DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

# Preliminary Volcano-Hazard Assessment for Augustine Volcano, Alaska

by

Christopher F. Waythomas and Richard B. Waitt

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director

For additional information:

U.S. Geological Survey
Alaska Volcano Observatory
4200 University Drive
Anchorage, AK 99508

www.avo.alaska.edu

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## CONVERSION FACTORS

| 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 ($m^3$) | 35.3 | cubic foot |
| meter per second (m/s) | 3.28 | foot per second |
| microgram per cubic centimeter ($\mu g/cm^3$) | $8.34 \times 10^{-9}$ | pounds per gallon |
| degree Celsius (°C) | °F = 1.8 x °C + 32 | degree Fahrenheit (°F) |

## VERTICAL DATUM

*Sea level:* In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929–A geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929. In the area of this report, datum is mean lower low water.

# Preliminary Volcano-Hazard Assessment for Augustine Volcano, Alaska

By Christopher F. Waythomas[1] and Richard B. Waitt[2]

## SUMMARY OF HAZARDS AT AUGUSTINE VOLCANO

Augustine Volcano is a 1250-meter-high stratovolcano in southwestern Cook Inlet about 280 kilometers southwest of Anchorage and within about 300 kilometers of more than half of the population of Alaska. Explosive eruptions have occurred six times since the early 1800s (1812, 1883, 1935, 1964–65, 1976, and 1986). The 1976 and 1986 eruptions began with an initial series of vent-clearing explosions and high vertical plumes of volcanic ash followed by pyroclastic flows, surges, and lahars on the volcano flanks. Unlike some prehistoric eruptions, a summit edifice collapse and debris avalanche did not occur in 1812, 1935, 1964–65, 1976, or 1986. However, early in the 1883 eruption, a portion of the volcano summit broke loose forming a debris avalanche that flowed to the sea. The avalanche initiated a small tsunami reported on the Kenai Peninsula at English Bay, 90 kilometers east of the volcano. Plumes of volcanic ash are a major hazard to jet aircraft using Anchorage International and other local airports. Ashfall from future eruptions could disrupt oil and gas operations and shipping activities in Cook Inlet. Eruptions similar to the historical and prehistoric eruptions are likely in Augustine's future. The greatest hazards in order of importance are described below and are shown on plate 1.

- **Volcanic ash clouds**

  *Clouds of fine volcanic ash will drift away from the volcano with the wind. These ash clouds are a hazard to all aircraft downwind. Airborne volcanic ash can drift thousands of kilometers from its source volcano. Ash from the recent Augustine eruptions was reported over Alaska, Canada, Arizona, Colorado, the Great Lakes, and Virginia where it interfered with air travel but did not bring about any serious mishaps or accidents.*

- **Volcanic ash fallout**

  *Ash fallout from historical eruptions of Augustine occurred over several parts of mainland Alaska where accumulations of several millimeters or more of ash were reported. Fine ash is a nuisance and may cause respiratory problems in some humans and animals. Heavy ashfall can disrupt many human activities and may interfere with power generation, affect visibility, and could damage electrical components and equipment. Resuspension of ash by wind could extend the unpleasant effects of ash fallout.*

- **Pyroclastic flow and surge**

  *Hot material expelled from the volcano may travel rapidly down the volcano flanks as flows of volcanic debris called pyroclastic flows and surges. Usually these flows do not reach the coast and rarely extend more than a few kilometers beyond the coastline of Augustine Island. They pose little hazard except to people or boats near the island.*

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[1]Alaska Volcano Observatory, Anchorage, Alaska
[2]Cascades Volcano Observatory, Vancouver, Washington

**THE ALASKA VOLCANO HAZARD ASSESSMENT SERIES**

*This report is part of a series of volcano hazard assessments being prepared by the Alaska Volcano Observatory. The reports are intended to describe the nature of volcanic hazards at Alaska volcanoes and show the extent of hazardous areas with maps, photographs, and other appropriate illustrations. The reports are preliminary and subject to revision as new data become available.*

- **Debris avalanche**

  *A debris avalanche is a rapidly moving mass of solid or incoherent blocks, boulders, and gravel initiated by a large-scale failure of the volcano flank. Multiple prehistoric and one historical debris avalanche have occurred at Augustine Volcano, and all of them reached the sea. Debris avalanches may move at velocities in the range of 50-100 meters per second; if they are large enough, they could initiate potentially hazardous tsunamis. However, the hazard from debris avalanches alone is limited to Augustine Island and its nearshore zone.*

- **Lahar and flood**

  *Hot volcanic debris interacts with snow and ice to form fast-moving slurries of water, mud, rocks, and sand. These flows, called lahars, are common and frequent during winter-spring eruptions of Augustine. They tend to follow streams and drainageways, and may extend to the coastline. Lahars pose no hazard except to people on the island during an eruption.*

Other hazardous phenomena that may occur but are uncommon during typical eruptions of Augustine Volcano include:

- **Volcanic tsunamis**

  *Large debris avalanches that rapidly descend the volcano flanks and enter the sea may initiate volcanic tsunamis. During the 1883 eruption, a tsunami was probably generated by a debris avalanche. A very large debris avalanche could initiate a tsunami that would pose a risk to low-lying coastal areas in the lower Cook Inlet Region.*

- **Directed blasts**

  *A directed blast is a lateral explosion of the volcano caused by rapid release of internal pressure commonly caused by a slope failure or landslide. Directed blasts are rare at Augustine Volcano and there is evidence for only one in the last 2500 years.*

- **Pumice rafts**

  *Pyroclastic flows and coarse proximal fallout into the sea, if voluminous enough, may form floating pods or "rafts" of pumice. Pumice rafts will move with the prevailing ocean currents as coherent bodies and could pose a risk to boats and ships in Cook Inlet, especially those operating close to the volcano and in small bays around the mainland in southern Cook Inlet.*

- **Volcanic gases**

  *Some volcanoes emit gases in concentrations that are harmful to humans. But the frequently windy conditions at Augustine and a lack of closed depressions that could collect gases, impede the buildup of volcanic gases. Thus the hazard from volcanic gases is minimal, unless one is actually in or around the active vent, on or near a new lava dome, or near an active fumarole.*

- **Lava flow**

  *Streams of molten rock (lava) may extend a few kilometers from the active vent. Augustine lava flows move slowly, only a few tens of meters per hour, and pose little hazard to humans. Some lava flows may develop steep, blocky fronts and avalanching of blocks could be hazardous to someone close to the flow front.*

**SUGGESTIONS FOR READING THIS REPORT**

*Readers who want a brief overview of the hazards at Augustine Volcano are encouraged to read the summary and consult plate 1 and the illustrations. Individual sections of this report provide a slightly more comprehensive overview of the various hazards at Augustine Volcano. A glossary of geologic terms is included and additional information about Augustine Volcano can be obtained by consulting the references cited in the text.*

## INTRODUCTION

Augustine Volcano is an active stratovolcano situated on a small uninhabited island in southwestern Cook Inlet (fig. 1). The volcano has experienced six explosive eruptive episodes since the early 1800s, most recently in 1986. Because the volcano is located within a few hundred kilometers of the major population, commerce, and industrial centers of south-central Alaska, future eruptions pose a hazard to the citizens and economy of the region. Typical eruptions of Augustine Volcano are capable of emitting large volumes of volcanic ash that may rise to more than 12,000 meters above sea level. These clouds of volcanic ash are hazardous to jet aircraft in the Cook Inlet region and for thousands of kilometers downwind from the volcano.

Because Augustine Island is uninhabited, life and property are not at risk in the immediate vicinity of the volcano. However, volcanic debris that falls or flows into the sea may initiate local wave phenomena (tsunamis) that may be hazardous to boats or people close to Augustine Island (less than about 5 kilometers). In the case of a very large slope failure from the volcano, a tsunami could be initiated that could pose a hazard to low-lying areas along the southern Cook Inlet coastline.

### Purpose and Scope

This report summarizes the principal volcanic hazards associated with eruptions of Augustine Volcano. Hazardous volcanic phenomena that occur on the volcano as well as distal effects of eruptions are described. Also discussed is the issue of whether Augustine can generate a tsunami large enough to pose a hazard to coastal communities and facilities in lower Cook Inlet. The present status of monitoring efforts to detect volcanic unrest and the procedure for eruption notification and dissemination of information also are presented. A series of maps and figures that indicate potential hazard zone boundaries are included. A glossary of geologic terms is at the end of the report.

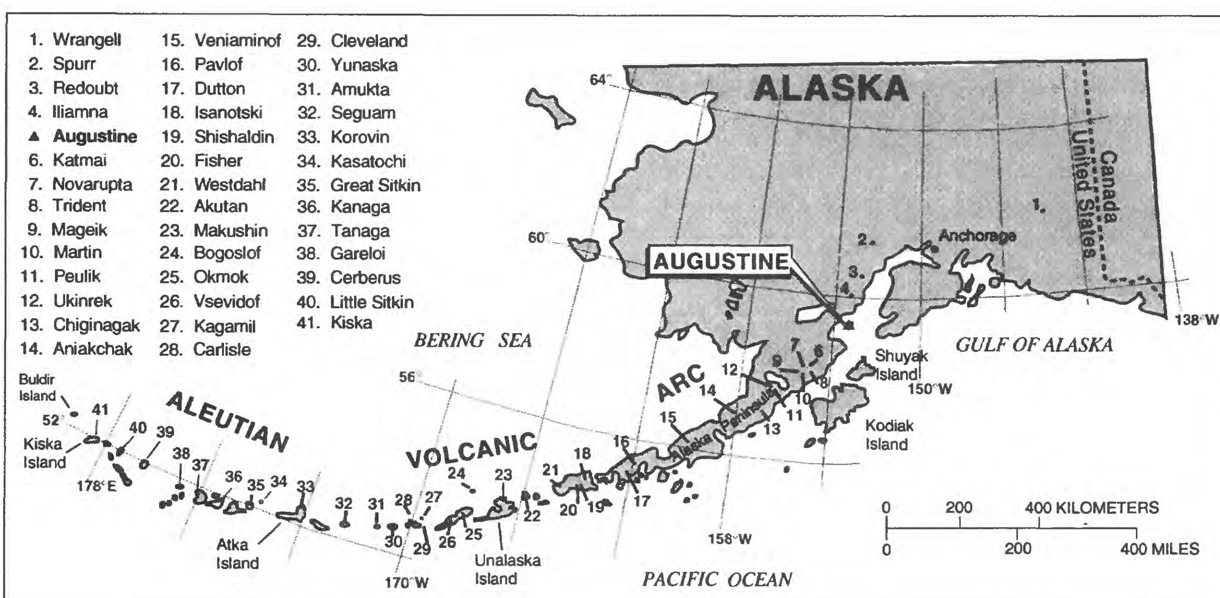



**Figure 1.** Location of Augustine Volcano with respect to other volcanoes in the Aleutian arc. All of these volcanoes except Wrangell, Iliamna, and Dutton have erupted in the last 200 years.

## Physical Setting of Augustine Volcano

Augustine Volcano is a cone-shaped, island volcano in lower Cook Inlet, about 280 kilometers southwest of Anchorage and about 120 kilometers southwest of Homer (fig. 2). The volcano forms most of Augustine Island, an 8- by 11-kilometer, nearly circular island (fig. 3) composed almost entirely of volcanic deposits (Waitt and others, 1996). Augustine Volcano consists of a summit lava-dome and -flow complex surrounded by an overlapping assemblage of pyroclastic flow, lahar, avalanche, and ash deposits. Repeated collapse of the summit dome has resulted in the formation of debris avalanches that moved down the volcano flanks into the sea.

Augustine Island is surrounded by the shallow waters of Cook Inlet; water depth a few kilometers offshore ranges from less than 5 meters to about 20 meters. The island is in the zone of uplift resulting from the 1964 Alaska earthquake and about 30 centimeters of uplift was measured on the northwest side of the island (Detterman, 1968). Numerous raised beach ridges on the southwest side of the island (fig. 3) indicate that sustained uplift probably occurred during the last 2000 to 3000 years.

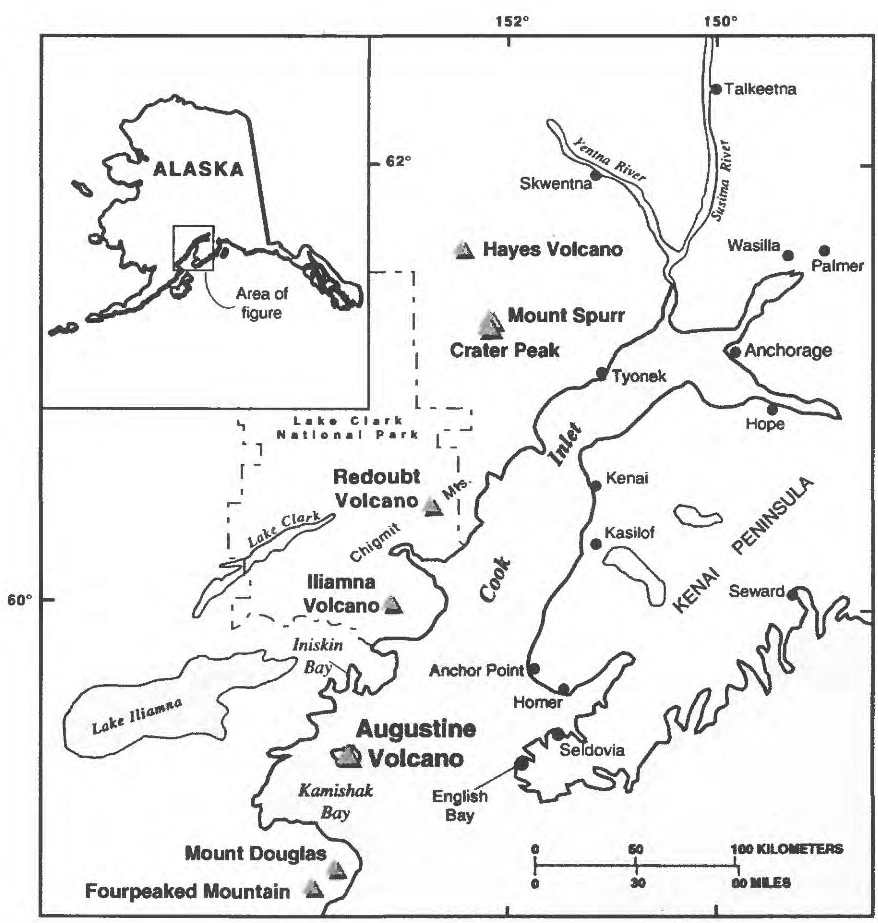



**Figure 2.** Location of Augustine Volcano with respect to other volcanoes in the Cook Inlet region.

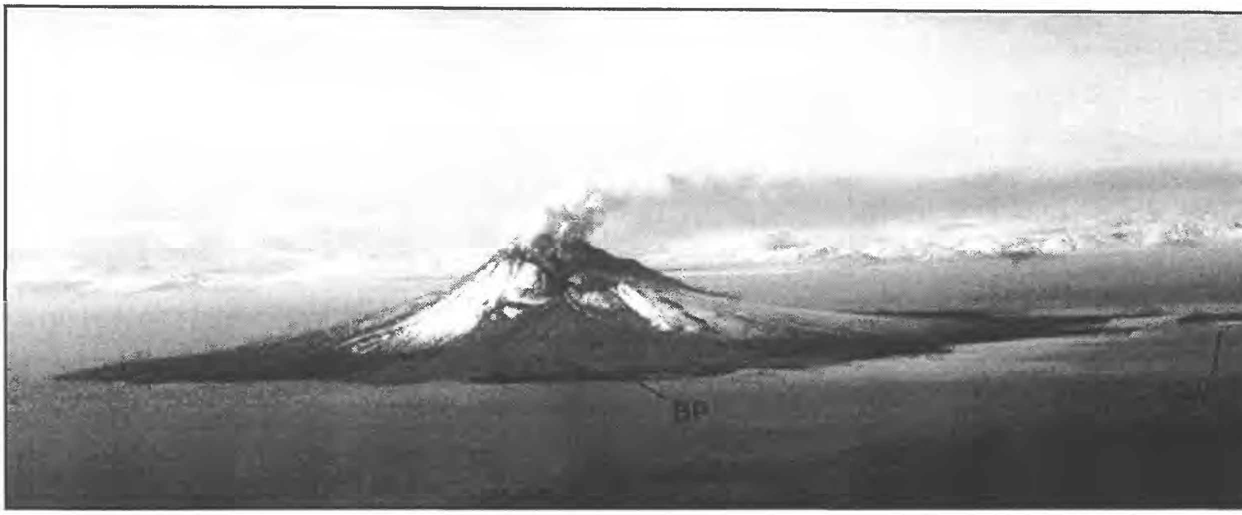



**Figure 3.** Augustine Volcano during 1986 eruption. View is to the south. Burr Point (BP) area in the foreground; West Island (WI) is on the far right. (Photograph by USGS, April 19, 1986.)

## Relation to Previous Studies on Augustine Hazards

Many scientists have commented on the hazards associated with eruptions from Augustine Volcano in various reports, articles, and books (see citations given in the "References Cited" section of this report). However, since the 1986 eruption, no single publication has provided a comprehensive synthesis of volcanic hazards and their potential impact on the inhabitants of south-central Alaska. This report enlarges upon and is complementary to a previous report on Augustine hazards by Kienle and Swanson (1980, reprinted in 1985) and incorporates new information from several more recent studies of Augustine volcanic activity and processes (Swanson and Kienle, 1988; Siebert and others, 1989, 1995; Kamata and others, 1991; Begét and Kienle, 1992; Waitt and others, 1996; Waythomas, 1997).

# PREHISTORIC ERUPTIVE HISTORY

Augustine Volcano may be the youngest of the Cook Inlet stratovolcanoes. Stratigraphic evidence indicates that the volcano began forming before the last glaciation of Cook Inlet (the Moosehorn advance of the Naptowne glaciation) 25,000 to 18,000 years ago (Johnston, 1979; Reger and Pinney, 1995). However, the oldest known volcanic deposits on Augustine Island have not been dated, and glacial deposits beneath them are also of unknown age. The development of the present cone began before 40,000 years ago; eruptions were probably explosive, similar to historical eruptions. During parts of the Pleistocene epoch, much of Cook Inlet and most of southern Alaska lay beneath a thick and areally extensive ice sheet. Early eruptions of Augustine Volcano may have been subglacial which would limit the preservation of proximal volcanic deposits and volcanic ash, therefore making it difficult to establish the early eruptive history.

The oldest known distal volcanic ash from Augustine Volcano was deposited about 3600 yr B.P. on Shuyak Island, 100 kilometers southeast of Augustine Volcano (fig. 1; Waitt and others, 1996). The history of eruptive activity since about 2200 yr B.P. (fig. 4) is known from study of stratigraphic relations exposed in sea cliffs and gullies on Augustine Island. Volcanic activity is episodic and long periods of nonactivity are punctuated by rapid deposition of volcanic sediments during eruptions. Vegetation and soil development may proceed during noneruptive periods. Soils and vegetation are buried by volcanic deposits during the next eruption and, over a period of time, a stacked, vertical sequence of buried soils, volcanic deposits, and volcanic ash develops. Because the stratigraphic sequence evolves in this manner over many thousands of years, it is possible to work out the eruptive history of the volcano by dating the "buried" soils and identifying the volcanic ash layers. This methodology has been applied on Augustine Island and is the basis for deciphering the eruptive history of the volcano.

A minimum of six, major, coarse-grained, volcanic ash (tephra) layers (fig. 4) and numerous thin, fine-grained ash layers are present on Augustine Island. The six major tephras consist mostly of sand-to-pebble-sized clasts of pumice and are designated layers G (oldest), I, H, C, M, and B (youngest). These tephra layers are within a vertical sequence of volcanic flowage deposits (primarily debris-avalanche deposits) and most of them rest on buried soil organic matter that has been radiocarbon dated (fig. 4; Waitt and others, 1996). Some of the tephra layers have distinctive physical characteristics that permit field recognition. The tephra beds are useful for correlation of stratigraphic sections on the lower flanks of the volcano.

Debris-avalanche deposits form much of the lower flanks and coast of Augustine Island (fig. 4). These deposits consist of poorly sorted, bouldery gravel and form when a portion of the summit dome or volcano flank collapses and falls or flows down the side of the volcano. At least 13 debris avalanche deposits younger than tephra G (about 2000 to 2500 years old), and one older than tephra G are recognized (fig. 4; Waitt and others, 1996). Some of the debris-avalanche deposits are related to eruptions, whereas others may have formed during non-eruptive periods (fig. 4).

During the last 2500 years, numerous lava domes were emplaced at the summit which subsequently collapsed and formed debris avalanches. Thus over time, the source for debris avalanches was continually renewed. Remnants of some of these former domes still remain near the present summit (Waitt and others, 1996).

Pumice-rich pyroclastic flows swept down the volcano flanks at least three times between 300 and 1300 years ago. These hot flows melted snow on the volcano and caused several volcanic mudflows, or lahars, to form.

| Age range of radiocarbon dated soils, in years before present | Major Tephra Fall and Debris Avalanche Deposits | Volcanic Events |
|---|---|---|
| (0-293) | | |
| | Rocky Point | Debris avalanche at Rocky Point |
| (315-507) | | |
| | West Island | Debris avalanche at West Island |
| | Grouse Point | Debris avalanche at Grouse Point |
| | Tephra B | Tephra fall |
| (335-535) | | |
| | Southeast Beach | Debris avalanche at Southeast Beach |
| | | Pyroclastic flow & lahar at West Lagoon |
| | Lagoon | Debris avalanche at West Lagoon |
| | Tephra M | Tephra fall |
| (652-729) | | |
| | | Lahar west of Southeast Point |
| | | Pyroclastic flow west of Augustine Ck. |
| (672-930) | | |
| | Tephra C | Tephra fall |
| | North Bench | Debris avalanche(?) near Grouse Pt. |
| | | Pyroclastic flow at Long Beach |
| | Long Beach | Debris avalanche at Long Beach |
| (1149-1291) | | |
| | South Point | Debris avalanche at South Point |
| | Tephra H | Tephra fall |
| (1310-1592) | | |
| | Northeast Point | Debris avalanche at Northeast Point |
| | Northeast Bench | Lahar(?) near Northeast Point |
| | Tephra I | Tephra fall |
| (1538-1925) | | |
| | Southeast Point | Debris avalanche at Southeast Point |
| | Yellow Cliffs | Debris avalanche south of East Point |
| | Tephra G | Tephra fall |
| (1951-2331) | | |
| | East Point | Debris avalanche at East Point |
| (>2500 yr B.P.) | | Numerous pyroclastic fall & flow deposits |

**Figure 4.** Chronology of prehistoric volcanic events at Augustine Volcano.

## HISTORICAL ERUPTIONS

Augustine Volcano has had six historical eruptions, the first in 1812 (fig. 5). These eruptions usually last for weeks to months and produce minor pyroclastic flows in addition to small volumes of volcanic ash that drift over parts of mainland Alaska. The pattern of eruption (Johnston, 1978) is usually an initial violent, vent-clearing phase associated with pumice-rich pyroclastic flows, high vertical eruption plumes of ash and steam, and extensive ash fallout. Later in the eruption, a lava dome is extruded, parts of which collapse and form hot block and ash flows. Extensive, regional fallout of ash is uncommon during this phase of the eruption. The 1883 eruption generated a small tsunami, when a debris avalanche entered the sea at Burr Point (fig. 6). Debris avalanches did not occur during any of the other historical eruptions, although summit domes were emplaced in the 1883 and each later eruption.

## HAZARDOUS PHENOMENA AT AUGUSTINE VOLCANO

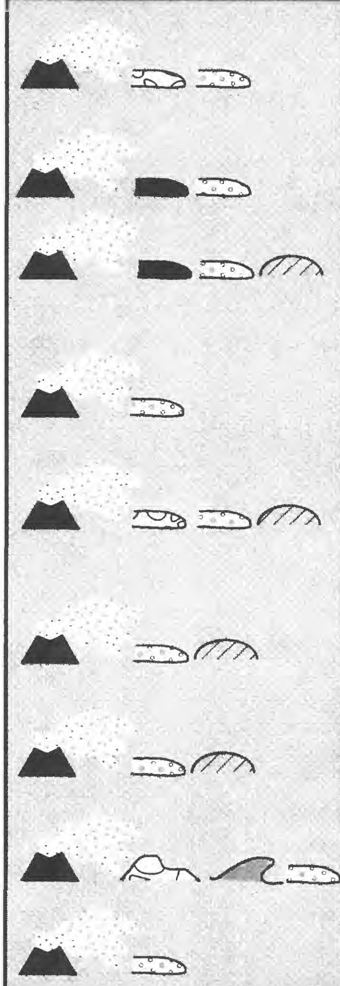
A volcanic hazard (fig. 7) is any volcanic phenomenon that is potentially threatening to life or property. Hazards associated with volcanic eruptions at Augustine Volcano are grouped as proximal or distal. The classification of hazardous phenomena at Augustine Volcano as proximal or distal is only approximate because the extent of a particular hazard is in part related to the scale of the eruption. Thus, a large eruption may cause some phenomena to affect areas well beyond the volcano, whereas during a smaller, more typical eruption, the same phenomena may only affect areas in the immediate vicinity of the volcano.

Proximal hazards are those phenomena that occur in the immediate vicinity of the volcano, typically within a few tens of kilometers of the active vent. This group of hazards is likely to, but may not always, result in death or injury to anyone within several kilometers of the vent, who would have no time to escape from the area in the advent of an eruption. Because Augustine Island is uninhabited, only the occasional visitor is at risk from the various proximal hazards.

Distal hazards pose less risk to people because there could be adequate time for warning and evacuation. This group of hazards affects people and structures that are more than about 10 kilometers from the active vent. Volcanic ash, either in explosive eruption columns or ash clouds that drift far away from the volcano can be both a proximal and a distal hazard, especially to aircraft.

A recently completed geologic map of Augustine Island (Waitt and others, 1996) depicts deposits formed by various volcanic phenomena. Most of these phenomena are limited to Augustine Island. Only volcanic ash clouds, fallout, and pyroclastic flow and surge could affect areas beyond Augustine Island. In the event of a very large debris avalanche, a tsunami could affect low-lying areas along the coast of lower Cook Inlet.

## HISTORICAL ERUPTIVE ACTIVITY AT AUGUSTINE VOLCANO



| ERUPTIVE PERIOD | ACTIVITY |
|---|---|
| 1986 March 27-April 2: | *Small-volume ash emissions, some reaching as high as 12,000 m, pyroclastic flows & lahars* |
| April 22-28: | *Small-volume lava flows, minor ash emissions to 3700 m, small pyroclastic flows* |
| August 22-September 1: | *Small-volume lava flows, minor ash emissions to 3700 m, small pyroclastic flows, dome growth* |
| 1976 January 22-25: | *At least 13 small-volume ash emissions & summit explosions, ash plumes reaching as high as 10,000 m, small pyroclastic flows* |
| February 6-April 19: | *Small-volume ash emissions, small pyroclastic flows & lahars, dome growth* |
| 1964 July 5 - September: | *Small-volume ash emissions, pyroclastic flows, dome growth* |
| 1963 October 11 - November 17: | *Small-volume ash emissions, pyroclastic flows* |
| 1935 March 13 - August 18: | *Small-volume ash emissions, pyroclastic flows, dome growth* |
| 1883 October 6- ? | *Small-volume ash emissions, pyroclastic flows, Burr Point debris avalanche & small tsunami* |
| 1812 | *Small-volume ash emissions, pyroclastic flows?* |

## EXPLANATION OF SYMBOLS

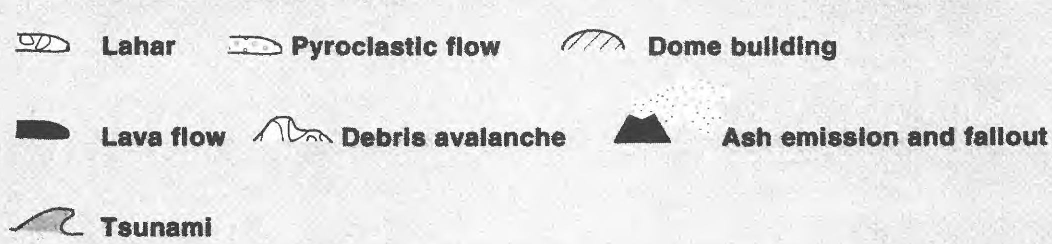



**Figure 5.** Summary of historical volcanic activity at Augustine Volcano.

**Figure 6.** Augustine Volcano and Burr Point debris-avalanche deposit. Arrows indicate avalanche flow path. Collapse of the summit edifice during the early part of the 1883 eruption generated a debris avalanche that flowed into the sea. This debris avalanche is the only one associated with a historical eruption (photograph by USGS, 1973).

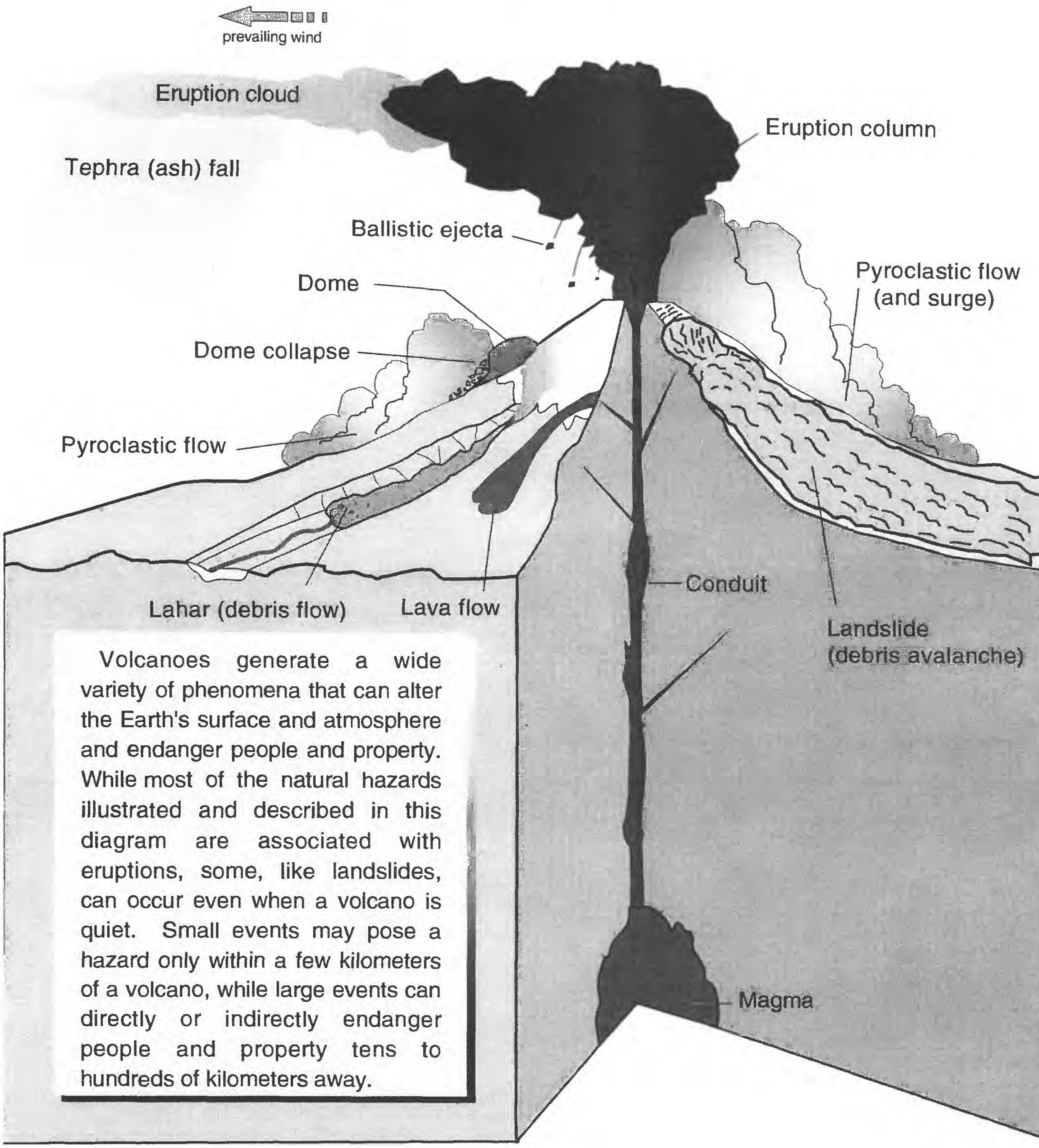



**Figure 7.** Simplified sketch of a stratovolcano and associated hazardous phenomena (from Myers and others, 1997).

# VOLCANIC HAZARDS

## Volcanic Ash Clouds

Augustine Volcano tends to erupt explosively, shattering magma into fragments and ejecting them into the atmosphere. The fragments from such eruptions range from meter-sized blocks to microscopic ash, collectively called *tephra*. Fine-grained tephra propelled skyward by the explosive nature of the eruption forms an eruption cloud (figs. 7, 8) that drifts away from the volcano with the wind. The fine ash particles may remain in the atmosphere for days to weeks depending on the size of the eruption. Volcanic ash clouds are a hazard to all aircraft downwind from the volcano (Casadevall, 1994).

Clouds of volcanic ash from the 1976 and 1986 eruptions of Augustine Volcano reached as high as 12,000 meters above sea level and generally drifted to the north and east (fig. 9). During the 1976 eruption, at least five jet aircraft (two military, three commercial) entered ash clouds and sustained severe abrasion on windshields, leading edges of wings and landing gear, and other forward parts of the aircraft. These aircraft were not disabled and no crashes occurred.

Volcanic ash clouds from March 27-31, 1986 (figs. 8, 9) drifted to the north and east

**Figure 8.** Vertical eruption column of ash and steam during the March 1986 eruption of Augustine Volcano. Rising plumes of volcanic ash like this one reached 12,000 meters above sea level during several historical eruptions. Clouds of volcanic ash are a serious hazard to aircraft, and fallout from drifting ash clouds commonly reaches parts of mainland Alaska. Several millimeters of ash fell over parts of the southern Kenai Peninsula during the 1986 eruption. (Photograph by Jürgen Kienle, March 31, 1986.)

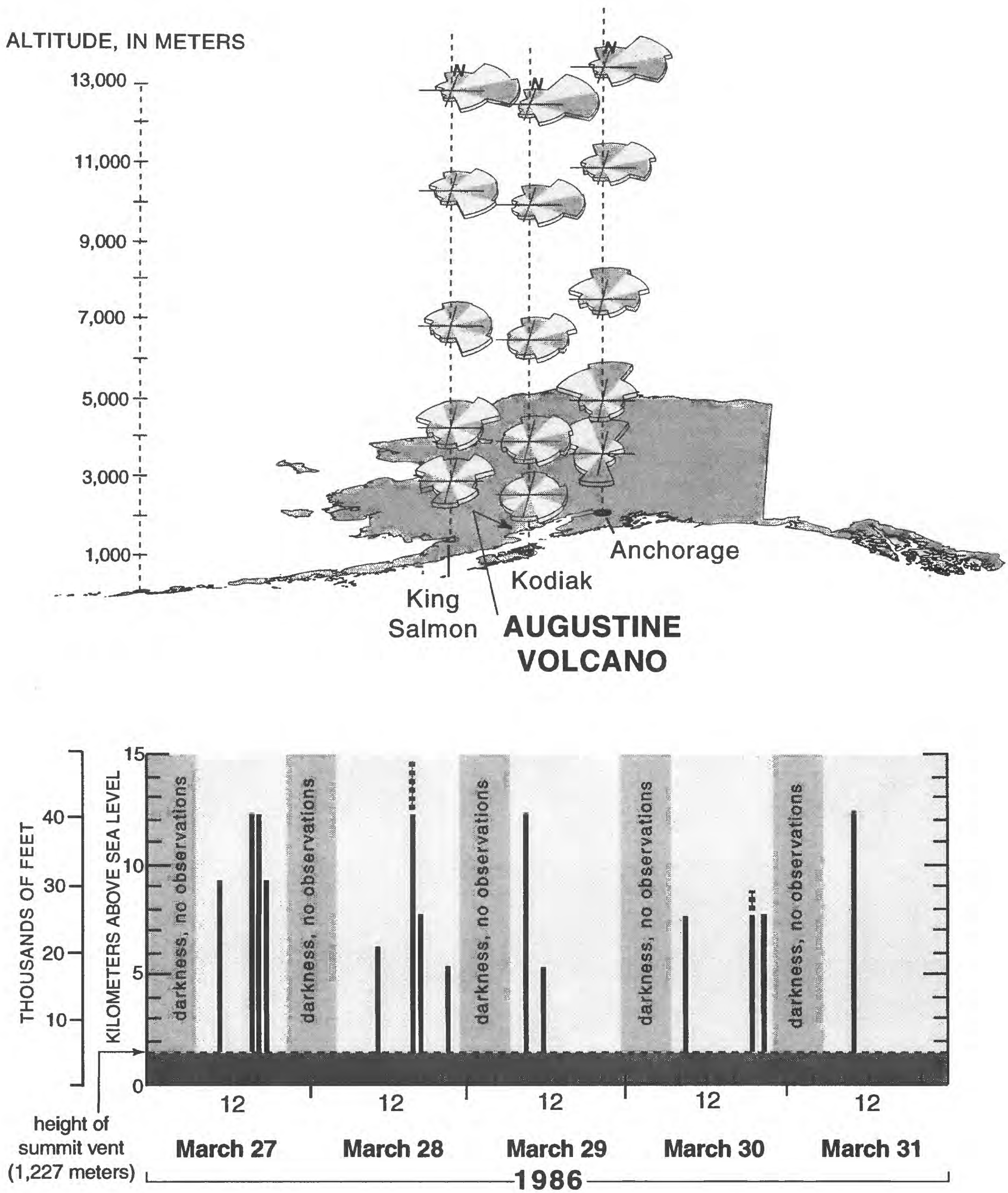



**Figure 9.** Average wind direction, likely travel paths, and observed heights of volcanic ash clouds from Augustine Volcano. Plume heights are relative to the summit vent. All times are Alaska Standard Time. Lack of observations during darkness accounts for apparent absence of explosive eruption plumes during night (modified from Yount and others, 1987). King Salmon wind data from 1953-60; Kodiak wind data from 1949-62; Anchorage wind data from 1948-72. Original data from the National Climatic Data Center, National Oceanic and Atmospheric Administration. Windrose section lengths are proportional to wind frequency determined by annual percent.

and forced the cancellation and diversion of many flights to and from the Anchorage International Airport (Kienle, 1994). Military aircraft were evacuated from Elmendorf Air Force Base near Anchorage and kept away for several days. Only one known aircraft-ash encounter occurred during the 1986 eruption when a DC-10 passed through an Augustine ash cloud while descending for landing at Anchorage International Airport (Swanson and Kienle, 1988). Airborne ash was detected as far north as the Brooks Range, although most of the ash was dispersed over the Cook Inlet area (Yount and others, 1987). Variable winds over Cook Inlet temporarily detained the drifting ash clouds causing dusty air to linger in the region. High winds after several significant ash falls resuspended some ash and prolonged foul air.

Ash clouds from the 1976 eruption drifted to the southeast over western Canada and over the western United States before turning to the northeast, passing over the midwestern United States, the Great Lakes, and eventually out across the Atlantic Ocean (fig. 10; Kienle and Shaw, 1979). An ash cloud was observed at dusk over Tucson, Arizona on January 25 and apparently the same cloud was detected over Hampton, Virginia on January 28; another cloud was reported over Boulder, Colorado in late January and early February. The 1976 eruption indicates that long-distance transport of volcanic ash is possible during future eruptions.

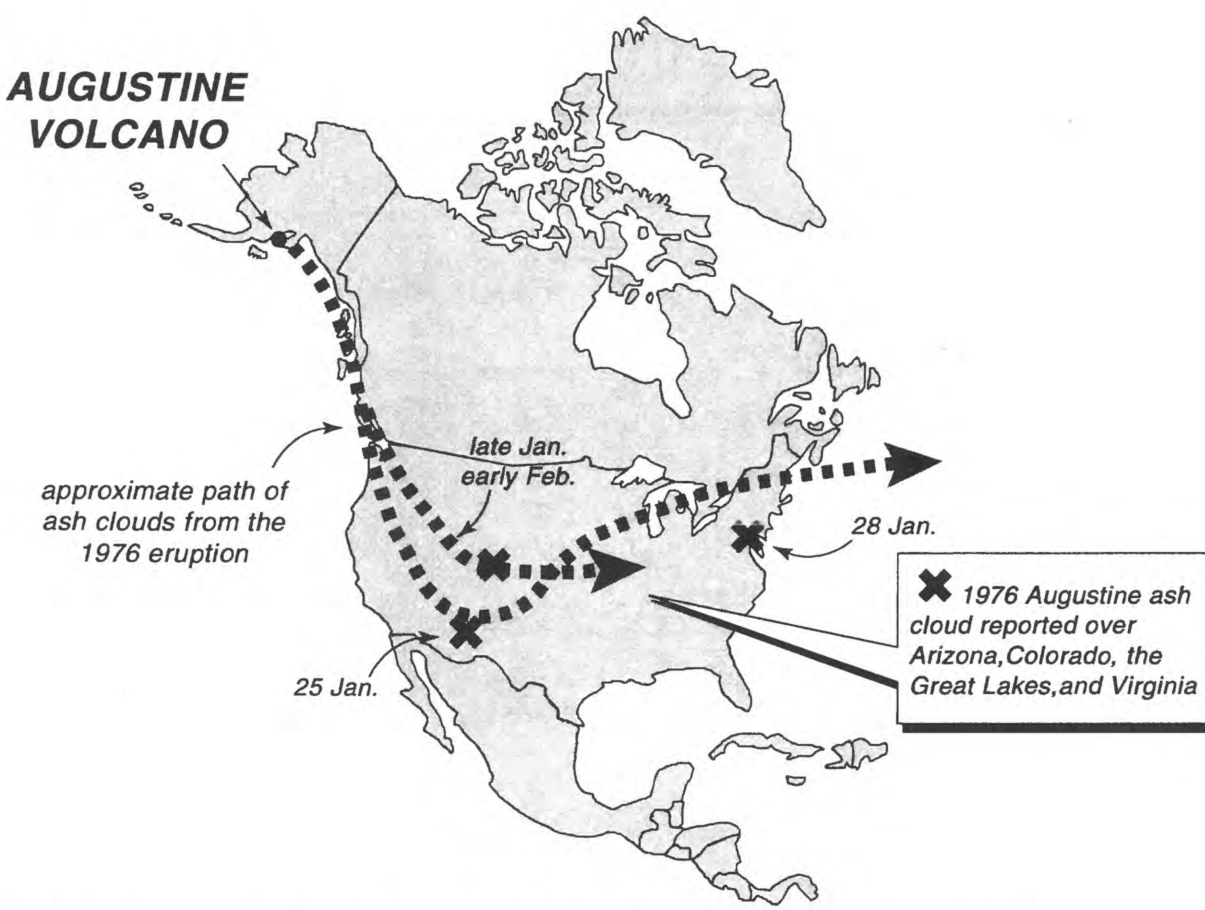



**Figure 10.** Approximate travel path of ash clouds from Augustine Volcano, 1976 eruption.

## Volcanic Ash Fallout and Volcanic Bombs

As clouds of volcanic ash drift from the volcano, a steady rain or fallout of ash usually occurs. Volcanic ash is one of the most troublesome and hazardous products of explosive volcanism. Because it may be transported long distances, it has the potential to affect areas many hundreds of kilometers from the volcano. People are not killed directly by falling ash, but the weight of a thick ashfall could cause structures to collapse and inhaling ash particles is a health hazard to some people. Sometimes a "mud rain" results if airborne volcanic ash mixes with falling rain or snow.

Blocks or bombs of volcanic rock debris (fig. 7) may be ejected as ballistic projectiles that fall or strike areas near the vent. In extreme cases, blocks may be ejected distances of 10 kilometers or more. Typically, the zone of bomb fallout is within a few kilometers of the vent. People or low-flying aircraft would be at risk only within a few kilometers of the vent.

Ashfall from eruptions of Augustine Volcano may be a public health concern for parts of south-central Alaska, especially the Kenai Peninsula. In anticipation of ashfall during the 1976 and 1986 eruptions, the public was advised to remain indoors, and many schools and businesses were closed. Some individuals experienced respiratory problems, and visibility in some places was reduced to 100 meters or less. On March 28, 1986, the concentration of particulate matter in the air over Anchorage was about 860 micrograms per cubic centimeter (Swanson and Kienle, 1988), just below the threshold for a health emergency.

In 1976, natural-gas-powered turbines at the Beluga power plant, the primary power supply for Anchorage, were damaged when airborne ash was ingested (Swanson and Kienle, 1988). Local officials considered shutting down the power plant in anticipation of the March 1986 eruption and sought to obtain power from sources outside the Cook Inlet region. An appeal for power conservation by public and commercial users was made on March 27, 1986.

The approximate extent of ash fallout from the 1976 and 1986 eruptions is shown on figure 11. The ash fallout hazard zone indicated on figure 11 shows areas that could be affected by ash fallout from a future eruption similar to the 1976 and 1986 eruptions. Because wind direction and speed will control the movement of the ash plume, the areas most likely to receive ashfall are those in the zone of prevailing winds. The strongest and most consistent winds are from the west, southwest, and northwest (fig. 9). The thickness of ash fallout will decrease in a downwind direction. During the 1986 eruption, about 6 millimeters of ash accumulated at Homer. Although it is impossible to predict how much ash will be emitted during an individual eruption, it is unlikely that more than 10 centimeters of ash would accumulate on the southwestern Kenai Peninsula and parts of the mainland north of the volcano. Industrial facilities in the upper Cook Inlet region such as oil drilling rigs, oil refineries, manufacturing plants, and power plants could be affected by ashfall.

## Pyroclastic Flow and Surge

A *pyroclastic flow* is a hot, dry mixture of volcanic rock debris and gas that flows rapidly downslope (fig. 7). These flows are relatively dense and tend to follow topographically low areas such as stream valleys. A *pyroclastic surge* is similar to a pyroclastic flow but has a higher gas content. Because it is mostly gas, a pyroclastic surge moves more rapidly than a pyroclastic flow. It may not be confined by topography and may climb up and over ridges. However, deeply incised river valleys and drainages are not present on Augustine Island, and pyroclastic flows and surges tend to spread laterally as unconfined flows as they move over

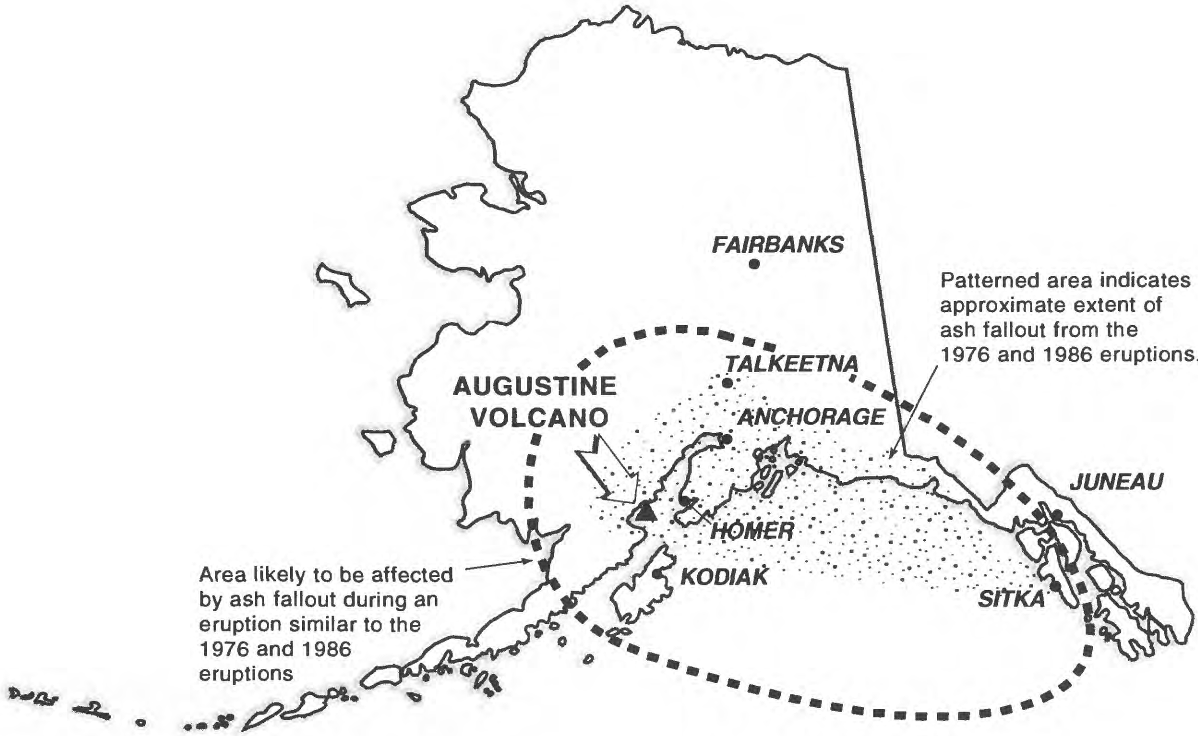



**Figure 11.** Area likely to be affected by ash fallout during a typical eruption of Augustine Volcano. Specific area of ash fallout depends on wind direction.

the lower slopes of the volcano. Because they are hot and fast-moving, both pyroclastic flows and surges could be lethal to anyone on Augustine Island during an eruption.

Pyroclastic flows and surges at Augustine Volcano form either by collapse of a cooling lava dome, or as the eruption column collapses and falls back toward the volcano (fig. 12). Pyroclastic flows and surges have formed during most or all of the historical eruptions of Augustine Volcano. Pyroclastic-flow and -surge deposits from older eruptions are present on the island (Waitt and others, 1996).

Pyroclastic flows and surges from most eruptions would be expected to reach at least several kilometers beyond the vent and could be directed along any azimuth. The average minimum runout distance of pyroclastic flows for five historical eruptions (not including 1812) is about 5 kilometers (fig. 13). Pyroclastic flows did not reach the sea during the 1935 eruption, but did in all other historical eruptions and during several prehistoric eruptions (fig. 13). Thus the basis for the hazard zone boundary indicated on figure 14 and plate 1 is the approximate extent of pyroclastic flows from historical eruptions. Runout distances greater than this are possible during an eruption larger than any of the five historical eruptions. However, pyroclastic flows and surges moving down the flanks of the volcano soon reach water, and traditional methods for estimating runout distance, which are based on overland flows, may not be appropriate. Pyroclastic flows and surges may travel over water; during the exceptional eruption of Krakatau near the island of Java in 1883, pyroclastic flows and surges reached more than 40 kilome-

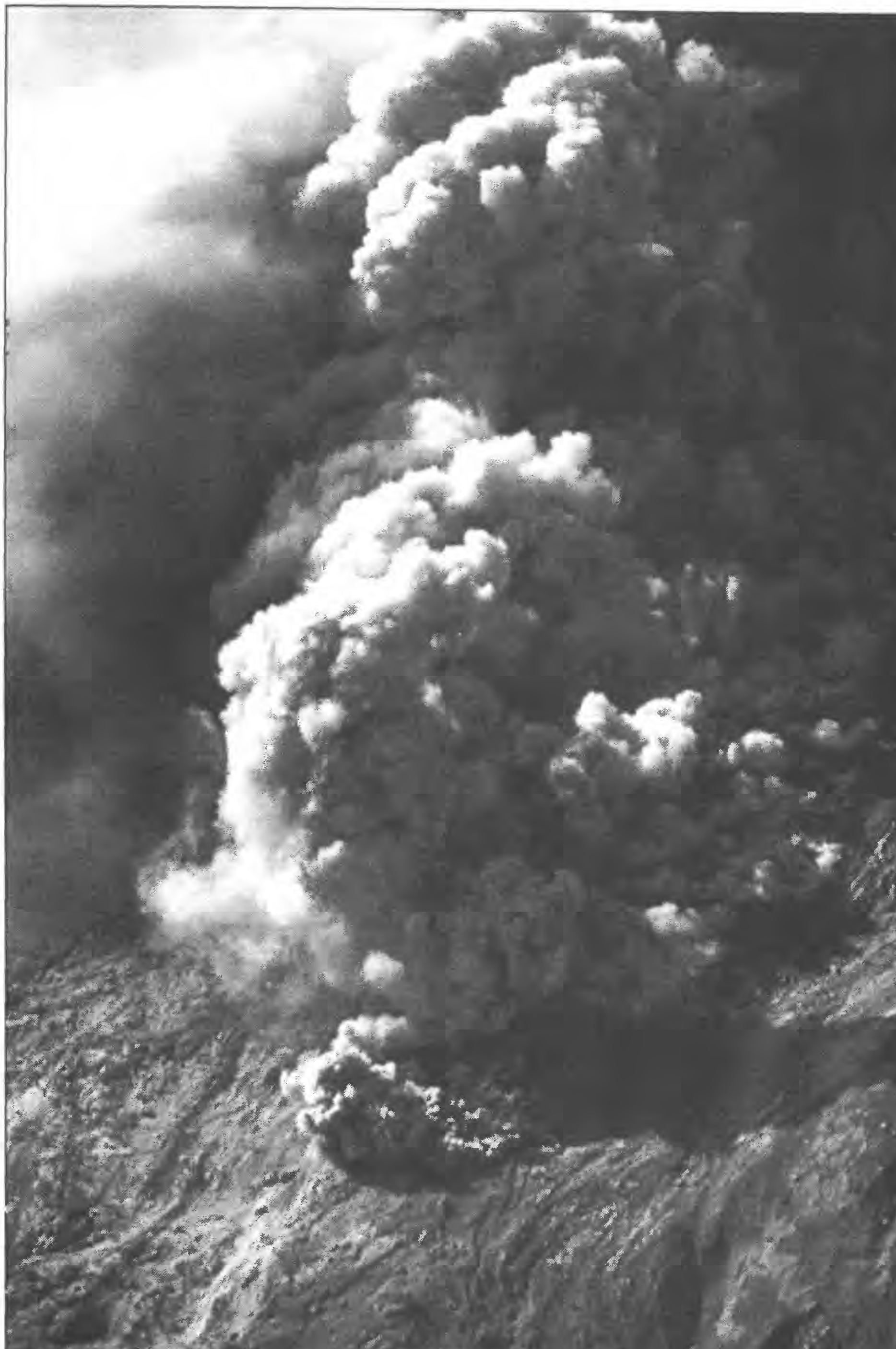


**Figure 12.** Small pyroclastic flow sweeping down the north flank of Augustine Volcano, March 30, 1986. (Photograph by Elizabeth Yount, USGS.)

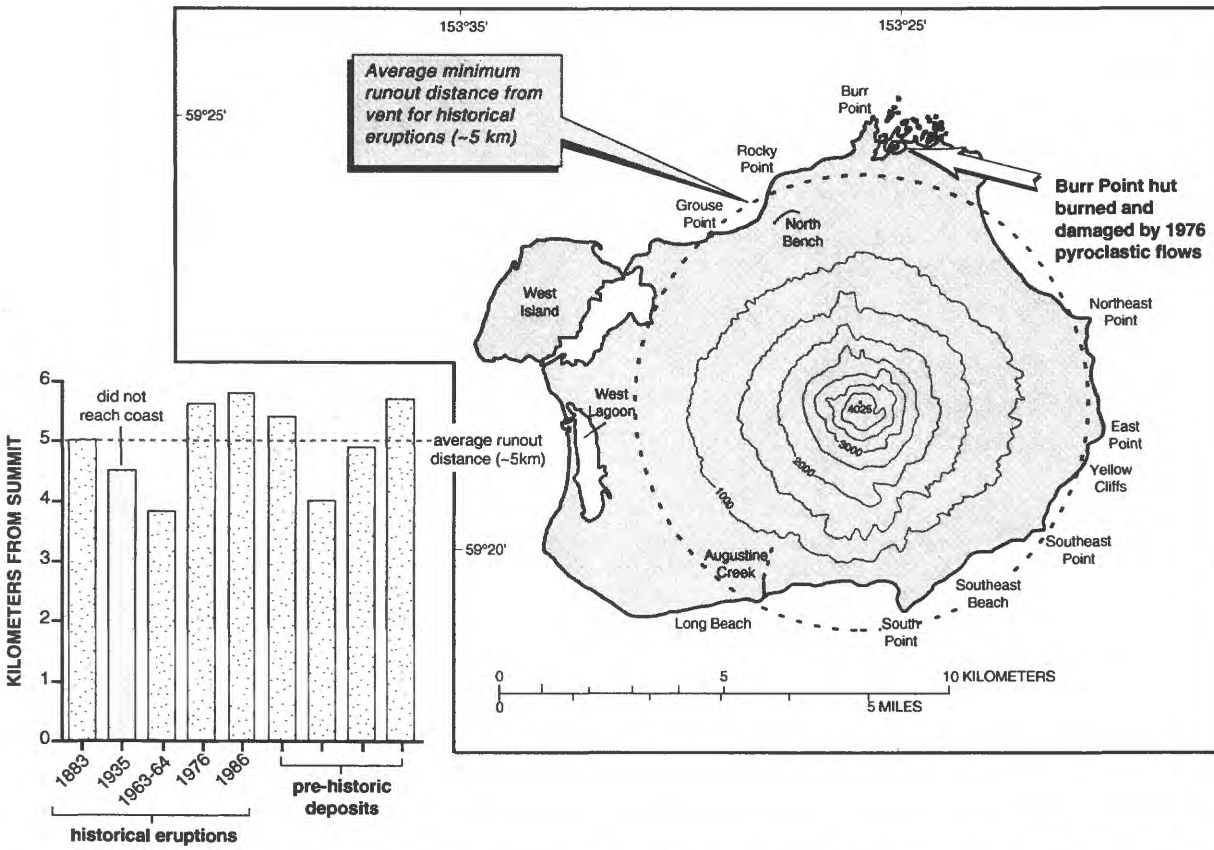



**Figure 13.** Area likely to be affected by pyroclastic flow from a typical Augustine eruption. Inset graph shows runout length of pyroclastic flows from historical and selected prehistoric eruptions (data from Kienle and Swanson, 1985).

ters from their source (Carey and others, 1996). Pyroclastic flows and surges extending this distance from Augustine Volcano would be unlikely except for a rare, extreme eruption, much larger than any of the historical eruptions.

It is difficult to accurately predict the extent of a pyroclastic surge. But because of their genetic relation to pyroclastic flows, they have a slightly greater lateral extent. Thus we are uncertain about the extent of the hazard boundary (fig. 14). Surges are hot (300 to 800 °C) and gaseous, and death or injury from asphyxiation and burning is likely. Because the surge cloud may travel very fast (at least tens of meters per second) pre-eruption evacuation of the area near the volcano is the only way to eliminate risk from pyroclastic surges.

## Debris Avalanche

Volcanic debris avalanches (fig. 7) typically form by structural collapse of the upper part of the volcano. The ensuing avalanche moves rapidly down the volcano flank and forms a bouldery deposit many kilometers from the source that exhibits a characteristic hummocky surface and broad areal extent. Recently formed debris avalanche deposits are usually traceable up the slopes of the volcano to a horseshoe-shaped scar at or near the volcano summit that marks the zone of collapse and origin of the debris avalanche. At Augustine, pyroclastic deposits have covered the debris avalanche deposits except near the coast, and growth of lava domes has obscured collapse scars.

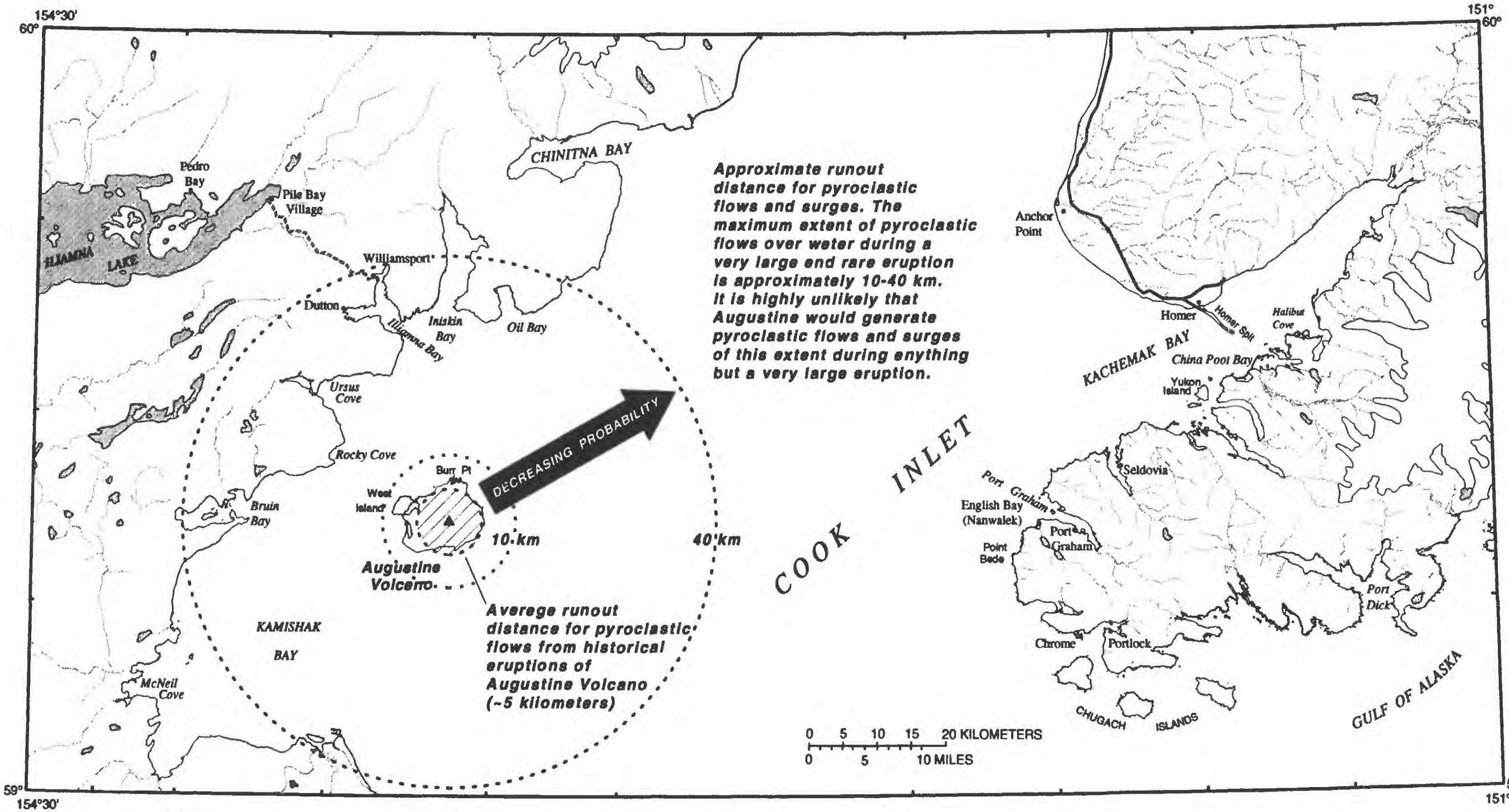



**Figure 14.** Maximum extent of pyroclastic flows and surges during a very large, rare eruption.

Although some debris avalanches occur during an eruption, large-scale collapse of a volcanic cone may occur during a distinctly non-eruptive period, sometimes as a result of long-term chemical alteration of volcanic rock by hot, acidic ground water. As the interior structure of the volcano becomes weakened, the flank may collapse and produce a debris avalanche. Debris avalanche deposits that form this way contain a significant amount of clay in the deposit matrix (usually more than 5 percent). The Yellow Cliffs debris-avalanche deposit exposed along the east coast of Augustine Island (fig. 15) contains abundant clay, indicating that Augustine may have had at least one flank collapse of this type. Other debris-avalanche deposits on Augustine Island probably formed during eruptions; however, a genetic relation between debris avalanche formation and eruptions has not been conclusively demonstrated for all known debris avalanche deposits.

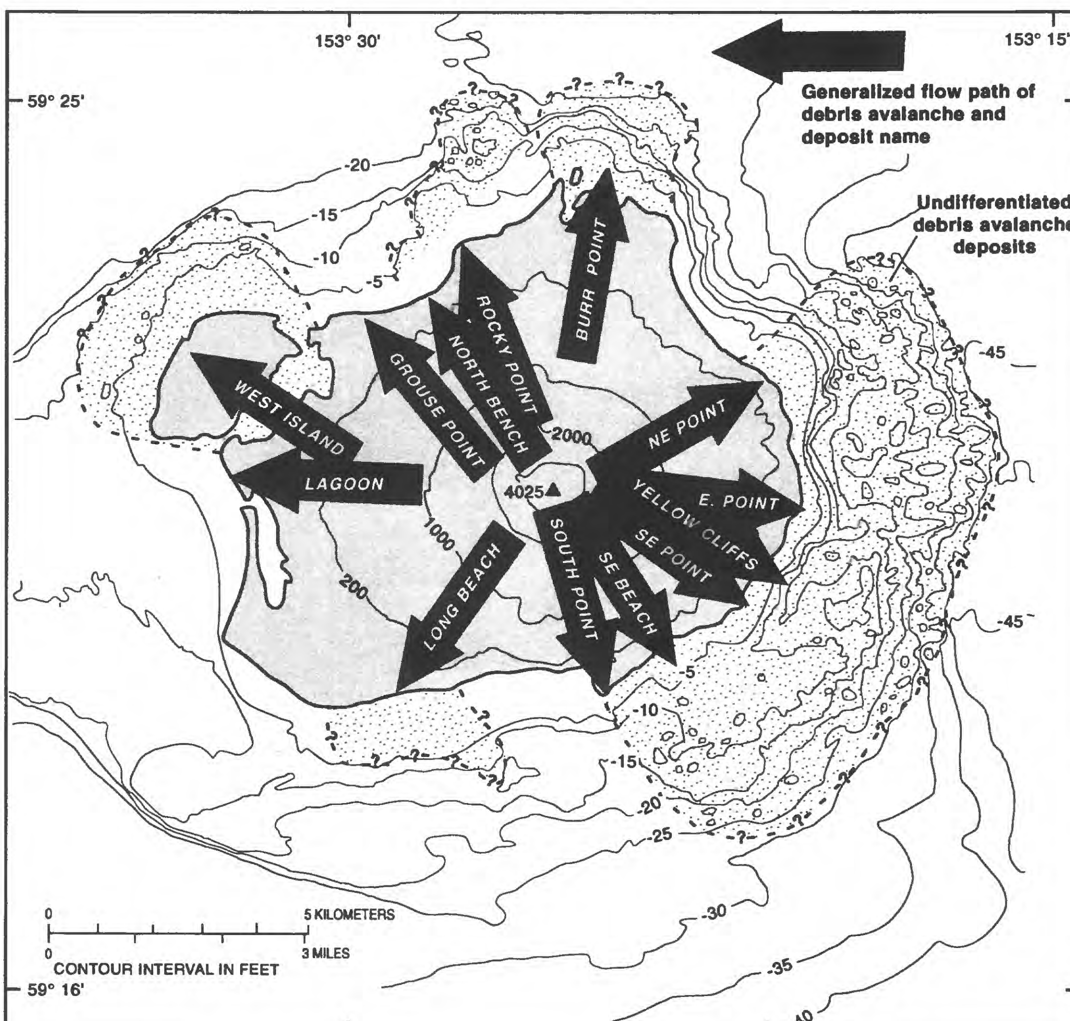



**Figure 15.** Generalized flow paths and names of major debris avalanche deposits on Augustine Island. Generalized topography and bathymetry also shown.

At least 13 debris-avalanche deposits younger than about 2200 yr B.P. are recognized on Augustine Island (figs. 4 and 15; Siebert and others, 1989; Begét and Kienle, 1992; Waitt and others, 1996). These deposits consist of angular gravel composed of poorly sorted mixtures of sand, cobbles, and boulders. The youngest debris-avalanche deposits, at Burr Point (fig. 16) and West Island (fig. 17), exhibit irregular swell and swale surface morphology and contain numerous huge boulders. Other deposits have minimal surface expression because they are mantled by younger volcanic debris. Areas of hummocky topography extending several kilometers seaward of the coastline also are likely debris-avalanche deposits (fig. 15).

Debris-avalanche deposits are preserved in sea cliffs around Augustine Island indicating that all debris avalanches reached the sea and have occurred along almost every azimuth of the volcano (fig. 15). A debris avalanche can move at speeds of 50 to 100 meters per second (180 to 360 kilometers per hour) and would obliterate anything in the flow path. Because Augustine Island is uninhabited, only the occasional visitor would be at risk from a debris avalanche. The extent of former debris avalanches denoted by irregular bathymetry in the nearshore zone of Augustine Island, indicates that a future debris avalanche would probably not extend more than a few kilometers offshore (fig. 18).

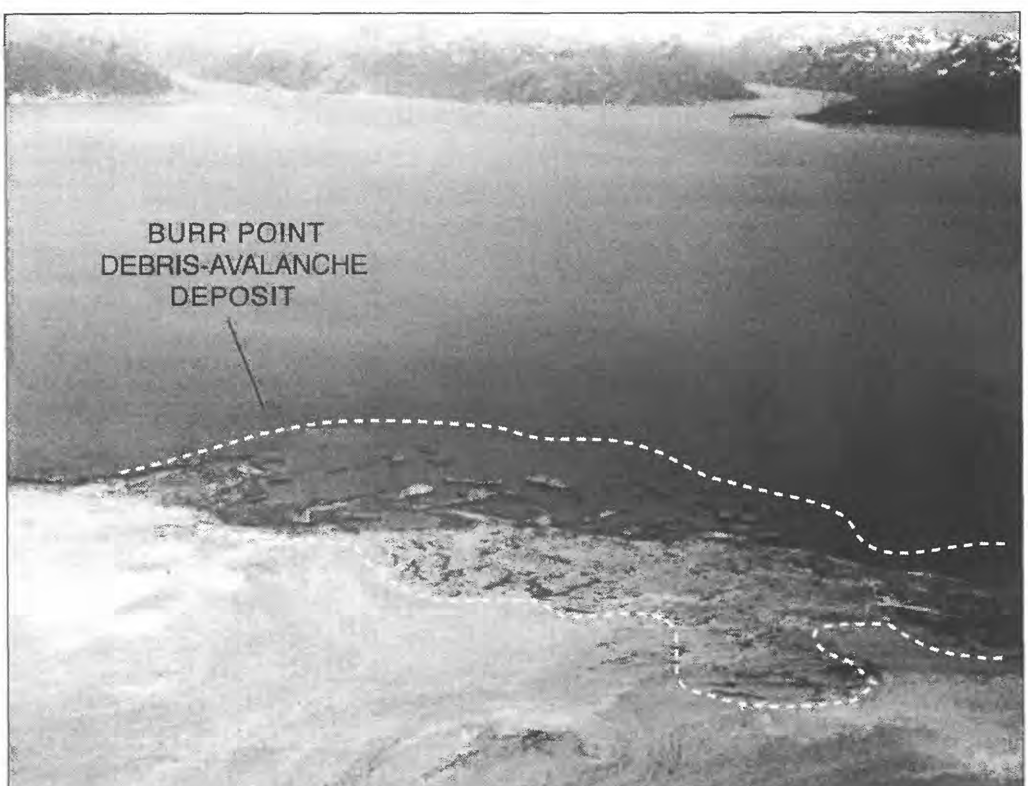



**Figure 16.** Burr Point debris-avalanche deposit. View is to the northeast toward Iniskin Bay. Surface in the foreground is mantled with post-1883 pyroclastic debris. Distance to the opposite coastline is about 25 kilometers. (Photograph by C.F. Waythomas, August 1995.)

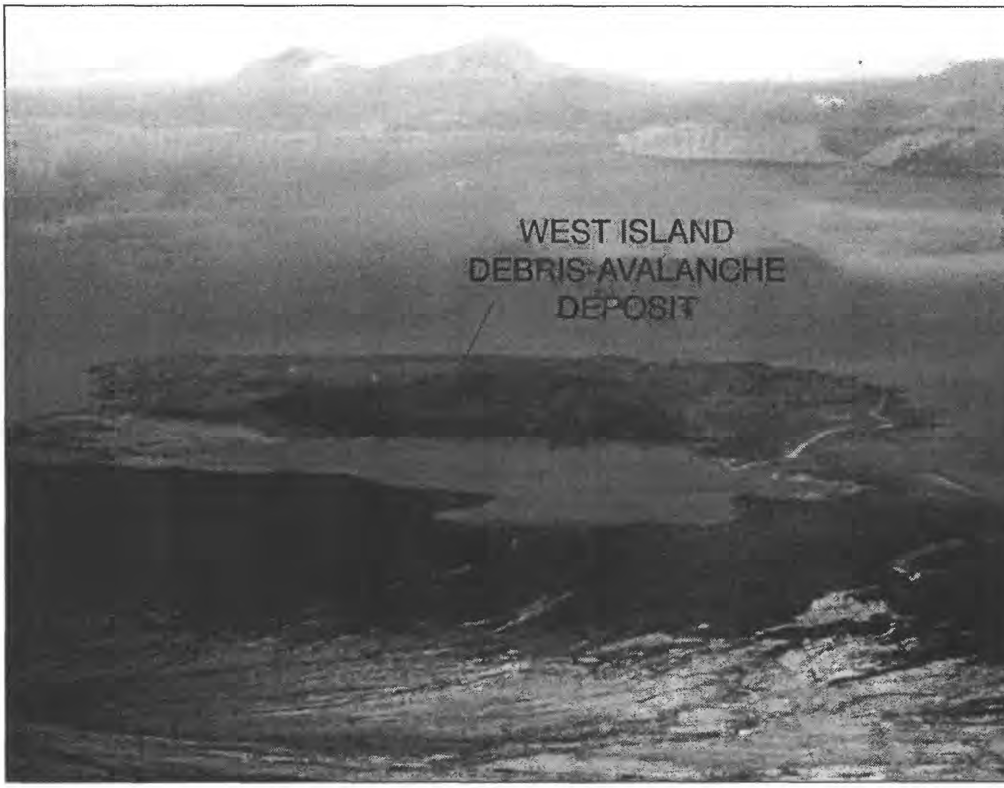



**Figure 17.** West Island debris-avalanche deposit. View is west across Kamishak Bay; distance to opposite coastline is about 11 kilometers. (Photograph by C.F. Waythomas, August 1995.)

## Tsunamis

Volcanoes that are situated in the sea or near the coastline are potentially capable of initiating tsunamis. Of 69 volcanic tsunamis discussed by Latter (1981), 22 percent were caused by earthquakes associated with eruptions, 20 percent were caused by pyroclastic flows entering the water, 19 percent were caused by submarine explosions, 12 percent were caused by volcanic debris avalanches (both hot and cold), 9 percent were caused by caldera collapse, 7 percent were caused by pyroclastic surges, about 10 percent were caused by lahars and air waves from explosions, and 1 percent were caused by lava avalanching into the sea. The setting of Augustine Volcano in lower Cook Inlet could lead to tsunami generation during eruptions if large volumes of volcanic debris were to enter the sea rapidly. The possibility of a substantial tsunami being generated is controversial.

Small volume pyroclastic flows and surges reached the sea during at least four of the six historical eruptions of Augustine Volcano, but no known tsunamis were initiated. The 1883 eruption appears to have caused a debris avalanche that formed Burr Point (fig. 15) and initiated the tsunami observed at English Bay (Nanwalek) about 90 kilometers east of Augustine Island (figs. 19 and 20). Debris avalanches did not occur during any of the four post-1883 eruptions, even though lava domes were emplaced at the summit. However, prior to the 1883 eruption, numerous debris avalanches reached the sea and may have initiated tsunamis (Begét and Kienle, 1992).

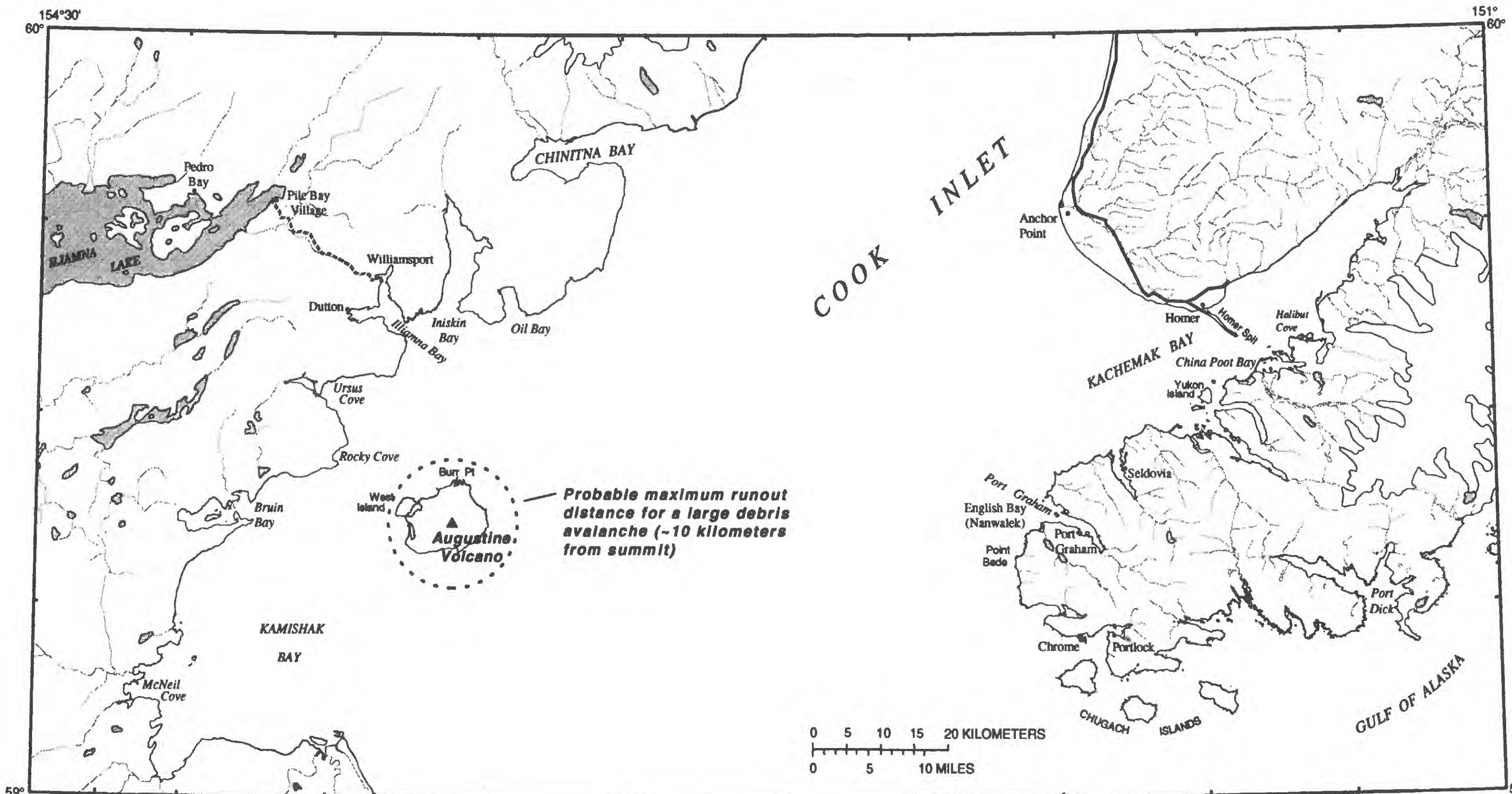



**Figure 18.** Maximum likely runout extent for a large debris avalanche.

**Figure 19.** English Bay, Alaska, July 16, 1995, at high tide. Arrow locates the approximate position of the Alaska Commercial Company trading post where the 1883 tsunami was reported to have been observed. The spit is 1 to 2 meters above high tide. (Photograph by C.F. Waythomas.)

Historical reports of the 1883 eruption describe waves that struck the coast east of the volcano on the morning of October 6, 1883. Minor discrepancies regarding wave height and arrival time make it difficult to decipher the details of the event (table 1). The historical information indicates that several waves, one about 6 meters above low tide and several smaller ones, reached English Bay. Apparently, these waves were not directly observed elsewhere in the region. The association of the wave at English Bay with the eruption-caused debris avalanche at Burr Point has led to speculation about tsunami generation by former debris avalanches (Siebert and others, 1989; Begét and Kienle, 1992). It is difficult to prove that each of the pre-1883 debris avalanches initiated tsunamis when they entered the sea. Geologic evidence of tsunamis and deposits of unequivocal tsunami origin have not been found, despite a thorough search of coastal settings most favorable for preserving such evidence and deposits (Waythomas, 1997).

The highest tides at English Bay reach about 6.7 meters above mean sea level and the spit at English Bay is about 1 to 2 meters above this or about 7.6 to 8.5 meters elevation. Low tide at English Bay ranges from -1.2 to +2.1 meters. Assuming that the reported 6 to 9 meter wave heights for the 1883 tsunami at English Bay are approximately correct, the wave would have inundated the spit only if low tide was about 2.1 meters. If low tide on October 6, 1883 was lower than this, inundation of the spit would not be expected. An Alaska Commercial Company trading post was located on the English Bay spit about 1 to 2 meters above high tide. An observer at the post reported a 20-foot (6-meter) wave on the morning of October 6, 1883, but did not report any wave damage or inundation (table 1). The lack of physical evidence for tsunami inundation at English Bay and no account of wave damage to the Alaska Commercial Company trading post could mean that the wave height (table 1) was erroneously reported or the position of low tide at the time the wave arrived was well below 2.1 meters (high low water).

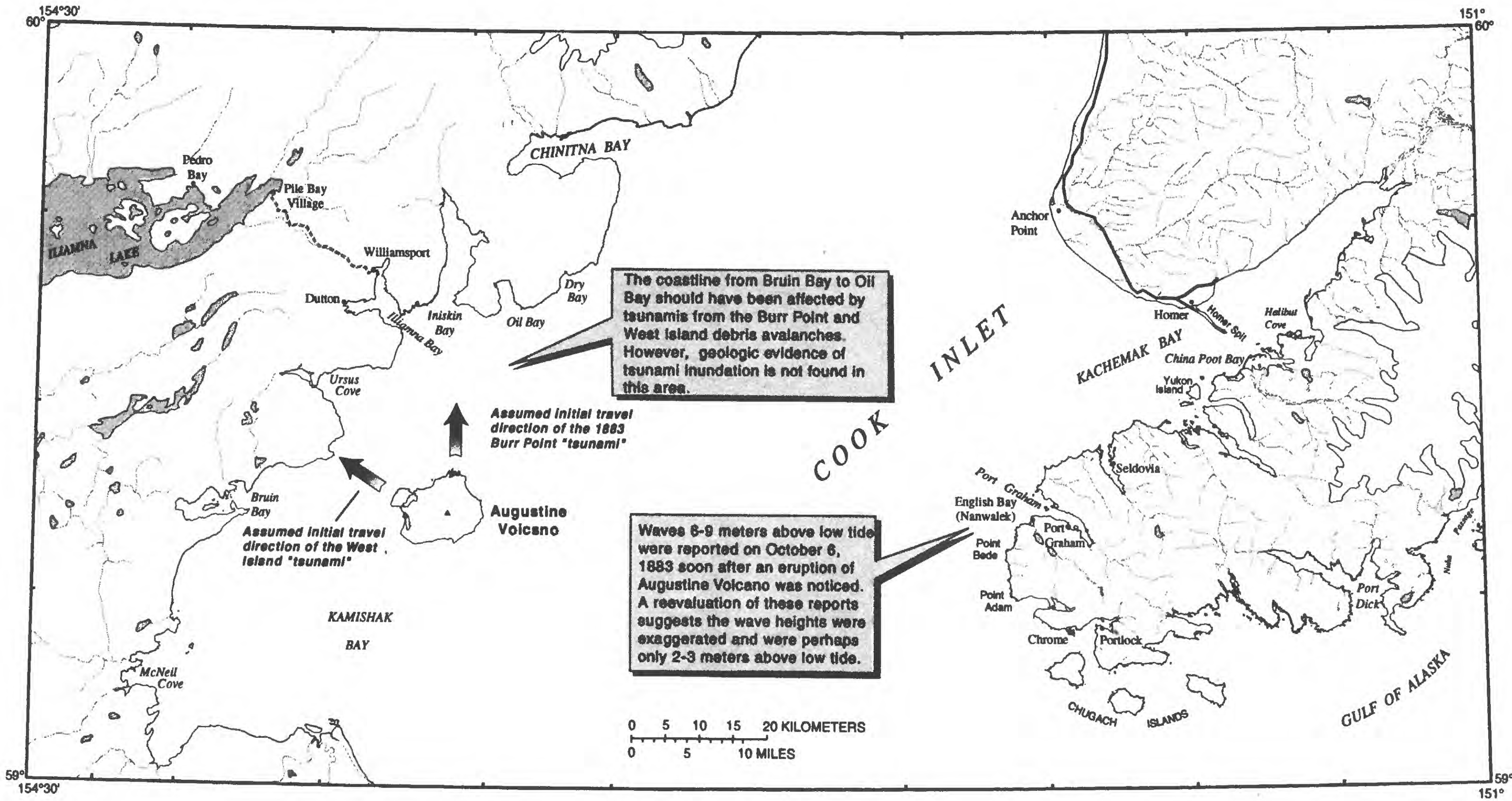



**Figure 20.** Travel directions of the 1883 Burr Point and ca. 450 yr. B.P. West Island tsunamis.

**Table 1.** Reports of waves possibly associated with the 1883 eruption of Augustine Volcano
[m, meter]

| Location where waves observed or reported | Arrival time | Number of waves | Wave height(s) | Comments | Reference |
|---|---|---|---|---|---|
| English Bay | ~8:25 a.m. Oct. 6, 1883 | • Three initial waves<br>• Several others throughout the day | (1) 7-9 m<br>(2) 5.5 m<br>(3) 4.5 m | • First 3 waves occurred at low tide<br>• Tide range ~4.5 m<br>• Boats swept inland and then back, but not damaged<br>• Houses were "deluged"<br>• Observer not named<br>• Third-hand account<br>• Much of this report was found to have exaggerated the effects of the eruption | Davidson (1884) |
| English Bay | ~8:15 a.m. Oct. 6, 1883 | Four waves | 6 m above the "usual" level | • Location of observer not given<br>• No mention of wave damage | Alaska Commercial Company daily log (University of Alaska Archives) |
| Katmai | Oct. 1880(?) | "Tidal" waves | Not given | • Third-hand account in the notes of USGS geologist J.A. Spurr<br>• Discrepancy in date of report (1880, not 1883) | U.S. Geological Survey Archives, Menlo Park, CA |
| St. Paul, Kodiak Island | ~8:21 a.m. Oct. 6, 1883 | Not given | Several centimeters | • Tide gage record<br>• Initial wave caused by air shock?<br>• Difficult to interpret tide record and thus not clear when "tsunami" wave arrived | Lander (1996) |
| Kenai | | Mentions "inundation" only | Not given | • Entry in the diary of Russian Orthodox priest Father Nikita, recorded on May 28, 1884, about 8 months after the eruption began<br>• Mentions inundation and Native people moving their huts to "higher ground" | Kienle and Swanson (1985) |

At other volcanoes on or near the coast, debris avalanche formation and runout into the sea has initiated tsunamis, some of which were lethal (Latter, 1981; Blong, 1984). The island setting of Augustine Volcano and its long history of debris avalanche activity indicate that tsunamis associated with future debris avalanches are plausible. The important factors governing tsunami magnitude include the volume of debris that enters the sea, the velocity of the avalanche, and the water depth in the runout zone. It is difficult to determine how much of the debris avalanche will enter the sea. In most cases, the debris avalanche volume is about 10 percent or less of the summit edifice volume (Siebert, 1984, 1996). The volume of the present summit edifice is about $2.6 \times 10^8$ cubic meters (Begét and Kienle, 1992) and 10 percent of this value is $2.6 \times 10^7$ cubic meters. Although some amount of volume increase will occur during transport, it is reasonable to expect a future debris avalanche to have a volume in the range of $10^7$ to $10^8$ cubic meters. This is a small amount compared to the volume of individual debris avalanche deposits at other volcanoes. For the 1883 Burr Point debris avalanche, approximately 12 to 23 percent of the total volume of the debris avalanche entered the sea (about 4 to 8 x $10^6$ cubic meters), perhaps less, because the avalanche happened at low tide. For the West Island debris avalanche, 40 to 50 percent of the avalanche entered the ocean (about 4 x $10^7$ cubic meters). For reference, the amount of material that entered the sea is approximately equivalent to 1000 1-meter-thick football fields stacked vertically. If the West Island and Burr Point debris-avalanche deposits represent the range of possible avalanche volumes expected at Augustine Volcano, a future debris avalanche could deliver about $10^6$ to $10^8$ cubic meters of debris to the ocean.

A second variable in the generation of tsunamis at Augustine Volcano is the velocity of the debris avalanche when it enters the sea. At present there is no satisfactory method for computing the velocity of complex flow phenomena like rock avalanches. It is theoretically possible to do this in controlled laboratory experiments, or to analyze debris avalanche motion as a sliding rigid block. The latter approach has been used to estimate the velocity of the Burr Point and West Island debris avalanches at the point of impact with the sea (Waythomas, 1997). Slide velocities up to about 100 meters per second are possible but are strongly dependent on estimates of frictional resistance to motion at the base of the slide. Higher values for frictional resistance give slower velocities, whereas lower values give faster velocities. Boundary layer interactions between the avalanche and the surface over which it moves are complex and are not accurately represented by a single variable. Likewise, debris-avalanche motion involves complicated interactions among the solid and fluid components of the flow, which are difficult to estimate with certainty.

Estimates of debris avalanche velocity based on eyewitness accounts are rare. Several individuals who experienced the famous Elm, Switzerland rock avalanche gave similar reports from which a velocity of about 50 meters per second was estimated (Hsü, 1978). Eyewitness reports of the 1925 lower Gros Ventre landslide in Wyoming suggest a peak velocity of less than 27 meters per second (Voight, 1978). Observations of the 1980 rockslide avalanche at Mount St. Helens, Washington indicate an initial minimum velocity of 70 to 80 meters per second (Voight and others, 1983). Although greater values for rock avalanche velocity are reported in the literature, most have been determined from simple slide-block, rigid-body calculations and overestimate observed values by 50 percent or more. Thus, a velocity of 100 meters per second for debris avalanches on Augustine Volcano is probably extreme.

A third factor governing tsunami generation at Augustine Volcano is water depth in the avalanche runout zone. The maximum water depth in this area is about 20 to 25 meters (fig. 15). Regardless of the debris avalanche impact velocity, if the water is shallow, large, fast-moving waves cannot develop. Additionally, the position of the tide would further limit the amount of water displaced by an avalanche. This must have been important during the 1883 Burr Point debris avalanche which apparently happened at low tide; the tide range at Augustine Island is 3 to 5 meters.

In view of the above discussion, it is clear that the tsunami hazard associated with debris avalanche runout at Augustine Volcano is somewhat uncertain (fig. 20). It is difficult to refute the reports of waves at English Bay early in the eruption of 1883. The lack of geologic evidence for wave damage and tsunami deposition or erosion is puzzling if large tsunamis had occurred throughout the recent geologic past. Small, local waves may have been produced when the debris avalanches entered Cook Inlet and may have had little effect on distal coastlines, except for a slight rise in water level. If so, the hazard to low-lying areas along the lower Cook Inlet coastline from future events would be very low.

An alternative explanation of the tsunami hazard favors accepting a 6-meter wave at English Bay and implies that a future debris avalanche similar in size to the 1883 deposit would have a similar result. This view indicates that the hazard to low-lying areas of the lower Cook Inlet coastline is high if the debris avalanche occurs during high tide (Troshina, 1996). In other parts of the world, tsunamis of 1 meter or less have caused significant damage.

## Directed Blasts

A directed blast is a large-scale lateral volcanic explosion caused by a major landslide or slope failure that uncaps the internal vent system of the volcano. Such an event is rare in the history of a volcano. Although geologic evidence indicates that Augustine generates debris avalanches more frequently than most volcanoes, evidence of directed blasts is rare. Of the 14 debris-avalanche deposits on the volcano, only one of them shows evidence, albeit sparse, of an attending directed blast (West Island, about 400 years ago; Siebert and others, 1989, 1995; Waitt and others, 1996). The hazard zone boundary showing the area most likely to be affected by a directed blast (fig. 21) is based on data from the 1980 eruption of Mount St. Helens. The directed blast associated with the 1980 Mount St. Helens eruption is one of the largest known historical events and thus is a "worst case" example. If a directed blast were to occur from the present summit dome of Augustine Volcano, it could affect a broad area, possibly a 180° sector from the dome. A directed blast will usually happen in the first few minutes of an eruption and thus there is no time for warning or evacuation. Living things in the path of a directed blast will be killed or destroyed by impact, burning, abrasion, burial, and heat.

## Lahars and Floods

Most of the volcanoes in Alaska are mantled with variable amounts of ice and snow and have significant amounts of unconsolidated volcanic debris on their flanking slopes. Because eruptive materials are hot, melting of the ice and snowpack can result. As meltwater mixes with available unconsolidated sediment, various types of flowage phenomena may form. Most of these phenomena are categorized as debris flows or more specifically as *lahars* (fig. 7). Typically, lahars consist of boulders, sand, and silt, but commonly they undergo downstream transformation to finer grained flows, sometimes referred to as hyperconcentrated flows or *lahar-runout flows.* If enough sediment is lost from the lahar during flowage, the lahar may transform into a normal streamflow or flood and consist mostly of water.

Small pyroclastic flows generated during historical eruptions of Augustine Volcano rapidly melted snow on the volcano and were transformed into lahars. The lahars flowed down the volcano flanks (fig. 22) and in some cases reached the coast. Because these flows move rapidly and can transport boulder-sized clasts, they are typically quite hazardous to life and property. Lahars pose no hazard on Augustine Island because it is uninhabited and has no permanent structures or facilities.

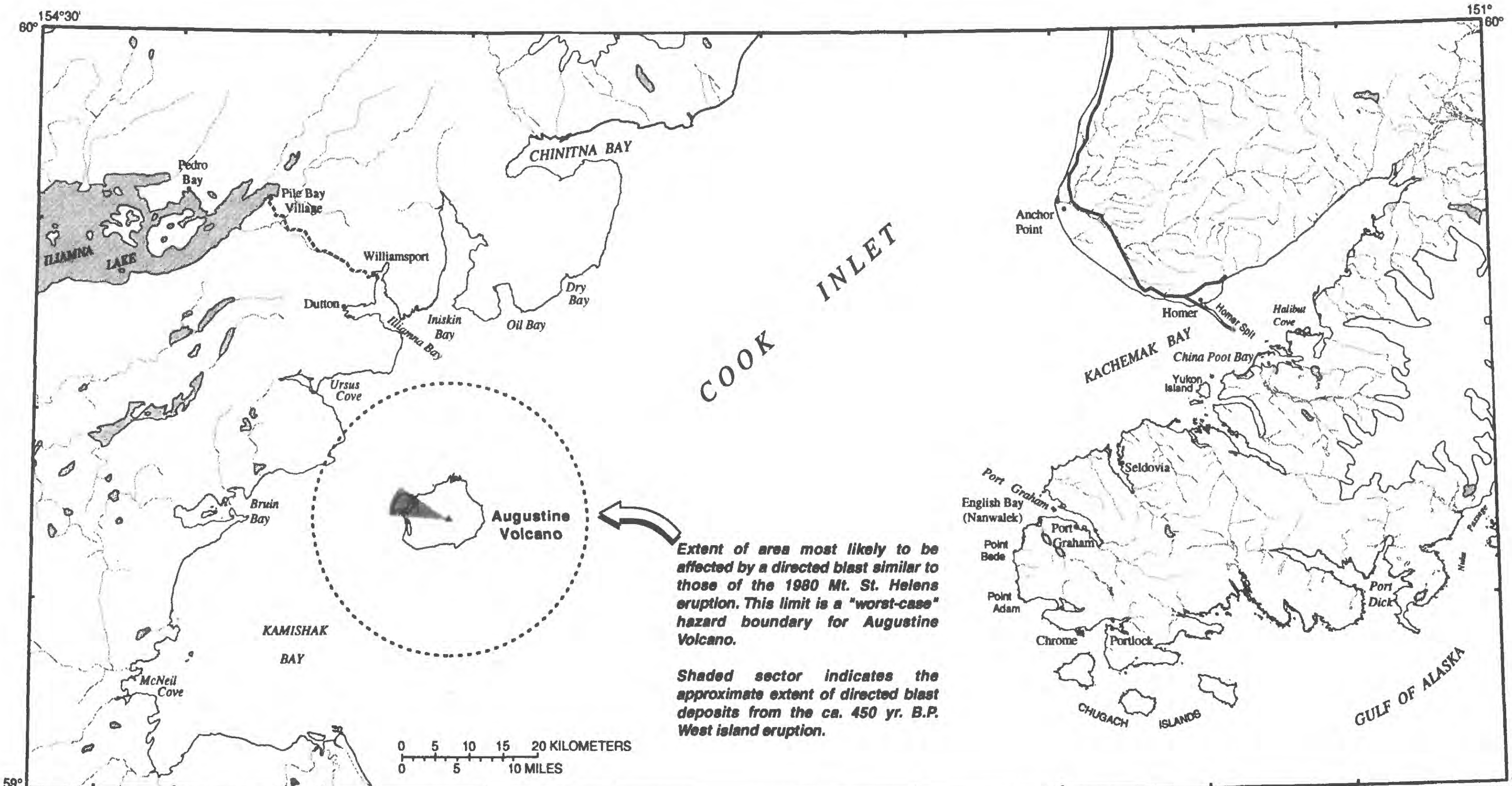



**Figure 21.** Area that could be affected by a directed blast during a very large, rare eruption.

**Figure 22.** Augustine Volcano, March 28, 1986. Dark linear features on volcano flanks are lahars generated by small volume pyroclastic flows. Only a few of these lahars reached the coast. (Photograph by USGS.)

## Pumice Rafts

During some eruptions, coarse pumice enters the sea from pyroclastic flows and fallout in large enough amounts to form an extensive sheet or "raft" of floating pumice. Pumice rafts were developed during the 1976 and 1986 eruptions (Kienle and Swanson, 1985). Pumice rafts can drift with the prevailing ocean currents for weeks to months and if large, could interfere with boats in Cook Inlet and especially small boats in bays and coves.

## Volcanic Gases

Gases are emitted by most active volcanoes, because magma (fig. 7) contains dissolved gases and boils off shallow ground water that is typically present within volcanoes. The most common volcanic gases are water vapor, carbon dioxide, carbon monoxide, sulfur dioxide, and hydrogen sulfide. Volcanic sulfur and halide gases that encounter water form large amounts of sulfuric acid ($H_2SO_4$) and minor amounts of hydrochloric ($HCl$) and hydrofluoric acid ($HF$) as aerosols or droplets. Both carbon monoxide and carbon dioxide are colorless and odorless and thus impossible to detect without some kind of measuring device. Although carbon dioxide is not toxic, it is heavier than air and may displace the available oxygen in confined spaces or low-lying areas causing suffocation. In high concentrations, both hydrogen sulfide and sulfur dioxide may be harmful or toxic to humans and may damage crops and vegetation downwind from the volcano. Acid precipitation may develop from the mixing of snow or rain with acidic volcanic aerosols, which may cause various types of skin and respiratory irritations and corrosive damage to paint, fabric, and structures. Wind tends to disperse volcanic gas and it is typically not found near the ground in concentrations hazardous to humans or animals more than about 10 kilometers from the volcano. During large eruptions, significant volumes of gas can travel high in the atmosphere downwind from the volcano for days and thousands of kilometers.

It is extremely unlikely that the hazard from volcanic gases will be greater than that posed by other volcanic phenomena. During non-eruptive periods, emission of volcanic gases may pose a health concern to someone actually in the active vent area; however, frequent windy conditions at Augustine Volcano and the absence of an efficient trapping mechanism preclude localized buildup of volcanic gas. Therefore, the hazard from volcanic gases is minor.

### Lava Flow

Narrow streams of molten rock or lava form only rarely at Augustine Volcano. Commonly, lava flows (fig. 7) develop after explosive activity at the volcano declines. Several lava flows exist on Augustine Volcano. Typical Augustine flows are andesitic in composition and when molten are relatively viscous. Thus, they tend to move slowly downslope, probably not more than a few tens of meters per hour. Lava flows of this type pose little hazard to people who could easily walk from them; however, lava flows at Augustine may develop steep fronts and are likely to shed blocks and debris downslope.

## EVENT FREQUENCY AND RISK AT AUGUSTINE VOLCANO

An explosive eruption of Augustine Volcano can be expected in the future, probably within a few decades. The primary hazard during a future eruption likely will be drifting clouds of volcanic ash. All aircraft, some facilities, and living things—including humans—downwind from the volcano are at risk from effects of volcanic ash clouds and fallout. Ash clouds from Augustine Volcano move into the flight path of jet aircraft using Anchorage International and other airports in south-central and central Alaska. The frequency at which dangerous clouds of volcanic ash are produced and the amount of ashfall can not be estimated with certainty. Signs of volcanic unrest may precede an eruption and permit reasonable estimates of the likelihood of volcanic ash emission once an eruptive phase is detected. However, it is not possible to determine the characteristics of the ash cloud before an eruption occurs, except that they are likely to be similar to those of previous eruptions.

Because Augustine Island is uninhabited and no permanent structures or facilities are on the island, nothing on the island is at risk from future eruptions. Four episodes of dome building have added rock mass to the volcano's summit (fig. 23), which may lead to a slope failure and debris avalanche. If a summit collapse and debris avalanche similar to or larger than the one in 1883 were to occur at high tide, low-lying areas along the eastern shore of lower Cook Inlet could be at risk from a tsunami. The height of tsunami inundation would depend on local nearshore bathymetry and coastline geometry. A fast-moving surge of water could potentially reach several meters above high tide. However, evidence for tsunami inundation along the lower Cook Inlet coastline has not been found or is ambiguous. Although some prehistoric debris avalanches at Augustine Volcano were relatively large (for example West Island), for some reason evidence of large devastating tsunamis that should have struck the coastline cannot be found. Energy losses during wave propagation across the shallow waters of Cook Inlet could have diminished the destructive power of former tsunamis, making them incapable of erosion and wave damage on opposing coastlines. If former debris-avalanche-induced tsunamis were large enough to be significant hazards, it is logical that some geologic evidence of them should be preserved along the coastline of lower Cook Inlet.

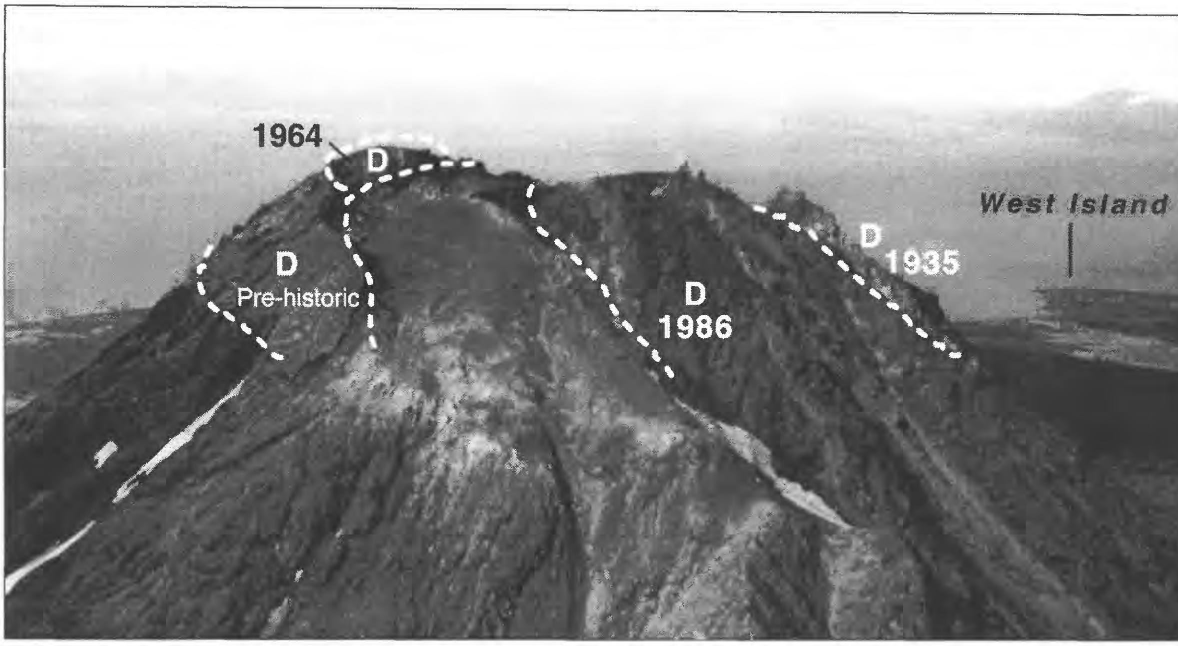



**Figure 23.** Summit of Augustine Volcano; view is to the west. Multiple summit domes are indicated (D). The addition of mass to the volcano summit by emplacement of lava domes during the 1935, 1964-65, 1976 (not visible), and 1986 eruptions may have created a potentially unstable situation and could lead to a flank collapse and debris avalanche. At present, there is no evidence indicating that a collapse is imminent; however, Augustine produces debris avalanches on a regular basis and a future debris avalanche would not be an unusual event.

## HAZARD WARNING AND MITIGATION

One of the primary roles of the Alaska Volcano Observatory (AVO) is to communicate timely warnings of volcanic unrest and potential eruptions (Eichelberger and others, 1995, p. 4). Each of the 1976 and 1986 eruptions of Augustine was preceded by nearly 9 months of precursory small earthquakes. This indicates a degree of seismic warning prior to the next eruption (fig. 24). The 1986 eruption was preceded by at least several weeks of increased steaming from the summit area, and a strong sulfur smell was noted downwind of the volcano several days prior to the eruption.

When volcanic unrest is detected, other monitoring techniques, such as satellite observations, measurement of volcanic gas flux, remote observation with real-time video or time-lapse cameras, and geodetic surveying, are used to develop a comprehensive assessment of the likelihood of an eruption and its potential effects.

The AVO monitors Augustine Volcano with a real-time seismic and geodetic network (fig. 25) equipped with an alarm system that is triggered by elevated levels of seismic (earthquake) activity indicating volcanic unrest. A network of nine radio-telemetered seismometers send real-time radio signals to AVO offices in Anchorage and Fairbanks. A three-station network of benchmarks, precisely located on the volcano with global positioning satellite (GPS) technology, are used to monitor small-scale changes in the shape of the volcano. GPS data also are radio-telemetered to AVO offices

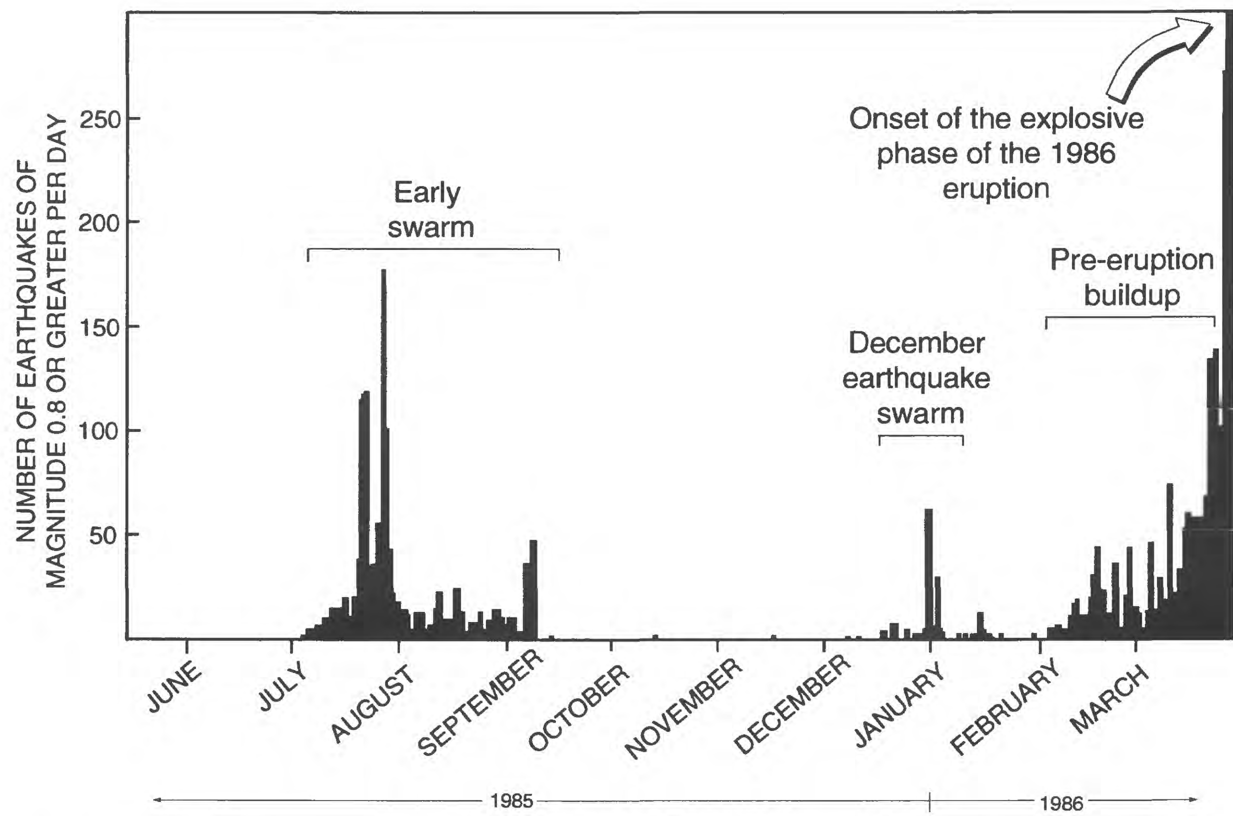



**Figure 24.** Earthquake count of precursory phase, July 1, 1985 to March 27, 1986. Note the distinct increase in the number of earthquakes per day just prior to the onset of the explosive phase of the eruption. Such an increase is common just before an eruption (modified from Power, 1988).

at one-hour time intervals and are able to detect surface displacements of one centimeter or less. In addition, a network of six radio-telemetered tiltmeters provide complementary data on deformation of the volcano surface. AVO also maintains a field-based data-collection program that includes additional geodetic, temperature, and gas measurements.

In general, the last three historical eruptions of Augustine Volcano have followed a similar pattern. Early in the eruption, explosively propelled vertical columns of volcanic ash spread tephra downwind; pyroclastic flows and lahars swept the volcano flanks, some reaching the sea. During the later stages of the eruptions, a lava dome is extruded at the summit, sometimes punctuated by its partial collapse into small pyroclastic flows. The most likely focus of future activity is on the north and northeast flanks. Pyroclastic flows over this area that are similar to those generated during the 1986, 1976, and 1883 eruptions are to be expected. Depending on the size of the eruption and the position of a new vent and dome, other flanks could be affected as well.

The AVO distributes by fax and electronic mail, a weekly update of volcanic activity that summarizes the status of the more than 40 historically active volcanoes along the Aleutian Arc. During periods of unrest or volcanic crises, updates are issued more frequently to advise the public of significant changes in activity. Recipients of these updates include the Federal Aviation Administration, the

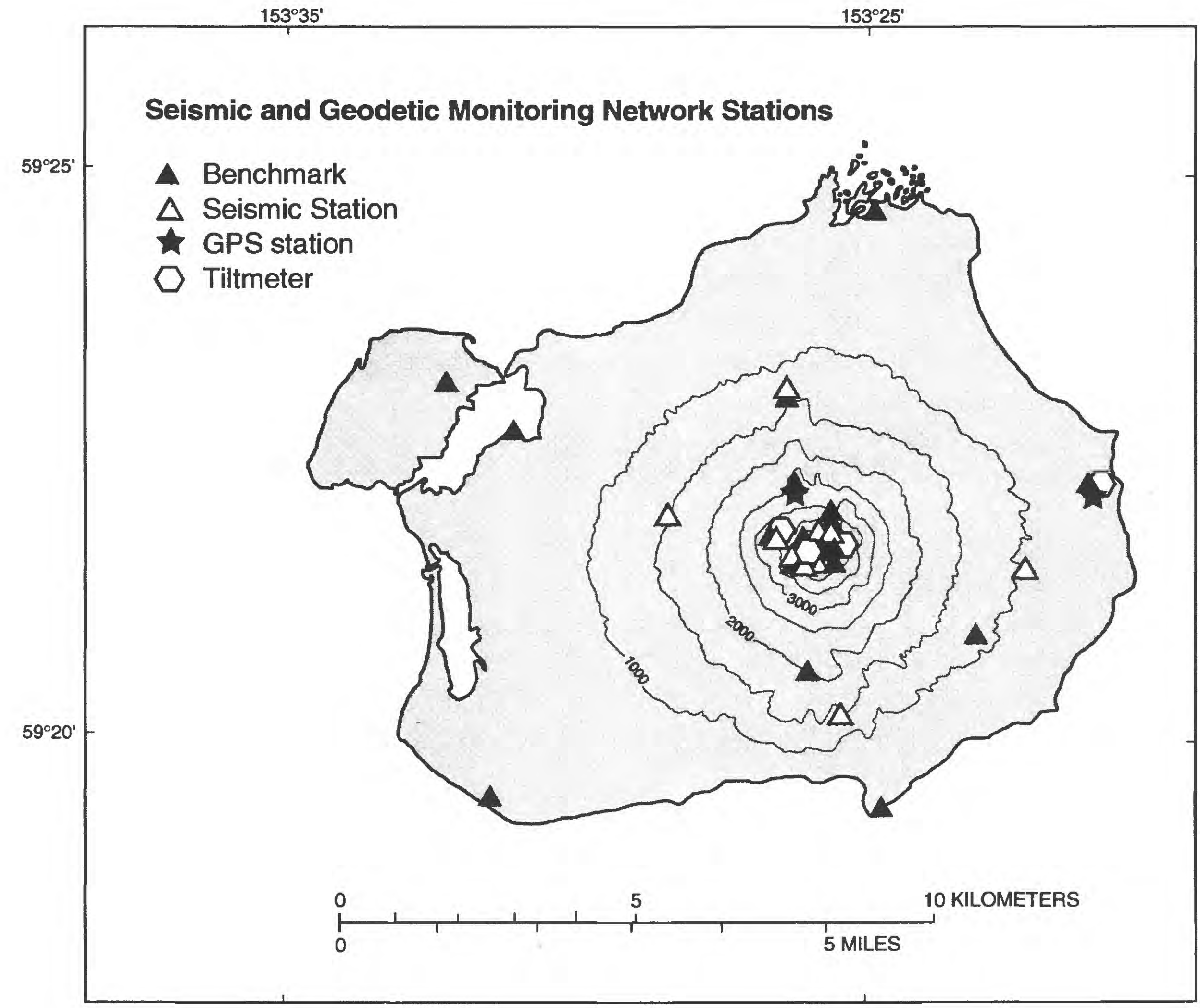



**Figure 25.** Location of seismic and geodetic monitoring stations on Augustine Island. With this network, it is possible to obtain real-time data on earthquakes beneath the volcano and to detect small amounts of ground displacement.

National Weather Service, the Alaska Department of Emergency Services, local military bases, the Governor's office, various State offices, television and radio stations, news wire services, air carriers, and others. Updates also are distributed by electronic mail to various volcano information networks.

During the 1989-90 eruptions of Redoubt Volcano, the AVO developed a "level of concern color code" (Brantley, 1990; fig. 26). This code provides efficient and simple information about the status of volcanic activity or unrest and conveys the AVO's interpretation of that activity or unrest in terms of the potential for an eruption and its likely effects. In the advent of a volcanic crisis, various Federal, State, and local officials are contacted by telephone, advised of the situation, and the level of concern color code is established while an update is being prepared. This approach has been used

## LEVEL OF CONCERN COLOR CODE

To more concisely describe our level of concern about possible or ongoing eruptive activity at an Alaskan volcano, the Alaska Volcano Observatory (AVO) uses the following color-coded classification system. Definitions of the colors reflect AVO's interpretations of the behavior of the volcano. Definitions are listed below followed by general descriptions of typical activity associated with each color.

| | |
|---|---|
| GREEN: | **Volcano is in its normal "dormant" state.** |
| YELLOW: | **Volcano is restless.**<br><br>*Possible precursor volcanic activity is occurring (increased seismicity, anomalous steam plume). An eruption (explosive or non-explosive) is possible over the next few weeks and may occur with little or no additional warning.* |
| ORANGE: | **Explosive (or non-explosive) eruption is possible within a few days; non-explosive eruption may be occurring at present.**<br><br>*Strong increase in precursor activity. Explosive eruption may occur with little or no additional warning. Extrusion of lava dome or lava flow may be occurring.* |
| RED: | **Major explosive eruption is in progress or expected within 24 hours.**<br><br>*Explosive eruption is confirmed or expected shortly. Potentially hazardous ash plume to 25,000 feet above sea level or more is expected or has been confirmed.* |

**Figure 26.** Alaska Volcano Observatory's level of concern color code. This code and eruption updates are distributed to government agencies, the media, airlines, and the public.

successfully during recent periods of volcanic unrest, such as the 1989-90 eruptions of Redoubt Volcano, the 1992 eruptions of Mount Spurr Volcano (Miller and Chouet, 1994; Keith, 1995), and the 1996-97 eruption of Pavlof Volcano.

Minimizing the risks posed by eruptions of Augustine Volcano is possible through adequate warning of potential hazards, such as drifting ash clouds and fallout, and by avoiding development or utilization of areas likely to be affected by future eruptions. Since Augustine Island is presently uninhabited and is at risk from all hazardous volcanic phenomena, future development on or around the volcano is unlikely. If for some reason, development is unavoidable in hazardous areas, engineering measures may be employed to minimize or prevent undesirable consequences.

Knowledge of potential hazards is required to assess the risk associated with a specific location on or near the volcano and to assess whether or not movement to another location would be safer. Recreational users of Augustine Island are advised that low-lying terrain along streams and gullies that extend toward the summit are subject to pyroclastic flow and surge, lahars, and floods. Given the present configuration of the summit area, a debris avalanche is most likely on the north and northeast flanks. In the advent of an eruption, evacuation from the island is the only adequate means of protection. However, significant hazards still exist from airborne debris, especially in areas close to or downwind from the volcano. During an eruption, access closer than about 10 kilometers from the volcano could be impossible and the risks to human life great. Small planes and helicopters seeking a view of an eruption could be at risk from intermittent and unpredictable discharge of ballistic projectiles (volcanic bombs) or sudden changes in the travel direction of the eruption plume.

People and facilities located farther away from the volcano may have additional time to prepare for the adverse effects of an eruption; however, an emergency plan should be developed and ready prior to the onset of an eruption. The planning for volcanic emergencies is similar to that for other emergencies, such as flooding or extreme weather. The sources of emergency information are often the same and the usual interruption of essential services may result. Thus, planning for interruptions in electrical service, transportation (especially air travel), and outdoor activities is appropriate for volcanic emergencies.

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## GLOSSARY

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

**Andesite.** A fine-grained volcanic rock made up of feldspars and ferromagnesian minerals; typically has a $SiO_2$ content of 54 to about 62 percent.

**Debris avalanche.** Rapidly moving, dry flows of disaggregated rock debris, sand, and silt. Volcanic debris avalanches often form by some type of structural collapse of the volcano, usually the steep front of the cooled lava dome, or other parts of the upper edifice. A large portion of the volcano may become unstable, break away from the volcanic massif, and become an avalanche. A debris avalanche may be triggered by an eruption or earthquake. Debris avalanches move at velocities ranging from a few tens of meters per second to more than 100 meters per second and behave like complex granular flows or slide flows. Often they are quite voluminous (greater than 10 cubic kilometers) and may run out considerable distances (up to 85 kilometers) from their source. The resulting debris avalanche deposit usually exhibits hummocky surface morphology.

**Directed blast.** Large-scale volcanic explosions caused by a major landslide or slope failure which results in a rapid drop in the pressure of the intruding magma near the surface of the volcanic edifice. The 1980 eruption of Mt. St. Helens was triggered by a massive slope failure and the subsequent laterally directed blast affected a 180° sector north of the volcano and extended for several tens of kilometers outward. A directed blast typically travels away from the volcano at a low angle and may not be deflected by ridges or other topographic barriers. Rock debris propelled by a directed blast moves much faster than typical landslides and rockfalls. For example, at Mt. St. Helens, the initial velocity of the directed blast cloud was about 600 kilometers per hour decreasing to about 100 kilometers per hour, at a distance 25 kilometers from the volcano.

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

**Eruption column.** The vertical portion of the eruption cloud that rises above a volcanic vent

**Ejecta.** General term for anything thrown into the air from a volcano during an eruption; synonymous with pyroclast which means "fire" and "broken piece."

**Fallout.** A general term for debris which falls to the earth from an eruption cloud.

**Lahar.** An Indonesian term for a debris flow containing angular clasts of volcanic material. For the purposes of this report, a lahar is any type of sediment/water mixture originating on or from the volcano. Most lahars move rapidly down the slopes of a volcano as channelized flows and deliver large amounts of sediment to the rivers and streams that drain the volcano. The flow velocity of some lahars may be as high as 20 to 40 meters per second (Blong, 1984) and sediment concentrations of >750,000 parts per million are not uncommon. Large volume lahars can travel great distances if they have an appreciable clay content (> 3 to 5 percent), remain confined to a stream channel, and do not significantly gain sediment while losing water. Thus, they may affect areas many tens to hundreds of kilometers downstream from a volcano.

**Lapilli.** Ejected rock or pumice fragments between 2 and 64 millimeters in diameter.

**Lava.** Molten rock that reaches the earth's surface.

**Lava dome.** A steep-sided mass of viscous and often blocky lava extruded from a vent; typically has a rounded top and roughly circular outline.

**Lithic.** Synonym for "rock" in volcanic deposits, refers to fragments of pre-existing rock as opposed to newly erupted material.

**Magma.** Molten rock beneath the earth's surface.

**Pumice.** Highly vesicular volcanic ejecta; due to its extremely low density, it often floats on water.

**Pyroclastic.** General term applied to volcanic products or processes that involve explosive ejection and fragmentation of erupting material.

**Pyroclastic flow.** A dense, hot, chaotic avalanche of rock fragments, gas, and ash that travels rapidly away from an explosive eruption column, often down the flanks of the volcano (synonymous with "ash flow"). Pyroclastic flows move at speeds ranging from 10 to several hundred meters per second and are typically at temperatures between 300 and 800 °C (Blong, 1984). Pyroclastic flows form either by collapse of the eruption column, or by failure of the front of a cooling lava dome. Once these flows are initiated, they may travel distances of several kilometers or more and easily override topographic obstacles in the flow path. A person could not outrun an advancing pyroclastic flow.

**Pyroclastic surge.** A low-density, turbulent flow of fine-grained volcanic rock debris and hot gas. Pyroclastic surges differ from pyroclastic flows in that they are less dense and tend to travel as a low, ground-hugging, but highly mobile cloud that can surmount topographic barriers. Surges often affect areas beyond the limits of pyroclastic flows.

**Stratovolcano.** (Also called a stratocone or composite cone.) A steep-sided volcano, usually conical in shape, built of lava flows and fragmental deposits from explosive eruptions.

**Tephra.** Tephra is any type of rock fragment that is forcibly ejected from the volcano during an eruption. Tephra may be fine-grained dust or "ash" (0.0625 to 2 millimeter diameter—silt to sand sized), coarser "lapilli" (2 to 64 millimeter diameter —sand to pebble sized), or consist of large blocks or bombs (>64 millimeter—cobble to boulder sized). When tephra is airborne, the coarsest fraction will be deposited close to the volcano, but the fine fraction may be transported long distances and can stay suspended in the atmosphere for many months. Tephra particles are typically sharp, angular, and abrasive, and are composed of volcanic glass, mineral, and rock fragments.

**Tsunami**. Widely spaced, fast-moving ocean waves most commonly initiated by sudden displacements of the sea floor during earthquakes or submarine landslides. Volcanic eruptions can also cause tsunamis if unconsolidated volcanic sediment flows rapidly or falls into the water as in a catastrophic slope failure from a steep-sided volcanic cone or edifice, or if explosive eruptions occur at or near sea level. Tsunamis are capable of inundating significant portions of the coastline, especially if the wave energy is focused by narrowing of inlets and bays.

**Vent.** An opening in the earth's surface through which magma erupts or volcanic gases are emitted.



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