and Mount Katmai. The 1912 vent depression extends 2.5 kilometers from Broken Mountain (left foreground) to 400-meter-high scarp of Falling Mountain dacite dome (right foreground). Vent funnel was backfilled by ignimbrite and fallback ejecta, deformed by compaction, and plugged by the 380-meter-wide Novarupta rhyolite dome, which is surrounded by a strongly asymmetrical ejecta ring that consists mostly of fallout from the eruptions of June 7–8, 1912. Katmai caldera (upper left) is centered 10 kilometers east of Novarupta; its inner southeast wall is visible through the saddle adjacent to twin summits on west rim. In central part of the crest of the range are four prominent peaks composing the Trident Volcano group: The eastern two are glaciated remnants of a volcano informally called East Trident; the highest peak is known as Trident I volcano, and the peak known as West Trident is 3 kilometers directly behind Novarupta. Partly hidden behind West Trident is the black cone known as Southwest Trident (erupted 1953–74) and its lava-flow apron in Katmai Pass and Mageik Creek. Low grey lobes in left middle-distance at foot of East Trident and Mount Katmai are The Knife Creek Glaciers, still covered by 1912 ejecta from Novarupta. On the horizon are Katmai Bay, Shelikof Strait, and Kodiak Island. Photograph taken in early 1980s.

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*By* Judy Fierstein and Wes Hildreth

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Anchorage, Alaska

2001

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

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



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## 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 meter ($m^3$) | 35.31 | cubic foot |
| cubic kilometer ($km^3$) | 0.2399 | cubic mile |
| meter per second (m/s) | 3.281 | foot per second |
| meter per second (m/s) | 2.237 | mile per hour |
| 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.

*“Events, by definition, are occurrences that interrupt routine processes and routine procedures; only in a world in which nothing of importance ever happens could the futurologists’ dream come true. Predictions of the future are never anything but projections of present automatic processes and procedures, that is, of occurrences that are likely to come to pass if men do not act and if nothing unexpected happens; every action, for better or worse, and every accident necessarily destroys the whole pattern in whose frame the prediction moves and where it finds its evidence.”*—Hannah Arendt (1969)

# Preliminary Volcano-Hazard Assessment for the Katmai Volcanic Cluster, Alaska

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## SUMMARY OF VOLCANO HAZARDS AT THE KATMAI VOLCANIC CLUSTER

The Katmai cluster is a 25-kilometer-long line of volcanoes along the Alaska Peninsula 450 kilometers southwest of Anchorage, including (from northeast to southwest) Snowy Mountain, Mount Griggs, Mount Katmai, Trident Volcano, Novarupta volcano, Mount Mageik, Mount Martin, and Alagogshak volcano. All but Alagogshak have erupted within the last 6,000 years, often explosively, to produce lava flows, domes, and widespread tephra (ash) deposits. No fewer than 15 eruptive episodes have originated from the Katmai cluster in postglacial time (within the last 10,000 years), each lasting days to tens of years and all of which could have produced ash clouds. Novarupta, a new vent in 1912, produced the world's largest eruption of the 20th century and sent ash around the globe. During that great eruption, nearby Mount Katmai collapsed, destroying its summit peaks and leaving behind a 2.5-kilometer-wide caldera, now filled with a 250-meter-deep lake. More recently, a new vent on Trident produced lava flows and ash plumes for at least 20 years, lasting from 1953 to 1974. Postglacial eruptions, vigorous fumaroles on Griggs, Trident, Mageik, and Martin, and continuing seismicity are good evidence of the potentially active state of the entire Katmai cluster. Any eruption of these volcanoes could affect air traffic, both overhead and on the ground, with severity of the ash-cloud hazard depending on the size of the eruption. An explosive eruption like that of Novarupta, 1912, could affect air traffic all over the North Pacific, Alaska, Canada, and the conterminous United States. Such an eruption might interrupt and inconvenience national and international commerce, perhaps for months, but Alaskan commerce would be temporarily devastated.

The activity status of these volcanoes is monitored by the Alaska Volcano Observatory, which provides the aviation community and general public with an early warning system in case of volcanic unrest. Awareness of the hazards posed by future eruptions is a key factor in minimizing impact. The greatest hazards are summarized below, and more complete explanations are in the text that follows.

### • Ash clouds

*The greatest hazard posed by future eruptions from the Katmai volcanic cluster is airborne volcanic ash, especially because the very busy North Pacific air corridor is directly overhead. Prevailing winds in the Katmai area are most commonly directed northeast, east, and southeast, and would carry ash preferentially toward those sectors, although transport in other directions is possible. The risk to aircraft can be significant, varying with the size of eruption. Smaller eruptions, such as those from Southwest Trident in the 1950s, would intermittently affect aircraft overhead for the duration of the episode of activity (likely tens of years). A large eruption like that of Novarupta in 1912 would have worldwide impact.*

### • Fallout

*Volcanic ash and coarser debris are significant hazards because they can interfere with many aspects of our communities. Ash can collapse buildings, contaminate water supplies, adversely affect birds, fish, and mammals, induce respiratory problems, and interfere with radio communication and anything electronic or motorized. Because volcanoes in the Katmai volcanic cluster are remote from large population centers, moderate and large eruptions, which distribute ash more widely than small ones, pose the highest risk to such centers. In 1912, the 30-cm-thick fallout in Kodiak village, 170 km downwind from Novarupta, immobilized the inhabitants for 3 days, disrupted their lives for months, and affected commercial salmon fishing for years. Once dry, volcanic ash deposits are easily remobilized by wind and can be troublesome long after an eruption is over.*

- **Pyroclastic flows and surges**

  *Large and small pyroclastic flows and pyroclastic surges have been produced from the Katmai volcanic cluster in the past, the largest having been from Mount Katmai and Novarupta, the most recent in 1912 (Novarupta). Local effects are always severe, as the hot avalanches and hurricane-force blasts of volcanic gas and ash destroy everything in their path. Ensuing ashy mudflows could affect downstream waterways on a scale dependent upon the size of the eruption. Regional effects would include mostly subsequent lofting of ash into the atmosphere, interfering with aviation. Even today, nearly a century after the large Novarupta eruption, so much ash from the surface of the Valley of Ten Thousand Smokes is picked up by strong winds (after several dry days) that tourists at Brooks Camp (50 km distant) wonder if an eruption is occurring.*

- **Lava flows and domes**

  *Hazards posed directly by lava flows and domes are confined to the immediate area around the vent where the flows tend to follow topographic lows. However, accompanying explosive blasts and ash eruptions could be a severe hazard for overflying aircraft. Accompanying avalanches of hot rocks, pyroclastic flows and surges, and ballistic showers could also affect a larger area. The eruptive episode that produced the Southwest Trident cone and lava flows spanned 20 years, which may represent a typical duration for many of the eruptive episodes that built the Katmai volcanic cluster.*

- **Lahars and floods**

  *Lahars and floods probably have been common in the history of these volcanoes, but the remoteness of the region mitigates the risk. Because this is now a wilderness area that has no permanent settlements nearby, lahars and floods generally threaten only wildlife, temporary camps, and recreational users of the backcountry. Only catastrophic lahars (like the 1915 breakout of the lake in Katmai Canyon) would impact areas farther than 10–20 km from the volcanoes.*

- **Hydrothermal explosions**

  *All the Katmai volcanoes have active hydrothermal systems, any of which could give rise to hydrothermal explosions. If strictly hydrothermal (no magmatic component to the explosion), the severe-hazard area from the explosions themselves would likely be restricted to within 1 to 2 km of the vent, with low-level steam and ash clouds. However, hot explosions and accompanying seismic unrest would likely trigger lahars, flooding, and(or) debris avalanches (see below), which could travel farther from the summit (or wherever the source).*

- **Debris avalanches, landslides, and rockfalls**

  *Debris avalanches are a significant hazard in areas close to the volcanoes, as are their smaller variants—rockfalls and landslides. Slope stability is critical in assessing the risks of these hazards, since rockfalls are daily events at these volcanoes, even without eruptions. The remoteness of the area restricts the direct risk of these hazards to those who might be downhill (and within 10–20 km) when the avalanches let loose. A broader area could be affected, however, if the debris mixes with rivers to cause flooding or lahars.*

- **Volcanic gases**

  *Concentrations of gases (predominantly water vapor and subordinate carbon dioxide, sulfur dioxide, and hydrogen sulfide from the Katmai cluster) dilute rapidly away from a volcano and seldom pose any threat to those more than a few kilometers from the active vent. The fumarolically active craters of Mounts Mageik and Martin and fumaroles on the south flank of Trident Volcano and west flank of Mount Griggs pose particular hazards because normal present-day emission levels of volcanic gases are high enough in those locations to constitute a real danger of asphyxiation to anyone who manages to get there.*

- **Eruptions through crater lakes**

  *Lakes in the craters of Mounts Martin, Mageik, and Katmai create the potential hazard of lake water and magma violently mixing to generate an explosive phreatomagmatic eruption. Because of the large volume of water in Katmai crater lake, and because there have been repeated silicic and fragmental eruptions from that volcano, an eruption through the Katmai caldera lake is considered both likely and quite dangerous. Although the volume of water in the Martin and Mageik crater lakes is small, it likely would add intensity to any eruption in the crater. The disruption of such acidic lakes also increases the possibility of local acid rainfall and of sending acid-water-rich lahars and debris flows into surrounding rivers.*

**THE ALASKA VOLCANO-HAZARD ASSESSMENT SERIES**

*This report is part of a series of volcano-hazard assessment reports being prepared by the Alaska Volcano Observatory. Geologic data, based on field and laboratory work, form the basis of these assessments. These reports are considered preliminary and are subject to revision as new data become available.*

**SUGGESTIONS FOR READING THIS REPORT**

*Readers who want a brief overview of volcano hazards for the Katmai volcanic cluster can read the summary section and consult plate 1. The remainder of the report provides a more comprehensive treatment of hazards from these volcanoes and assessment of the risks posed by these hazards. Selected terms are defined in a glossary at the end of the report.*

## INTRODUCTION

The world's largest volcanic eruption of the 20th century broke out at Novarupta (fig. 1) in June 1912, filling with hot *ash* what came to be called the Valley of Ten Thousand Smokes and spreading downwind more *fallout* than all other historical Alaskan eruptions combined. Although almost all the *magma* vented at Novarupta, most of it had been stored beneath Mount Katmai 10 km away, which collapsed during the eruption. Airborne ash from the 3-day event blanketed all of southern Alaska, and its gritty fallout was reported as far away as Dawson, Ketchikan, and Puget Sound (fig. 21). Volcanic dust and sulfurous aerosol were detected within days over Wisconsin and Virginia; within 2 weeks over California, Europe, and North Africa; and in latter-day ice cores recently drilled on the Greenland ice cap.

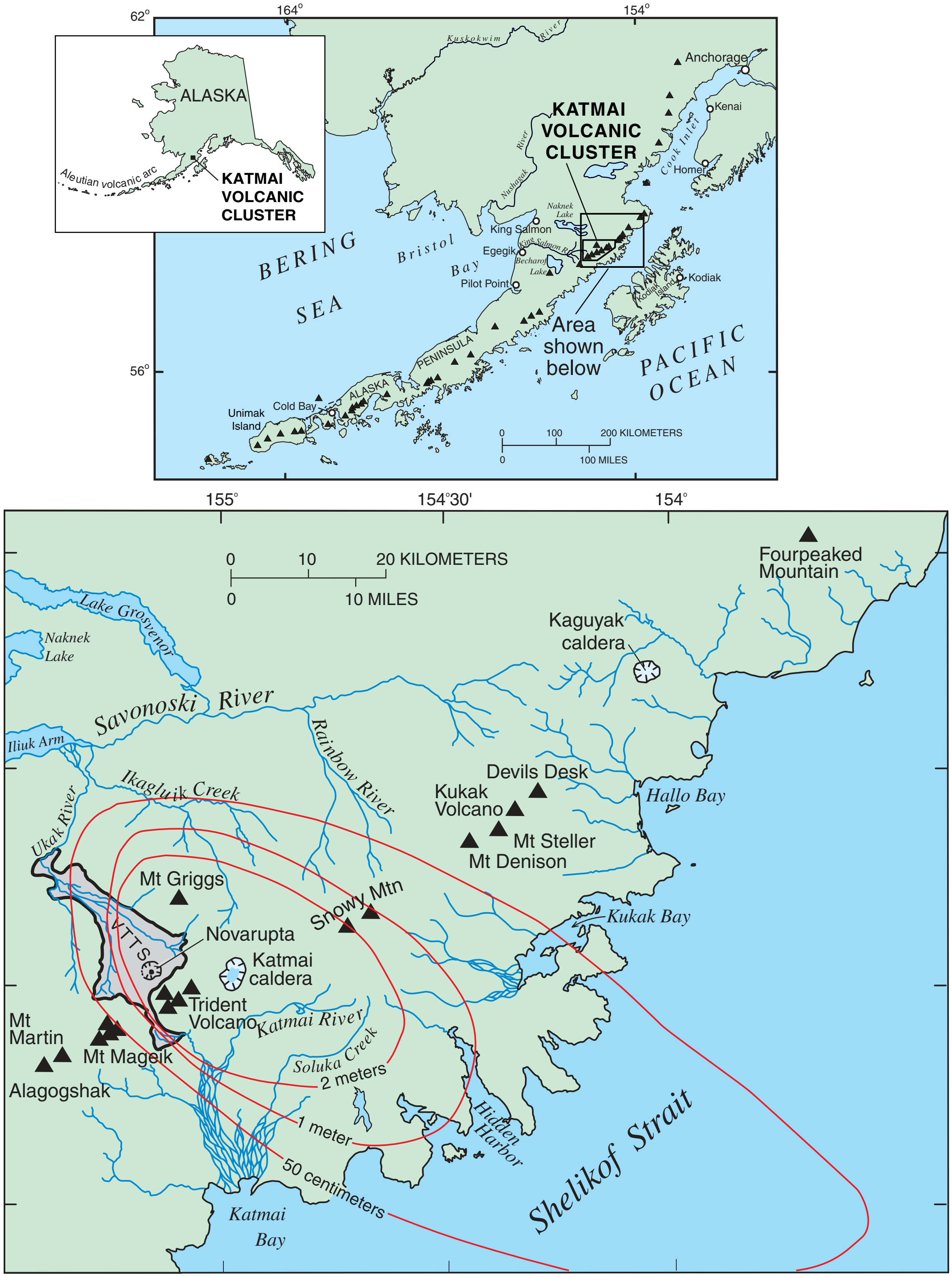
There were no aircraft in Alaska in 1912—fortunately! Corrosive acid aerosols damage aircraft, and ingestion of volcanic ash can cause abrupt jet-engine failure. Today, more than 200 flights a day transport 20,000 people and a fortune in cargo within range of dozens of restless volcanoes in the North Pacific. Air routes from the Far East to Europe and North America pass over and near Alaska, many flights refueling in Anchorage. Had this been so in 1912, every airport from Dillingham to Dawson and from Fairbanks to Seattle would have been enveloped in ash, leaving pilots no safe option but to turn back or find refuge at an Aleutian airstrip west of the *ash cloud*. Downwind dust and aerosol could have disrupted air traffic anywhere within a broad swath across Canada and the Midwest, perhaps even to the Atlantic coast.

The great eruption of 1912 focused scientific attention on Novarupta, and subsequent research there has taught us much about the processes and hazards associated with such large explosive events (Fierstein and Hildreth, 1992). Moreover, work in the last decade has identified no fewer than 20 discrete volcanic *vents* within 15 km of Novarupta (Hildreth and others, 1999, 2000, 2001; Hildreth and Fierstein, 2000), only half of which had been named previously—the four *stratovolcanoes* Mounts Katmai, Mageik, Martin, and Griggs; the cone cluster called Trident Volcano; Snowy Mountain; and the three *lava domes* Novarupta, Mount Cerberus, and Falling Mountain. The most recent eruptions were from Trident Volcano (1953–74), but there have been at least eight other, probably larger, explosive events from the volcanoes of this area in the past 10,000 years. This report summarizes what has been learned about the volcanic histories and styles of eruption of all these volcanoes.

Many large earthquakes occurred before and during the 1912 eruption, and the cluster of Katmai volcanoes remains seismically active. Because we expect an increase in seismicity before eruptions, seismic monitoring efforts to detect volcanic unrest and procedures for eruption notification and dissemination of information are included in this report. Most at risk from future eruptions of the Katmai volcanic cluster are (1) air-traffic corridors of the North Pacific, including those approaching Anchorage, one of the Pacific's busiest international airports, (2) several regional airports and military air bases, (3) fisheries and navigation on the Naknek Lake system and Shelikof Strait, (4) pristine wildlife habitat, particularly that of the Alaskan brown bear, and (5) tourist facilities in and near Katmai National Park.

### Physical Setting and Features of the Katmai Volcanic Cluster

The volcanoes near Novarupta form a 25-km-long line of contiguous stratovolcanoes on the drainage divide of the Alaska Peninsula, 450 km southwest of Anchorage, 250 km southwest of Homer, 170 km west-northwest of Kodiak, and 100 km east-southeast of King Salmon. This is part of the Aleutian volcanic arc (fig. 1), the curving chain of volcanoes extending from south-central Alaska to the far western end of the Aleutian Islands and one of the most active volcanic regions in the world (Simkin and Siebert, 1994). Even here, however, the Katmai cluster is unusual in its density of volcanoes. Mount Katmai, Trident Volcano, Mount Mageik, and Mount Martin are aligned along a portion of the volcanic arc that trends N65°E, whereas Mount Griggs and Novarupta are centered behind the front (at 12 km and 5 km, respectively). This frontal trend additionally includes Snowy Mountain volcano, 15 km northeast of Mount Katmai, and extinct Alagogshak volcano, centered 3 km southwest of Mount Martin (fig. 2) but not recognized as a separate center until recently (Hildreth and others, 1999). All the frontal volcanoes of this arc segment, from Snowy Mountain to Alagogshak, were constructed along the preexisting range crest (the Pacific–Bristol Bay drainage divide), where the rugged prevolcanic basement




EXPLANATION

- Valley of Ten Thousand Smokes (VTTS) ash-flow sheet, which erupted from Novarupta in June 1912
- Original thickness of Novarupta 1912 ashfall
- Andesite–dacite stratovolcano

typically reaches elevations of 4,000 to 5,300 ft. As the volcanic summits reach 6,000 to 7,600 ft and lie in a region of high precipitation, all these centers are extensively ice covered, as (to a lesser degree) is Mount Griggs, northwest of the frontal axis.

All of these volcanoes are in the Katmai National Park and Preserve, much of which is pristine wilderness and sparsely populated. It is, however, a world-renowned tourist area for brown-bear watching, fishing, kayaking, and hiking. Local pilots give “flight-seeing” tours of the picturesque, snow-and-ice-clad stratovolcanoes, which on a clear day provide spectacular aerial views of the sulfurous steam jets in Mount Martin’s summit *crater*, the “boiling” yellow-green acid lake near the top of Mount Mageik, and the robin-egg-blue lake of Katmai *caldera*, formed by collapse in 1912. The 1953–60 Trident *lava* flows, black and blocky, stand out in strong contrast to the more subdued surrounding slopes mantled with light-colored *pumice* from the 1912 eruption of nearby Novarupta. Mount Griggs, too, has yellow sulfurous *fumaroles* discharging vigorously near its summit.

**Mount Griggs** (fig. 3; formerly known as Knife Peak), tallest peak in the district, rises to 7,600 ft in elevation on the eastern margin of the Valley of Ten Thousand Smokes. Mount Griggs is a relatively symmetrical cone with three nested summit craters and several small glaciers radiating from its summit. *Mafic andesite* lava flows make up most of the volcano and have chemical compositions consistently distinguishable from products erupted by all the other Katmai volcanoes. Andesites make up a larger proportion of the lavas at Mount Griggs than at other volcanoes of the cluster, with *dacite* lavas quite sparse and no large fallout-producing explosive events recognized.

**Mount Katmai**, centered 10 km east of Novarupta, is a compound stratovolcano that consisted of a pair of large interfingered cones before both were beheaded by the caldera collapse of 1912 (fig. 4). The walls of Katmai caldera expose stacks of lava flows; no lava domes have survived on Mount Katmai, although one or more summit domes may have been destroyed in 1912. Fragmental materials, including products of *explosive eruptions*, are fairly abundant. Although commonest of these are relatively small-volume and short-traveled lava-flow *breccias*, also present are phreatomagmatic deposits (from magma–water interactions), massive block-and-ash units, and *scoria* and pumice falls—all products of significantly more explosive eruptions. Mount Katmai has a varied volcanic history—erupting products that extend from *basalt* to *rhyodacite*. One of the largest and most explosive events ever to occur at the Katmai volcanic cluster took place about 23 k.y. ago.

**Figure 1.** Regional geographic setting of the Katmai volcanic cluster with respect to other young volcanoes of Aleutian arc. VTTS, Valley of Ten Thousand Smokes.

**Trident Volcano** (fig. 5) is a group of four andesite–dacite stratocones and several lava domes. Although more severely dissected glacially and in part older than adjacent Mageik and Katmai volcanoes, Trident Volcano nonetheless produced the area’s most recent eruptive episode—from 1953 to 1974. The central and highest edifice, informally called Trident I, is glacially ravaged and certainly inactive over the last 10,000 years but nonetheless supports a vigorous field of sulfur-producing fumaroles on its lower southeast flank, first recorded in 1916 by botanist R.F. Griggs (Griggs, 1922). Another fumarole, visible on 1951 aerial photographs as a 60-m-wide steaming pit on the southwest ridge of Trident I, became the vent site for the new volcanic cone (Southwest Trident) that began to grow in 1953. No large explosive deposits have been recognized as having come from any of the Trident peaks; most of the eruptions of Trident Volcano have been small lava domes and short-traveled blocky lava flows accompanied sporadically by minor ash plumes and local showers of *ballistic* bombs.

**Mount Mageik**, an andesite–dacite compound stratovolcano just higher than 7,100 ft, rivals Mount Katmai as the most extensive (80-km$^2$) and most productive (30-km$^3$) edifice in the Katmai cluster. Each of its four ice-mantled summits is a discrete eruptive center, and each is the source of numerous lava flows (figs. 2 and 6). Three of them, the North, East, and Southwest Summits, have small fragmental summit cones with ice-filled craters, but the fourth and highest Central Summit is topped by a dacite dome. Just west,

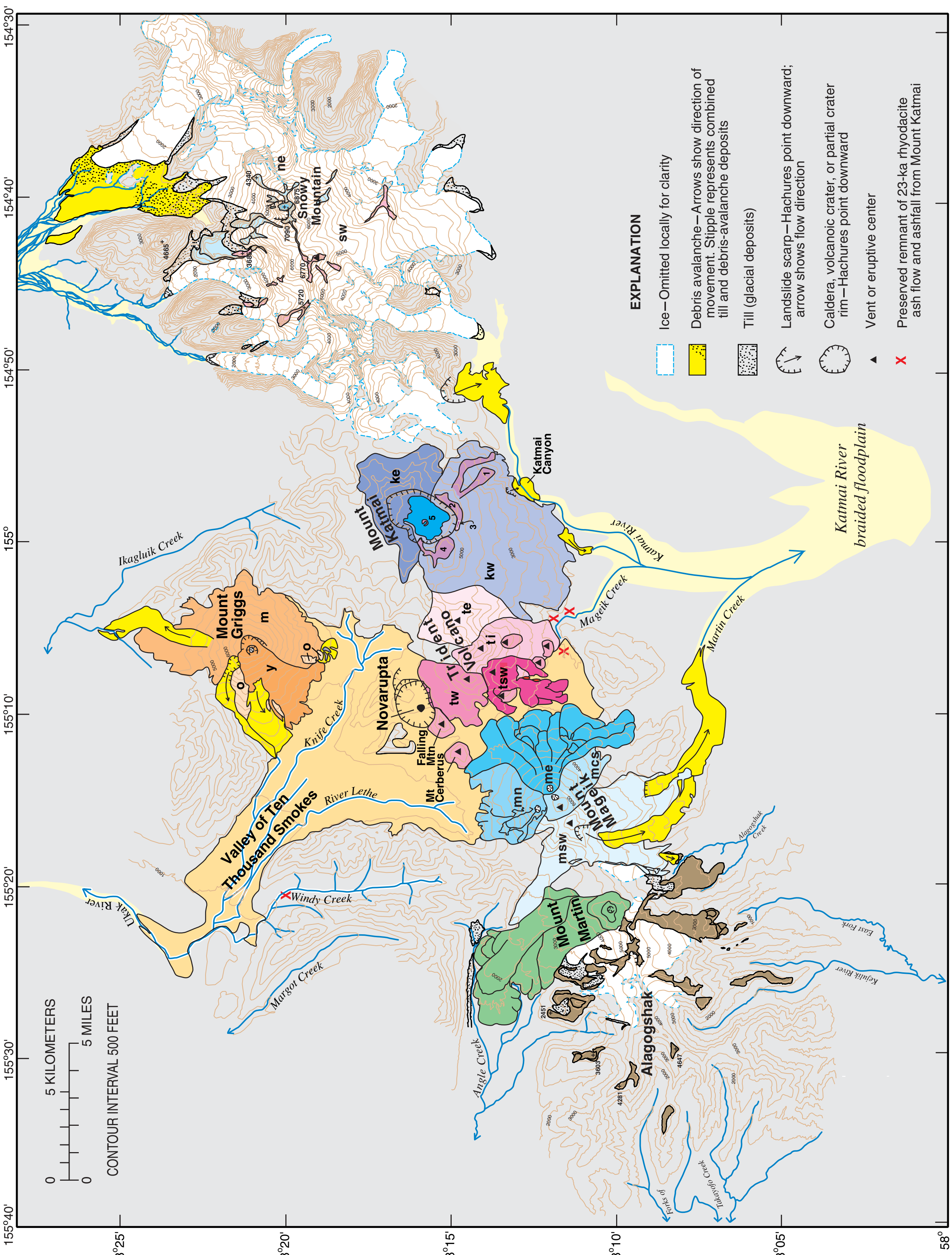

EXPLANATION
Ice—Omitted locally for clarity
Debris avalanche—Arrows show direction of movement. Stipple represents combined till and debris-avalanche deposits
Till (glacial deposits)
Landslide scarp—Hachures point downward; arrow shows flow direction
Caldera, volcanic crater, or partial crater rim—Hachures point downward
Vent or eruptive center
Preserved remnant of 23-ka rhyodacite ash flow and ashfall from Mount Katmai
0 5 KILOMETERS
0 5 MILES
CONTOUR INTERVAL 500 FEET
Snowy Mountain
ne
sw
Mount Katmai
ke
kw
Katmai Canyon
Katmai River
Katmai River braided floodplain
Mount Griggs
Trident Volcano
te
ti
tw
tsw
Novarupta
Falling Mtn
Mt Cerberus
Mount Mageik
me
mn
mcs
msw
Mount Martin
Alagogshak
Valley of Ten Thousand Smokes
Ikagluik Creek
Knife Creek
River Lethe
Windy Creek
Ukak River
Margot Creek
Angle Creek
Mageik Creek
Martin Creek
Alagogshak Creek
East Fork
Kejulik River
Takayofo Creek
Forks of
154°30'
154°40'
154°50'
155°
155°10'
155°20'
155°30'
155°40'
58°25'
58°20'
58°15'
58°10'
58°05'
58°

**Figure 2.** Geology of the Katmai volcanic cluster, showing eruptive products from each volcano. Triangles or hachured circles (for craters) mark the multiple vents of Mount Mageik and Trident Volcano: Southwest Mageik (msw), Central Summit of Mageik (mcs), East Summit of Mageik (me), and North Summit of Mageik (mn); Southwest Katmai (kw) and Northeast Katmai (ke). Falling Mountain and Mount Cerberus are dacite domes related to Trident Volcano. Youngest eruptive units from Mount Katmai are labeled 1 through 5. Two edifices of Snowy Mountain are also labeled: Northeast Snowy (ne) and Southwest Snowy (sw). Like Snowy Mountain, Alagogshak lavas have been severely eroded by glaciers. Lines within a single-colored map unit bound different, overlapping flows. Mount Griggs' lavas are shown grouped by relative age: y, younger; m, middle; o, older. Prevolcanic basement (much of the light-gray background) is not delineated on this map. Although all of the stratovolcanoes are covered with snow and ice, many glaciers have been omitted for clarity.

across Katmai Pass from Trident Volcano, several lava flows from Mageik's East Summit nearly touch the toes of those from Trident. A yellow-green acid lake in a crater between the East and Central Summits of Mount Mageik sends up curls of steam often mistaken for an eruption plume, but the crater never erupted any juvenile magma. It was reamed by *phreatic* explosions through the edge of the Central Summit dome.

**Mount Martin**, just southwest of Mount Mageik, consists of a small vent cone of fragmental andesite and a staircase of 10 overlapping coulees of blocky dacite that descends northwestward for 10 km (fig. 7). Although its summit exceeds 6,100 ft in elevation, the 2-km-wide cone itself has local relief of only 500 m, owing to its construction upon the high ridge of much older basement rocks. 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.

The edifice of **Alagogshak** volcano, the southwesternmost member of the Katmai volcanic cluster, is marked by hydrothermally altered remnants of a cratered fragmental cone on the main drainage divide (fig. 8). The summit forms the east rim of a glacially gutted vent complex, from which andesite and dacite lavas extend 6 to 10 km in most directions, all of them glacially incised.

**Snowy Mountain**, the northeasternmost volcano of the Katmai cluster, is made up of a pair of small, heavily glaciated andesite–dacite volcanoes as well as a young lava dome that fills what was the northeastern summit crater. All are extensively ice covered. Along the range crest, the Snowy Mountain volcanic center exhibits three principal summits, Peaks 6770, 7090, and 6875 (figs. 2 and 9). Only Peak 6875, the young lava dome, marks a vent. Peak 7090, the true summit of Snowy Mountain, is an ice-ravaged remnant of old Northeast Snowy. Similarly, Peak 6770 is a remnant of the lava flows from Southwest Snowy, its vent (Peak 6600+) lying 500 m southeast.

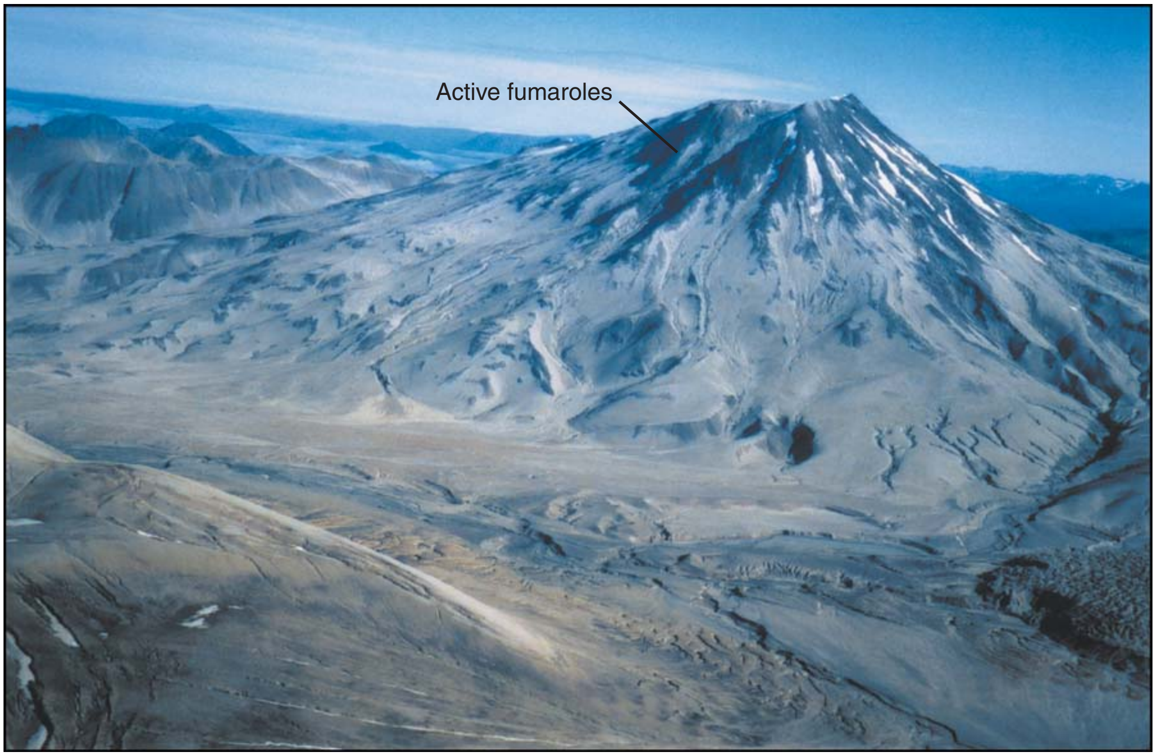



**Figure 3.** Aerial view northward of Mount Griggs, showing location of active fumaroles just below summit crater. Flanks are covered with ashfall deposits (lighter color) from 1912 eruption of Novarupta. Knife Creek cuts through 1912 ash-flow sheet at foot of Mount Griggs (flowing down valley, right to left). Photograph by author Judy Fierstein, August 1999.

At the north foot of Trident Volcano is the **Novarupta** vent, a 2-km-wide depression filled with pumice and ash from its own eruption in 1912. Fault scarps caused by collapse and subsidence in 1912 encircle this area that was the vent for the first day of the eruption and produced the ashfall and ash flows that filled what became known as the **Valley of Ten Thousand Smokes** (fig. 10). The volume and rate at which the pumice and ash were ejected from this vent were so great that some of it went upward in a towering *eruption column* to be distributed widely by regional and stratospheric winds (as ashfall or *pyroclastic* fall), and some flooded the vent area, flowing down the surrounding valleys and filling them as much as 200 m deep. These ash flows (or pumiceous *pyroclastic flows*) remained hot for several decades, earning the name “Ten Thousand Smokes” for the many steaming cracks and fissures where surface waters that entered the hot ash-flow deposits were expelled as steam. Within this larger ash-flow vent, a smaller vent that produced the ashfalls of the subsequent two days also built a ring of pumice-rich *ejecta*, within which the Novarupta lava dome, the last product of the eruption, is nested.

Griggs, Katmai, Trident, and Mageik partially surround the head of the flat-floored Valley of Ten Thousand Smokes, which, although no longer “smoking,” is still largely vegetation free. Glacier-fed forks of Knife Creek and the River Lethe have incised deeply into the 1912 ash deposits; they flow at the bottom of steep-walled gorges as deep as 10 to 30 m in the lower and middle parts of the Valley, and, although not as deeply incised upstream, are filled nearly to the brim there with muddy, very cold and swift water—the bane of a number of hikers over the last 50 years.

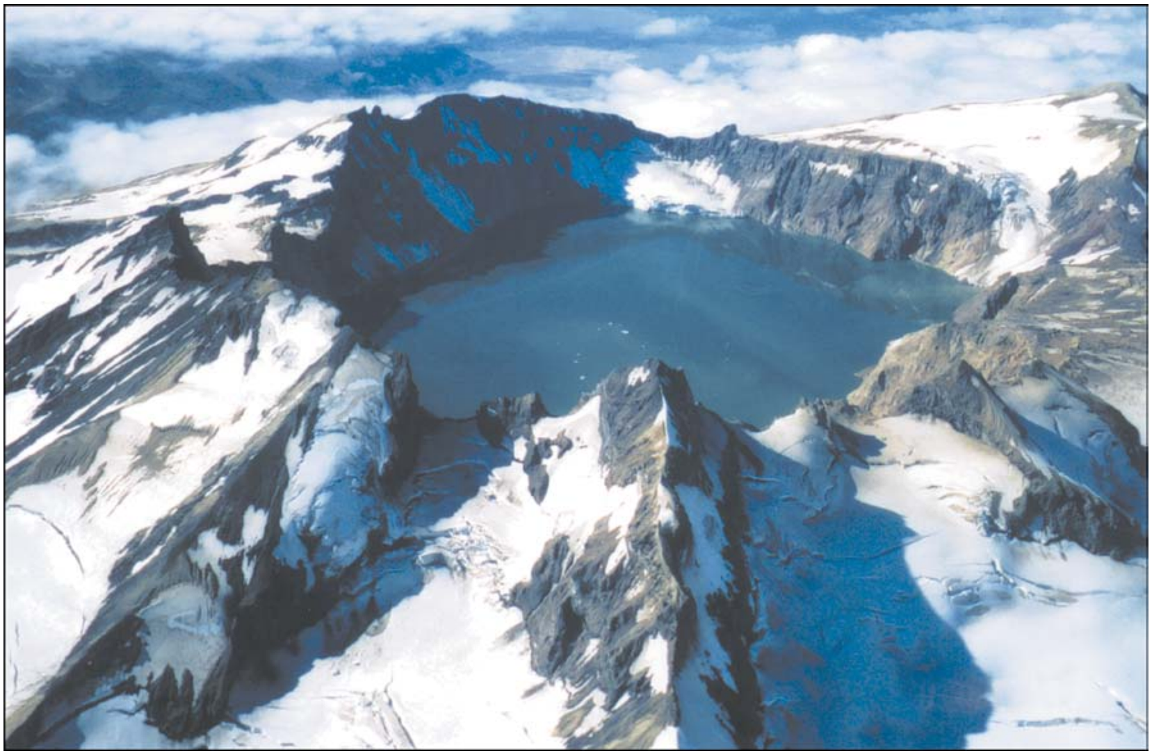


**Figure 4.** Aerial view southward overlooking Katmai caldera, formed by collapse in 1912, when Novarupta erupted 10 kilometers away. Steep walls of caldera truncate glacier-filled valleys that formerly continued upward to summits of two distinct edifices, informally called Northeast Katmai (closer wall) and Southwest Katmai (far wall); “beheaded” glaciers are still active. The lake, now 250 meters deep, apparently has reached a steady state and is no longer rising. Photograph by author Judy Fierstein, August 1999.

## Previous Studies of the Katmai Volcanic Cluster

Much of the geologic work in the Katmai area has centered on the great 1912 eruption of Novarupta. The first reconnaissance study, prompted by coast-to-coast news reports, was by the U.S. Geological Survey soon after the eruption (Martin, 1913). A series of expeditions between 1915 and 1919 sponsored by the National Geographic Society began as an effort to study revegetation after the eruption, but they expanded to include investigations of the 1912 eruptive products themselves (Griggs, 1918, 1922; Fenner, 1923, 1950). The high-temperature fumaroles (the “Ten Thousand Smokes”) in the ash-flow sheet persisted vigorously for about 15 years and attracted attention not only scientifically (Allen and Zies, 1923; Zies, 1929; Ramdohr, 1962; Keith, 1991; Papike, 1992; Lowenstern, 1993) but also so inspired Griggs that he convinced the Wilson administration to preserve the district for popular scenic and scientific interest for generations to come. Thus, the area was set aside as Katmai National Monument in 1918. Stratospheric dispersal of the Novarupta ash cloud, reported as a dust veil as far east as Greece and Algeria, led to pioneering work on atmospheric turbidity and the effect of aerosols on climate (Kimball, 1913; Volz, 1975). Still, the eruption and its products remained poorly understood, owing in part to remoteness and difficult field conditions but also because of a poor understanding of explosive eruptions in general and failure to identify the actual vent for the 1912 ejecta. Curtis (1968) set most of the record straight about the eruption, most importantly establishing that the vent was Novarupta, not Mount Katmai as had previously been supposed.

**Figure 5.** Aerial view southwestward of four eroded peaks of Trident Volcano: East Trident (elevation 6,010 feet or 1,832 meters) has ice-filled bowl at base of sheer north-facing scarp (left center). Smaller dark peak to its right is also an eroded remnant of East Trident edifice. Trident I (elevation 6,115 feet or 1,864 meters), on central skyline, is highest summit. West Trident (far right; elevation 5,605 feet or 1,708 meters) is younger than other two and much less eroded. Youngest peak of all, Southwest Trident, is hidden behind West Trident and Trident I. Shadowed knob (lower left) is nonvolcanic basement. Lower snow-covered slopes of Mount Mageik are visible in distance (uppermost right). Novarupta 1912 pumice and ash (tan in color) mantles The Knife Creek Glaciers (rough terrain in foreground) and all but steepest slopes. Photograph by author Judy Fierstein, August 1999.

Over the last two decades, detailed studies of Novarupta deposits have contributed to a better understanding of how volcanoes work, the concurrent production of stratosphere-reaching ash plumes and valley-filling ash flows, the timing of caldera collapse relative to magma withdrawal, and how the pumice and ash were distributed so far from the source (Hildreth, 1983, 1987, 1991; Fierstein and Hildreth, 1992; Fierstein and Nathenson, 1992; Fierstein and others, 1997). Until the current investigation, however, most other volcanoes in the district have been little studied. Even Mount Katmai, mentioned in most of the Novarupta studies and long thought (mistakenly) to be the vent for the 1912 eruption, had not been investigated for its own volcanic history. Small eruptions from Trident Volcano between 1953 and 1974 led to some topical studies (Snyder, 1954; Ray, 1967), and a reconnaissance geologic map of the Katmai region generally shows the extent of the young stratovolcanoes (Riehle and others, 1993). Heightened awareness of the dangerous mix of aircraft and volcanoes, and recognition of the abundance of both in this part of Alaska, prompted the comprehensive evaluation of the eruptive history of the whole Katmai volcanic cluster summarized in this report.

**Figure 6.** Ice-clad Mount Mageik, as viewed southwestward, rising above head of flat-floored Valley of Ten Thousand Smokes. East Summit is on left skyline. North Summit, to the right, is topped by an ice-filled crater, from which several thick lava flows extend. Highest point on mountain (just over 7,100 feet, or 2,165 meters; on rear skyline), is the Central Summit, with a fumarolically active crater below it to its left. Southwest Summit is hidden. Steaming cone of Mount Martin rises on right skyline, 7 kilometers southwest of Mageik's North Summit. Falling Mountain (in shadow at left) and Mount Cerberus (center, at foot of Mount Mageik) are two dacite domes that are related to Trident Volcano. Photograph by author Judy Fierstein, summer 1997.

# ERUPTIVE ACTIVITY OF THE KATMAI VOLCANIC CLUSTER

## Historical Eruptive Activity

### Great Eruption of 1912, at Novarupta—The Exceptional Event

First observed around 1 p.m. (Alaska local time) on June 6, 1912, the *eruption cloud* from Novarupta rapidly rose to a height greater than 100,000 ft, where the jet stream carried much of it eastward. Ashfall began at Kodiak within 4 hours and by the next day had spread 1,000 km east and at least 100 km west (figs. 11 and 12). From the vent at Novarupta, the towering column of ash jetted skyward with little interruption for some 60 hours, concurrently distributing ash flows that filled what became the Valley of Ten Thousand Smokes and feeding a high umbrella cloud more than 1,600 km wide that soon shrouded all of southern Alaska and the Yukon Territory. By midnight of the first day, 11 hours into the eruption, enough magma had escaped from beneath Mount Katmai that about 5 km$^3$ of its summit collapsed to form a 2.5-km-wide caldera, which has since accumulated a lake 250 m deep (fig. 4). Caldera collapse was accompanied by 14 earthquakes of magnitudes 6 to 7, as many as 100 greater than magnitude 5, and countless smaller shocks. By June 9, when the main outpouring finally ceased at Novarupta, the advancing downwind ash cloud had begun dropping sulfur-permeated fallout on Puget Sound. On the following day the cloud passed over Virginia, and by June 17 it reached Algeria.

**Figure 7.** East side of fumarolically active Mount Martin summit cone (relief, about 500 meters), built mostly by accumulation of bombs, ash, and scoria on top of massive lava flows that flowed generally northwestward. Low rim of summit crater is open to southeast. Plume carries enough sulfur to induce headaches in close observers. Photograph by author Wes Hildreth, summer 1997.

Few historical eruptions have been as provocative for volcanologists. Among historical eruptions it is virtually unique in having generated a large volume of pumiceous pyroclastic flows that—unlike those of the island-volcanoes Krakatau (Indonesia) and Santorini (Greece)—came to rest on land. It was the 20th century's most voluminous eruption by far, and one of the five largest in recorded history. At least 17 $km^3$ of fall deposits and about 11 $km^3$ of ash-flow tuff (*ignimbrite*) were emplaced in about 60 hours, representing a magma volume of about 13 $km^3$ (Fierstein and Hildreth, 1992). This volume is larger than that erupted by Krakatau in 1883 and is known to have been exceeded by only four eruptions in the last 1,000 years. The syneruptive collapse of Mount Katmai caldera, 10 km east of the eruption site, generated earthquakes that represent about 250 times the total seismic energy released during the 1991 caldera-forming eruption of Pinatubo volcano in the Philippine Islands (Abe, 1992; Newhall and Punongbayan, 1996; Hildreth and Fierstein, 2000). Some of these earthquakes—both during and after the eruption—were felt as far as 200 km from Novarupta. Explosions were heard throughout the eruption as far away as 600 km at Cordova.

The magnitude and volume of the eruption at Novarupta during those 3 days in June of 1912 were exceptional—far larger than any other historical eruptions anywhere in North America. Although recurrence after less than a century of this kind of event from the same volcano is unlikely, there have been similar cataclysmic outbursts from Mounts Katmai and Mageik in the past. Although not as frequent as smaller scale events, the effects of another 1912-scale explosive eruption would be devastating and widespread, indeed.

**Trident Volcano Eruptions of 1953 to 1974—The Normal Episode**

Beginning in February 1953, a new andesitic edifice (0.7 $km^3$) was built at the southwest margin of the Trident volcanic group (Snyder, 1954; Ray,1967) (fig. 13). Although referred to informally as "New Trident," we prefer calling it Southwest Trident, in anticipation of the day it ceases to be Trident Volcano's youngest component. Eruptive activity began with an ash plume that rose to about 33,000 ft (10 km), followed by repeated intervals of lesser gas and ash emission and effusion of lava flows (Snyder, 1954). During two decades of sporadic explosive activity (largely minor explosive eruptions and low-level ash emission), 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 5,000 ft (1,515 m; global-positioning-system (GPS) measurement by M. Coombs, 1997), on the site of a former fumarole at about 3,870 ft (1,174 m) on the steep southwest flank of an older portion of Trident Volcano (fig. 14). Although relief on the south slope of the new cone exceeds 700 m, its volume is only about 0.3 $km^3$ (Hildreth and others, 2000). 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. Each flow may have been emplaced over a period of several months. Each flow is 30 to 70 m thick and 2.5 to 4.5 km long, and altogether they add about 0.35 $km^3$ to the eruptive volume. The cone's summit today is marked by a shallow crater 350 m wide (Hildreth and others, 2000) that was the site of several small interim lava plugs, which were emplaced after the final lava flow and were repeatedly destroyed by intermittent explosive activity (1960–74). Black ash clouds rose 6 to 9 km (above sea level) several times during 1953–68 and perhaps to 12 km once or twice; ballistic blocks of unknown year are strewn as far as 3 km from the vent. A single layer of coarse ash, typically 5 to 17 cm thick, is preserved at a few protected sites as far as Mount Katmai and upper Knife Creek. Liberal estimates of total fallout yield less than 0.05 $km^3$. Most of the fallout and at least half the total volume of lava and proximal ejecta were emplaced before June 1953 (Snyder, 1954). Minor ejections of *tephra*, some involving explosive destruction of the lava plug, took place during 1963–74, but volumetrically significant eruptions were over by 1963. Numerous sulfurous fumaroles, superheated in the 1960s but near boiling or subboiling today, persist on upper parts of the cone.

**Figure 8.** Glacially eroded summit of Alagogshak volcano, 3 kilometers southwest of Mount Martin (left cone). Shaded cirque on right skyline is gutted crater of Alagogshak. View toward southwest. Photograph by author Wes Hildreth, summer 1997.


**Figure 9.** Aerial view northeastward over clouds from near Katmai Lake to multiple summits of Snowy Mountain volcanic center. Highest summit (7,090 feet, or 2,161 meters) is a remnant of the west flank of Northeast Snowy, and 6,875-foot (2,096-meter) peak is a young lava dome filling the summit crater of same edifice. Peak that exceeds 6,600 feet (2,012 meters) is the vent complex for Southwest Snowy, and the peak that is 6,770 feet (2,064 meters) high is an eroded remnant of that volcano's north flank. Mounts Denison and Steller, next volcanoes northeast along chain (fig. 1), are on right skyline. Photograph by author Wes Hildreth, summer 1998.

The Southwest Trident ejecta cone, its four blocky lava flows, several obliterated lava plugs, and the thin local ash layer, were all emplaced over a 20-year period during 1953–74. The total volume erupted was about 0.7 km$^3$ of lava and scoria—about 18 times smaller than that erupted during the 3 days in 1912. These Trident eruptions are fairly representative of the sorts of eruptions that, over millennia, built up most of the surrounding stratovolcanoes (Mount Katmai, Trident Volcano, Mount Mageik, Mount Martin, and Mount Griggs). Most striking is the similarity between Southwest Trident and the four summits of Mount Mageik (fig. 6), each a discrete eruptive center, each the source of numerous lava flows from a simple fixed vent, each with a discrete conduit system independent of those of its companions, and each having undergone separate independent periods of activity. The morphological, structural, and compositional similarity of all four Mageik centers to the Southwest Trident edifice, which was built from scratch starting in 1953, is striking and instructive. Had the cone and lavas of 1953–74 vented on the other side of Katmai Pass, they would no doubt have been regarded as a fifth component of Mount Mageik. Although we do not know how long the eruptive lifetime of each Mageik cone lasted, whether 20 or 200 or 2,000 years, it is likely that each component cone grew fairly rapidly, and that the eruption of Southwest Trident can be viewed as an analog to most of the eruptions that, over time, built Mount Mageik.

**Figure 10.** Aerial view northeastward of flat-floored Valley of Ten Thousand Smokes (no longer "smoking"). Ash flows came out of the large pumice-filled depression south of the three truncated spurs of Baked Mountain (ash-covered hill, center). Small Novarupta lava dome (center) is encircled by ring of pumice-rich ejecta. River Lethe cuts through soft ash-flow deposits along west (left) side of the Valley, and Knife Creek along northeast (upper right) side. Light-colored 1912 pumice and ashfall mantles surrounding countryside. Photograph by author Judy Fierstein, summer 1982.

### Seismicity

Since the early 1960s, researchers have used seismic data to attempt to detect magma beneath the Katmai volcanoes. Because renewed volcanic activity normally would be preceded and accompanied by earthquakes, the Katmai area has been monitored intermittently for seismicity. Matumoto (1971) interpreted the early data as being evidence for the presence of scattered small magma bodies in the Earth's crust, and Ward and others (1991) suggested that such a magma body was present beneath the Katmai Pass area (between Mount Mageik and Southwest Trident). The pattern of seismicity recognized by Ward and others (1991) has persisted during the 1990s, as the Alaska Volcano Observatory (AVO) continues to locate 40–130 earthquakes each month along and near the volcanic axis of the Katmai cluster (fig. 15). Nearly all the earthquakes are smaller than magnitude 2.5, and only a few events have been in the range magnitude 3.0–4.5. Many of the earthquakes are fairly shallow (less than 5 km), and nearly all are shallower than 10 km. Because earthquakes are propagated better through brittle rock than through liquid (magma), the dense shallow seismicity in this region suggests that there is not a large-volume reservoir of magma (such as gave rise to the 1912 eruption) ready to erupt within 10 km of the surface beneath the seismically active areas.

The Alaska Volcano Observatory also has installed carefully located benchmarks for GPS measurements. These are periodically remeasured to detect any changes in ground elevation that may be related to precursory volcanic activity. Measurements during 1990–95 revealed no indication so far of elevation changes centered at Novarupta. Data do suggest very small elevation changes, interpreted to be caused by deformation outside the GPS network (Kleinman and others, 1997). Based on an early application of a satellite-based radar technique (Synthetic Aperture Radar interferometry), Lu and others (1997) suggested inflation beneath the Southwest Trident cone, but this finding needs to be confirmed by further measurements.

**Figure 11.** Drifts of ash in village of Kodiak, June 1912. Primary ashfall was 30 centimeters (about 1 foot) thick at a distance of 170 kilometers (100 miles) downwind from Novarupta. Drifting or sloughing from steep slopes and roofs made it locally much thicker. Photo by W.J. Erskine, 1912 (courtesy of National Geographic Society).

### Fumarolic Activity

Vigorous sulfur and carbon dioxide-emitting fumaroles in the Katmai volcanic cluster are good evidence that magma stored somewhere below is actively degassing, though this tells us little about how deep the magma may be, how much is there, or if it is cooling down or heating up.

Mount Mageik's fuming crater is about 100 m deep, 450 m long, and 280 to 400 m wide at the rim (fig. 16*A*). Fumarolic discharge through the lake keeps the water yellow-green, acidic (pH, 1 to 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 superheated, emerge vigorously from the talus south and northeast of the lake as well as beneath it; the hottest one measured in 1979 was 172°C. Depending on wind and condensation conditions, the combined plume from these jets is commonly visible from afar, but it rarely rises as high as 1 km above the crater rim and is rarely as large as the fumarolic plume from nearby Mount Martin (fig. 6). Martin, too, has a yellow-green crater lake; at least 20 fumarolic jets ring its perimeter, all precipitating abundant sulfur (figs. 7 and 16*B*). Probably also superheated, they combine to discharge the biggest and (olfactorily) hydrogen sulfide-richest plume in the Katmai district.

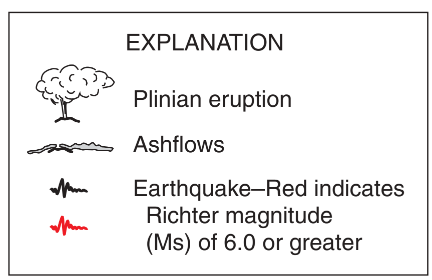



**Figure 12.** Chronology of 1912 eruption of Novarupta. Earthquakes felt by local residents during preceding 5 days prompted evacuation to what they hoped were safer havens. Ms, earthquake surface-wave magnitude as measured on Richter scale.

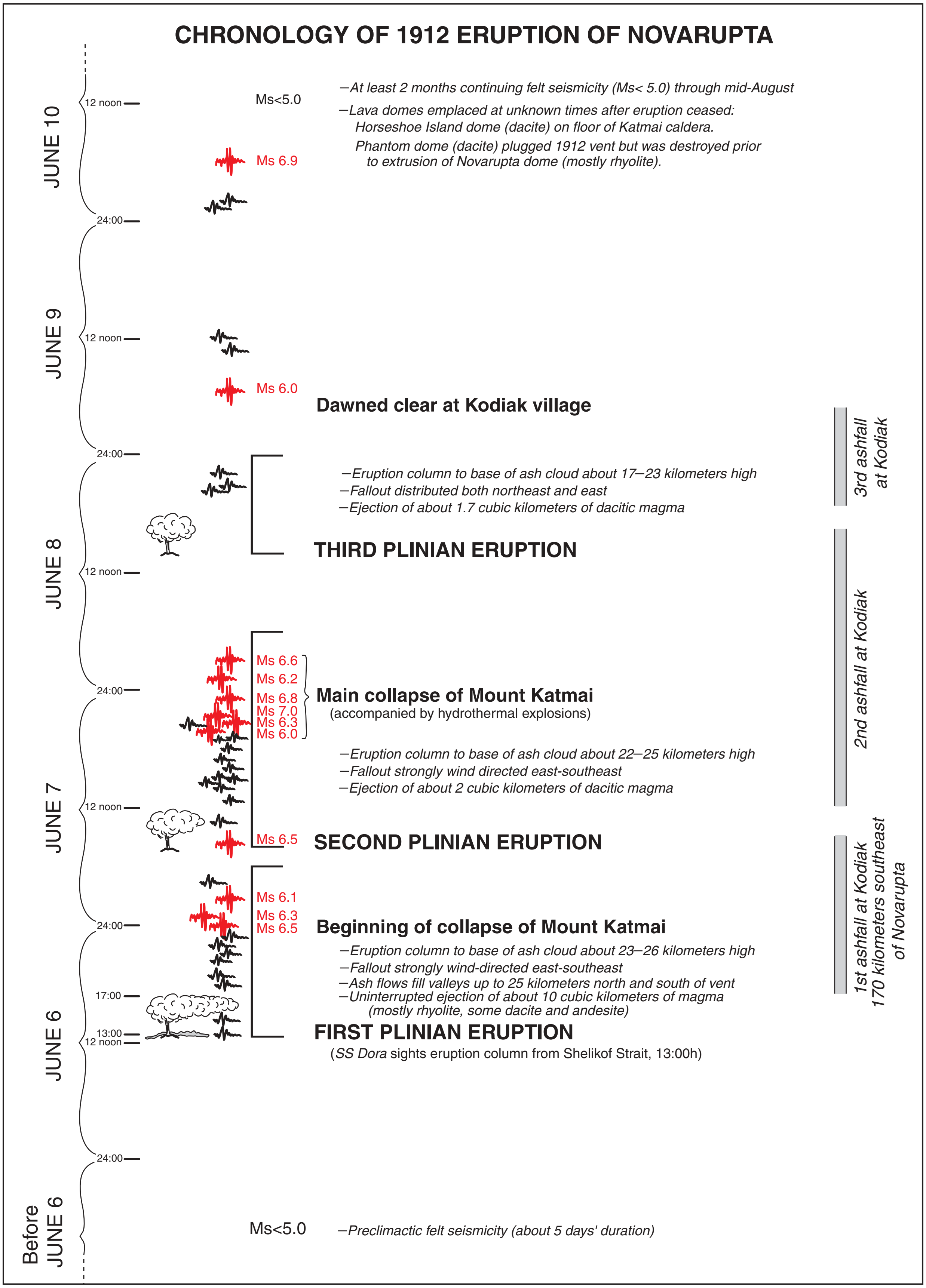

CHRONOLOGY OF 1912 ERUPTION OF NOVARUPTA
JUNE 10
12 noon
24:00
JUNE 9
12 noon
24:00
JUNE 8
12 noon
24:00
JUNE 7
12 noon
24:00
JUNE 6
17:00
13:00
12 noon
24:00
Before JUNE 6
Ms<5.0
—At least 2 months continuing felt seismicity (Ms< 5.0) through mid-August
—Lava domes emplaced at unknown times after eruption ceased:
Horseshoe Island dome (dacite) on floor of Katmai caldera.
Phantom dome (dacite) plugged 1912 vent but was destroyed prior to extrusion of Novarupta dome (mostly rhyolite).
Ms 6.9
Ms 6.0
Dawned clear at Kodiak village
—Eruption column to base of ash cloud about 17–23 kilometers high
—Fallout distributed both northeast and east
—Ejection of about 1.7 cubic kilometers of dacitic magma
THIRD PLINIAN ERUPTION
Ms 6.6
Ms 6.2
Ms 6.8
Ms 7.0
Ms 6.3
Ms 6.0
Main collapse of Mount Katmai
(accompanied by hydrothermal explosions)
—Eruption column to base of ash cloud about 22–25 kilometers high
—Fallout strongly wind directed east-southeast
—Ejection of about 2 cubic kilometers of dacitic magma
Ms 6.5
SECOND PLINIAN ERUPTION
Ms 6.1
Ms 6.3
Ms 6.5
Beginning of collapse of Mount Katmai
—Eruption column to base of ash cloud about 23–26 kilometers high
—Fallout strongly wind-directed east-southeast
—Ash flows fill valleys up to 25 kilometers north and south of vent
—Uninterrupted ejection of about 10 cubic kilometers of magma (mostly rhyolite, some dacite and andesite)
FIRST PLINIAN ERUPTION
(SS Dora sights eruption column from Shelikof Strait, 13:00h)
Ms<5.0
—Preclimactic felt seismicity (about 5 days' duration)
3rd ashfall at Kodiak
2nd ashfall at Kodiak
1st ashfall at Kodiak 170 kilometers southeast of Novarupta

**Figure 13.** View northeastward of Trident Volcano cones and flows. Southwest Trident cone is perched between older West Trident (skyline left) and snow-covered Trident I (tall peak). Blocky, dark young lavas are free of light-colored 1912 ash, which they overran. They flowed around an older Trident dome (center left edge) and are on top of 1912 ash-flow sheet along Katmai Pass and Mageik Creek (foreground). Photograph by author Judy Fierstein, summer 1987.

Superheated jets high on Mount Griggs can be seen from a distance by the yellow sulfur coating on the ground surface around the jet orifices (fig. 3). These, and those around the crater lake of Mount Mageik, are dominated by steam but are rich in carbon dioxide, hydrogen sulfide, and hydrogen chloride, which indicate a magmatic component. Boiling-temperature fumaroles on the southeast flank of Trident I also have magmatic signatures and have discharged vigorously since before 1916 when first witnessed (Griggs, 1922). The vigorous fumaroles on Martin, Mageik, Trident I, and Griggs have apparently been continuously active with little change in style or configuration since they were first photographed during 1913–17 (Griggs, 1922). Although no evidence has been found that any of these volcanoes produced any ejecta in 1912 or erupted at any time since, there is clearly an active hydrothermal system beneath each. In contrast, fumaroles at the three vents that did erupt in the 20th century have been in decline.

The fumaroles on top of the Southwest Trident cone were surely 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 hydrogen sulfide output (R.B. Symonds, oral commun., 1998). The many fumaroles on the Katmai caldera floor (Fenner, 1930), although drowned under rising lake water by 1930, continued for decades to discharge beneath the lake (Muller and Coulter, 1957; Motyka, 1977). These weakened appreciably during the 1990s, however, and the lake now freezes completely in the winter months. In the 1912 vent area, numerous high-temperature fumaroles (Allen and Zies, 1923) declined gradually, leaving today only odorless wisps of wet steam that discharge weakly within 1.5 km of the lava dome at 20–80°C (Keith, 1991). The myriad valley-filling fumaroles that prompted Griggs to coin the name “Valley of Ten Thousand Smokes” stayed vigorous until the early 1930s (fig. 17). However, because the “smokes” outside the immediate vent area at Novarupta were caused only by the heat of the valley-filling ash deposit and not by any deep heat source, they waned as the ash-flow deposit itself was cooled by snowmelt, rain, and ground water. Colorful linear fractures and mounds—ghost fumaroles—now mark those places where the steam once rose, where the ash was altered, and a variety of precipitates were deposited by the hot acid steam and percolating fluids.

### Spurious Eruption Reports

Mount Mageik’s conspicuous fumarolic plume, like that of adjacent Mount Martin (fig. 6), has animated many spurious eruption reports. Not a single one of the 20th-century tephra eruptions of Mageik listed in Simkin and Siebert’s (1994) “Volcanoes of the World” seems plausible. Configuration of the crater has not changed since it was first photographed in 1923; there are no juvenile ejecta in the crater or around its rim (except a scattering of 1912 pumice clasts from Novarupta); 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.

In particular, Jaggar (1927) repeated a fisherman’s story reported in Seattle and Tacoma newspapers that 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. The report also mentioned fine white ash falling on the decks, but fine white ash still falls 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 *SS Starr* at Halibut Bay on the southwest corner of Kodiak Island, 95 km south of Mount Mageik. Although the writer did not land, the captain “brought back some interesting specimens of pumice stone with which the water 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.” The floating pumice was, of course, that of 1912, which lines the beaches

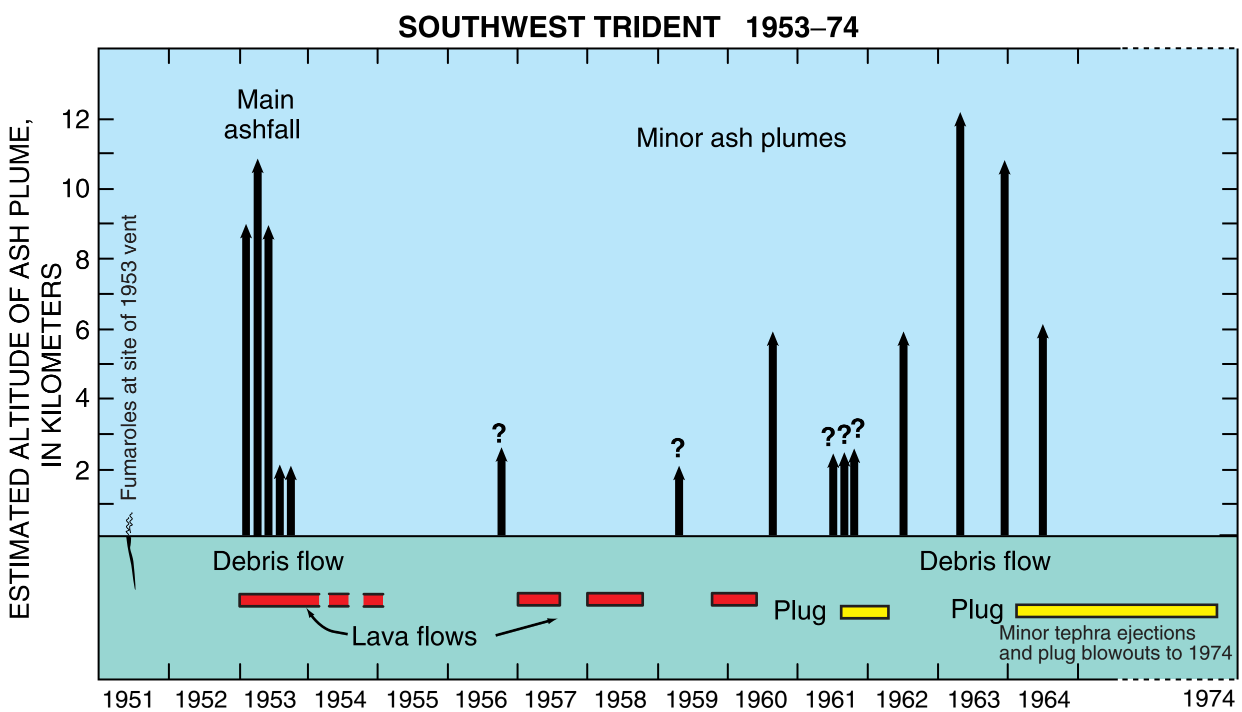
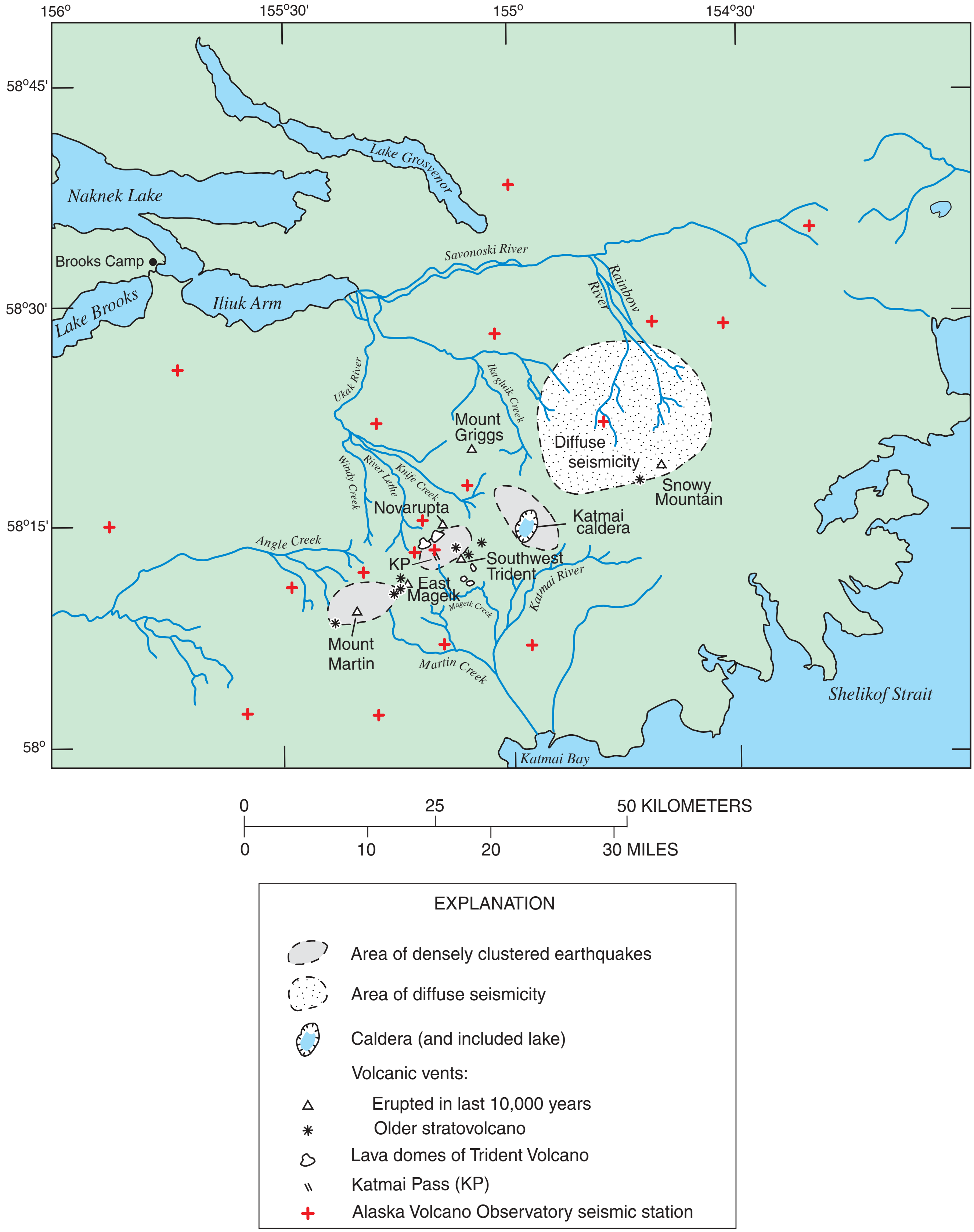



**Figure 14.** Chronology of Southwest Trident 1953–64 eruptions. Minor ejections of tephra continued intermittently until 1974.



156°
155°30'
155°
154°30'
58°45'
58°30'
58°15'
58°0
Naknek Lake
Lake Grosvenor
Brooks Camp
Lake Brooks
Iliuk Arm
Savonoski River
Rainbow River
Ukak River
Ikagluik Creek
Mount Griggs
Diffuse seismicity
Snowy Mountain
Windy Creek
River Lethe
Knife Creek
Novarupta
Katmai caldera
Angle Creek
KP
Southwest Trident
East Mageik
Mageik Creek
Katmai River
Mount Martin
Martin Creek
Shelikof Strait
Katmai Bay
0
25
50 KILOMETERS
0
10
20
30 MILES
EXPLANATION
Area of densely clustered earthquakes
Area of diffuse seismicity
Caldera (and included lake)
Volcanic vents:
Erupted in last 10,000 years
Older stratovolcano
Lava domes of Trident Volcano
Katmai Pass (KP)
Alaska Volcano Observatory seismic station

of Shelikof Strait to this day. On a trip to Katmai Bay in 1934, Hubbard (1935) 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 did during much of the 20th.

## Prehistoric Eruptive Activity

Since their beginnings a few hundred thousand years ago, the Katmai volcanoes have been mostly quiet, punctuated only sporadically by short periods of eruptive activity (fig. 18). Studying the volcanic deposits that built each edifice tells us what to expect in eruptive styles, scales, and frequency of those events. From such a record, we can infer what are the most likely patterns of future eruptive activity. Most volcanoes are long lived compared with timeframes of human activities. Although each active period can be decades to millenia long and is short relative to the active lifetime of a volcano, it can affect generations of humans.

Our recent work in the Katmai area has established an eruptive history for each of these volcanoes by mapping the distribution of eruptive products (fig. 2). Radiometric dating puts minimum and maximum ages on stacks of lava flows, providing age constraints for each volcano and, combined with the mapping, constrains the timing and frequency of past eruptions (table 1, fig. 18). Although the limits of analytical precision are such that we do not know if particular stacks of lava flows were erupted over tens or thousands of years, by analogy with younger volcanic deposits, in the rest of this section we present a summary of prehistoric eruptive activity that is of importance to our hazards analysis of the Katmai volcanic cluster.

**Figure 15.** Clustering of shallow earthquakes (mostly less than 10 kilometers deep) close to Katmai volcanoes, 1987–2000. At least 90 percent of several thousand located earthquakes occurred within three dense clusters, and about 5 percent more occurred in region of diffuse seismicity north of Snowy Mountain. Patterns were generalized from Ward and others' (1991) data and from ongoing monitoring by Alaska Volcano Observatory (Jolly and McNutt, 1999). Seismic stations are also shown.

### Older Eruptive Activity of Importance to Hazards Assessment

Most of the volcanic centers in the Katmai cluster have eruptive histories longer than 70,000 years. This hazards assessment is based on what we know about the entire lifetime of each volcano; how often each erupted, what fraction was characterized by explosive ash eruptions or effusive lava flows, how large were the eruptive volumes, and what were the extents of distribution of the deposits. The volcanic activity includes many recent episodes, and most of the volcanoes remain fumarolically active today. Within the Katmai volcanic cluster, only Alagogshak has failed to erupt within the last 10,000 years, and Mount Martin and Novarupta are short lived, entirely *postglacial* volcanoes.

Intermittent episodes of activity that built each of the Katmai stratovolcanoes spanned years to millenia, and each episode included multiple eruptive events. Eruptive episodes dominated by small-volume lava-flow extrusion tend to last tens of years (like Southwest Trident) to thousands of years. Such episodes typically include many separate events of ash ejection and lava-flow extrusions. Large explosive eruptions like Novarupta typically last a few days—here considered a single eruptive episode—and can be followed by weeks to years of smaller scale eruptive events (like lava-dome extrusion, small-scale explosions, and continuing seismicity).

Soft, unconsolidated ash layers and pumice deposits from such explosive eruptions are more vulnerable to erosion and glacial scour and are more poorly preserved than lava flows. Thus, explosive eruptions (of special hazard interest to the aviation industry) are relatively underrepresented in the volcanic record. Records of explosive eruptions are generally best preserved as ashfall layers in postglacial soil deposits and peat bogs.

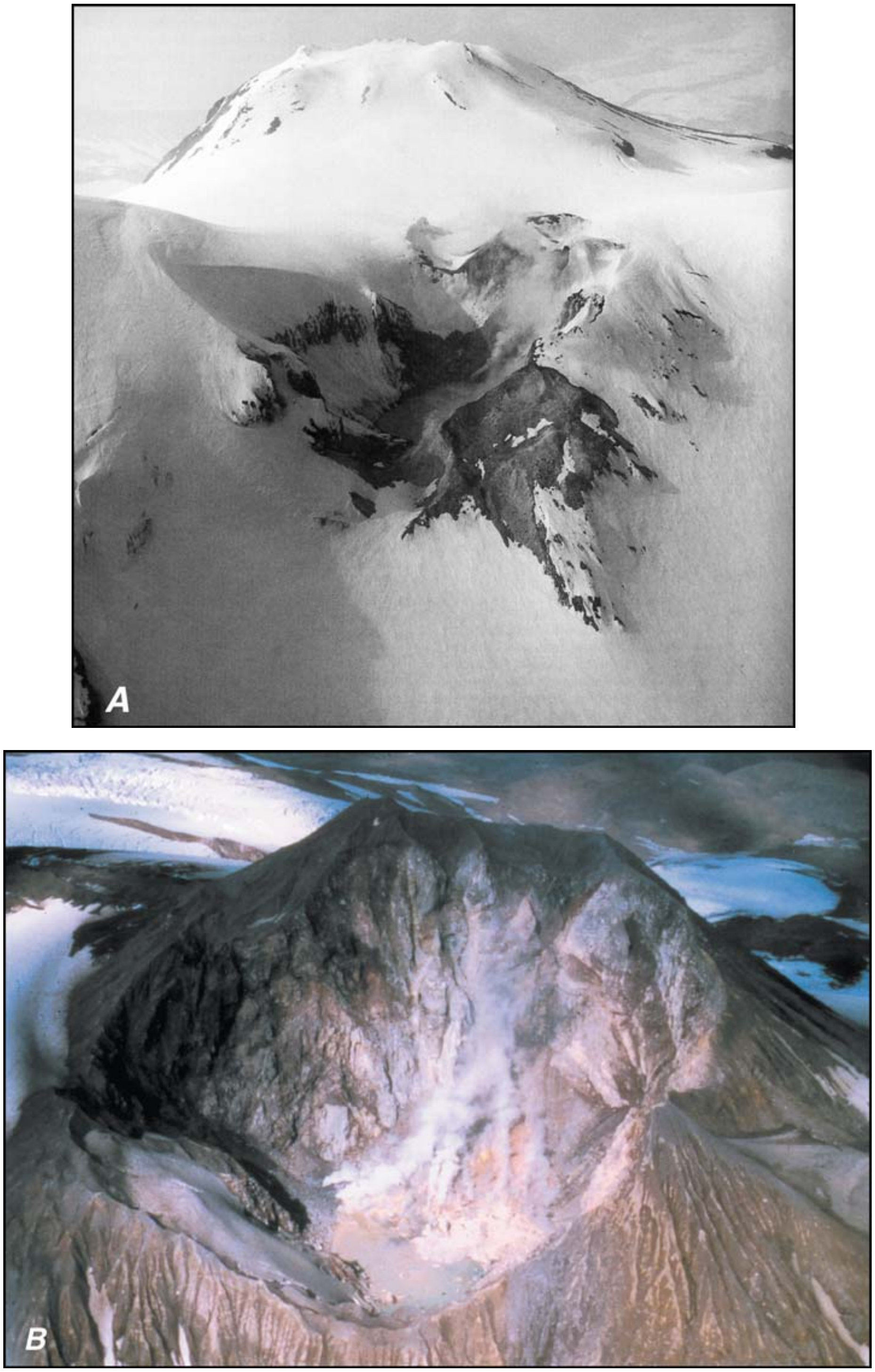



**Figure 16.** Fumarolically active (steaming) summit craters. *A*, Mount Mageik, aerial view northwestward of active crater and North Summit of Mageik. Rock walls and talus around crater are from the Central Summit (part within view, left side). Crater contains fumarole groups visible to south and northeast of its 125-meter-wide acid lake. Just discernible atop snow-draped North Summit is flat surface of its own ice-filled crater and part of its northwest rim. Photograph by W.S. Keller, National Park Service, summer 1969. *B*, Mount Martin, aerial view northwestward into summit crater. Vigorous fumarolic jets discharge through talus above lake. Photograph by Lynn Fuller, National Park Service, summer 1980.

Fairly young lava flows armor much of **Mount Griggs**, but a few windows of older lava show that the volcano has existed for at least 290,000 years. Although extensive cover by younger lavas makes any estimate of eruption rates during Griggs' older history impossible, it is clear that a large portion of the volcano was built by dozens of effusive lava flows between 85 and 10 k.y. ago (table 2). Small-volume lavas have characterized the activity of Mount Griggs for a long time, and the volcano has had no recognized large fallout-producing explosive events.

Three of the four overlapping subedifices of **Mount Mageik** are old and severely glacially eroded; the oldest lavas, from Southwest Summit, are as old as 93 ka. The 25 (or so) exposed lava flows derived from that vent probably erupted in several episodes, but all are older than the set of lava flows from the Central Summit, the oldest of which is dated at 71 ka. The North Summit vent originated about 59 k.y. ago and is entirely younger than the Central Summit. Thus, each of Mageik's three older subedifices was built during an interval 10,000 to 20,000 years long (table 2). Most eruptive episodes at Mount Mageik were apparently similar to the Southwest Trident eruptions in the 1950s—short-lived episodes of lava eruptions and small cone building.

All but 3 percent (by volume) of **Trident Volcano** erupted over a span of about 90,000 years, from more than 140 ka to about 44 ka. The eruptive focus moved generally westward through time, with short-lived East Trident the oldest (about 143 ka), followed by Trident I (140–100 ka). Extrusion of the Trident Domes took place during and after the active interval of Trident I. The oldest lava flow from West Trident is dated at 44 ka, about 55,000 years after Trident I last erupted. Most eruptive episodes from each of these Trident edifices have been lava-flow and lava-dome extrusions. Several have included small to moderate-sized pyroclastic flows, typically caused by dome collapse. One of these, preserved only as small remnants near the south foot of Trident I, was thick enough that it would be expected to have dammed streams, engendering later breakout floods and *lahars* that could have flowed all the way to the coast.

**Figure 17.** Steaming Valley of Ten Thousand Smokes, 1919. Photograph taken during Robert F. Griggs expedition; used by permission of National Geographic Society.

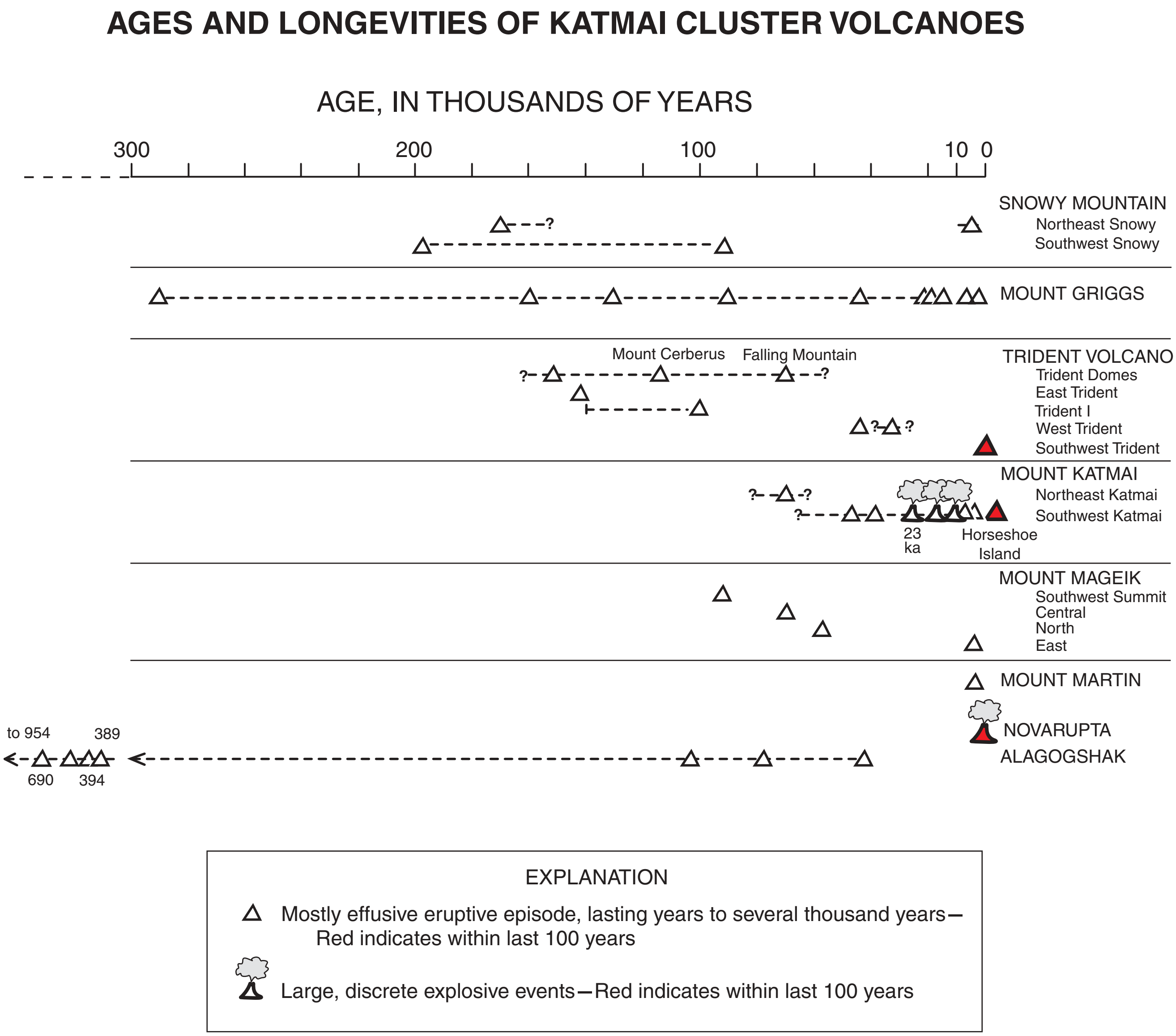



**Figure 18.** Eruptive episodes (ages and longevities) of Katmai cluster volcanoes and domes, as constrained by radiometric dating. Episodes can be decades to millennia in duration, whereas large discrete explosive events were short lived. The large, explosive rhyodacite eruption that occurred 23 k.y. ago from Mount Katmai is labeled "23 ka." The Horseshoe Island lava dome erupted on Katmai caldera floor after the 1912 eruption of Novarupta.

The two cones of **Mount Katmai**, both beheaded by the caldera collapse of 1912, had been active for more than 70,000 years. Northeast Katmai is mostly older than 70 ka, and Southwest Katmai is mostly younger. Thick stacks of lavas and sequences of pyroclastic deposits from explosive eruptions are exposed in the caldera walls, products of at least 20 episodes exposed on the caldera walls. It is clear that Mount Katmai has a history that includes more explosive eruptions than any of the other stratovolcanoes in the cluster.

### Youngest Eruptive Episodes

Trident Volcano, Snowy Mountain, and Mounts Katmai, Mageik, Martin, and Griggs have each erupted since withdrawal of extensive Pleistocene glaciers that blanketed most of the landscape (Riehle and Detterman, 1993). Younger products of volcanoes are generally better preserved than older counterparts, especially so for easily eroded fragmental deposits. Younger deposits may also represent better the current state of the system and the most likely styles of eruption in the near future. Thus, we highlight here all

**Table 1.** Data for Katmai cluster volcanoes

[Compositional range of products analysed is given as weight percent silica ($SiO_2$). Age of activity: “recent” means within last 10,000 years. Parenthetical values of elevation and volume refer to Katmai summits prior to caldera collapse in 1912. Estimates of volume are no better than 20%, owing to glacial erosion and present-day ice cover. ka, thousands of years before present. %, percent; >, greater than; <, less than; —, not applicable; ~, about]

| | Novarupta | Mount Katmai | | Trident Volcano | | | | | Mount Mageik | Mount Martin | Mount Griggs | Alagogshak | Snowy Mountain | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Northeast Katmai | Southwest Katmai | East Trident | Trident I | West Trident | Trident Domes | Southwest Trident | | | | | Northeast Snowy | Southwest Snowy |
| **$SiO_2$, in weight percent:** | | | | | | | | | | | | | | |
| | 50–77.5 | 52–66 | 52–72 | 58–65 | 53–67.5 | 54–64 | 62–65 | 57–65 | 56–68 | 59–64 | 54–63 | 52–65 | 62–64 | 55–62 |
| **Dominant eruptive style:** | | | | | | | | | | | | | | |
| | Caldera-forming eruption | Lava flows, pyroclastic flows, small ash falls | Lava flows, pyroclastic flows, small ash falls | Lava flows, domes | Lava flows, domes | Lava flows, domes | Lava domes | Lava flows | Lava flows | Lava flows | Lava flows | Lava flows | Lava flows, domes | Lava flows |
| **Age of activity:** | | | | | | | | | | | | | | |
| | Year 1912 | >70 to <50 ka | <50 ka to year 1912 | >140 ka | >100 ka | <50 ka | ~150 to 50 ka | Years 1953–74 | 90 ka to recent | Recent | 290 ka to recent | 680 ka to >40 ka* | <170 ka to recent | 200 to 100 ka |
| **Elevation of summit, in feet:** | | | | | | | | | | | | | | |
| | 2,640 | 6,750 (7,400) | 6,240 (7,550) | 6,045 | 6,150 | 5,640 | 2,460–3,900 | 5,000 | 7,150 | 6,100 | 7,600 | 6,020 | 7,090 | 6,770 |
| **Present-day areal extent, in square kilometers:** | | | | | | | | | | | | | | |
| | >120,000 | 25 | 61 | 8 | 14 | 9 | — | 8.5 | 80 | 33 | 60 | — | 6.5 | 2.4 |
| **Volume, in cubic kilometers:** | | | | | | | | | | | | | | |
| Preserved...................... | ~10 | 10 | 20 | 2.3 | 4 | 2.4 | 0.7 | 0.65 | 20 | 7 | 20 | — | 3 | 2 |
| Erupted (estimated)...... | 13 | (15) | (30) | 8 | 8 | 3 | 1 | 0.7 | 30 | 8 | >30 | 10–18 | 8 | 5 |
| Eroded.......................... | — | 33% | 33% | 70% | 50% | 20% | 30% | 7% | 33% | 12.5% | >33% | 70–90% | ~60% | ~60% |

* Four outlying lava remnants as old as 954 ka are probably older components of Alagogshak but are not included here.

**Table 2.** Eruptive episodes of the Katmai volcanic cluster

[ka, thousands of years before present. <, less than; >, greater than; —, not applicable; ~, about; ?, unknown or uncertain]

| Component | Age range | Constraining K/Ar ages | Number of lava flows, ashfalls, or pyroclastic flows | Number of episodes |
|---|---|---|---|---|
| **Mount Griggs** | | | | |
| Youngest | <10 ka | — | ~12 lava flows | 1–2 |
| Middle | 15–90 ka | — | Dozens of lava flows | ? |
| Oldest | 100–300 ka | — | ? | ? |
| **Mount Mageik** | | | | |
| East Summit | <10 ka (4–10 ka likely*) | — | ~14 lava flows | 2–4 |
| North Summit | 50–60 ka | 59 ka | 10–12 lava flows | 1–2 |
| Central Summit | 60–70 ka | 71 ka | ~6 lava flows | ? |
| Southwest Summit | 70–90 ka | 93 ka | ~25 lava flows | ? |
| **Trident Volcano** | | | | |
| Southwest Trident | Years 1953–74 | — | 4 lava flows | 1 |
| West Trident | ~30–45 ka | — | ~5 lava flows | 2 or more |
| Trident Domes | 50–150 ka | — | 5–8 lava flows | 5–8 |
| Trident I | 100–140 ka | — | 10–15 lava flows | ? |
| East Trident | 142–143 ka | — | 20–30 lava flows | ? |
| **Mount Katmai** | | | | |
| Recent | <10 ka | — | Caldera collapse and explosions, 2 lava flows, 1 ashfall | 4 |
| Southwest Katmai | 10–23 ka | — | 1 lava flow, 3 ashfalls and pyroclastic flows | 3 or more |
| | 25–70 ka | — | ? | ? |
| Northeast Katmai | >70 ka | — | ? | ? |
| **Mount Martin** | | | | |
| Recent | <10 ka | — | 12 | 1–2 |
| **Alagogshak** | | | | |
| Southeast remnant | 35–45 ka | 43 ka | 1 | 1 |
| South remnant | 100–110 ka | 104 ka | 7 | 1? |
| Southwest remnant | 380–395 ka | 389 and 394 ka | 6 | 1? |
| Northwest remnant | 650–700 ka | 680 ka | 4 | 1? |
| Outliers | 800–955 ka | 954 ka | 9 | ? |
| **Snowy Mountain** | | | | |
| Northeast Snowy; recent | <10 ka | — | 1 | 1 |
| Northeast Snowy | <170 ka | — | 12–15 | ? |
| Southwest Snowy | 100–200 ka | — | 12–15 | ? |

*Based on carbon–14 dating of soils under and overlying ash layers associated with these lava flows.

units of the Katmai cluster that we recognize as having erupted during the relatively recent past, from approximately 23 k.y. ago to the present (fig. 19).

The largest and most explosive events in the Katmai cluster occurred at **Mount Katmai** 23 k.y. ago. Rhyodacitic ash-flow and pumice-fall deposits were once widely distributed, but glaciers have scoured most of them away. Surviving pumice-fall remnants (represented by red **x** symbol in fig. 2), 7 m thick in Mageik Creek and 5 m thick in Windy Creek, suggest that the eruption was more voluminous than that of Novarupta in 1912.

Mount Katmai erupted at least four more times since then, producing the following:

- A stratified, largely agglutinated dacite fallout that widely caps the west rim of Katmai caldera, drapes the summit of Peak 6128, and thickens into a pre-1912 crater (largely obliterated in 1912). Remnants of pumice-rich debris-flow and *hyperconcentrated sand-flow* deposits, derived from this eruption, are preserved along and near lower Windy Creek and the lower River Lethe. The flows must have traveled 20–25 km from the volcano on top of ice, when glaciers occupied the valleys now filled by the Valley of Ten Thousand Smokes ash-flow deposit. Reger and others (1996) suggest that an ash layer equivalent to these deposits in the Katmai region is found on the Kenai Peninsula (225 km away). The eruption is thought to have occurred 16 to 12 k.y. ago.
- A branching set of leveed lava flows of blocky dacite that poured 4 km down the southeast slope to the floor of Katmai River canyon. Although eroded proximally by present-day glaciers, these flows are young enough that they retain primary surfaces—glassy, vesicular, blocky, even craggy.
- A coarse proximal scoria fall on the south wall of the caldera that zones upward from dacite to andesite. This eruption may have also emplaced the pyroclastic flow now preserved only as small remnants at the southwest foot of Mount Griggs.
- A small dacite lava dome, called “Horseshoe Island” by Griggs (1922), which erupted sometime during 1912–16 on the floor of Katmai caldera. It is now submerged beneath 250 m of lake water.

Another dacite fall deposit preserved locally on the lower slopes of Mount Katmai, 6 km northwest of the summit, probably originated from Katmai between 8.3 and 4 k.y. ago (based on carbon-14 dates of soils above and below the fall layer).

All of these most recent eruptions from Mount Katmai were dacitic or rhyodacitic, and at least three were explosive (fig. 18). Although only small remnants of the pumice-rich deposits are preserved, their presence underscores that explosive events have occurred from Mount Katmai with some frequency.

From the **East Summit of Mount Mageik**, the only Mageik subedifice built during the last 10,000 years, a dozen leveed lava flows (60–64 percent *silica*) have descended toward Katmai Pass and Mageik Creek. These flows were emplaced (judging by their relative degradation) in at least two (and probably four or more) eruptive episodes, yielding a total postglacial eruptive volume of 5 to 6 $km^3$. The youngest of the lavas, a Y-branching flow that banks against Mount Cerberus, has no soil developed on its surface and is glassy and less degraded than any of the others from that summit. A 4,000-year-old pumice-fall deposit, chemically very similar to this youngest lava flow and thought to have erupted during the same episode, is found widely throughout Windy Creek, in soil sections in the lower Valley of Ten Thousand Smokes, and on top of lava flows from older East Mageik episodes. Thus, the youngest eruptives are apparently about 4,000 years old, and the entire subedifice was built between 10 and 4 k.y. ago. Accumulation of aeolian silt and incipient soil development on some of the older lobes from the East Summit suggest at least hundreds, if not thousands, of years between eruptive episodes. The average postglacial eruptive rate for the East Summit is 0.5 $km^3$ per 1,000 years, released in two to four main episodes.

**Mount Martin** lavas are so blocky, glassy, and barely eroded that, despite a cone-encircling collar of active glaciers, it is clear that the edifice was built entirely within the last 10,000 years (table 1). Of the 7-$km^3$ present-day volume estimated for the volcano, the cone represents less than 5 percent and the 31-$km^2$ lava-flow field about 95 percent. The stack of lavas,

# CHRONOLOGY OF

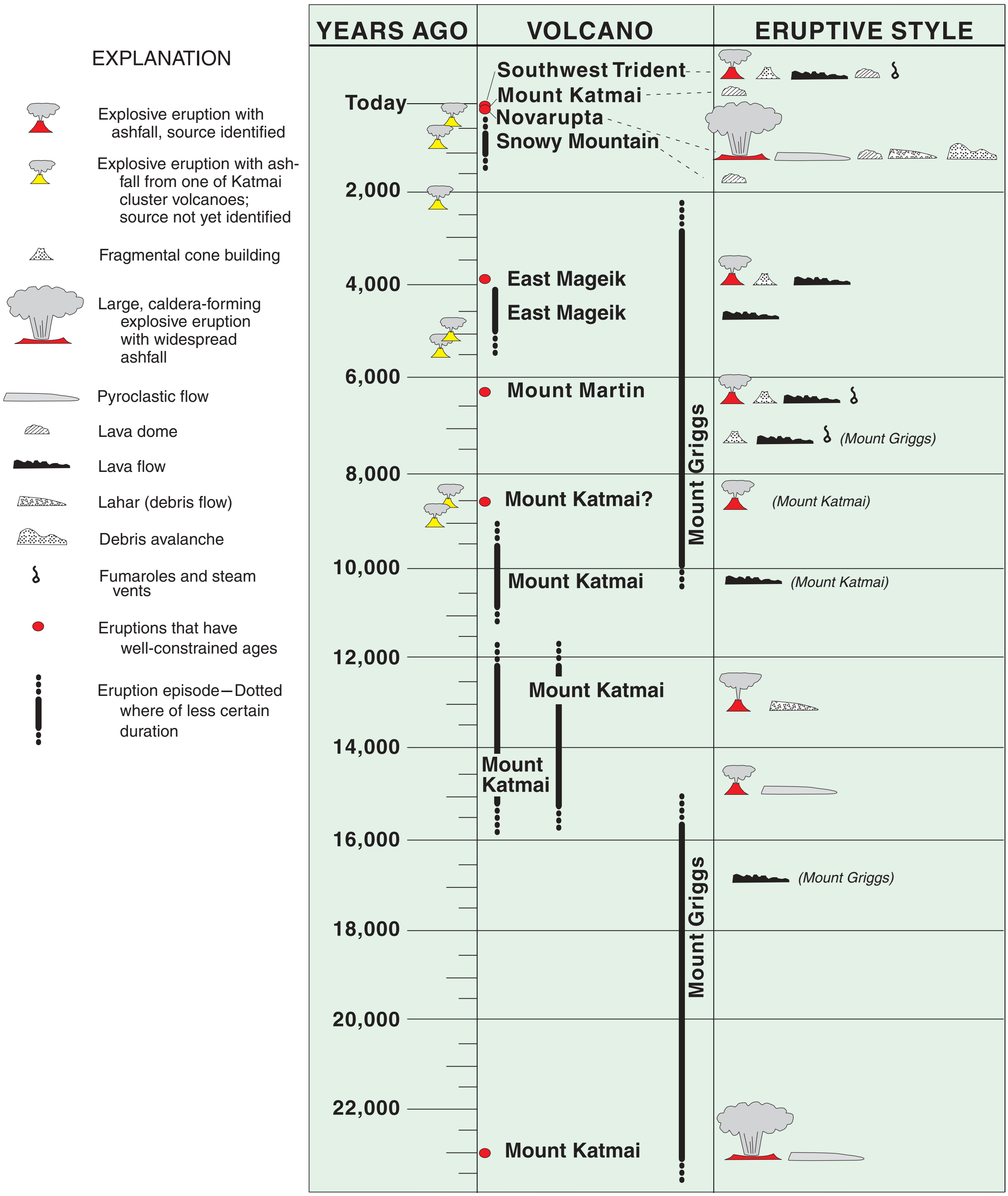



**Figure 19.** Chronology of youngest eruptive

# YOUNGEST EVENTS

| ERUPTIVE PERIOD | ACTIVITY |
|---|---|
| • 20 years (1953–74)<br>• Less than 4 years<br>• 3 days (June 6–9, 1912)<br>• Several years? | • Sporadic, small explosive eruptions as high as 10,000 meters, with minor gas and ash emission; new cone was built producing effusive lava in four stages; several transient plugs, destroyed by intermittent explosive activity. Fumaroles in modern crater<br>• Small lava dome grew on floor of Katmai caldera after the 1912 eruption of Novarupta<br>• Large caldera-forming event with plinian eruption columns as high as 26 kilometers; produced voluminous ashfall and pyroclastic flows. Strong earthquakes triggered lahars and debris avalanches; withdrawal of 13 cubic kilometers of magma caused collapse of Mount Katmai, 10 kilometers away<br>• Small lava dome grew in what was the summit crater of Northeast Snowy Mountain |
| • About four episodes, a few decades each, separated by decades to a few thousand years | • 12-18 lava flows plus summit cone, built over at least two, maybe four, eruptive episodes; youngest included moderate-sized explosive ash-producing eruption and lava flows; others included small-volume ash emissions and lava flows, and minor small-volume pyroclastic flows |
| • A few decades<br>• Decades to a few thousand years | • Small-volume ash emissions; 10 lava flows plus fragmental cone. Vigorous steam jets in modern crater, with acidic lake<br>• About 12 small-volume lava flows erupted in two episodes; built nested craters at summit; vigorous fumaroles precipitate sulphur in crater |
| • Several days? | • Moderate-sized explosive eruption with ashfall and minor gas emission<br>• About 25 small-volume lava flows |
| • Several years to a decade | • Two small-volume lava flows |
| • Days to months? | • Moderate to large explosive eruption with significant ashfall, debris flows (lahars), and hyperconcentrated sand flows |
| • Days to months? | • Moderate-sized explosive eruption with moderate ashfall and pyroclastic flows |
| • Several periods, decades to several thousand years each | • Dozens of small-volume lava flows |
| | |
| • Several days? | • Very large, caldera-forming event with plinian eruption column; produced voluminous ashfall and pyroclastic flows; may have been larger than the 1912 eruption of Novarupta |

events at the Katmai volcanic cluster.

confined to a 75-degree northerly sector and all fairly similar compositionally, could represent a single eruptive episode only years or decades long.

**Mount Griggs** has had numerous postglacial eruptions that produced at least a dozen lava flows that now cover about 20 percent of the volcano's surface. Although no large fallout-producing eruptions have been recognized as having come from Mount Griggs, postglacial activity has included several large *debris avalanches* (discussed below).

The only postglacial eruption from either of the two **Snowy Mountain** volcanoes was extrusion of Peak 6875, a young dacite lava dome. The dome sits in a 1.5-$km^2$ amphitheater created by collapse of the hydrothermally weakened upper part of the northeastern cone that produced a 22-$km^2$ debris avalanche. Carbon-14 ages of soil on top of this debris avalanche suggest it was emplaced within the last 1,500 years. The lava dome, therefore, is younger still.

## VOLCANO HAZARDS AT THE KATMAI VOLCANIC CLUSTER

A volcano hazard is any volcano-related process that potentially threatens life or property, with or without eruptive activity (fig. 20). Typically, several kinds of hazard will result from an eruption, the attendant risks depending upon the type and size of the eruption, and location relative to the volcano. The most threatening hazards from the Katmai cluster include volcanic ash clouds and pyroclastic fallout, pyroclastic flows, surges, and blasts, lava extrusions (domes and flows), lahars and floods, pumice rafts on Shelikof Strait, hydrothermal explosions, debris avalanches, volcanic gases, and eruptions through crater lakes. In any given area, the effects and extent of these volcano hazards will vary, depending on many factors, including (1) the size and duration of the eruption (which are difficult to predict even with modern instrumentation and monitoring techniques), (2) eruption type (for example, lava flow or explosive eruption), which can vary in time during an eruptive episode, (3) distance from the volcano, (4) proximity to any stream drainage that might become a pathway for any type of flow (lahar, flood, pyroclastic), (5) the amount of snow and ice that interacts with the eruption and eruptive products, and (6) wind speed and direction and general weather conditions (table 3).

### Local and Regional Hazards

**Local hazards**—those that occur in the immediate vicinity of the volcano, typically within a few tens of kilometers of the active vent—are likely to result in death or injury to anyone within that area. These would affect "nearby," "medial," and "overhead" areas (table 3). **Regional hazards**—those phenomena that are far reaching—usually provide greater lead times for warning but can affect large areas and numbers of people. Farther reaching than local hazards, these hazards would affect distal areas as well. These designations based on distance are variable, depending upon the scale of the eruption. Larger eruptions will have more severe impacts farther from the vent than smaller ones. In general, because the energy of most volcanic processes decreases with distance from source, the areas near an active vent will be affected most severely by whatever the hazard, with the impact lessened with distance (table 3). In the case of floods, lahars, and anything that flows, the hazard also decreases gradually with height above the flow path. In the remote area of the Katmai cluster of volcanoes, the area most at risk is airspace overhead (table 3). Aircraft can be gravely affected by airborne ash near the vent as well as at distances far from the volcano itself. Thus, eruptive style is important in assessing impacts of eruptions, and in this report, we present hazards in terms of the most likely eruption scenarios expected from the Katmai volcanoes (table 4). Based on our knowledge of each volcano's past eruptive history, the next section outlines the principal hazards from these volcanoes and the most likely extent of the danger zones associated with each.

### Volcanic Ash Clouds and Aircraft

The greatest hazard from future eruptions of the Katmai cluster is airborne volcanic ash. Whether large or small, explosive eruptions send fine ash particles upward. The ash, initially thrust upward as high as several kilometers by the power of the volcanic eruption, is carried upward higher still by convection of heated air, until the entrained particles and accompanying gas are captured by prevailing winds and carried away from the volcano as an ash cloud. The height and volume of an ash column and subsequent ash cloud depend on the size, duration, and type of eruption.

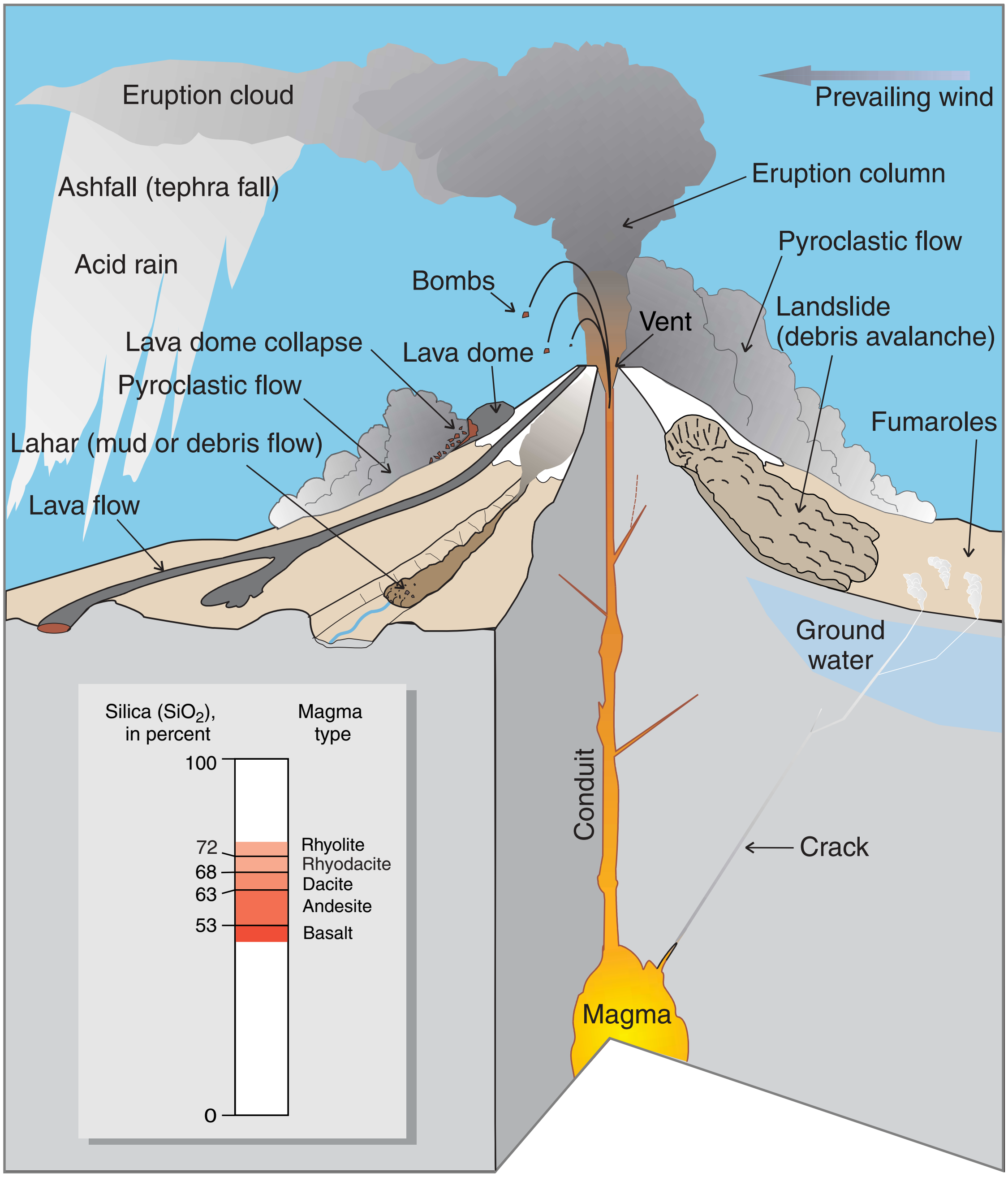



**Figure 20.** Hazardous phenomena associated with active volcanoes. Small eruptions typically pose hazards only within several kilometers of a volcano, whereas larger eruptions can endanger people and property at tens to hundreds of kilometers distant. Ash clouds can travel thousands of kilometers from a volcano and pose hazards to aircraft far downwind. Silicic magmas (rhyolite, rhyodacite, dacite) tend to erupt more explosively than mafic (andesite and basalt) magmas. (Modified from Meyers and others, 1997.)

**Table 3.** Summary of volcano hazards at the Katmai volcanic cluster

[See fig. 20 and text for schematic representation and description of some of these processes]

| Type of hazard | Degree affected* | | | | Comments |
|---|---|---|---|---|---|
| | Nearby area | Medial area | Distal area | Overhead | |
| Ash clouds | Major | Major to slight | Major to slight | Major | Severe hazard to aircraft even hundreds to thousands of kilometers downwind. Large eruptions produce large ash clouds, and stratospheric winds distribute ash clouds widely. |
| Fallout | Major | Major to slight | Major to nil | Major | Significant hazard to anyone on or around the volcano and to nearby communities during large eruptions. Major hazard in medial and distal locations during large eruptions. |
| Ballistics | Major | Nil | Nil | Nil | Significant hazard to anyone on or around the volcano during explosive eruptions. |
| Pyroclastic flows and surges | Major | Major | Nil | Slight | Significant hazard to anyone near the vent during eruptions; possible hazard within 10 to 30 kilometers of the volcano during large eruptions. |
| Lava flows and domes | Major | Slight | Nil | Nil | Significant hazard in immediate vicinity of lava flow or dome; attendant pyroclastic surges, ash clouds, fallout, or ballistics increase area potentially affected. |
| Debris avalanches | Major | Major to slight | Nil | Slight to nil | Significant hazard to anyone on or around the volcano during event, especially in valleys and low-lying areas near the volcano. |
| Rockfalls and landslides | Major | Slight to nil | Nil | Nil | Persistent hazard to anyone near steep walls of the volcanoes. |
| Lahars and floods | Major | Major to slight | Slight to nil | Nil | Significant hazard in all drainages downslope from eruption site and especially fords on River Lethe and Knife Creek. Greatest hazard when snowmelt is high and during or after heavy rains. Can be the downslope runout of debris avalanches and can be triggered by rockfalls and landslides. |
| Volcanic gases and fumaroles | Major | Nil | Nil | Nil | Significant hazard at present to anyone in and around actively degassing summit craters of Mounts Griggs, Mageik, and Martin and of Southwest Trident or near flank fumaroles on Trident I. |
| Volcanic earthquakes | Slight | Slight | Nil | Nil | Minor hazard except for secondary effects such as rockfalls and landslides. Volcanic seismicity before the 1912 eruption prompted residents of villages 20 kilometers from vent to leave. |
| Tsunami or waves | Nil | Nil | Nil | Nil | Tsunami in Shelikof Strait extremely low probability hazard; disruption of Naknek Lake by earthquakes, landslides, and other mass flows would pose a hazard to shoreline and areas near mouth of Ukak River. |

*"Nearby" implies near source, approximately to the base of the volcanic cone. "Medial" implies as much as a couple of dozen kilometers downstream from source (for instance, to Shelikof Strait or Naknek Lake). "Distal" implies locations far from the volcanoes, like King Salmon and Kodiak. "Overhead" means above the volcanoes (i.e., overflying aircraft).

Even the modest eruption that began the building of Southwest Trident in 1953 sent an ash plume as high as 12 km, and airplanes would have given it wide berth for at least several days. Although subsequent eruptions were less explosive, the intermittent ash clouds being less than 10 km high, they would have necessitated diversion of aircraft, for hours to days at a time, throughout the 20 years of activity at Trident. Large explosive eruptions, like Novarupta in 1912, produce vertical columns of ash and gas that can ascend to 35 km (21 mi, or 115,000 ft) or more above sea level. Disruption of air traffic (had there been any) would have been severe and long lived in 1912—planes would have been grounded throughout much of Alaska for at least several days and diverted from the Aleutian corridor for at least months.

The most immediate hazard from an explosive eruption in Alaska is to aircraft that inadvertently enter its ash cloud. Volcanic ash can interfere with aircraft-engine operation, damage electronics, and abrade lead-

**Table 4.** Probability of eruption scenarios and principal hazards associated with each volcano in the Katmai cluster

[ka, thousands of years before present; <, less than]

| Style or activity | Example | Principal hazards | Probability for each volcano | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Alagogshak | Mount Martin | Mount Mageik | Trident Volcano | Mount Katmai | Novarupta | Mount Griggs | Snowy Mountain |
| Quiescence | Most volcanoes, most of the time | Resuspended ash, rockfall, local earthquakes | High | High | High | High | High | High | High | High |
| Phreatic explosion | Mount Mageik summit crater | Ballistics, pyroclastic surges, ashfall | Low | High | High | Medium | High | Low | Medium | Medium |
| Strombolian eruption: lava flow | Southwest Trident, 1953–74<br>Mount Martin, about 6 ka<br>Mount Mageik, 4 ka | Lava flows, steam explosions, ballistics, ashfall | Low | High | High | High | High | Low | High | Medium |
| Phreatomagmatic eruption | Mount Katmai, 1912 | Widespread ashfall, pyroclastic surges, ballistics, lava flows | Low | Low | High | Low | High | Low | Low | Low |
| Dome formation | Novarupta, 1912<br>Snowy Mountain, <1.5 ka | Pyroclastic surges and flows, local ashfall, ballistics | Low | Medium | High | Medium | Medium | Low | Low | Medium |
| Subplinian eruption | Mount Mageik, 4 ka<br>Mount Katmai, <10 ka | Pyroclastic surges and flows, local to medial ashfall, ballistics | Low | Low | Medium | Low | High | Low | Low | Low |
| Plinian eruption | Mount Katmai, <16 ka<br>Mount Katmai, 23 ka | Pyroclastic surges and flows, regional ashfall, ballistics | Low | Low | Medium | Low | High | Low | Low | Low |
| Caldera-forming eruption | Novarupta, 1912 | Catastrophic: widespread ashfall, ash flows, earthquakes | Low | Low | Low | Low | Medium | Low | Low | Low |

ing edges of wings, windscreen, and other surfaces (Casadevall, 1994a, b). The consequences of such an encounter could be fatal. In 1989, a Boeing 747 jet bound for Anchorage entered an ash cloud from Redoubt Volcano and lost power in all four engines. For 5 minutes, the airplane fell toward the mountains before the flight crew was able to restart the engines and land safely (Casadevall, 1994a). Although the danger is greatest to jet aircraft owing to the high operating temperatures of jet engines and consequent melting of ingested ash, volcanic ash can be hazardous to other aircraft as well. In addition to impacts of solid ash particles on aircraft, acidic gases released in volcanic eruptions can form aerosol-laden clouds that remain in the atmosphere for months, accelerating corrosion of airplane parts.

**Ash dispersal, magma type, and hazards:** The severity of the ash-cloud hazard to aviation depends on the distance from the volcano and other characteristics of the plume such as the concentration and size of ash particles, the rise rate, and dispersal pattern. These are all strongly influenced by the type of magma erupted. Magmas are classified according to silica ($SiO_2$) content, which controls their viscosity (resistance to flow or to bubble escape) and hence influences eruptive styles. When the gases dissolved in a highly viscous magma escape during eruption, they tear the magma apart violently and explosively. The largest and most explosive eruptions are those involving gas-rich magma high in $SiO_2$. Although the most *silicic magma* of all—*rhyolite*—is not very common among Aleutian volcanoes, it was high-$SiO_2$ rhyolite that erupted during the great eruption of Novarupta in 1912. The Novarupta outburst had 600 times the ash volume of the 1989–90 eruption of Redoubt (of intermediate composition—andesite), and fallout dispersal that dwarfs all other historic eruptions in Alaska (fig. 21*A*).

In contrast to Novarupta, little of the ash from the 1953–74 eruptions of Southwest Trident traveled farther than a few kilometers from the vent, and the highest eruption columns were about 12 km. This much more restricted ash distribution is typical for magmas of intermediate composition (andesites to dacites, 53–68 percent $SiO_2$). Although the recurrence interval for very large explosive eruptions is long, there have been many smaller explosive events from the Katmai group of volcanoes that ranged in size from the typically small andesite–dacite ash eruptions, like those of Southwest Trident and Mount Martin, to medium-sized dacitic eruptions from Mounts Mageik and Katmai that sent ash columns well into the stratosphere. Besides the large event of 1912, there have been no fewer than 15 eruptive episodes from the Katmai cluster in the last 10,000 years, each lasting days to tens of years and all of which could have produced ash clouds large enough to affect air traffic (figs. 19 and 21*B*).

Although the severity of the ash cloud hazard to aviation depends on the size of the eruption, any ash cloud is potentially harmful to aircraft and should be avoided. The ash-cloud hazard from eruptions in the Katmai group of volcanoes includes potential impacts over Canada and the conterminous United States (fig. 21).

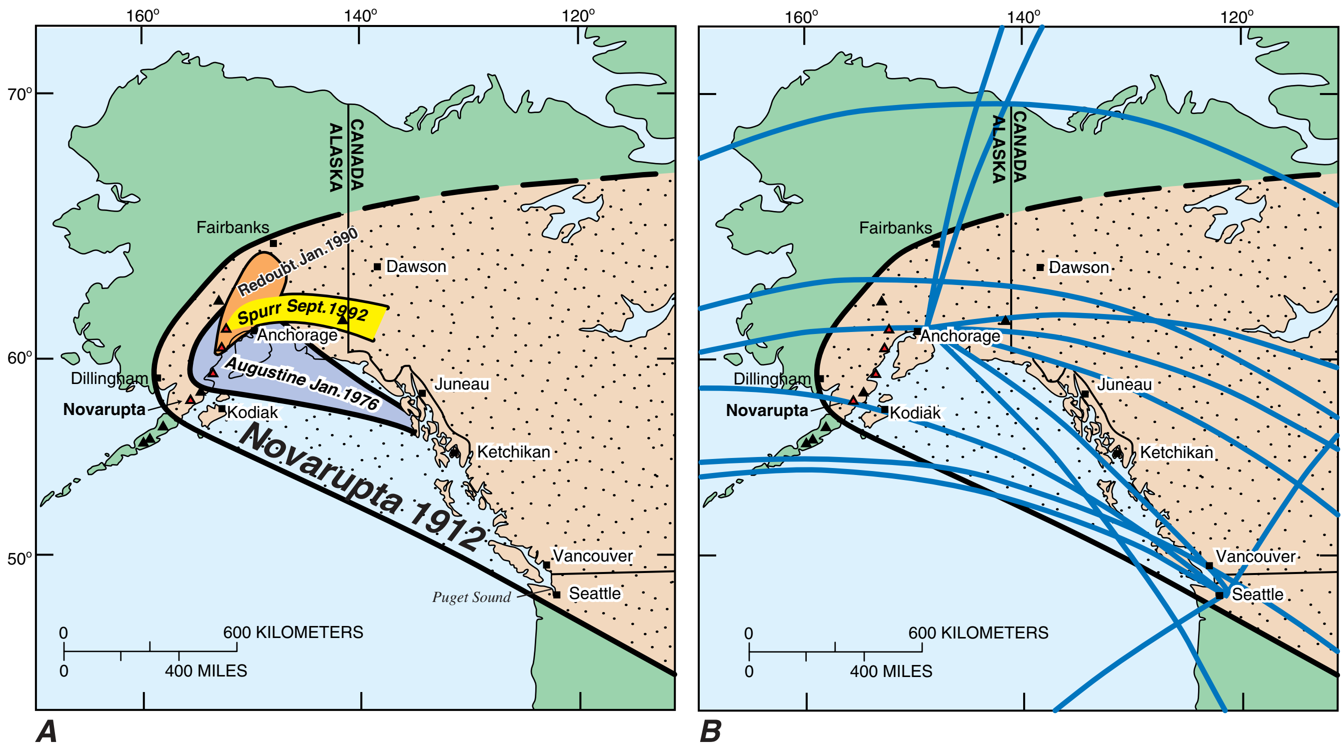



**Figure 21.** Ash clouds from 1912 Novarupta and more recent Alaska eruptions compared to air-traffic routes. *A*, Ashfall from the cataclysmic 1912 eruption of Novarupta dwarfs that produced by recent eruptions of Augustine Volcano, Redoubt Volcano, and Mount Spurr. Beyond areas shown here, ashfall from these recent eruptions was negligible, but ultrafine ash and sulfurous aerosols were held aloft and transported worldwide by high-altitude winds. *B*, Great-circle and other air-traffic routes (blue lines) between selected cities (Casadevall and others, 1999) would have been disrupted greatly by 1912 ashfall from Novarupta.

## Fallout

Pyroclastic fall deposits are made of material that rains out from an eruption column. The largest fragments (blocks and bombs) follow ballistic trajectories and rarely land more than 2 km from the vent. These can be very dangerous for anyone close to the volcano. Finer ejecta rise convectively upward in the eruption column before being transported downwind, then slowly settles to the ground to form a blanketing deposit called fallout. In general, fallout deposits decrease in thickness and grain size with increasing distance from the volcano. The height of the eruption column—usually a measure of the size of the eruption—and wind speed during the eruption are important factors in how much ash accumulates at any given point downwind. Near the eruption site, the fallout may be tens of meters thick for larger eruptions and contain bombs up to a meter or more across, although proximal fallout would be thinner for smaller eruptions (tens of centimeters to a few meters). At distances of 100 km, fallout of ash is typically less than 10 cm thick for larger eruptions, and it may be only a fine dusting of ash for smaller events. The finest ash from large eruptions can be deposited hundreds, or even thousands, of kilometers from source, thus—of all volcanic hazards—having the potential to affect the largest area.

The 1912 eruption of Novarupta was so large that fallout was 30 cm thick in Kodiak (fig. 11), 170 km southeast of the volcano along the axis of heaviest ash dispersal. In 1912, intermittent darkness and suffocating conditions immobilized the population for three days, roofs collapsed from the weight of the ash, ash avalanches from nearby hillslopes wrecked buildings, and ash-induced lightning struck and burned others. Water was undrinkable. Sore eyes and respiratory distress were rampant. With visibility nil, ships could not dock. Radio communication was down for days. Several villages were abandoned forever. So much ash fell across much of the region, that ash and acid rain blighted plant life and killed mussels, barnacles, kelp, and shallow-water fish. Millions of birds, ash coated and blinded, fell like flies. Mice and ground squirrels were decimated; hares and bears were blinded and starved; even mosquitoes were exterminated. Salmon suffocated in turbid lakes and streams or starved owing to destruction of the crustacea, molluscs, worms, and insect larvae they feed upon. The commercial sockeye salmon catch was hardest hit from 1915 to 1919 because of mortality and failure to spawn in the ash-choked streams of 1912–14. The biological impact was far worse overall than that of the Exxon Valdez oil spill of 1989.

Large explosive plinian events like Novarupta can devastate large areas, but they are infrequent. More common are the smaller scale events that built most of the volcanoes in the Katmai district. These included modest-sized eruptive episodes, lasting decades to centuries; many (though not all) included intermittent steam and ash clouds that had relatively small eruption columns which would have disrupted air traffic for hours to days at a time, intermittently throughout the duration of the eruptions.

## Lava Flows and Domes

When molten rock extrudes nonexplosively at the Earth’s surface, it can move downslope in elongate streams or fan-shaped lobes called lava flows, or it can pile up over the vent in rounded heaps of rubble called lava domes. The distance traveled depends on the viscosity (ease of flow) of the lava, eruption rate, eruption volume, steepness of the slope, and topography. Dacite and rhyolite lavas have high viscosity and typically form short, thick flows or domes. Andesite flows are less viscous and commonly travel several kilometers. All the Katmai volcanoes have been built in large part by successive lava flows and(or) domes stacked on top of one another through time, and future eruptions that produce lava flows and domes are likely.

In the last 10,000 years, lava flows have issued from most of the Katmai volcanoes, most recently at Southwest Trident in the1950s. Domes were extruded at Novarupta and in Katmai caldera, both just after the explosive eruptions of 1912. Hazards posed directly by lava flows are confined to the immediate area around the vent where the flows tend to follow topographic lows. Unlike pyroclastic flows and surges, lava flows at Katmai will seldom threaten human life because they move slowly enough that escape is almost always possible. Sudden explosions can occur, however, where lava enters water or ramps against snow or ice—likely events at Katmai where all the volcanoes support glaciers. Such events might generate enough meltwater to cause flooding. In some cases, thick, steep fronts of viscous lava flows can become unstable and collapse, releasing small but locally devastating pyroclastic flows.

Lava dome emplacement is commonly accompanied by explosive phenomena that are quite hazardous. As the viscous lava is forced out of the vent and accumulates on the surface—usually into a steep-sided pile of large blocks—unstable sections can collapse suddenly and generate avalanches of hot rocks, pyroclastic flows and surges, and ballistic showers. Such a dome disruption in 1912 scattered large lava blocks around the vent before the Novarupta lava dome was extruded. Moreover, quiet effusion of a lava dome can abruptly change character and produce explosive tephra columns without significant warning. Such explosions took place several times during the 1953–74 Southwest Trident episode. Similar events, probably larger, occurred at Mount Martin between 6 and 5 k.y. ago and at Mount Mageik about 4 k.y. ago.

The hazard areas for potential inundation by lava-flow and lava-dome eruptions for each of the volcanoes is based on the volumes and styles of past eruptions at each vent and local topography. The small-volume andesite lavas of Mount Griggs are unlikely to erupt explosively or to flow far, but blockage of either of the forks of Knife Creek could cause flooding that would certainly have downstream affects until new stream channels were established. Eruptions from the more silicic centers—Mounts Martin, Mageik, and Katmai—are likely to produce intermittent ash columns with dome or lava-flow emplacement. Much of Mount Katmai was built from hot rock avalanches and pyroclastic flows, which likely started erupting as domes or lava flows near its (now-beheaded) summit. A lava-dome or lava-flow eruption on the present-day Katmai caldera floor, as well as at Mounts Martin and Mageik, could be especially explosive because there are now crater lakes to interact with hot magma.

## Pyroclastic Flows, Surges, and Blasts

Among the most dangerous phenomena resulting from explosive eruptions are hot (as much as 800°C) mixtures of gas, ash, and volcanic rock fragments that travel at speeds as great as tens of meters per second away from the vent. Called pyroclastic flows, these are produced either during the explosive or gravitational collapse of a growing lava dome, or from the collapse of all or part of an overloaded eruption column that falls back to the ground and descends the volcano's flanks at high speeds. Small and moderate-sized pyroclastic flows tend to be ground-hugging, to follow topographic lows, and to travel several kilometers from the volcano. Large pyroclastic flows form during cataclysmic eruptions of enormous quantities of magma; some can be highly mobile, crossing mountains and ridges, and traveling 100 km or more.

Some of the pyroclastic flows from Novarupta in 1912 penetrated the nearby 5,000-foot saddles of Trident Volcano, and others traveled as far as 25 km from the vent. Because of their speed, pyroclastic flows offer no time for evacuation once they occur. As a result, pyroclastic flows typically kill nearly everything in their path. These flows will destroy vegetation by uprooting and stripping foliage, branches, and bark. They can start fires, causing even more widespread damage to vegetation and wildlife. Buildings would provide little protection, even on the periphery of the flow path. The pyroclastic flows that filled the Valley of Ten Thousand Smokes buried whatever was in that glacial valley in 1912—from willows to bears—with 11 $km^3$ of ash and pumice. It remains largely unvegetated, nearly a century later.

Flows that are highly dilute, gas rich, and turbulent are called "surges." They too are extremely mobile, form from collapsing lava domes, separate from the top of a denser pyroclastic flow, or issue directly from the vent as explosive blasts that can travel at speeds in excess of 100 m/s. The presence of water, either as shallow ground water, snow or ice, or in lakes near the erupting vent, increases the likelihood of *pyroclastic surges* due to steam-driven explosions as hot magma or rock fragments contact water.

One small pyroclastic flow from East Mageik partially buried the flank of that volcano 6 to 4 k.y. ago, and several small pyroclastic flows from Trident Volcano traveled at least several kilometers down its flanks and into Mageik Creek earlier than 10 k.y. ago. Mount Katmai, however, has had a long history of small pyroclastic flows and at least three large explosive eruptions in the not-too-distant past: (1) the rhyolitic eruption about 23 k.y. ago that generated large-volume fallout and pyroclastic flows which traveled at least 25 km from the volcano, (2) a large dacitic eruption 16 to 12 k.y. ago that apparently sent ashfall at least as far as the Kenai Peninsula, and quite likely had moderate-sized pyroclastic flows associated with it that generated flood deposits downstream, and (3) another dacitic event of similar age or slightly older that erupted pyroclastic flows large enough to have flowed more than 20 km—even to the Ukak River.

Only a small remnant is preserved, on the southwest foot of Mount Griggs.

Future eruptions from the Katmai cluster are likely to originate near the current summits or on the flanks of the volcanoes. The higher in elevation the source vent, the more likely that pyroclastic flows could be generated, especially those produced by lava-dome or lava-flow failure, simply due to the steepness of the slopes. Drainages that head on the volcanoes are at greatest risk from pyroclastic flows and surges of any size, especially within several kilometers of the vent. Explosive eruptions that could affect larger areas by producing small, but more mobile, pyroclastic flows, would not be unexpected from Mount Mageik and are considered likely from Mount Katmai (table 4). Such flows could travel downslope nearly unimpeded, their travel distances confined most strongly by the volume of the flow.

### Lahars and Floods

Lahars are volcano-derived *debris flows*, rapidly flowing mixtures of water, mud, and rock debris. Including all sizes of material, from boulders to silt, they can range from dense, viscous slurries resembling wet concrete (as much as two-thirds sediment and one-third water by volume) to turbulent muddy flows that are mostly water. Some lahars can begin as simple floods of water that incorporate volcanic debris as they travel downslope. Others form directly from pyroclastic flows or debris avalanches that mix with water as they travel down stream valleys. Lahars commonly get bigger as they move downstream and are channeled into river valleys, traveling as quickly as 20 m/s in steep channels close to a volcano and 5 to 10 m/s on more gentle gradients. Especially when highly laden with sediment, a lahar can be enormously destructive, commonly traveling tens of kilometers and inundating everything in its path.

Any of the steep snow-covered slopes of the Katmai volcanoes are potential sources of lahars. Pumice from the 1912 eruption of Novarupta mantles many of the surrounding hillslopes and forms an ample source of sediment to be funneled into the radial drainages cut into each of the volcanoes. Additionally, the volcanic cones have been dissected by glaciers, which commonly leave steep-sided, unstable rock cliffs perched above glacial troughs; these, too, provide a ready source of boulders and debris. Always unstable and contributing to small rockfall, these steep upper flanks could become the sources of lahars, with or without a concurrent eruption. Triggered by heavy rain, earthquakes, or volcanic explosions, any kind of slope failure on the upper reaches of the volcanoes would be lubricated by snow and ice. Hot lava melting snow or ice, explosive expulsion of water from the crater lakes on Mounts Katmai, Mageik, and Martin during an eruption, or exceptionally high storm runoff could all supply water sufficient to entrain sediment and entrain a debris flow. Farther downstream, as the coarsest material drops out, the flow can become “hyperconcentrated” (20 to 60 percent sandy sediment by volume). If enough sediment is lost during flow, but the volume of water remains sufficient, the lahar may transform into normal streamflow or flood (having sediment concentrations below 20 percent).

Lower on the volcano flanks, along margins and toes of the glaciers that head on all these peaks, seasonal subglacial outburst floods are not uncommon. Although glacial streams are always muddy, the sudden addition of significant amounts of water due to heavy rains or melting of snow and ice from a volcanic eruption, or addition of sediment due to a volcanic eruption, can cause these already sediment-laden streams to transform into lahars and floods. Sometime during 1998–99, an especially large outburst flood changed the course of the stream on the west margin of Glacier 1 (north flank of Trident Volcano) at the head of the Valley of Ten Thousand Smokes, cutting a new channel through the 1912 pumice deposits.

Although all the Katmai stratovolcanoes are steep and snow-clad and could generate lahars of all sizes, the remoteness of the region mitigates the risk. Because this is now a wilderness area with no permanent settlements nearby, lahars and floods generally threaten only wildlife, temporary camps, and recreational users of the backcountry. Only larger scale lahars would have drastic effects farther than 10 to 20 km from the volcanoes, but there have been and will be many small to moderate-sized lahars with significant impacts for those nearby. At present, no warning system exists to alert people of lahars or glacial outbursts, unless they are triggered by eruptive activity.

A number of moderate-sized lahars were associated with the 1912 eruption. At the southern foot of Mount Katmai is a remnant of a debris flow as much as 18 m thick. It is made up entirely of pumice and ash that erupted at Novarupta, fell on the snow-covered slopes of Mount Katmai, and was then remobilized into a steep canyon on the southern flank of Mount Katmai soon after the 1912 eruption ended. This lahar, which traveled at least 10 km downslope and had a total volume as much as 10,000,000 $m^3$, may have been triggered by seismicity resulting from caldera collapse at Mount Katmai at the end of the 1912 eruption. Flooding and lahars in Martin Creek were caused by an avalanche from the south flank of Mount Mageik, also triggered by 1912 seismicity. Lahars also swept the surface of the Valley of Ten Thousand Smokes ash-flow sheet soon after the eruption; they were supplied by meltwater from glaciers mantled with hot ash and by catastrophic breaching of a lake temporarily impounded by 1912 deposits in upper Knife Creek. Because the deep gorges that now drain the Valley of Ten Thousand Smokes were not yet cut, these lahars overran the ash-flow sheet and poured beyond its terminus more than 20 km from Novarupta. The old Savonoski village site, where the Savonoski and Ukak Rivers join Naknek Lake, was affected by these lahars and progressively buried by the greatly enhanced supply of stream alluvium eroded from the 1912 pyroclastic deposits.

Perhaps the best publicized lahars associated with Novarupta occurred a few years after the eruption itself. A landslide, triggered by 1912 seismicity, dammed Katmai River in Katmai Canyon during the eruption. Katmai River remained dammed for three years, but, after a very heavy snowmelt in 1915, the dam was breached and an enormous flood broke out through Katmai Canyon. When Griggs (1922) landed on the shore of Katmai Bay in 1915—nearly 30 km downstream from Katmai Canyon—he “found the countryside ravaged by a great flood whose waters were just subsiding.” Although Griggs called it a “flood,” a great volume of debris was transported. The 10-km-wide tidal-flat area was choked with pumice and ash, making upriver stretches like quicksand and destroying Katmai village (already abandoned in 1912). Trees were snapped off near ground level for several kilometers by the violent impact of the water, a fan of huge boulders was deposited at the mouth of the canyon, and the water volume was so great that it flooded the 10-km-wide valley as deep as 3 km. Whereas in 1912 a 35-foot schooner could enter the river mouth at Katmai Bay, after the flood it was so choked by ash that even a rowboat could not navigate the main channel (Griggs, 1922).

Lahars and floods have occurred sporadically as long as there have been volcanoes in the district. Eroded remnants of such lahars from Trident Volcano traveled several kilometers down its southern flank before entering the canyon of Mageik Creek. A good-sized explosive eruption from Mount Katmai 16 to 12 k.y. ago was the source of laharic and hyperconcentrated sand-flow deposits that are still preserved as much as 28 km northwest from source and are clearly visible from the one road in Katmai National Park between Brooks Camp and the Valley of Ten Thousand Smokes. These lahars probably overran glaciers then occupying the Valley.

Beyond the immediate vicinity of the volcanoes, the most significant risk from lahars is inundation of waterways by pumice and ash (fig. 22). Still today, pumice clasts from the 1912 eruption are washed into Naknek Lake and can be found along the beach at Brooks Camp. Most of the rivers that drain northward from the Katmai volcanoes empty into Naknek Lake. Rivers that drain the southern flanks of the volcanic chain empty into Katmai Bay on Shelikof Strait. Kejulik River, which drains the southwest flank of Mount Martin and Alagogshak volcano, flows toward Becharof Lake. Angle Creek, which drains the north flank of Mount Martin, is a tributary of the King Salmon River that makes its way more than 100 km westward—first through Katmai National Park, then through Becharof National Wildlife Refuge—before it reaches Egegik, near the Bristol Bay coast. These drainages are long and convolute—the small edifices of Alagogshak and Mount Martin are unlikely sources of lahars large enough to impact settlements near their mouths. Small to moderate-sized lahars (caused by destabilizing existing Mount Martin lavas) or newly erupted lava could be funneled down these drainages.

## Pumice Rafts

Coarse pumice erupted during moderate to large explosive eruptions can be carried to the sea or lakes by lahars, pyroclastic flows, and fallout in such large amounts that they form extensive sheets, or “rafts,” of floating pumice. Such rafts drift with the prevailing ocean currents for weeks, months, even years, and, in the Katmai area, could interfere with boats on Naknek Lake or Shelikof Strait. Hubbard (1935) reported great rafts of 1912 pumice still floating in Shelikof Strait 22 years after the eruption.

## Hydrothermal Explosions

When magma heats ground water circulating in a volcano, it creates a "hydrothermal system." The hot water typically dissolves rock material, like silica, iron, calcium, and sulfur, which tend to precipitate near the cooler ground surface and clog pathways for convecting hot waters. If the water gets hot enough and is converted to steam, its volume is increased significantly. (At the Earth's surface, heating water to 1,000°C increases its volume by a factor of 6,000.) This volume increase can generate powerful "hydrothermal explosions" that erupt steam, mud, and rock fragments. Although violent, such eruptions do not necessarily involve new magma coming to the surface, and the hazardous area is generally relatively close to the explosion site. At least six hydrothermal explosions accompanied caldera collapse at Mount Katmai during the three days of the 1912 eruption of Novarupta. This is known because the mud and rock fragments ejected from Mount Katmai are intercalated with the pumice fallout layers that were erupting

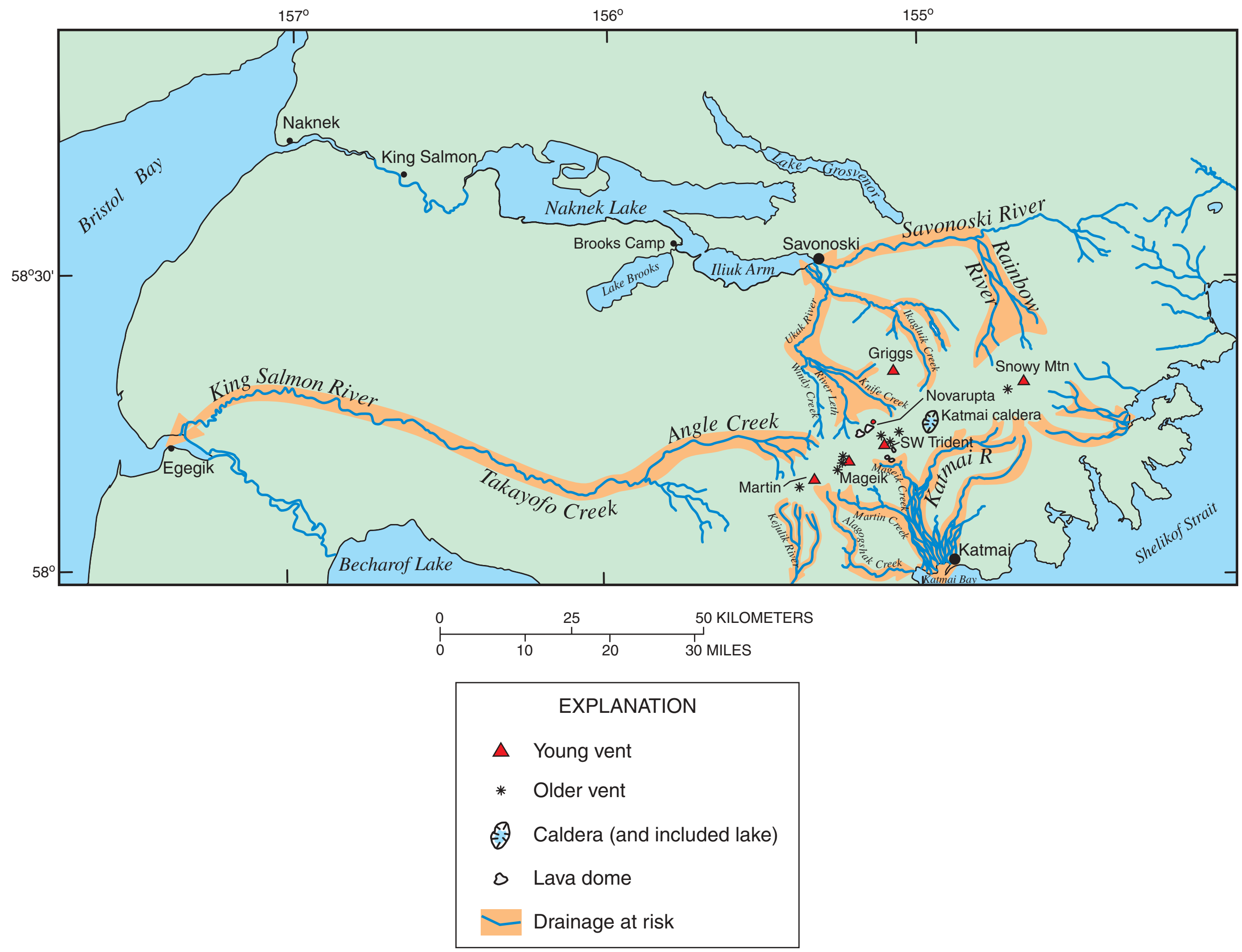



**Figure 22.** Drainages at risk as pathways for lahars and floods, which can inundate waterways with pumice and ash. Most rivers that drain northward from the Katmai volcanoes empty into Naknek Lake via the Savonoski River. Rivers that drain the southern flanks of the volcanic chain join Katmai River, which empties into Katmai Bay on Shelikof Strait. Angle Creek drains the northern flank of Mount Martin and flows westward, eventually joining King Salmon River, which flows onward to Bristol Bay coast. Drainage off south flank of Mount Martin enters Kejulik River, which flows into Becharof Lake (fig. 1). Savonoski and Katmai are abandoned village sites.

concurrently at Novarupta. The Katmai-derived mud layers contain chunks of rock as big as 17 cm as far as 5 to 8 km from the caldera rim, and on the rim itself they contain blocks bigger than 1 m.

All the Katmai volcanoes have active hydrothermal systems, any of which could give rise to hydrothermal explosions. Such activity, especially if accompanied by magma intrusion, might have precursory earthquakes hours to days beforehand. Hydrothermal explosions can occur without warning, however, especially if there is no new (seismicity-inducing) magma associated with the event. If strictly hydrothermal (no magmatic component to the explosion), the severe hazards from the explosions themselves would likely be restricted to within 1 to 2 km of the vent with low-level steam and ash clouds. However, hot explosions and seismic unrest would likely trigger lahars, flooding, and(or) debris avalanches (see next section), which could travel farther from the summit.

## Debris Avalanches, Landslides, Rockfalls, and Slope Stability

A debris avalanche is a rapidly moving mass or landslide of incoherent rock, soil, and debris. Formed during structural failure of a steep slope, such an avalanche can be triggered on volcanoes by intrusion of magma, seismicity, erosive undercutting, gradual weakening of edifice rocks by hydrothermal alteration, or heavy rain that may saturate and weaken parts of the cone. Failure along downslope-dipping bedding planes in layers of rock (dip-slope failure) is a common precondition for debris avalanches and landslides. Debris avalanches can travel a considerable distance from the source area but generally are confined to one sector of the volcano. Most volcanoes have steep, outward-sloping flanks, which add momentum to any debris avalanche initiated near the summit. Typically traveling at moderate speeds, debris avalanches commonly destroy everything in their path, and can occur with little or no warning. The remoteness of the area restricts the direct risk of these hazards to those who might be downhill and within 10 to 20 km when the avalanches let loose. A broader area could be affected, however, through transformation of a debris avalanche by mixing with rivers overrun and causing flooding and lahars (see section titled “Lahars and Floods”).

The hydrothermally weakened core of Northeast Snowy Mountain, deeply eroded by glaciers, was the source of a large debris avalanche that is no more than 10 ka in age, and is probably little more than 1.5 ka. The hummocky deposit—orange and yellow due to all the hydrothermally altered rock—still fills much of upper Rainbow River. Lahar and flood deposits (also full of hydrothermally altered clasts) are locally preserved downstream and are small remnants of the extensive flooding caused by the debris avalanche as the rivers were reestablished.

Several debris avalanches exposed on Mount Griggs (fig. 2) stand out as orange-colored deposits on the north, west, and south flanks of the volcano. The largest is the oldest (greater than 6,700 years old, by carbon-14 dating). The northern avalanche was emplaced more than 6,250 years ago. Distinctive avalanche blocks from Mount Griggs are also preserved as hummocks on top of early Holocene glacial deposits in the lower part of the Valley of Ten Thousand Smokes, 18 km from the volcano.

The hydrothermally weakened core of Mount Mageik, deeply eroded by glaciers, was the source of another large debris avalanche. Carbon-14 dating of associated deposits indicates that the debris avalanche is not much more than 3,400 years old. The hummocky orange and yellow deposit still fills much of Martin Creek. A younger debris avalanche triggered by 1912 seismicity overran the hummocky orange deposit. In stark morphologic and color contrast, the younger deposit is made entirely of black, glassy lava blocks that originated from dip-slope failure of steep rubbly lava stacks on the lower south flank of Mount Mageik.

Dip-slope bedding planes have been the sliding surface for many landslides and debris avalanches in the Katmai area, some of the largest of which are along the east side of Observation Mountain (14 km southwest of Mount Katmai). Although these are in nonvolcanic rocks of the Naknek Formation, such avalanches can be triggered by volcano-related seismicity, like those in Katmai River Canyon in 1912.

Debris avalanches are a significant hazard in areas close to the volcanoes, as are their smaller variants—rockfalls and landslides. Because rockfalls are daily events at these volcanoes, slope stability is critical in assessing the risks of these hazards even without eruptions. Just southwest of the summit of Mount Martin is the extinct Alagogshak volcano. Although no eruptions are expected from this center, glaciers have carved it deeply, leaving a hydrothermally altered north-facing summit headwall that has more than 1,500 ft of relief. Steep, unstable, glacially eroded headwalls that ring all the volcanoes, the inner walls of Katmai caldera and steep scarp of Falling Mountain, as well as several oversteepened places in Mageik Creek canyon and Katmai Canyon, provide a ready source of material for rockfalls and landslides. These range from the small trickles of pebbles and gravel-sized fragments that fall daily to large avalanches of boulder- and house-sized debris. Snow and ice avalanches occur at all scales, as well, and small falls are a daily occurrence in the summer months. Having summits over 6,000 ft, these steep-sided, snow-covered peaks can funnel debris as rockfall, landslides, and avalanches into any of the drainages that head on the volcanoes, with valleys and low-lying areas near the volcanoes being most at risk.

### Tsunamis

It is unlikely that even the largest eruptions, lahars, or debris avalanches possible from the Katmai area would be large enough to reach Shelikof Strait or Naknek Lake and initiate a *tsunami*; it is considered an extremely low probability event. (Great regional earthquakes, not directly related to the volcanoes, are nonetheless capable of causing major tsunamis along Shelikof Strait.)

### Volcanic Gases

Volcanic gases here consist predominantly of water vapor (steam) and subordinate carbon dioxide, sulfur dioxide, and hydrogen sulfide. Minor additional components are hydrogen, helium, carbon monoxide, hydrochloric acid, and hydrofluoric acid. Such gases are emitted in large amounts during an eruption, as well as in lesser quantities from cracks in the ground or from thermal areas known as fumaroles even when the volcano is quiet. Compounds in volcanic gases can affect eyes and respiration and can corrode metals and other materials. Heavier-than-air gases such as carbon dioxide are of special concern because they can collect in depressions and, in sufficient concentrations, will asphyxiate people and animals. Concentrations of gases dilute rapidly away from a volcano and seldom pose any threat to those more than a few kilometers from the active vent. The fumarolically active craters of Mounts Mageik and Martin and fumaroles on the south flank of Trident Volcano and west flank of Mount Griggs pose particular hazards because normal present-day emission levels of volcanic gases are high enough in those locations to constitute a real danger to anyone who manages to get there. The lakes in both the Martin and Mageik craters are yellow-green due to the high amount of sulfurous particles. The gases rising through the water in the Mageik crater actually bubble up so vigorously that it looks like a boiling cauldron. Visitors should only enter the crater areas, or be downhill from them, when the wind is strong enough to preclude the buildup of pockets of suffocating gases.

Steam jets from both Mounts Martin and Mageik condense to form clouds above the peaks in clear weather. A similar phenomenon—steam clouds rising from hot fumaroles—was the inspiration for the naming of the “Valley of Ten Thousand Smokes” by Robert F. Griggs in 1916. Although Hubbard (1935) wore a gas mask to protect himself from the unknown volcanic gases while he explored the valley in the late 1920s, the “smokes” were mostly water vapor that had been flashed to steam as it percolated through the still-hot ash flow, emplaced only a dozen years before during the 1912 eruption of Novarupta. Today, only a few warm spots can be found even near the 1912 vent. At present, there is no dangerously hot ground around Novarupta.

### Eruptions Through Crater Lakes

Lakes in the craters of Mounts Martin, Mageik, and Katmai create the potential hazard of lake water and magma violently mixing to generate an explosive *phreatomagmatic eruption*. The water–magma interaction acts as an intensifier for the eruption; the violence of the interaction is controlled by a number of factors, including magma type, volume, rate of extrusion, degree to which the magma is fragmented by expanding internal gas bubbles, and water depth.

Typically, the most explosive water–magma mixing occurs if the water is shallow (a few meters to tens of meters deep), if the magma extrudes rapidly, and if the magma breaks into coarse particles before it is quenched. These conditions allow rapid transfer of heat from the magma to the water, generating steam and explosive eruptions (Wohletz, 1986). Eruptions beneath deep water, where the pressure is high enough to inhibit the expansion of steam, tend to be much less violent than those through shallow water. Slow rates of lava extrusion typical of lava flows and silicic domes also inhibit violent mixing with water. Faster extrusion rates and large volumes of gas-rich silicic magma could overcome even deeper water, with explosive results.

The depth of water in the crater lakes of Mounts Martin and Mageik is very shallow, but the water in Katmai caldera is known to be more than 250 m deep today because the lake floor was exposed in 1923. With a surface area of 4.3 $km^2$, the lake volume is more than 1 $km^3$. In contrast, the areas covered by the Martin and Mageik lakes are each less than 0.03 $km^2$, and they are probably only a few meters deep. Because of the large volume of water in Katmai crater lake, and because of repeated silicic and fragmental eruptions from that volcano, an eruption through the Katmai caldera lake is considered both likely and quite dangerous. Although the volume of water in the Martin and Mageik crater lakes is small, it would likely add intensity to any crater-derived eruption. The disruption of such acidic lakes also increases the possibility of local acid rainfall and of sending acid-water-rich lahars and debris flows downhill from those summits.

## What's in a Name?

Had we written this report in 1950, we might have judged Trident Volcano, the most severely eroded and longest inactive center in the Katmai cluster, the one least likely to erupt. However, it erupted vigorously starting in 1953, sending ash clouds to 30,000 ft, that year and several times subsequently.

Moreover, had the Trident eruptions of 1953–74 broken out 3 km farther west (across Katmai Pass), we and everyone else would have called it a new eruptive episode (and component cone) of Mount Mageik—not of Trident. The eruptive style, morphology, and composition, in many ways, indeed resemble those of Mageik more closely than older components of Trident.

Such thoughts should temper any analysis of greater or lesser probability of future eruptions from adjacent volcanoes, however conventionally defined.

## Event Frequency and Risk

Explosive, ash-producing eruptions pose the greatest risk to life and property in this remote Alaska wilderness; aircraft are most at risk. Eruptive histories of the Katmai volcanic cluster show Mount Katmai and (to a lesser degree) Mount Mageik most likely to erupt explosively, conceivably on the scale of the great 1912 outburst (table 4). Such eruptions would be less likely from Trident Volcano, Snowy Mountain, Mount Martin, or Mount Griggs, where lava extrusion, dome building, and small ash-plume episodes have been the norm. Although any volcanic ash plume ejected into the atmosphere is of concern for aircraft, the scale of an eruption significantly affects the extent of its associated hazards and areas at risk.

"Normal" eruptive events in the Katmai district are characterized by the 1950s Trident eruptions, which sent several ash columns 2 to 6 km (6,600–20,000 ft) and a few 9 to 12 km (30,000–40,000 ft) into the atmosphere. Nearly 20 years of wind data from the National Oceanic and Atmospheric Administration show that prevailing winds at altitudes of more than 5.5 km would most commonly direct ash toward the southeast, whereas lower altitude winds (3 km) are most likely to direct ash toward the northeast (fig. 23). Although less common, winds do sometimes come from the Pacific, blowing northward and northwestward. Such were conditions that directed most of the 1953 Trident ash (Ray, 1967). Only rarely do winds in this area at any altitude blow westward, thus it is unlikely that significant amounts of ash (even from large eruptions) would be distributed more than a couple hundred kilometers west or southwest of the erupting volcano.

The size of the sector and extent of ash distribution depends mostly on the scale of eruption; large eruptions affect much larger areas than small ones. Ash clouds from Southwest Trident would have severely affected aircraft overhead and in the immediate Katmai area. The larger (but still moderate-sized) eruptions of Redoubt Volcano in 1990, Mount Spurr in 1992, and Augustine Volcano in 1976 and 1986 affected considerably larger areas several hundred kilometers away. The 1912 eruption of Novarupta was exceptional; ash distribution dwarfed that of all the other historic eruptions combined (fig. 21*A*).

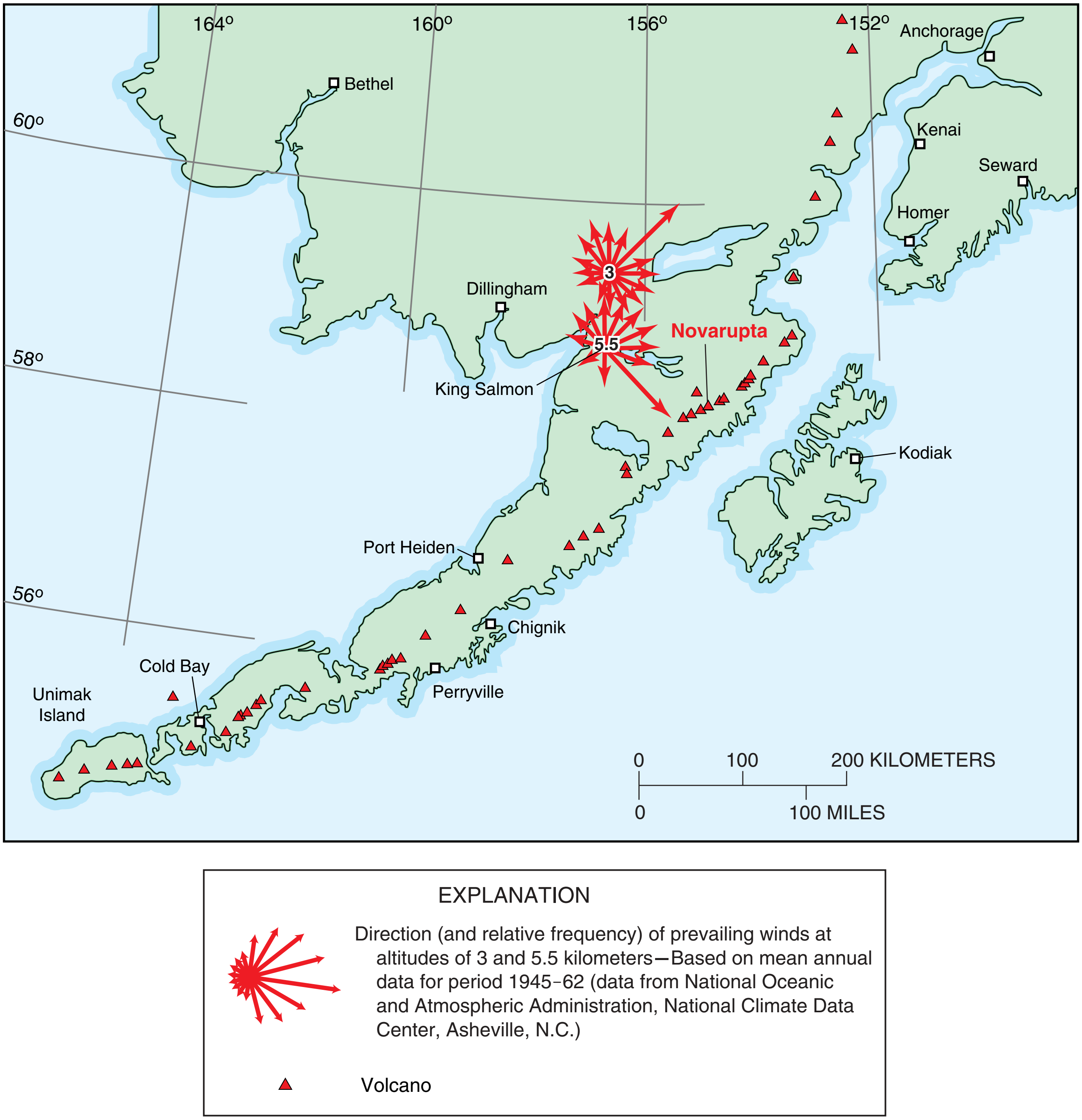



**Figure 23.** Prevailing-wind directions in vicinity of the Katmai volcanic cluster. Vector lengths (red arrows) indicate relative frequency of those wind directions at altitudes of 3 and 5.5 kilometers during year. Based on 18 years of National Oceanic and Atmospheric Administration daily data from King Salmon, Alaska.

Although small to moderate-sized eruptions have been common throughout the eruptive histories of the Katmai volcanoes (no fewer than 15 such episodes in postglacial time) and will continue to be, there have been three exceptional events and a few subplinian pumice falls from this cluster. Possibly the largest of all erupted about 23 k.y. ago, another about 16 k.y. ago (poorly preserved but clearly large), and, the most recent, less than a century ago (Novarupta). All three originated beneath Mount Katmai.

Although exceptionally large events occur infrequently, the potential effects are far reaching and severe. Now-populous Cook Inlet was severely blanketed with ash when Novarupta exploded (as it also was 23 and 16 k.y. ago). The Pacific Slope, too, was heavily mantled with pumice and ash (much of it remaining so today), and pumice rafts clogged Shelikof Strait and many of the bays along that coast. Ash was strongly wind directed east-southeast in 1912; the plight of inhabitants of Kodiak (fig. 11; 170 km directly downwind) made news headlines from San Francisco to Boston. Because of the sheer size of that eruption, significant amounts of ash fell even as far as 150 km upwind, to the northwest, covering what are today prime fishing and tourist areas.

### Potential Economic Effects

A normal Trident-scale eruption would affect mostly overhead aircraft and backcountry hikers. Given good communication between the AVO volcano-monitoring network and the aviation industry, and satellite ash-detection efforts by both AVO and the National Weather Service, air traffic could likely be rerouted much of the time to avoid intermittent ash plumes. Ash plumes thus could disrupt air traffic for days to weeks at a time, and such inconveniences could occur sporadically for a decade or more. Local small aircraft might be anticipated to even take the opportunity to make such an eruption a tourist attraction! Backcountry hikers, too, could be drawn to such a phenomenon. Such intrepid adventurers would be at risk for unexpected explosions, lahars, debris avalanches, and ballistic bomb showers that accompany such eruptions.

An exceptional Novarupta 1912-scale eruption, however, would have severe and long-lasting economic effects for Alaska. Today, in most fallout-affected settlements and airstrips, concerted cleanup might restore safe flying and working conditions in a week or so after a small event (like the eruption of Mount Spurr in 1992), but it could take many weeks to months after a large eruption like that of 1912. Even after initial cleanup, within 100 to 200 mi of the volcano, normal Alaskan windstorms would remobilize loose dust from devastated ash-covered slopes, lofting it high into the atmosphere. In 1912, such wind-driven recycling, probably assisted by ash-laden steam plumes from Katmai caldera, kept ash clouds aloft all summer. Aircraft would have remained at risk from Dillingham to Kodiak to Anchorage for at least several months. Automobile, snowmobile, and boat engines, even chain saws, also would be damaged by recurrence of such an eruption. Clinics would be overwhelmed by people with eye, throat, and lung damage. City water systems would be affected. Computer systems, bank-card machines, hospital circulation systems, and anything depending on outside air would have to switch to an internal air supply or be shut down. Commercial and recreational fishing would be hurt not only in the season of the ashfall but, owing to the impact on fry, smolt, and spawning adults, for years thereafter. Tourism would drop for at least the first year and in areas of heaviest ashfall probably for much longer. National and international commerce would be interrupted and inconvenienced briefly, North America–Asia commerce significantly so, with costly impacts, but Alaskan commerce would be temporarily devastated.

## VOLCANO MONITORING AND ERUPTION RESPONSE AT THE KATMAI VOLCANIC CLUSTER

The Alaska Volcano Observatory operates a network of 19 seismometers to detect earthquakes around the Katmai cluster of volcanoes (fig. 15). Volcanic earthquakes, caused by movement of magma or hydrothermal fluids beneath an edifice, are used to monitor the activity level of volcanoes, because most eruptions are typically preceded for hours to months by increased seismicity.

AVO uses other tools to monitor volcanic unrest: daily satellite observations (to look for thermal anomalies or the presence of ash in the atmosphere), airborne and ground-based volcanic-gas measurements, lake- and spring-water chemistry, fumarole temperature measurements, and surveys of ground deformation. Gas components, water chemistry, and fumarole temperatures have been measured sporadically since the Valley of Ten Thousand Smokes was first discovered. In 1990, a five-station array of permanent benchmarks was installed around Novarupta (Kleinman and others, 1997). These benchmarks were reoccupied in 1993 and 1995, using GPS surveying equipment to detect any changes in ground elevation related to volcanic activity. Periodic reoccupation of these benchmarks will continue during this monitoring effort, although expansion of the network would be required to monitor the other volcanoes in this manner.

Pilots and hikers commonly provide AVO with observations that are used to direct further investigations of reported phenomena. Sightings of new steaming ground, increased fumarolic activity, and possible ash plumes all prompt further investigation by AVO personnel.

If seismic activity, unusual steaming of the summit craters, or other signs of volcanic unrest were verified at any of the Katmai volcanoes, AVO would increase its monitoring efforts. Local, State, and Federal officials (including the National Park Service and U.S. Fish and Wildlife Service), as well as commercial air carriers, the Federal Aviation Administration, National Weather Service, emergency officials, and the media, would be alerted and advised of any changes in activity. If an eruption were imminent, AVO would provide explanations of likely events and impacts. A graduated color code explains the degrees of concern regarding the likelihood and consequences of an eruption (table 5).

During heightened volcanic unrest and throughout and after any eruptive activity, AVO's role is to provide information to appropriate authorities and the general public about the nature and status of the eruption. Many channels are already established for distributing this information: FAX, telephone, electronic mail, television, and radio (fig. 24). Once a volcanic crisis has passed, AVO continues monitoring efforts for signs of activity, and begins scientific studies of the new deposits and(or) data in order to better understand the volcano and volcanic processes. This, in turn, improves monitoring capabilities at the Observatory.

**Table 5.** Alaska Volcano Observatory Level-of-Concern color code

| Color | Intensity of unrest at volcano | Forecast |
|---|---|---|
| GREEN | Volcano is in quiet, "dormant" state | No eruption anticipated. |
| YELLOW | Small earthquakes detected locally and (or) increased levels of volcanic-gas emissions | Eruption is possible in next few weeks and may occur with little or no additional warning. |
| ORANGE | Increased numbers of local earthquakes. Extrusion of lava dome or lava flows (nonexplosive eruption) may be occurring | Explosive eruption is possible within a few days and may occur with little or no warning. Ash plume(s) not expected to reach 25,000 feet above sea level. |
| RED | Strong earthquake activity detected even at distant monitoring stations. Explosive eruption may be in progress | Major explosive eruption expected within 24 hours. Large ash plume(s) expected to reach at least 25,000 feet above sea level. |

**ALASKA VOLCANO OBSERVATORY**

**INFORMATION RELEASE**

Friday, March 17, 1995 10:00 am AST (19:00 UT)

**MOUNT MARTIN**
58°10'N 155°21'W
LEVEL OF CONCERN COLOR CODE: **GREEN**

On Wednesday, the National Weather Service received a report from King Salmon of steam plumes rising 2000-3000 feet over the general vicinity of Mount Martin volcano in Katmai National Park. Analysis of satellite imagery confirmed that no eruptive activity had occurred. Mount Martin is a 1860-m-high (6100 feet) volcano with no known historical eruptions. However, vigorous steam plumes from its summit crater are common.

ADDITIONAL INFORMATION

A voice recording of the current update is available by calling 907-786-7478. Information on the Alaskan volcanoes and AVO is posted on the Internet: http://www.avo.alaska.edu

PLEASE CONTACT AVO IF YOU HAVE ANY QUESTIONS OR COMMENTS

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**Figure 24.** Example of hypothetical information release from Alaska Volcano Observatory in response to probable volcanic unrest at the Katmai volcanic cluster.

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## GLOSSARY

**Agglutinate.** Fragments of volcanic rock, generally near-*vent fallout*, welded together by their own heat.

**Andesite.** Volcanic rock, usually dark grey, that contains about 54 to 63 percent *silica*. Andesite is the predominant rock type of most volcanoes on the Alaska Peninsula.

**Ash.** Fine fragments (less than 2 mm across) of volcanic rock formed in an explosive volcanic eruption.

**Ash cloud.** Cloud of gas, steam, *ash*, dust, and coarser fragments that forms during an explosive volcanic eruption and commonly gets blown long distances downwind. Also called an *eruption cloud*.

**Ballistic.** Fragments ejected explosively from a volcanic *vent* on an arcuate, ballistic trajectory, much like a cannonball. Ballistic fragments seldom land farther than a few kilometers from the volcano; concurrently erupted *ash clouds* go much farther. Also called a volcanic bomb.

**Basalt.** Volcanic rock with about 45 to 53 percent *silica*. Basaltic *lavas* are more fluid than andesitic or dacitic *lavas*, which contain more silica.

**Breccia.** Mixture of angular fragments in a finer grained matrix. Flow breccias typically form by partial breakup of *lava* flows on slopes. Hydrothermal or phreatomagmatic explosions commonly dump sheets of coarse breccia around their source *vents*.

**Caldera.** Crudely circular depression, generally larger than a *crater*, typically more than 2 km across, formed by collapse of a volcano during withdrawal or ejection of a large volume of *magma* that leaves the roof of the magma reservoir unsupported.

**Crater.** Bowl-shaped, funnel-shaped, or cylindrical depression, normally near the top of a volcano, and commonly less than 2 km across. Formed by volcanic explosions and usually involving constructive buildup of crater-rimming deposits rather than subsidence of the floor. Compare *caldera*.

**Dacite.** Volcanic rock that contains about 64 to 68 percent *silica*. Dacite *lavas* are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called *lava domes*. Dacitic *magmas* tend to erupt explosively, thus also ejecting abundant *ash* and *pumice*.

**Debris avalanche.** Rapidly moving slide masses of rock debris, sand, and silt that commonly form by structural collapse of a volcano. Can travel considerable distances from their source, and the resulting deposits are characterized by a hummocky surface.

**Debris flow.** Rapidly flowing mixture of water, mud, and rock debris. A volcano-derived debris flow is commonly called a *lahar*. Parts of *debris avalanches* can transform into debris flows by mixing intimately with the water in overrun rivers or lakes.

**Effusive eruption.** An eruption that produces mainly *lava* flows and domes (as opposed to an *explosive eruption*).

**Eruption cloud.** Cloud of gas, steam, *ash*, and other fragments that forms during an explosive volcanic eruption and travels long distances with the prevailing winds. Also called an *ash cloud*.

**Eruption column.** The ascending, vertical part of the mass of erupting debris and volcanic gas that rises directly above a volcanic *vent*. Once higher in the atmosphere, columns usually spread laterally into plumes or umbrella clouds.

**Ejecta.** General term for anything thrown into the air from a volcano during an eruption. Synonymous with pyroclast.

**Explosive eruption.** An energetic eruption that produces mainly *ash*, *pumice*, and fragmental *ballistic* debris (as opposed to an *effusive eruption*).

**Fallout.** A general term for all the *ash* and debris that falls to Earth from an *eruption cloud*.

**Fumarole.** A small opening, crack, or *vent* from which hot gases are emitted. Commonly on the floor of a volcanic *crater* but may be on a volcano's flanks. Short-lived fumaroles also issue from hot *lava* flows and *pyroclastic* deposits during their period of cooling.

**Hyperconcentrated sand flow.** A thick mixture of mostly sand and granules with enough water to enable it to flow downstream (typically 20 to 60 percent sandy sediment by volume). Commonly a downstream derivative of a water-saturated *debris flow* from which the larger fragments have already dropped out en route.

**Ignimbrite.** The deposit of a hot chaotic mixture of *pumice*, *ash*, and gas that travels rapidly (as fast as tens of meters per second) away from a volcanic *vent* during an *explosive eruption*. Ignimbrite is a pumice-rich type of *pyroclastic flow* that commonly accompanies *plinian eruption* columns. Synonymous with ash-flow tuff.

**Lahar.** A mixture of water and volcanic debris that moves rapidly downstream. Consistency can range from that of muddy dishwater to that of wet cement, depending on ratio of water to debris. Compare *debris flow*.

**Lava.** Molten rock that reaches the Earth's surface and maintains its integrity as a fluid or viscous mass, rather than exploding into fragments. Compare *magma*.

**Lava dome.** A steep-sided mass of viscous and often blocky *lava* extruded from a *vent*; typically has a rounded top and covers a roughly circular area. May be isolated (like Novarupta) or may be associated with lobes or flows of lava from the same vent.

**Mafic magma.** *Magma* that contains lower amounts of *silica* and is generally less viscous and less gas rich than *silicic magma*. Tends to erupt effusively, as *lava* flows. Includes *andesites* (54–63% $SiO_2$) and *basalts* (45–53% $SiO_2$).

**Magma.** Molten rock beneath the Earth's surface. Compare *lava*.

**Magma chamber.** A storage area or reservoir of molten rock (or *magma*) beneath the Earth's surface.

**Phreatic eruption.** An eruption that primarily involves steam explosions, usually ground water flashed by the heat of subsurface *magma*.

**Phreatomagmatic eruption.** An eruption that involves both *magma* and water, which typically interact explosively, and leads to concurrent ejection of steam and pyroclasts.

**Plinian eruption.** A large *explosive eruption* that produces a steady vertical *eruption column* of *pumice* and *ash*, that may reach tens of kilometers above a volcano. Results in far-traveled *ash clouds* and widespread *fallout* of *pyroclastic* debris and can have accompanying *pyroclastic flows* and *surges*. (Named for Pliny, who observed and reported on the eruption that devastated Pompeii in A.D. 79.)

**Postglacial**. Refers to the end of the last major ice age, about 10 k.y. ago—geologically the transition from Pleistocene (>10 ka) to Holocene (<10 ka) time. (The actual withdrawal of major Pleistocene ice sheets varied by location and latitude, from well before to a few thousand years after 10 ka.)

**Pumice.** Highly vesicular volcanic *ejecta*, essentially *magma* that has been frothed up by escaping gases and solidified during eruptive cooling. Rhyolitic pumice is typically of low enough density that it floats on water.

**Pyroclastic.** General term applied to volcanic products or processes that involve explosive ejection and fragmentation of erupting material. The Greek roots of the word mean "fire" and "broken."

**Pyroclastic flow.** A hot (typically greater than 800°C), chaotic mixture of rock fragments, gas, and *ash* that travels rapidly (tens of meters per second) away from a volcanic *vent*. Pyroclastic flows that form from an *explosive eruption column* contain a high proportion of fine ash and *pumice* and also are called ash flows or *ignimbrites*; pyroclastic flows that form by failure of the front of a cooling *lava dome* or flow are called block-and-ash flows.

**Pyroclastic surge.** A turbulent hurricane of volcanic *ash*, rock debris, and hot gas. Pyroclastic surges are low-density, turbulent types of *pyroclastic flows* that typically accompany *explosive eruptions*.

**Rhyodacite.** Volcanic rock with 68 to 72 percent *silica*. Rhyodacitic *lavas* are viscous and tend to form thick blocky lava flows or steep-sided piles of *lava* called *lava domes*. Rhyodacite *magmas* tend to erupt explosively, commonly also producing abundant *ash* and *pumice*.

**Rhyolite.** Volcanic rock with more than 72 percent *silica*. Rhyolitic *lavas* are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called *lava domes*. Rhyolite *magmas* tend to erupt explosively, commonly also producing abundant *ash* and *pumice*.

**Scoria.** Vesicular volcanic *ejecta*, essentially *magma* that has been frothed up by escaping gases. A textural variant of *pumice*, scoria typically is less vesicular, denser, and commonly andesitic or basaltic.

**Silica.** Predominant molecular constituent ($SiO_2$) of volcanic rocks and *magmas*. Tends to polymerize into molecular chains, increasing the viscosity of the magma. Basaltic magma, relatively lower in silica, is fairly fluid, but with increasing contents of silica, *andesite*, *dacite*, *rhyodacite*, and *rhyolite* magmas become progressively more viscous. The greater difficulty for dissolved gas to escape from more viscous magma makes higher silica magmas generally more explosive.

**Silicic magma.** *Magma* that contains more than about 63 percent *silica*. Generally viscous and gas rich, it tends to erupt explosively. Includes *rhyolite*, *rhyodacite*, and *dacite* in the Katmai cluster.

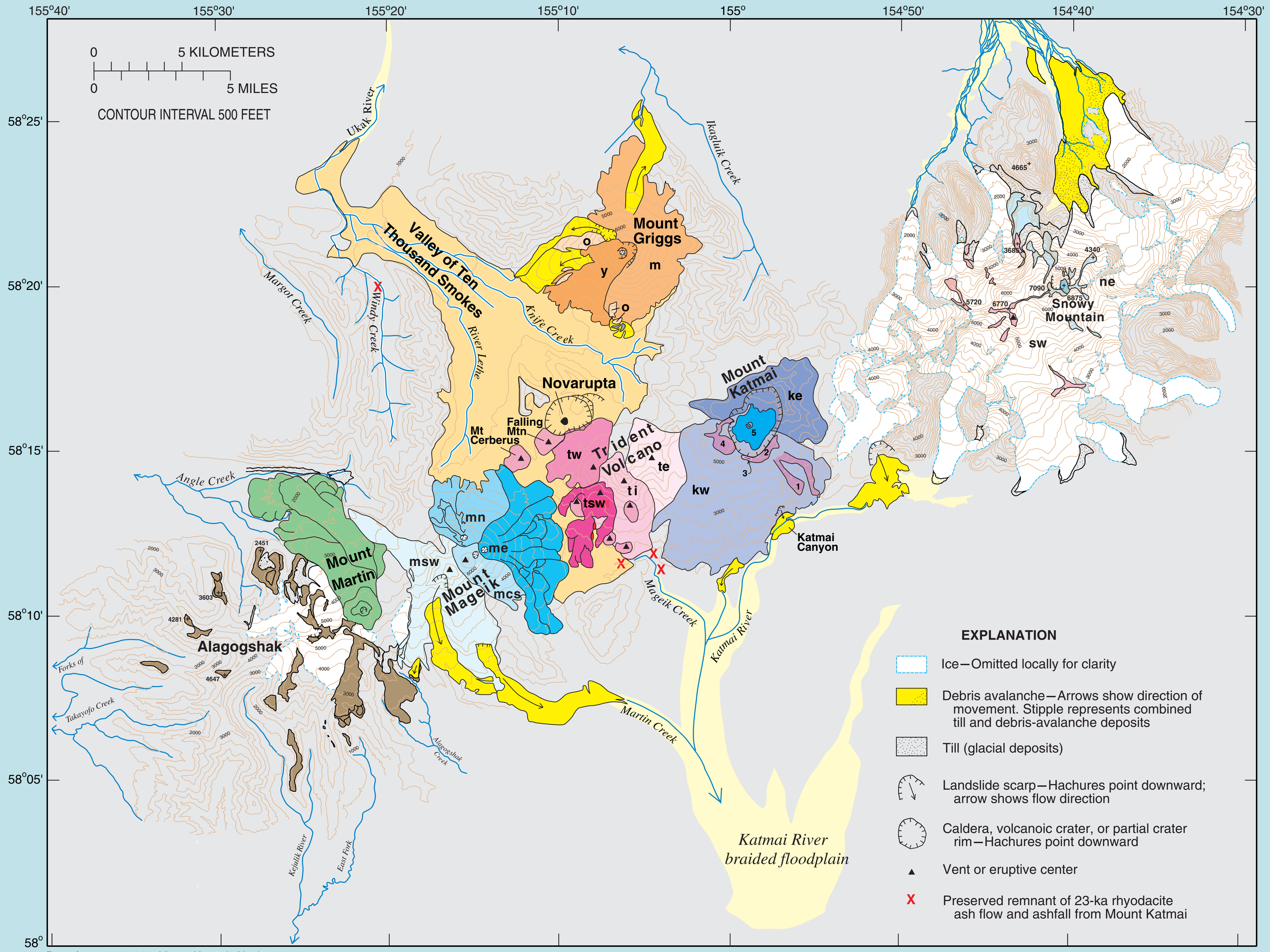
**Stratovolcano.** A steep-sided volcano, commonly conical in shape if there is only one central *vent*; built of *lava* flows and fragmental deposits from many periods of eruptive activity. Also called a stratocone or composite cone.

**Tephra.** Any type and size of rock fragment that is forcibly ejected from the volcano and travels an airborne path during an eruption (*ash*, bombs, *scoria*, cinders, etc.). Generally synonymous with *fallout*, but sometimes used more loosely to embrace *pyroclastic-flow* material as well.

**Tsunami.** Seismic sea waves typically initiated by sudden displacements of the sea floor during earthquakes. Collapse of oceanic volcanoes can initiate some tsunamis.

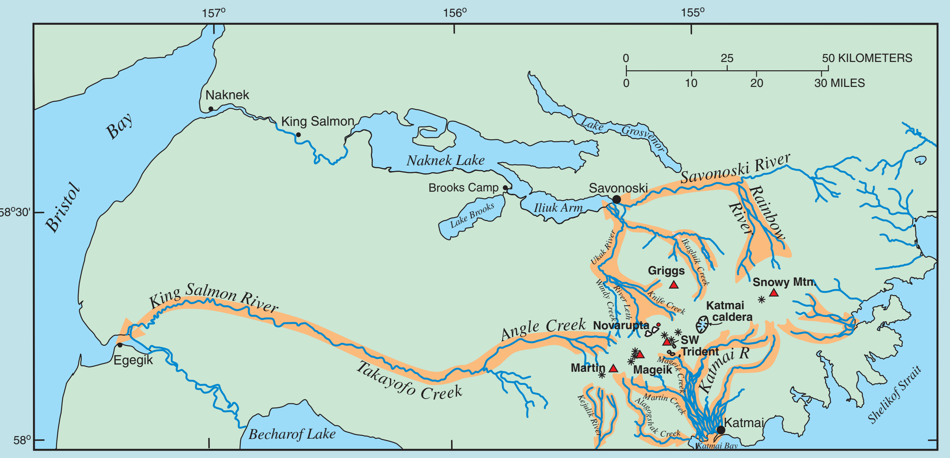
**Vent.** Any opening at the Earth's surface through which *magma* erupts or volcanic gases are emitted.

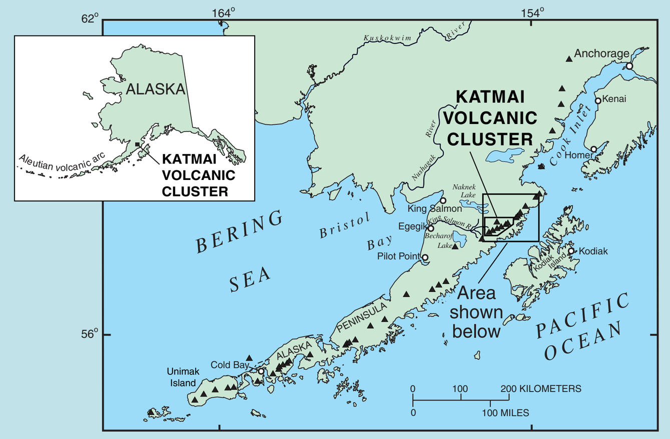
OPEN-FILE REPORT 00–489
PLATE 1




Base from 1:250,000, Mount Katmai, Alaska, 1951

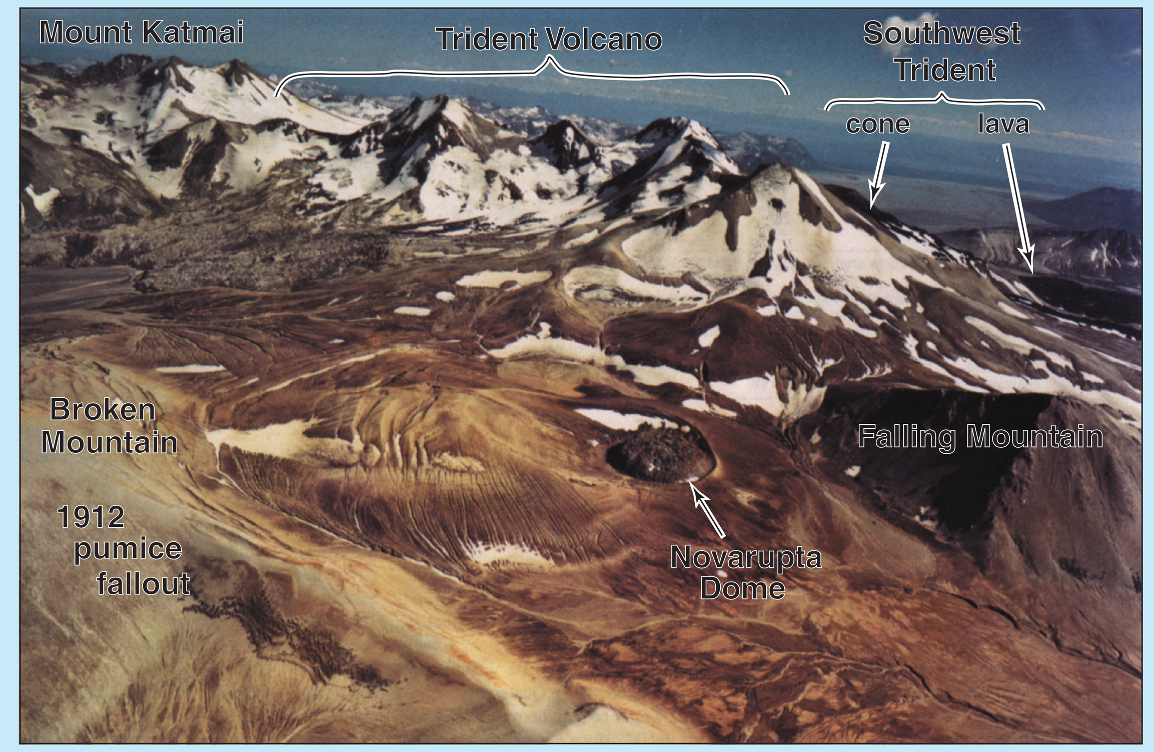
Geology of the Katmai volcanic cluster, showing eruptive products from each volcano. Triangles or hachured circles (for craters) mark the multiple vents of Mount Mageik and Trident Volcano: Southwest Mageik (msw), Central Summit of Mageik (mcs), East Summit of Mageik (me), and North Summit of Mageik (mn): Southwest Katmai (kw) and Northeast Katmai (ke). Falling Mountain and Mount Cerberus are dacite domes related to Trident Volcano. Youngest eruptive units from Mount Katmai are labeled 1 through 5. Two edifices of Snowy Mountain are also labeled: Northeast Snowy (ne) and Southwest Snowy (sw). Lines within a single-colored map unit bound different, overlapping flows. Mount Griggs' lavas are shown grouped by relative age: y, younger; m, middle; o, older. Although all of the stratovolcanoes are covered with snow and ice, many glaciers have been omitted for clarity.



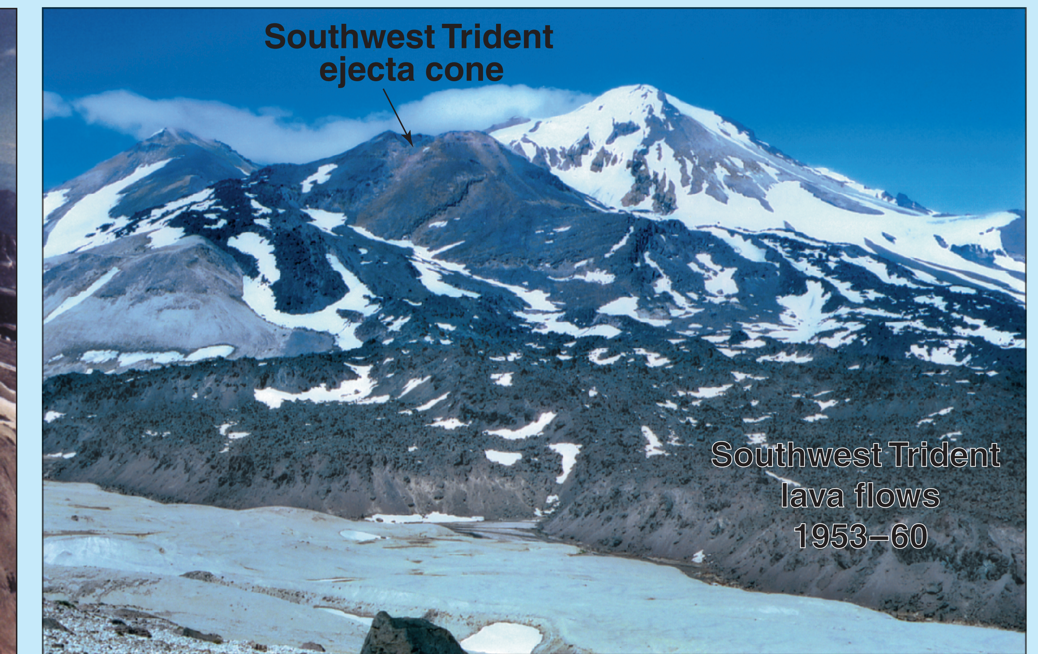




All of the Katmai cluster volcanoes are in Katmai National Park and Preserve, much of which is pristine wilderness and sparsely populated. It is, however, a world-renowned tourist area and has a very busy Alaska air corridor directly overhead. The most recent eruptions were during 1953–74 from Southwest Trident and in June 1912, when Novarupta produced the world's largest 20th-century eruption. Except for Alagogshak, all of these volcanoes have erupted in relatively recent geologic time. Vigorous fumaroles on Mounts Martin, Mageik, and Griggs and on Trident I clearly indicate that an active hydrothermal system is beneath each volcano. All the stratovolcanoes are covered with snow and ice. Lahars and floods have occurred sporadically as long as there have been volcanoes in the district, the most significant risk being inundation of waterways by pumice and ash. Most of the debris funneled down rivers that drain northward from the Katmai volcanoes would empty into Naknek Lake, whereas most debris funneled southward would empty into Shelikof Strait. Some debris flows could be directed into Kejulik River, which empties into Becharof Lake, and larger events could flow down Angle Creek to King Salmon River, even to Egegik, near the Bristol Bay coast. Eroded deposits of debris avalanches and lahars are only remnants of previously more extensive material like that which inundated the villages of Katmai and Savonoski by alluvial aggradation in the years after the 1912 eruption, or which filled the Rainbow River drainage and caused extensive flooding downstream as the Savonoski River tried to reestablish its route to Naknek Lake.


The Katmai volcanic cluster, a 25-kilometer-long line of volcanoes along the Alaska Peninsula 450 kilometers southwest of Anchorage, includes Snowy Mountain, Mount Griggs, Mount Katmai, Trident Volcano, Novarupta volcano, Mount Mageik, Mount Martin, and Alagogshak volcano. Novarupta, a new vent in 1912, sent ash around the globe. Labeled red lines (2 meters, 1 meter, and 50 centimeters) show original thickness of 1912 ashfall within each ellipse.




The world's largest volcanic eruption of the 20th century broke out at Novarupta in June of 1912, filling with hot ash what came to be called the Valley of Ten Thousand Smokes and spreading downwind more fallout than all other historical Alaskan eruptions combined. Although almost all magma vented at Novarupta, most of it had been stored beneath Mount Katmai 10 kilometers away, which collapsed during eruption. Aerial view southeastward over Novarupta toward Trident Volcano and Mount Katmai. In the foreground, the 1912 vent depression extends 2.5 kilometers from Broken Mountain at left to 400-meter-high scarp of Falling Mountain dacite dome at right. The vent funnel was backfilled by ash flows and fallback ejecta, deformed by compaction, and plugged by the Novarupta rhyolite dome, which is surrounded by a strongly asymmetrical ejecta ring that consists mostly of fallout from eruptions of June 7–8, 1912. On the central range crest are four prominent peaks of the Trident group, which partly hide the black cone of Southwest Trident, which erupted 1953–74, its lava-flow apron in Katmai Pass, and Mageik Creek.



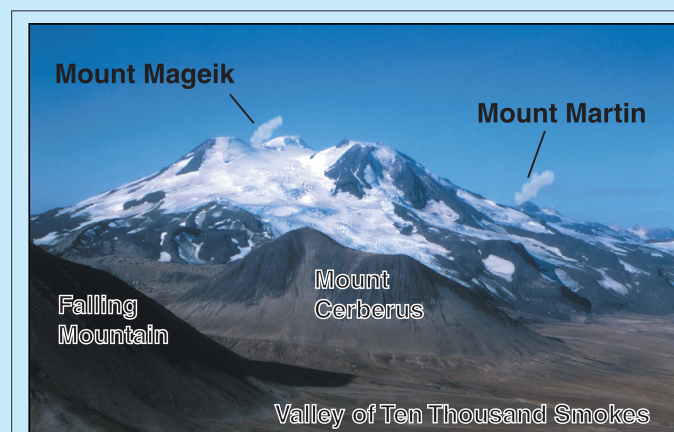

The modest eruption that began the building of Southwest Trident in 1953 sent an ash plume as high as 12 kilometers, and airplanes would have given it wide berth for at least several days. At successive stages of cone construction, in 1953, 1957, 1958, and the winter of 1959–60, four blocky lava flows effused from its central vent. Each flow was emplaced over a period of several months. Although subsequent eruptions were less explosive, intermittent ash clouds being less than 10 kilometers high, they would have necessitated diversion of aircraft, for hours to days at a time, throughout the 20 years of activity at Trident Volcano. In the photograph, Southwest Trident is flanked by older West Trident (on left) and Trident I (on right).

## Summary of volcano hazards at the Katmai volcanic cluster

[See fig. 20 and text for schematic representation and description of some of these processes]

| Type of hazard | Degree affected*: Nearby area | Medial area | Distal area | Overhead | Comments |
|---|---|---|---|---|---|
| Ash clouds | Major | Major to slight | Major to slight | Major | Severe hazard to aircraft even hundreds to thousands of kilometers downwind. Large eruptions produce large ash clouds, and stratospheric winds distribute ash clouds widely. |
| Fallout | Major | Major to slight | Major to nil | Major | Significant hazard to anyone on or around the volcano and to nearby communities during large eruptions. Major hazard in medial and distal locations during large eruptions. |
| Ballistics | Major | Nil | Nil | Nil | Significant hazard to anyone on or around the volcano during explosive eruptions. |
| Pyroclastic flows and surges | Major | Major | Nil | Slight | Significant hazard to anyone near the vent during eruptions; possible hazard within 10 to 30 kilometers of the volcano during large eruptions. |
| Lava flows and domes | Major | Slight | Nil | Nil | Significant hazard in immediate vicinity of lava flow or dome; attendant pyroclastic surges, ash clouds, fallout, or ballistics increase area potentially affected. |
| Debris avalanches | Major | Major to slight | Nil | Slight to nil | Significant hazard to anyone on or around the volcano during event, especially in valleys and low-lying areas near the volcano. |
| Rockfalls and landslides | Major | Slight to nil | Nil | Nil | Persistent hazard to anyone near steep walls of the volcanoes. |
| Lahars and floods | Major | Major to slight | Slight to nil | Nil | Significant hazard in all drainages downslope from eruption site and especially fords on River Lethe and Knife Creek. Greatest hazard when snowmelt is high and during or after heavy rains. Can be the downslope runout of debris avalanches and can be triggered by rockfalls and landslides. |
| Volcanic gases and fumaroles | Major | Nil | Nil | Nil | Significant hazard at present to anyone in and around actively degassing summit craters of Mounts Griggs, Mageik, and Martin and of Southwest Trident or near flank fumaroles on Trident I. |
| Volcanic earthquakes | Slight | Slight | Nil | Nil | Minor hazard except for secondary effects such as rockfalls and landslides. Volcanic seismicity before the 1912 eruption prompted residents of villages 20 kilometers from vent to leave. |
| Tsunami or waves | Nil | Nil | Nil | Nil | Tsunami in Shelikof Strait extremely low probability hazard; disruption of Naknek Lake by earthquakes, landslides, and other mass flows would pose a hazard to shoreline and areas near mouth of Ukak River. |

*"Nearby" implies near source, approximately to the base of the volcanic cone. "Medial" implies as much as a couple of dozen kilometers downstream from source (for instance, to Shelikof Strait or Naknek Lake). "Distal" implies locations far from the volcanoes, like King Salmon and Kodiak. "Overhead" means above the volcanoes (i.e., overflying aircraft).




Fumarolic plumes rising from craters of Mounts Mageik and Martin show that hydrothermal systems under both are quite active. Lower slopes of Mount Cerberus are covered with tan apron of sloughed 1912 pumice and ash. Falling Mountain and Cerberus are dacite domes that frame Katmai Pass. In flat-floored valley is the ash flow of the Valley of Ten Thousand Smokes, emplaced during the1912 eruption of Novarupta. The many steaming cracks and fissures that earned the Valley its name are no longer hot, but the Valley is still largely vegetation free.

## PRINCIPAL HAZARDS FROM THE KATMAI VOLCANIC CLUSTER

### Ash Clouds

Volcanic-ash clouds from this group of volcanoes most likely will travel toward the northeast, east, and southeast, although transport in other directions is possible. Airborne volcanic ash is the greatest hazard posed by future eruptions from the Katmai volcanic cluster and could affect aircraft thousands of kilometers away.

### Fallout

Pyroclastic fall deposits are made of material that rains out from an eruption column. Large fragments (ballistics) rarely land more than 2 kilometers from the vent and can be very dangerous for anyone close to the vent. Finer ejecta rise convectively upward in the eruption column and are transported downwind, forming a blanketing deposit that is thicker near the vent and thinner farther away. At distances of 100 kilometers, ash fallout is typically less than 10 centimeters thick for larger eruptions, and it may be only a fine dusting of ash for smaller events. In 1912, however, the entire landscape near the Novarupta vent was blanketed by meters of fallout; the fall deposit was as thick as 30 centimeters at Kodiak village, 100 kilometers downwind. The finest ash from large eruptions can be deposited hundreds, or even thousands, of kilometers from its source and thus—of all volcanic hazards—has the potential to affect the largest area.

### Lava Flows and Domes

Hazards posed directly by lava flows are confined to the immediate area around the vent where the flows tend to follow topographic lows. However, accompanying explosive blasts and ash eruptions could be a severe hazard for overflying aircraft. Accompanying avalanches of hot rocks, pyroclastic flows and surges, and ballistic showers could also affect a larger area. All the Katmai volcanoes have been built in large part by successive lava flows and(or) domes stacked on top of one another through time, and future eruptions that produce lava flows and domes are likely.

### Pyroclastic Flows, Surges, and Blasts

Among the most dangerous phenomena resulting from explosive eruptions are hot mixtures of rock fragments, gas, and ash that travel at speeds in excess of tens of meters per second away from a volcanic vent, typically killing everything in their path. Small and moderate-sized ash-rich pyroclastic flows tend to follow valleys, although larger flows can be highly mobile, crossing mountains and ridges. Highly dilute, turbulent, gas-rich flows (surges) are extremely mobile and can form from collapsing lava domes, separate from the top of a denser pyroclastic flow, or issue directly from the vent as explosive blasts. The presence of water (ground water, snow, ice, and lakes) near the vent increases the likelihood of steam-driven explosions and pyroclastic surges. Drainages that head on any of the Katmai volcanoes are at greatest risk from pyroclastic flows and surges of any size, especially within several kilometers of the vent. Explosive eruptions could affect larger areas by producing more mobile pyroclastic flows, with travel distances confined most strongly by the volume of the flow.

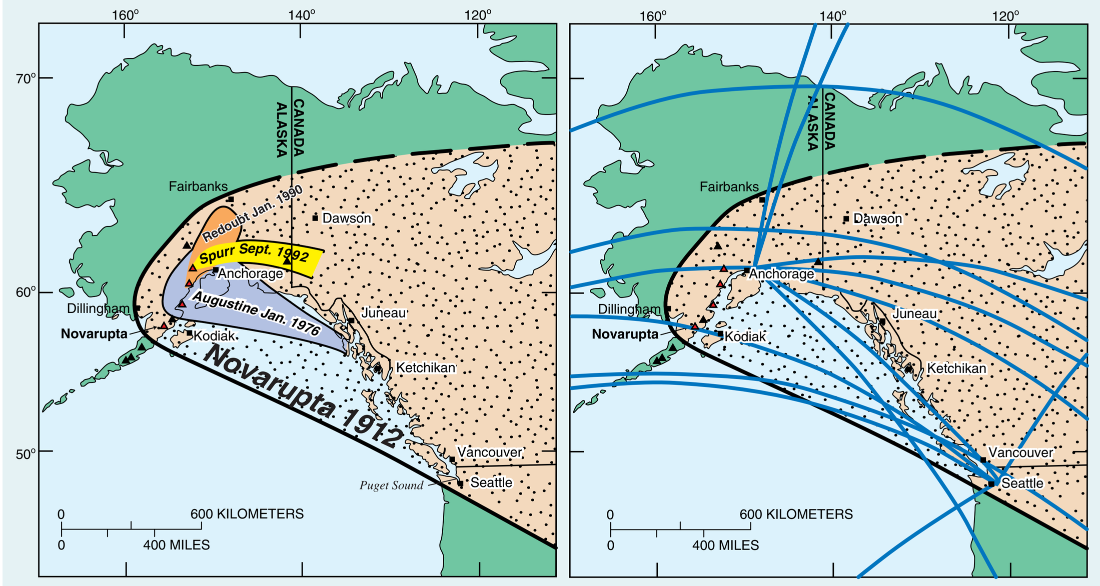
### Lahars and floods

Lahars are rapidly flowing mixtures of water, mud, and rock debris. They can range from dense, viscous slurries that have a high fraction of sediment to turbulent muddy flows that are mostly water. Lahars and floods have probably been common in the history of these volcanoes, but the remoteness of the region mitigates the risk. Because this is now a wilderness area with no permanent settlements nearby, lahars and floods generally threaten only wildlife, temporary camps, and recreational users of the backcountry. Only catastrophic lahars would impact areas farther than 10 to 20 kilometers from the volcanoes.

### Debris Avalanches, Landslides, and Rockfalls

Debris avalanches, a rapidly moving mass or landslide of incoherent rock, soil, and debris, are a significant hazard in areas close to the volcanoes, as are their smaller variants—rockfalls and landslides. Slope stability is critical in assessing the risks of these hazards, since rockfalls are daily events at these volcanoes, even without eruptions. The remoteness of the area restricts the direct risk of these hazards to those who might be downhill (and within 10 to 20 kilometers) when the avalanches let loose. A broader area could be affected, however, through transformation of a debris avalanche by mixing with rivers overrun and causing flooding and lahars.

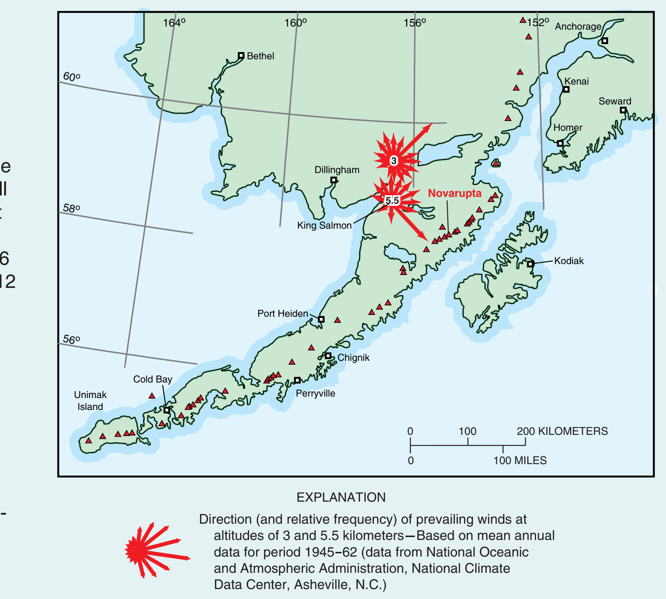
## AIRBORNE VOLCANIC ASH




A resident of the town of Kodiak, 170 kilometers southeast of Novarupta, standing in deep drifts of ash shortly after the June 1912 eruption (photograph courtesy National Geographic Society). Actual primary fallout in Kodiak was 30 centimeters thick, although drifts of ash locally piled up much higher.

Ashfall from the cataclysmic 1912 eruption of Novarupta dwarfs that produced by recent eruptions of Augustine, Redoubt, and Spurr volcanoes. Airborne ash from the 3-day eruption of Novarupta blanketed all of southern Alaska, and its gritty fallout was reported as far away as Dawson, Ketchikan, and Puget Sound. Volcanic dust and sulfurous aerosol were detected within days over Wisconsin and Virginia; within 2 weeks over California, Europe, and North Africa; and in latter-day ice cores recently drilled on the Greenland ice cap. Great-circle and other air-traffic routes (blue lines) between selected cities would have been greatly disrupted by 1912 ashfall and drifting ash clouds from Novarupta. Although small to moderate-sized eruptions have been common throughout the eruptive histories of the Katmai volcanoes (no fewer than 15 such episodes in postglacial time) and will continue to be, there have been three exceptional events from this cluster, one of which was probably even larger than that of 1912. Although exceptionally large events occur infrequently, the potential effects are far reaching and severe.

Size of sector and extent of ash distribution depend mostly on the scale of the eruption; large eruptions affect much larger areas than do small ones. Most eruptive events in the Katmai district are characterized by the 1950s Trident Volcano eruptions, which sent several ash columns 2 to 6 kilometers into the atmosphere, and a few 9 to 12 kilometers high. Smaller than the eruptions of Redoubt, Spurr, and Augustine, the Southwest Trident ash clouds would have affected aircraft overhead and in the immediate Katmai area. Nearly 20 years of wind data from the National Oceanic and Atmospheric Administration show that prevailing winds at altitudes greater than 5.5 kilometers would most commonly direct ash southeastward, whereas lower altitude winds (3 kilometers) are most likely to direct ash northeastward. Although less common, prevailing winds can come from the Pacific, blowing north and northwestward. Such were conditions that directed most of the Trident ash.




## Probability of eruption scenarios and principal hazards associated with each volcano in the Katmai cluster

[ka, thousands of years before present; <, less than]

| Style or activity | Example | Principal hazards | Probability for each volcano: Alagogshak | Mount Martin | Mount Mageik | Trident Volcano | Mount Katmai | Novarupta | Mount Griggs | Snowy Mountain |
|---|---|---|---|---|---|---|---|---|---|---|
| Quiescence | Most volcanoes, most of the time | Resuspended ash, rockfall, local earthquakes | High | High | High | High | High | High | High | High |
| Phreatic explosion | Mount Mageik summit crater | Ballistics, pyroclastic surges, ashfall | Low | High | High | Medium | High | Low | Medium | Medium |
| Strombolian eruption: lava flow | Southwest Trident, 1953–74; Mount Martin, about 6 ka; Mount Mageik, 4 ka | Lava flows, steam explosions, ballistics, ashfall | Low | High | High | High | High | Low | High | Medium |
| Phreatomagmatic eruption | Mount Katmai, 1912 | Widespread ashfall, pyroclastic surges, ballistics, lava flows | Low | Low | High | Low | High | Low | Low | Low |
| Dome formation | Novarupta, 1912; Snowy Mountain, <1.5 ka | Pyroclastic surges and flows, local ashfall, ballistics | Low | Medium | High | Medium | Medium | Low | Low | Medium |
| Subplinian eruption | Mount Mageik, 4 ka; Mount Katmai, <10 ka | Pyroclastic surges and flows, local to medial ashfall, ballistics | Low | Low | Medium | Low | High | Low | Low | Low |
| Plinian eruption | Mount Katmai, <16 ka; Mount Katmai, 23 ka | Pyroclastic surges and flows, regional ashfall, ballistics | Low | Low | Medium | Low | High | Low | Low | Low |
| Caldera-forming eruption | Novarupta, 1912 | Catastrophic: widespread ashfall, ash flows, earthquakes | Low | Low | Low | Low | Medium | Low | Low | Low |

# PRELIMINARY VOLCANO-HAZARD ASSESSMENT FOR THE KATMAI VOLCANIC CLUSTER

by
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2001