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

Preliminary Volcano-Hazard Assessment for Hayes Volcano, Alaska

Open-File Report 02–072

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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 of Hayes Volcano in the Tordrillo Mountains near Mount Gerdine (highest peak in background). Most of the volcanic cone of Hayes Volcano was destroyed during the most recent eruption of the volcano, about 3,600 years ago. Because the remaining parts of the cone are obscured by glacier ice and snow, identifying the volcano is difficult. Photograph taken by author T.P. Miller, September 1981.

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By Christopher F. Waythomas and Thomas P. Miller

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Alaska Volcano Observatory

Anchorage, Alaska

2002

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

U.S. GEOLOGICAL SURVEY
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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
square meter (m^2)	10.76	square foot
cubic meter (m^3)	35.31	cubic foot
cubic kilometer (km^3)	0.2399	cubic mile
cubic meter per second (m^3/s)	35.31	cubic foot per second

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

$$°F = (1.8 \times °C) + 32)$$

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

Preliminary Volcano-Hazard Assessment for Hayes Volcano, Alaska

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SUMMARY OF HAZARDS AT HAYES VOLCANO

Hayes Volcano is an ice- and snow-mantled, deeply eroded volcanic massif located in the northern Tordrillo Mountains of the north-central Cook Inlet region about 135 kilometers northwest of Anchorage, Alaska. Hayes Volcano consists of a glacially dissected, poorly exposed cluster of *lava domes*. No historical eruptions of Hayes Volcano are known, and the last period of major eruptive activity occurred within a time interval of 4,400 to 3,600 years ago. During this period, explosive *Plinian*-style eruptions occurred that dispersed volcanic *ash* over large areas of interior, south-central, and southeastern Alaska. *Pyroclastic flows* produced during these eruptions descended Hayes Glacier and entered the Hayes River drainage. The pyroclastic flows initiated volcanic debris flows or *lahars* that flowed down the Hayes River, into the Skwentna River, and probably reached the Yentna River about 110 kilometers downstream from the volcano. The last major eruptive period of Hayes Volcano may have spanned about 200 years, and at least one of the eruptions during this interval was possibly the largest eruption of any volcano in the Cook Inlet region in the past 10,000 years.

The distribution and thickness of volcanic-ash deposits from Hayes Volcano in the Cook Inlet region indicate that volcanic-ash clouds from prehistoric eruptions were voluminous. Clouds of volcanic ash generated during a future eruption of Hayes Volcano would be a major hazard to all aircraft using Ted Stevens Anchorage International Airport and other local airports, and, depending on wind direction, ash clouds could drift a considerable distance beyond the volcano. Ash *fallout* from future eruptions could disrupt many types of economic and social activities, including oil and gas operations, shipping activities, and power generation in the Cook Inlet area. An eruption of Hayes Volcano—even a minor episode—would likely melt a significant amount of ice and snow, and the meltwater could result in the formation of large lahars and downstream flooding. The greatest hazards in order of importance are summarized below and are shown on plate 1.

• Volcanic-ash clouds

Clouds of fine volcanic ash will drift away from the volcano with the wind. Ash clouds are a hazard to all aircraft downwind. Airborne volcanic ash can drift thousands of kilometers from its source volcano. Ash from future eruptions could interfere with air travel, especially during a large sustained eruption.

• Volcanic-ash fallout

Ash fallout from prehistoric eruptions of the Hayes Volcano reached parts of south-central Alaska where accumulations of several millimeters or more of fine ash are known. Fine ash may cause respiratory problems in some humans and animals. Heavy ash fall 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 and ground traffic could extend the unpleasant effects of ash fallout.

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. 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. Considered preliminary, these reports are subject to revision as new data become available.

• **Lahar and flood**

Hot volcanic debris interacts with snow and ice to form fast-moving slurries of water, mud, rocks, and sand. Because of the extensive snow and ice cover on Hayes Volcano, these flows, called lahars, are expected to form quickly during future eruptions. Lahars will follow streams and drainage ways, and they could flow a considerable distance down the Skwentna River and possibly into the Yentna River. Lahars could be hazardous to people and facilities in the Hayes, Skwentna, and upper Yentna River valleys during an eruption of Hayes Volcano.

• **Pyroclastic flow and surge**

Hot material expelled from the volcano may travel rapidly down surrounding slopes as flows of volcanic debris called pyroclastic flows and surges. These flows will primarily travel along valleys and low-lying topography and are not expected to reach more than about 40 kilometers from the volcano. However, in proximal areas, pyroclastic flows and surges can surmount topographic barriers. They pose little hazard except to people on or near the volcano during an eruption.

• **Lava dome collapse**

*Extrusion of pluglike, dome-shaped bodies of molten rock (*lava*) may occur within the active* vent. *The outer portion of these lava domes are commonly unstable and prone to failure. When a recently emplaced lava dome collapses, it usually releases hot gas and rock debris that forms a pyroclastic flow.*

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

•**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. Debris avalanches could form during a future eruption but they are not likely to be voluminous.*

• **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 volcanic events. Evidence for a directed blast has not been identified at the Hayes Volcano.*

• **Volcanic gases**

Some volcanoes emit gases in concentrations that are harmful to humans. The vent area on Hayes Volcano is concealed by glacier ice and emissions of volcanic gas have not been detected. If the volcano were to become active, volcanic gases may be emitted. However, the frequently windy conditions around Hayes Volcano will likely prevent the buildup of volcanic gases to levels toxic to humans. Thus, the hazard from volcanic gases is minimal.

• **Lava flow**

Streams of molten rock (lava), if they are generated, may extend a few kilometers from the vent. 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 volcano hazards at Hayes Volcano are encouraged to read the summary section and consult plate 1 and the illustrations. Individual sections of this report provide a slightly more comprehensive overview of the various hazards at Hayes Volcano. A glossary of relevant geologic terms is included. Additional information about Hayes Volcano can be obtained by consulting the references cited at the end of this report or by visiting the Alaska Volcano Observatory web site (URL: <http://www.avo.alaska.edu>*).*

INTRODUCTION

Hayes Volcano is a glacially dissected, poorly exposed lava dome complex largely obscured by an extensive cover of snow and ice. The volcano is in south-central Alaska, about 135 kilometers northwest of Anchorage and about 90 kilometers north of Mount Spurr volcano. Hayes is in the northern Tordrillo Mountains and is the easternmost volcano in the Aleutian volcanic arc (figs. 1 and 2). The volcano was discovered in 1975 (Miller and Smith, 1976), and little is known about its eruptive character and history. Although the volcano has not been active historically, it is located within a few hundred kilometers of major population, commerce, and industrial centers of south-central and interior Alaska. Future eruptions of Hayes Volcano are not as likely as eruptions of other volcanoes in the Cook Inlet region; however, because of its most recent explosive history, an eruption of this volcano could have a significant impact on the citizens and economy of southern Alaska.

Hayes Volcano is situated deep in the Tordrillo Mountains between the Alaska Range to the north and Cook Inlet to the south (fig. 2). The volcano has neither classic conical form nor a true summit, although high points along the rim of the massif are between 2,400 and 2,800 meters in altitude above sea level. Almost ninety percent of Hayes Volcano is covered by glacier ice and perennial snow. Several large glaciers emanate from nearby Mount Gerdine, a nonvolcanic massif, and cover the slopes around the volcano. This extensive ice cover is a source of water for volcanic debris flows or lahars. The volume of snow and ice on Hayes Volcano is comparable to that found on nearby Mount Spurr volcano, which supports about 67 cubic kilometers of ice and perennial snow (March and others, 1997).

The Hayes River is the principal drainage on the north side of Hayes Volcano (fig. 3). It flows northeast a short distance before joining the Skwentna River, which flows into the Yentna River just downstream from the community of Skwentna. The Yentna in turn empties into the Susitna River, which flows to Cook Inlet.

Most of the area around Hayes Volcano is wilderness and is uninhabited. Recreational use of the area is minimal because of the remote location, although the area is visited by small groups of people in summer and winter. An electrical-power transmission line crosses the Susitna valley near the Cook Inlet coastline; two small communities, Tyonek and Skwentna, and scattered residences in the lower Susitna valley are located downwind from the volcano (fig. 3). Life and property are not at risk in the immediate vicinity of the volcano.

Figure 1. Location of Hayes Volcano with respect to historically active volcanoes in Aleutian volcanic arc and southern Alaska. Hayes Volcano is easternmost volcano in Aleutian arc and was discovered only recently, in 1975 (Miller and Smith, 1976).

Figure 2. Location of Hayes Volcano in south-central Alaska. Also shown are other Cook Inlet area volcanoes, cities, towns, and place names mentioned in text.

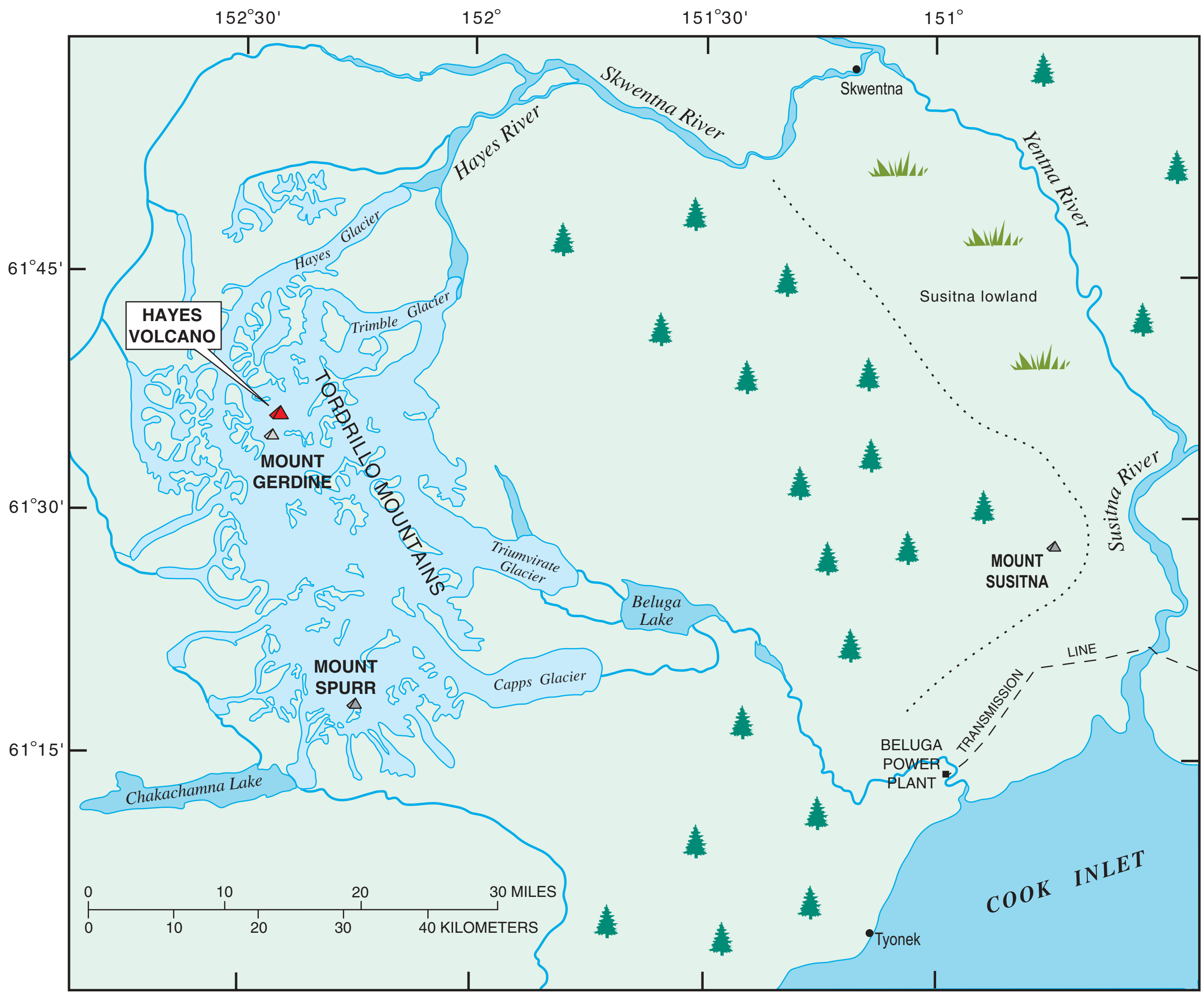


Figure 3. Location of Hayes Volcano in Tordrillo Mountains and principal drainages in region. Dotted line is approximate boundary between bottomland area of Susitna lowland and uplands to west.

Purpose and Scope

This report summarizes the principal volcano hazards likely to be associated with a future eruption of Hayes Volcano. Hazardous volcanic phenomena that could occur on or near the volcano as well as distal effects of eruptions are described. 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 illustrations that show potentially hazardous areas are included. A glossary of geologic terms is at the end of the report. Terms defined in the glossary are set in different type (italic or roman) at their first appearance in the text.

Physical Setting of Hayes Volcano

Hayes Volcano is an ice-shrouded, glacially scoured eruptive center of *Quaternary* age composed of *pyroclastic* deposits, volcanic breccia, and lava domes (fig. 4). Although the *edifice* of the volcano is largely covered by glacier ice, parts of small lava domes, dome debris, and pyroclastic deposits project through the ice at altitudes of 2,400 to 2,800 meters above sea level. The volcano is nestled within the Tordrillo Mountains, a rugged, glacier-clad mountain range, between the Alaska Range and Cook Inlet, that is composed primarily of older plutonic igneous rocks (Magoon and others, 1976). Most of the area is in high

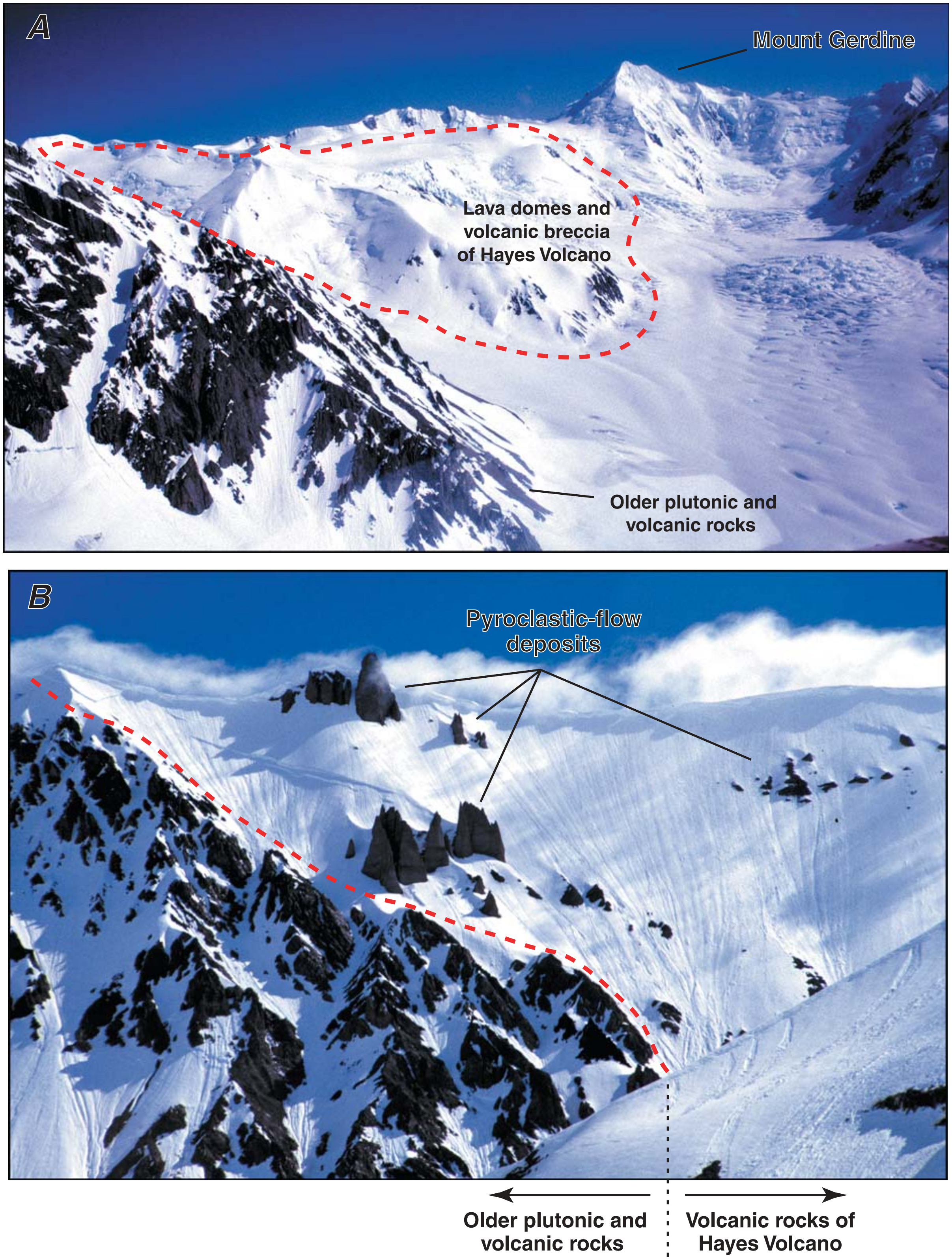


Figure 4. Northwest side of Hayes Volcano as viewed from Hayes Glacier looking southeast. *A*, Area of lava domes and volcanic breccia on the upper part of Hayes Volcano. This area probably included vent for 4,400–3,600-year-B.P. eruption. *B*, Pyroclastic-flow deposits filling a preeruption depression in older volcanic and plutonic rocks. These deposits are located just north of area shown in *A*.

relief (greater than 1,500 meters) and supports an extensive complex of glacier ice that covers most of the mountainous terrain. The volume of perennial snow and glacier ice on Hayes Volcano is not known but is comparable to the ice volume present on Mount Spurr volcano (to the south), which supports about 67 cubic kilometers of ice and perennial snow (March and others, 1997).

Unlike the other volcanoes in the Cook Inlet area, Hayes Volcano lacks a well-defined cone, and deposits from eruptions older than the 4,400-to-3,600-year-old eruption are not known. The volcano is unusual in this regard because all other volcanoes in the Cook Inlet area consist of relatively voluminous assemblages of volcanic rock and debris that formed over many tens of thousands of years.

Hayes Volcano is in a remote wilderness area of State-owned land and is only occasionally visited by people. The major drainages downstream from the volcano are important for sport fishing, and recreational use of the major valleys is common in summer and winter. Residential areas and developments near the Cook Inlet coastline and in the Susitna lowland are more than 50 kilometers from the volcano but could be at risk from ash fallout should an explosive eruption occur in the future.

ERUPTIVE ACTIVITY AT HAYES VOLCANO

Prehistoric Eruptive Activity

Little is known about the geologic history of Hayes Volcano. The volcano was discovered only recently, in 1975 (Miller and Smith, 1976), and because of its relatively inaccessible location high in the Tordrillo Mountains, it has not been studied as much as other volcanoes in the Cook Inlet region. Although more than 90 percent of the volcano is covered by ice and snow, exposed bedrock indicates that the volcano consists chiefly of lava domes, dome debris, and volcanic breccia (fig. 5). The age of these rocks is not known, but they probably formed during the Quaternary period.

The lower flanks of the volcano, at the head of Hayes Glacier, are mantled by light-colored *pumice*-rich pyroclastic-flow deposits (Qvpf, fig. 5) that probably formed during a major eruption of the volcano about 4,400 to 3,600 years ago (fig. 6). Similar deposits are found near the terminus of Hayes Glacier, and they grade downstream into lahar deposits, which can be found along the Hayes and Skwentna Rivers. Deposits of sand-to-silt-sized volcanic ash from the 4,400-to-3,600-year-B.P. eruption of Hayes Volcano are common in many areas of south-central Alaska (Riehle and others, 1990; Begét and others, 1991). These deposits indicate that the last major eruption of Hayes Volcano was probably a Plinian-style eruption, characterized by multiple, explosively generated ash clouds that likely extended high into the atmosphere, possibly reaching stratospheric levels. Detailed studies of volcanic-ash deposits from Hayes Volcano indicate that the 4,400-to-3,600-year-B.P. eruption may have taken place over several hundred years (Riehle and others, 1990).

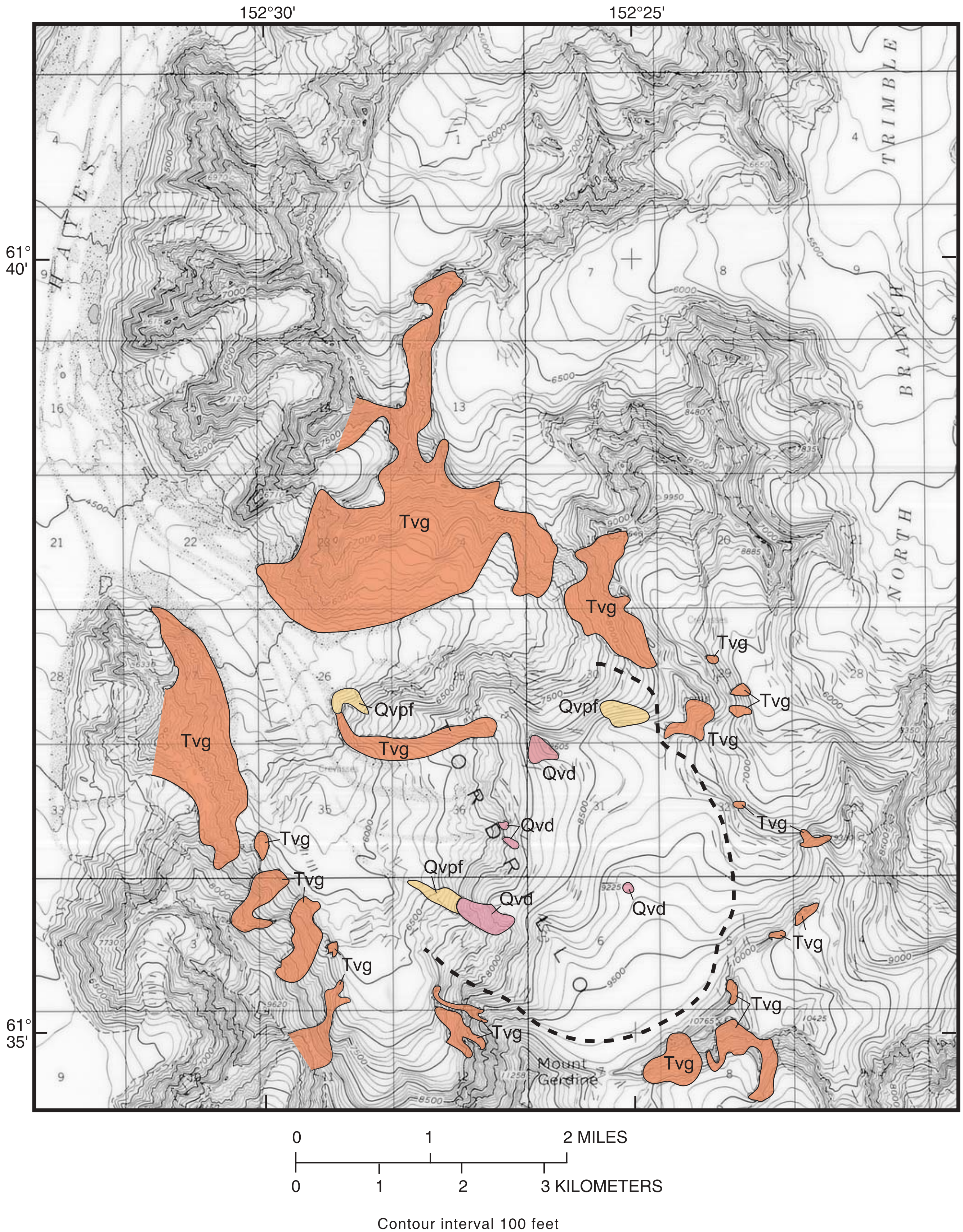
After about 3,600 years B.P., Hayes Volcano appears to have been largely inactive. A single bed of volcanic ash (fig. 6), geochemically similar to the other known Hayes ashes, was erupted about 500 years ago (Riehle, 1985). Although the aerial extent of this ash deposit is not well known, the ash bed probably records a minor eruption of the volcano about 500 years ago.

Historical Eruptions

Historical eruptions of Hayes Volcano are not known and evidence of recent eruptive activity is not apparent on the volcano. During trips to the volcano in 1999 and 2000, signs of volcanic unrest, such as melting of glacier ice, steaming, or discoloration of the ice surface by volcanic ash were not observed.

HAZARDOUS PHENOMENA ASSOCIATED WITH ERUPTIONS

A volcano hazard (fig. 7) is any volcanic phenomenon that is potentially threatening to life or property. In general, hazards associated with volcanic eruptions are grouped as proximal or distal relative to the areas most likely to be affected by specific volcanic phenomena as a function of distance from the vent (fig. 8). The classification of hazardous phenomena at Hayes Volcano as proximal or distal is an approximate classification 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


152°30'
152°25'
61° 40'
61° 35'
HAYES
TRIMBLE
BRANCH
NORTH
Tvg
Qvpf
Qvd
Mount Gerdine
0 1 2 MILES
0 1 2 3 KILOMETERS
Contour interval 100 feet

areas well beyond the volcano, whereas during a smaller 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. The proximal hazard zone is delineated by the ratio of the volcano-summit height (*H*) to the runout length (*L*) of on-ground hazardous phenomena such as pyroclastic flows, debris avalanches, and lahars. Typical *H*/*L* values range from 0.1 to 0.3 and are used to estimate the extent of a particular on-ground hazard. Life and property within the proximal hazard zone may be at risk during eruptions depending on the eruptive style and duration of activity. Anyone in this zone would have little or no time to escape from the area in the event of an eruption. Because most of the area around the Hayes Volcano is uninhabited, only the occasional visitor is at risk from the various proximal hazards (fig. 7).

Distal hazards pose less risk to people because there is usually adequate time for warning and evacuation. This group of hazards affects people and structures that are more than about 10 to 30 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. Fallout of volcanic ash also can be a proximal and a distal hazard.

EXPLANATION

QUATERNARY

Qvpf — Pyroclastic-flow deposits

Qvd — Lava domes and breccia

TERTIARY

Tvg — Undifferentiated volcanic and plutonic rocks

- - - Outline of Hayes Volcano

Figure 5. Generalized geologic map of Hayes Vol-

The processes that produced the volcanic deposits depicted on the geologic map of Hayes Volcano (fig. 5) are generally confined to the flanks of the volcano and the major drainages that extend from the summit, primarily the Hayes Glacier and Hayes River drainage (fig. 3). Only volcanic ash clouds, ash fallout, pyroclastic flow and surge, and large-volume lahars are most likely to affect areas more than a few tens of kilometers from the volcano.

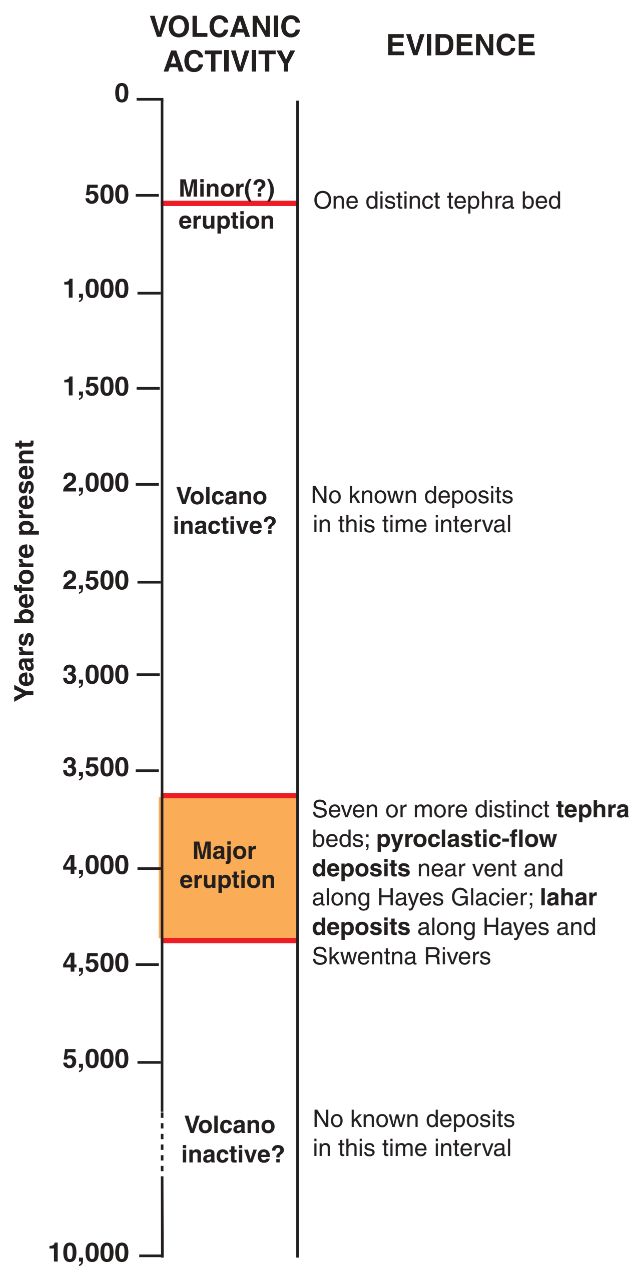


Figure 6. Holocene volcanic activity at Hayes Volcano. Summarized from Riehle (1985), Riehle and others (1990), and Begét and others (1991).

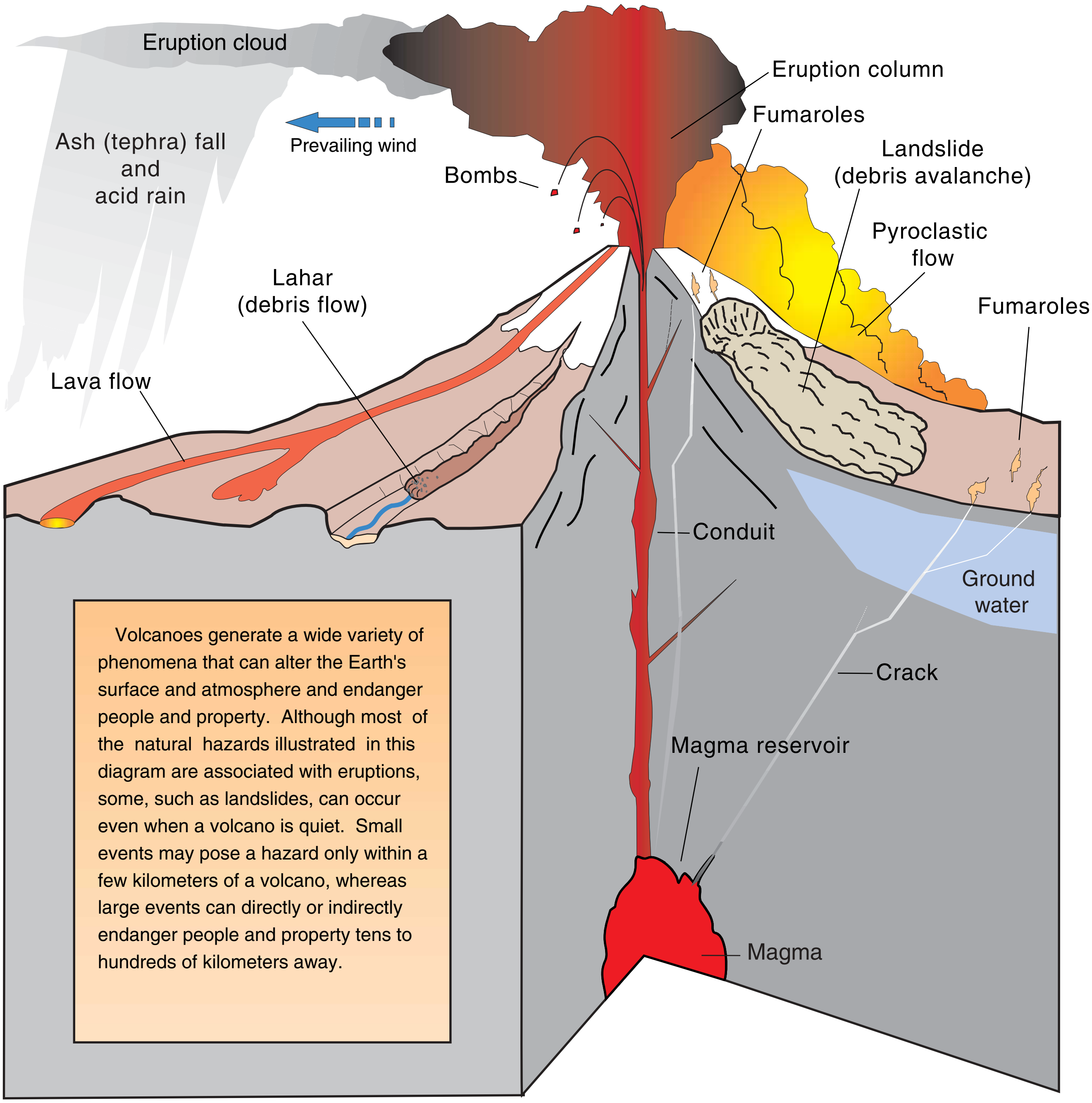


Figure 7. Simplified sketch of *stratovolcano* and associated hazardous phenomena (modified from Myers and others, 1997).

VOLCANIC HAZARDS

Volcanic-Ash Clouds

At least twice in the past 10,000 years, explosive eruptions of Hayes Volcano ejected significant quantities of fine ash particles or *tephra* into the atmosphere forming an *eruption cloud* (fig. 7). Eruption clouds are carried by the wind and drift away from the volcano almost immediately (figs. 9 and 10). 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 potential hazard to all aircraft downwind from the volcano (Casadevall, 1994).

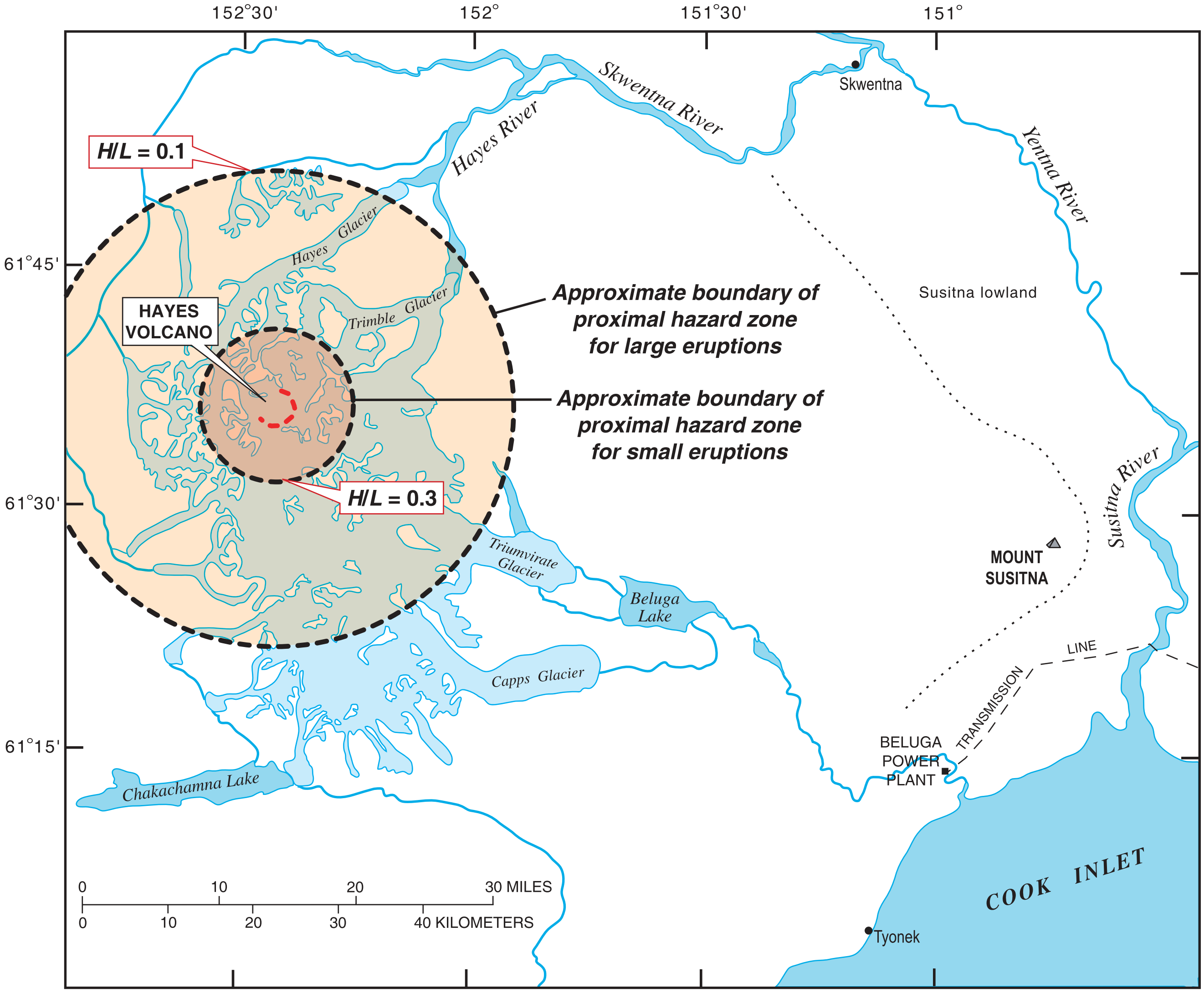


Figure 8. Proximal and distal hazard zones at Hayes Volcano. Areas within colored circle defined by $H/L = 0.1$ are generally regarded as within proximal hazard zone for large eruptions. Areas within colored circle defined by $H/L = 0.3$ are generally regarded as within proximal hazard zone for small eruptions. Dashed line indicates boundary of bottomland areas in Susitna lowland. *H*, height of volcano summit; *L*, runout length of flowage hazard.

Eruptions from Hayes Volcano could produce ash clouds that would likely reach altitudes of more than 10 kilometers above sea level. These ash clouds may drift in a variety of directions depending on prevailing wind and can be tracked by satellite for thousands of kilometers from the volcano (Schneider and others, 1995). For example, an ash cloud produced during the 1992 eruption of Crater Peak volcano on the south flank of Mount Spurr (fig. 2) drifted southeastward over western Canada, parts of the United States, and eventually out across the Atlantic Ocean and significantly disrupted air travel over these regions but caused no direct damage to flying aircraft (Casadevall and Krohn, 1995).

During future eruptions of Hayes Volcano, ash likely will be dispersed over interior and south-central Alaska and beyond, and fallout could occur over this area and parts of western Canada. Variable winds over the zone of fallout could temporarily detain a drifting ash cloud and thus cause dusty ash-laden air to linger in the region.

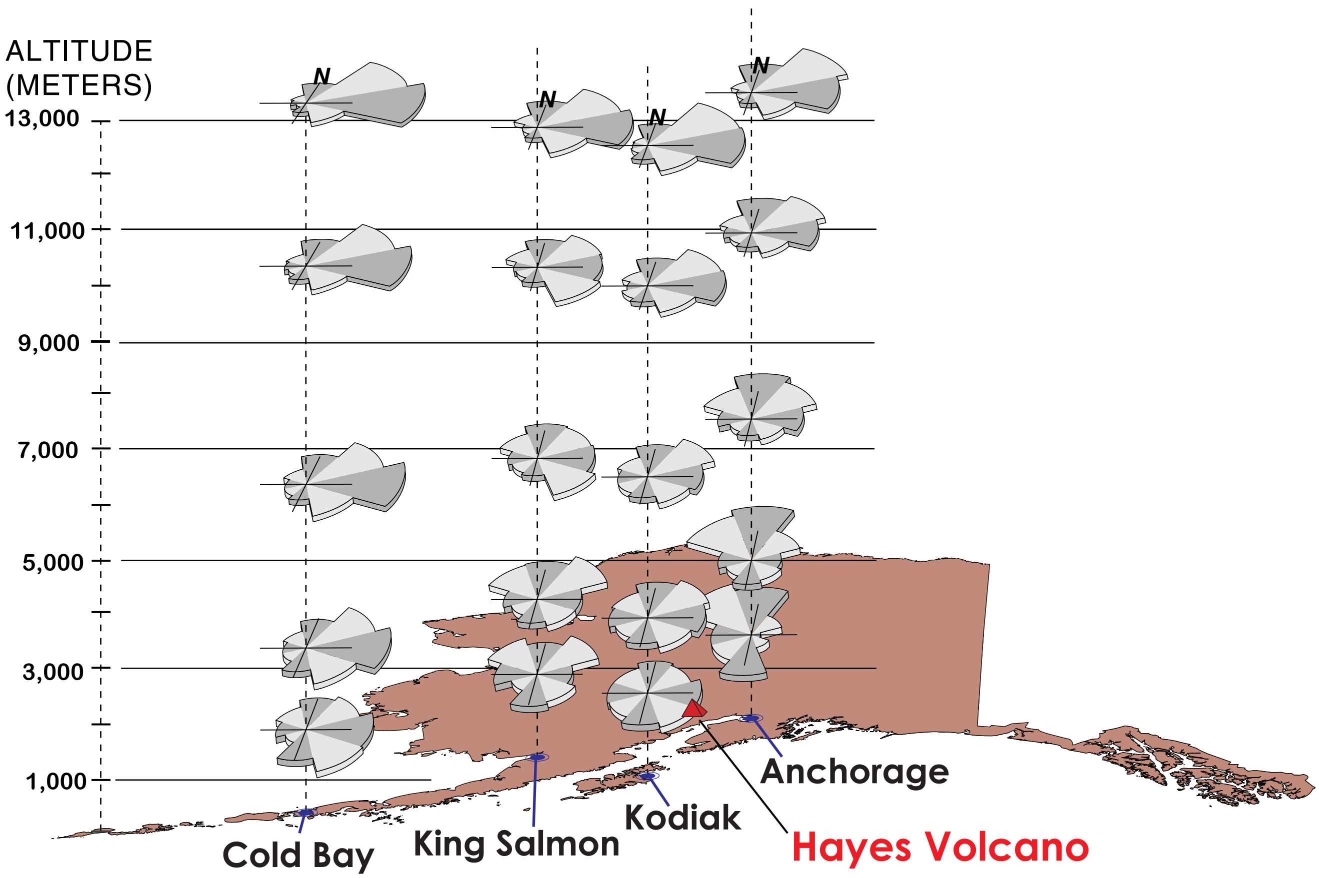


Figure 9. Average wind directions for south-central and southwestern Alaska. Wind data from National Climatic Data Center, Ashville, N.C. Rose diagrams indicate prevailing wind direction; wind-rose vector lengths are proportional to annual wind frequency.

Volcanic-Ash Fallout and Volcanic Bombs

Volcanic ash is one of the most hazardous products of explosive volcanism. Clouds of volcanic ash produced during explosive eruptions are carried by the wind away from the volcano, and a steady rain or fallout of ash usually occurs. Volcanic ash in the atmosphere may be transported long distances and has the potential to affect areas many hundreds of kilometers from the volcano. Few people have ever been killed directly by falling ash, but the weight of a thick ash fall could cause structures to collapse, and inhaling fine ash particles is a health hazard that can be life threatening to some people with respiratory problems. Sometimes a "mud rain" results if airborne volcanic ash mixes with falling rain or snow.

Holocene eruptions of Hayes Volcano spread ash over areas north, east, and south of the volcano. The ash cloud from the 4,400-to-3,600-year-B.P. eruption deposited significant amounts of tephra on parts of south-central Alaska (fig. 11; Riehle and others, 1990), and deposits of the so-called Hayes tephra are preserved at a variety of locations in south-central Alaska (Riehle and others, 1990). Based on field studies of the Hayes tephra, at least 2 centimeters of ash fell on the Anchorage area, and at least 1 centimeter of ash fell on Homer and Kenai (fig. 11). As much as 50 centimeters of tephra was deposited in areas within a few kilometers of the volcano (fig. 11). A small amount of fine ash (<5 millimeters) is sufficient to severely curtail the daily activities of residents in the affected areas.

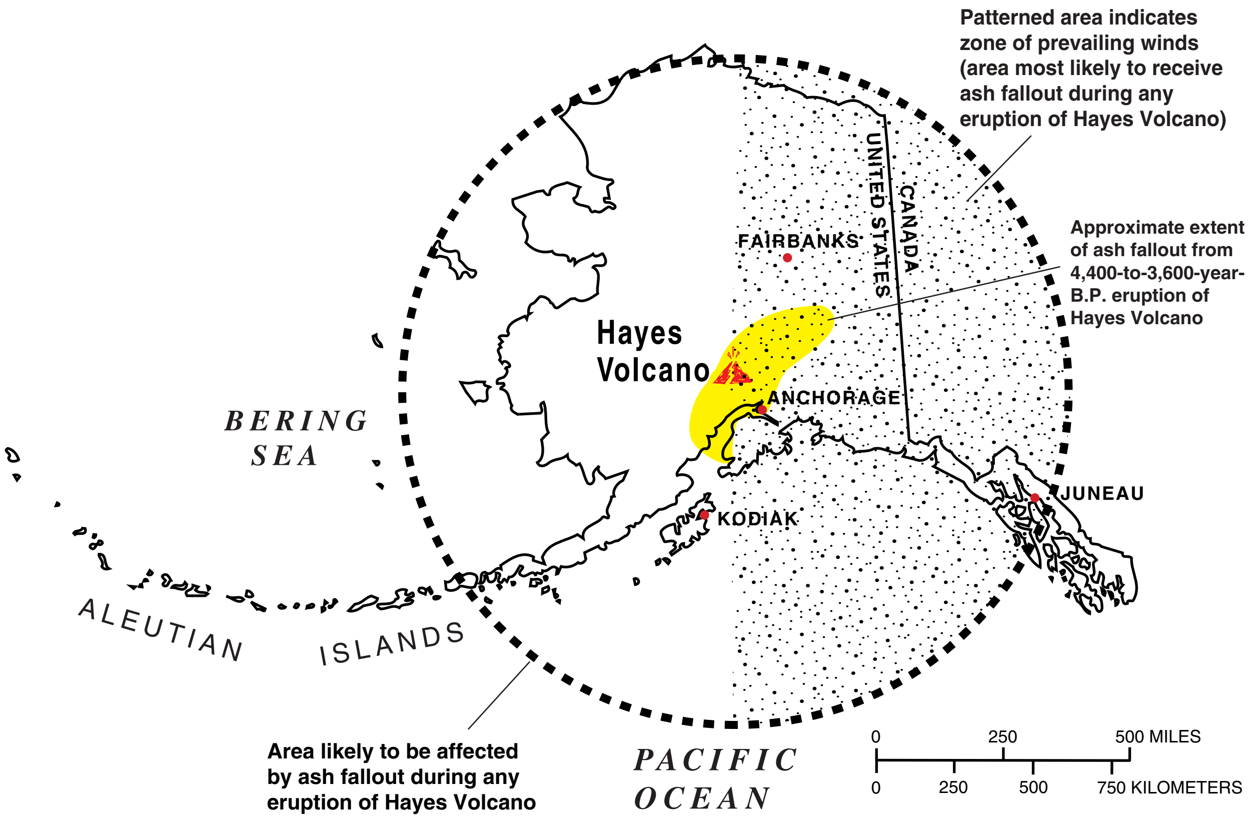


Figure 10. Probable travel paths of volcanic-ash clouds from Hayes Volcano. Based on prevailing winds, map indicates areas most likely to receive ash fallout during an eruption of Hayes Volcano.

Should an eruption similar to the late Holocene eruption of Hayes Volcano occur today, the ash cloud and its fallout would disrupt air traffic over Alaska and would likely force a temporary closure of airports in the area. Ash fall from future eruptions of Hayes Volcano could be a serious, but short-lived, public health concern for parts of south-central and southeastern Alaska or wherever fallout occurs. If an eruption occurs during a prolonged period of dry weather, ash particles may persist in the atmosphere or be periodically resuspended by wind. This condition could significantly diminish air quality for days to weeks after the eruption.

Wind direction and speed will control the movement of an ash plume, and the areas most likely to receive ash fall are those in the zone of prevailing winds (figs. 9 and 10). The strongest and most consistent winds in the vicinity of Hayes Volcano are from the west, southwest, and northwest. The thickness of ash fallout will typically decrease in a downwind direction, but it is impossible to predict how much ash will be produced during an individual eruption, although any amount of ash fall could be disruptive. Industrial facilities in the Cook Inlet region such as oil drilling rigs, oil refineries, manufacturing plants, and power plants could be affected by ash fall.

Blocks and bombs of volcanic-rock debris may be ejected as ballistic projectiles during explosive eruptions. Usually, ballistic fallout occurs in areas near the vent, but in extreme cases, bombs may be ejected distances of 10 to more than 30 kilometers from the vent. Typically, the zone of ballistic fallout is within a few kilometers of the vent and people or low-flying aircraft would be at risk only within this zone.

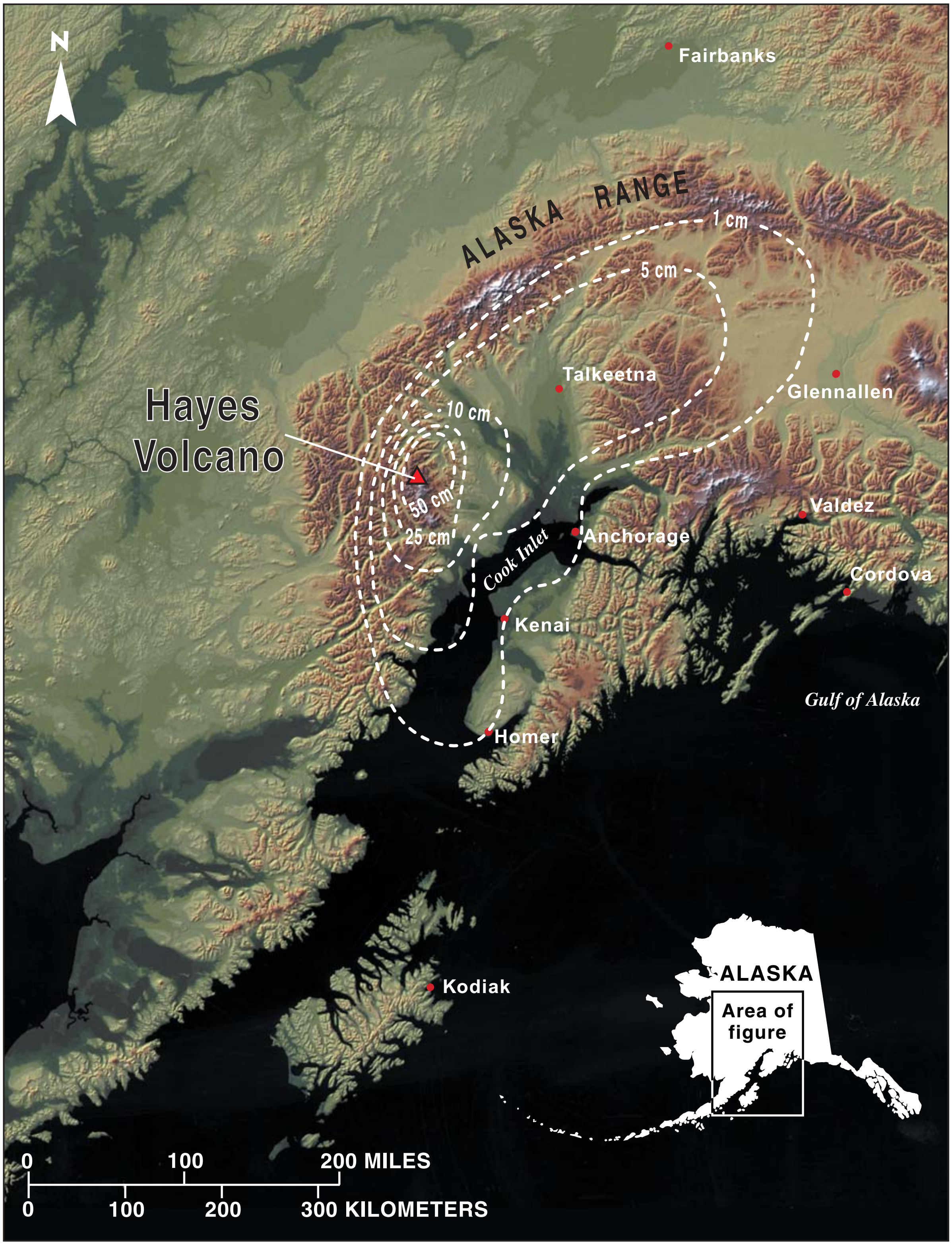


Figure 11. Areas in south-central Alaska that received tephra fallout associated with 4,400-to-3,600-year-B.P. eruption of Hayes Volcano. Contours indicating aggregate thickness of so-called Hayes tephra (modified from Riehle and others, 1990) are overlaid on composite false-color infrared satellite image. Contour interval variable, in centimeters (cm).

Lahars, Lahar-Runout Flows, and Floods

Most of the volcanoes in Alaska support glaciers or are snow-covered most of the year. During typical eruptions, hot pyroclastic debris expelled from the volcano interacts dynamically with the snowpack or glacier cover, thereby causing rapid, extensive melting and water production. As meltwater mixes with available unconsolidated volcanic debris, various types of flowage phenomena may occur on the volcano flanks and in stream channels and drainages downstream from the volcano. Most of these phenomena are categorized as debris flows (fig. 7) or more specifically as noncohesive (clay-poor) *lahars*. Lahars consist of a poorly sorted mixture of boulders, sand, silt, and water that has the consistency of wet concrete. As a lahar flows downstream, it gradually drops some of its sediment load and typically transforms to a finer grained, watery flow, called hyperconcentrated flow or lahar-runout flow. If enough sediment is lost from a lahar during flowage, the lahar may transform into a sediment-laden stream flow or flood consisting mostly of water.

Lahars also may form directly from water-saturated, clay-rich, volcanic rock avalanches (Hoblitt and others, 1995; Vallance and Scott, 1997; Vallance, 1999). Such lahars are called *cohesive* (clay-rich) lahars because the matrix sediment of typical deposits contains more than about 3 to 5 percent clay. Lahars of this type have not been found at Hayes Volcano.

Noncohesive lahar and lahar-runout deposits of Holocene age are present along the Hayes and Skwentna Rivers (fig. 12). These deposits were generated during the 4,400-to-3,600-year-B.P. eruption of Hayes Volcano, in response to widespread melting of glacier ice near the volcano. Known lahar deposits along the Hayes and Skwenta Rivers are as much as 2 meters thick in several areas indicating a substantial flow occurred as a result of the eruption. The lahar deposits contain abundant amounts of pumice derived from the large pyroclastic flows that initiated the lahars (fig. 13). The lahars probably transformed to sediment-laden water floods by the time they reached the Yentna River (fig. 12).

Hazard zones for lahars, lahar-runout flows, and floods generated by eruptions of Hayes Volcano are shown in figure 14 and on plate 1. Three hazard zones (L1, L2, and L3) depict differing degrees of hazard: Zone L1 indicates areas that could be inundated by lahars, lahar-runout flows, and floods that exit the proximal hazard zone and have volumes of 1 million to 1 billion cubic meters. Lahars of this size could occur during any eruption of Hayes Volcano, but only if substantial amounts of the ice and snow cover are melted. Zone L2 includes areas that are susceptible to inundation by lahars, lahar-runout flows, and floods, but this zone is less likely to be affected by large lahars than zone L1 during most eruptions of Hayes Volcano. Lahar volumes could be as large as 1 billion cubic meters where they exit the proximal hazard zone (fig. 14). Zone L3 includes areas that could be affected by lahars, lahar-runout flows, and floods only during large, sustained eruptions, if lahars having volumes greater than 1 billion cubic meters are generated (fig. 14). Lahar flows of all sizes that enter the Skwentna and Yentna Rivers would be rapidly diluted to lahar-runout flows or sediment-laden stream flows.

Because lahars, lahar-runout flows, and floods move rapidly, are typically several meters deep, and can transport boulder- and block-size particles, they would be hazardous to life and property in the flow path, particularly in hazard zone L1. The distribution of lahar deposits along the Hayes and Skwentna Rivers indicates that future developments in these areas could be at risk from lahars, lahar-runout flows, and floods. At present however, lahars pose only a limited hazard in this area because most of the riparian corridor is only seasonally occupied by few people and, except for the town of Skwentna, no permanent structures or facilities are present.

Pyroclastic Flows and Surges

A pyroclastic flow is a hot, dry mixture of volcanic-rock debris and gas that flows rapidly downslope (fig. 7). A *pyroclastic surge* is similar to and often occurs with a pyroclastic flow but has a higher gas content and transports mainly fine particles. Because it is mostly gas, a pyroclastic surge moves more rapidly than a pyroclastic flow; a surge may not be confined by topography and therefore may climb up and over ridges. Pyroclastic flows are relatively dense and will generally follow topographically low areas such as stream valleys. Any of the major drainages that begin on or near Hayes Volcano could be engulfed by pyroclastic flows even during modest eruptions. Because they are hot (300–800°C) and fast moving (typically 80–100 kilometers per hour but may be more), both pyroclastic flows and surges could be lethal to anyone

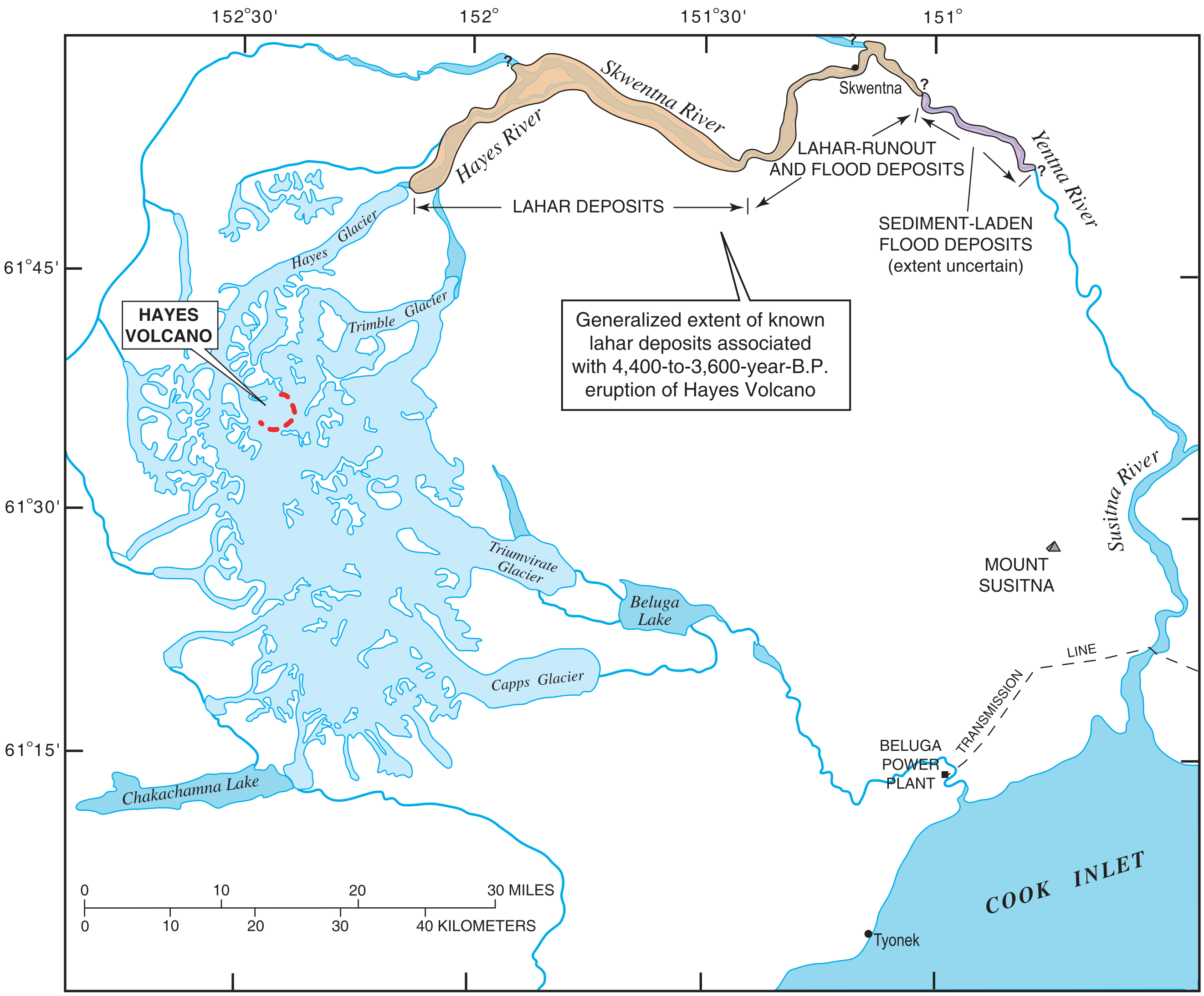


Figure 12. Generalized extent of lahar deposits formed during 4,400-to-3,600-year-B.P. eruption of Hayes Volcano. Downstream extent of sediment-laden flooding is not known and could be more extensive than shown.

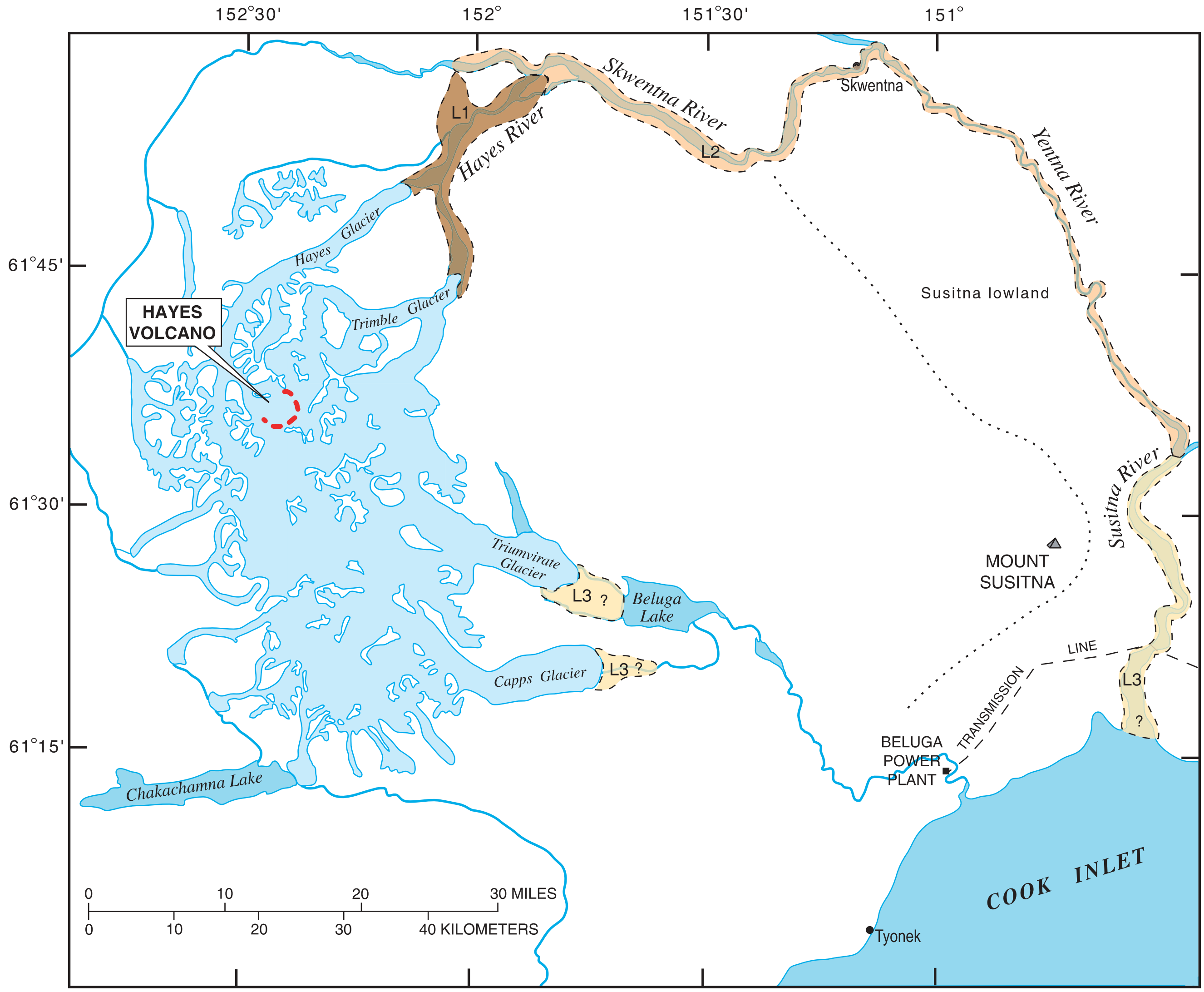
in the glacial valleys surrounding Hayes Volcano during an eruption. During explosive Plinian-style eruptions, characterized by high vertical eruption columns, the eruption column will typically collapse and fall back toward the volcano to form a fast-moving pyroclastic flow. Pyroclastic flows of this type have a greater aerial extent, can sweep down all sides of the volcano, and are likely to be directed by topographically low areas such as incised river or glacial valleys.

Pyroclastic flows generated by the 4,400-to-3,600-year-B.P. eruption of Hayes Volcano flowed about 40 kilometers down Hayes Glacier on the north side of the volcano (fig. 15). The pyroclastic-flow deposits consist mostly of rounded clasts of pumice in an ashy matrix and were likely produced by collapse of the dense near-vent portion of the eruption column. Apparently, the Hayes River drainage was the only drainage on the volcano to be swept by pyroclastic flows during this eruption, although other deposits may have been removed by glaciers. This may indicate that the orientation of the vent, which can change from eruption to eruption, was inclined to the northwest and controlled the emplacement direction of pyroclastic flows during the eruption.

Figure 13. Typical outcrop of lahar deposits along Hayes River. Deposits like these are exposed along Hayes River from Hayes Glacier to confluence with Skwentna River and intermittently along Skwentna River. Length of tape on outcrop is about 1.5 meters.

Pyroclastic flows and surges from most eruptions would be expected to reach at least several tens of kilometers beyond the vent and are likely to flow down the major valleys surrounding the volcano (fig. 16). The runout distance (*L*) of a typical pyroclastic flow is estimated using a ratio of fall height (*H*) to runout length of 0.1 to 0.37 (Hayashi and Self, 1992; Hoblitt and others, 1995). These values are typical of most small-to-moderate-volume pyroclastic flows. For *H*, we use an altitude of 2,800 meters (approximate summit altitude of the volcano) and obtain runout distances of 7 to 28 kilometers (fig. 16). These values are most relevant to pyroclastic flows generated by a lava-dome collapse or low-altitude column collapse. During a large (and therefore rare) eruption, the eruption column could extend high into the atmosphere and upon collapse could generate pyroclastic flows that might flow as far as 50 to 80 kilometers from the volcano. The highly complex terrain surrounding Hayes Volcano makes it difficult to predict the specific flow path of a pyroclastic flow. The glacial valleys near the volcano would certainly be inundated, and if the flows are confined by the topography, they could extend beyond the hazard boundaries shown in figure 16.

It is difficult to accurately predict the extent of a pyroclastic surge. However, because of their greater mobility relative to a pyroclastic flow, they can have a greater lateral extent. The location of the hazard boundary is uncertain and is not shown in figure 16 or on plate 1. The boundary is conservatively approximated by the hazard boundary for pyroclastic flow, although we expect that a pyroclastic surge will extend beyond this boundary, perhaps by several kilometers or more. Pyroclastic surges are hot (300–800°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), detach itself from the pyroclastic flow, and surmount topographic barriers, preeruption evacuation of the area near the volcano is the only way to eliminate risk from pyroclastic surges.



EXPLANATION

Degree of Hazard		
Greater	L1	Areas likely to be inundated by lahars, lahar-runout flows, and floods during most eruptions
	L2	Areas susceptible to inundation by lahars, lahar-runout flows, and floods during moderate to large eruptions. Lahar and lahar-runout flows will be more common in upstream areas, whereas sediment-laden floods will be more common in downstream areas
Lesser	L3	Areas susceptible to inundation by lahars, lahar-runout flows, and floods, during large, rare eruptions

Figure 14. Hazard zonation for lahars, lahar-runout flows, and floods. During a future eruption of any size, substantial amounts of glacier ice could be melted and proximal lahar flows would extend from Hayes Volcano downvalley over Hayes and Trimble Glaciers.

Figure 15. Pyroclastic-flow deposits near terminus of Hayes Glacier (fig. 16). These deposits consist mostly of dacitic pumice and were emplaced during last major eruption of Hayes Volcano, 4,400 to 3,600 years ago. Person in left center of photograph gives scale.

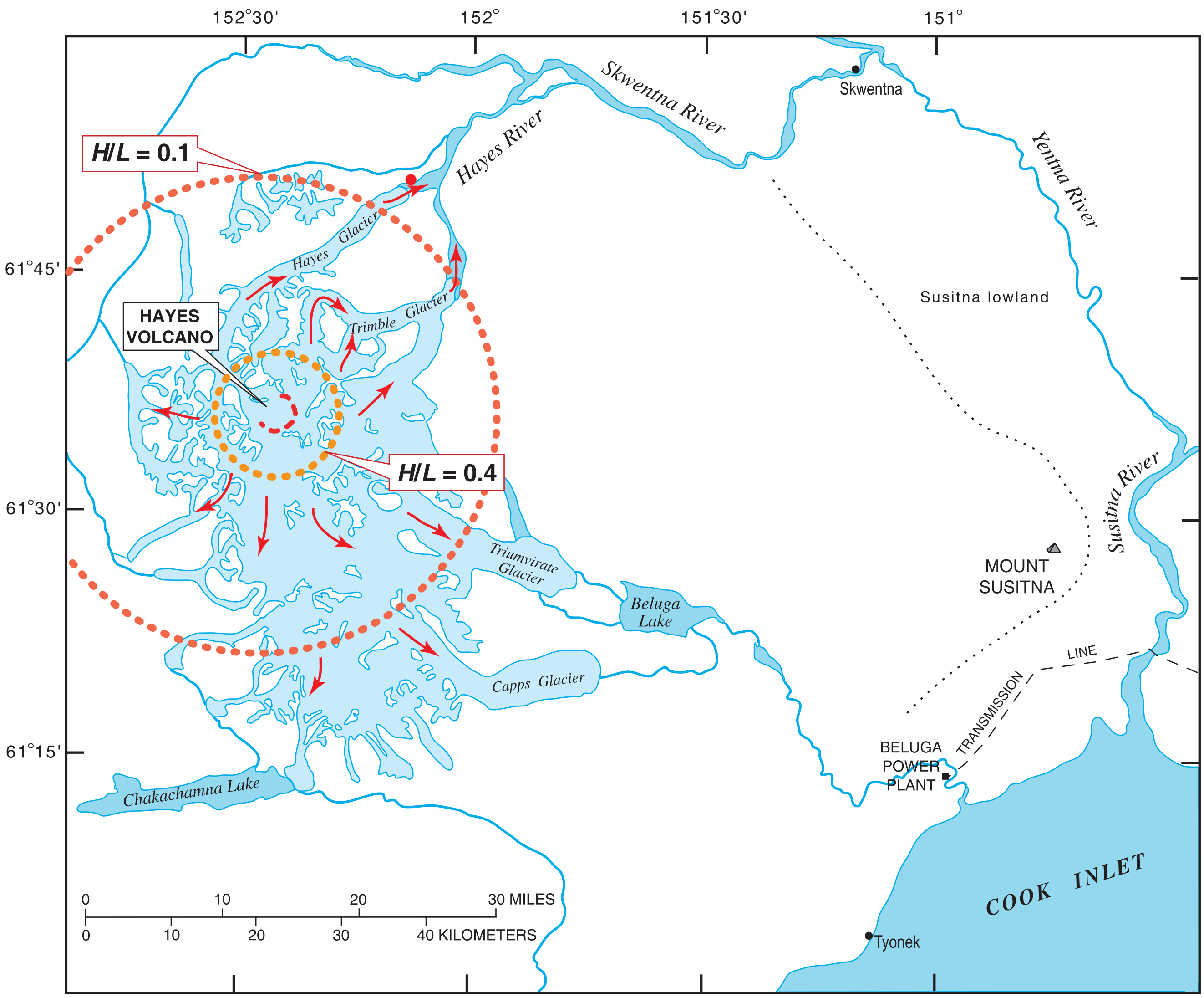
Lava-Dome Collapse

Lava domes are pluglike masses of molten rock that are sluggishly extruded from the vent during an eruption. As the domes are extruded, their outer margins commonly become oversteepened and unstable. This leads to failure of the lava dome by gravitational collapse and results in the rapid release of hot, pressurized gas and rock debris from inside the cooling lava dome to form a pyroclastic flow.

The hazard zone for pyroclastic flows generated by dome collapse is the same as the hazard zone for pyroclastic flows generated by eruption-column collapse (fig. 16). Pyroclastic flows generated by dome collapse typically affect only a specific sector of the volcano and do not have the broad aerial extent common to pyroclastic flows initiated by eruption-column collapse. Although lava domes make up a portion of the volcanic rock that defines Hayes Volcano, we have yet to find any *block-and-ash-flow* deposits, a type of pyroclastic-flow deposit that forms when a lava dome collapses. During a future eruption, lava domes could develop and may initiate pyroclastic flows if they collapse. The flows likely will be confined to the deep glacial valleys surrounding Hayes Volcano and may travel tens of kilometers from their source.

Debris Avalanches

Volcanic rock or debris avalanches (fig. 7) typically form by large-scale structural collapse of the upper part of the volcano. The ensuing avalanche moves rapidly down the volcano flank and forms a bouldery unsorted deposit many kilometers from the source that characteristically has a hummocky surface and broad aerial extent. Most debris-avalanche deposits are traceable up the slopes of the volcano to an arcuate or horseshoe-shaped scar at or near the volcano summit; the scar marks the zone of collapse and origin of the avalanche. Most large debris avalanches



EXPLANATION

Extent of pyroclastic flows for *H*/*L* = 0.1. Pyroclastic flows generated by collapse of eruption column could extend to at least this boundary during moderate to large eruptions

Extent of pyroclastic flows for *H*/*L* = 0.4. Pyroclastic flows generated by collapse of eruption column could extend to at least this boundary during small eruptions

Most likely flow paths for pyroclastic flows and surges. During moderate to large eruptions, pyroclastic flows and surges could be directed along topographically low areas, such as glacial valleys and stream drainages, and could extend beyond indicated hazard-zone boundaries in these areas

Pyroclastic-flow deposit (fig. 15) formed by 4,400-to-3,600-year-B.P. eruption of Hayes Volcano

Figure 16. Hazard zonation for pyroclastic flows. *H*, fall height; *L*, runout distance.

(greater than 1 cubic kilometer) occur during eruptions (Siebert, 1996). However, 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 in the edifice by hot, acidic ground water.

Debris-avalanche deposits are not known at Hayes Volcano. Because most of the volcano is covered by ice and snow and because the volcanic edifice does not have areas of high relief, the possibility of a large-scale debris avalanche is very low. Given the present configuration of Hayes Volcano, debris avalanches are not an expected hazard unless conditions at the volcano change significantly.

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, and evidence for a directed blast has not been discovered at Hayes Volcano. The hazard-zone boundary showing the area most likely to be affected by a directed blast (fig. 17) 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 considered to be a "worst-case" example. If a directed blast were to occur at Hayes Volcano, it could affect a broad area, possibly a 180° sector from the vent; however, the possibility of a directed blast is minor. Because a directed blast usually happens in the first few minutes of an eruption, there is no time for warning or evacuation once the eruption is imminent. Living things in the path of a directed blast will be killed or destroyed by impact, burning, abrasion, burial, and heat.

Volcanic Gases

Gases are emitted by most active volcanoes because *magma* contains dissolved gases and boils off shallow ground water. 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 can 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 a measuring device. Carbon dioxide is heavier than air and may displace the available oxygen in confined spaces or low-lying areas and thus cause suffocation. In high concentrations, carbon dioxide, hydrogen sulfide, and sulfur dioxide may be harmful or toxic to humans and may damage 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 cause corrosive damage to materials. Because wind tends to disperse volcanic gas, 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 for thousands of kilometers.

At present, volcanic gases are not a hazard at Hayes Volcano. Emission of volcanic gases has never been detected over the volcano, nor is there any evidence of recent or historical release of volcanic gas. Should the volcano become active, volcanic gas may pose a health concern to someone near the vent or in the upper Hayes River drainage close to the volcano, and some gases, such as carbon dioxide, may accumulate under or within the snowpack. However, as in many of the mountainous areas of Alaska, the frequently windy conditions around Hayes Volcano would inhibit localized buildup of volcanic gas. Therefore, the hazard from volcanic gases is of little concern.

Lava Flows

Narrow streams of molten rock or lava may form during a future eruption of Hayes Volcano. Commonly, lava flows (fig. 7) develop after explosive activity at the volcano declines. Typical lava flows produced by Aleutian arc volcanoes are either basaltic or *andesitic* in composition and are relatively viscous when molten. Future eruptions will probably generate lava flows similar to those preserved on the volcano.

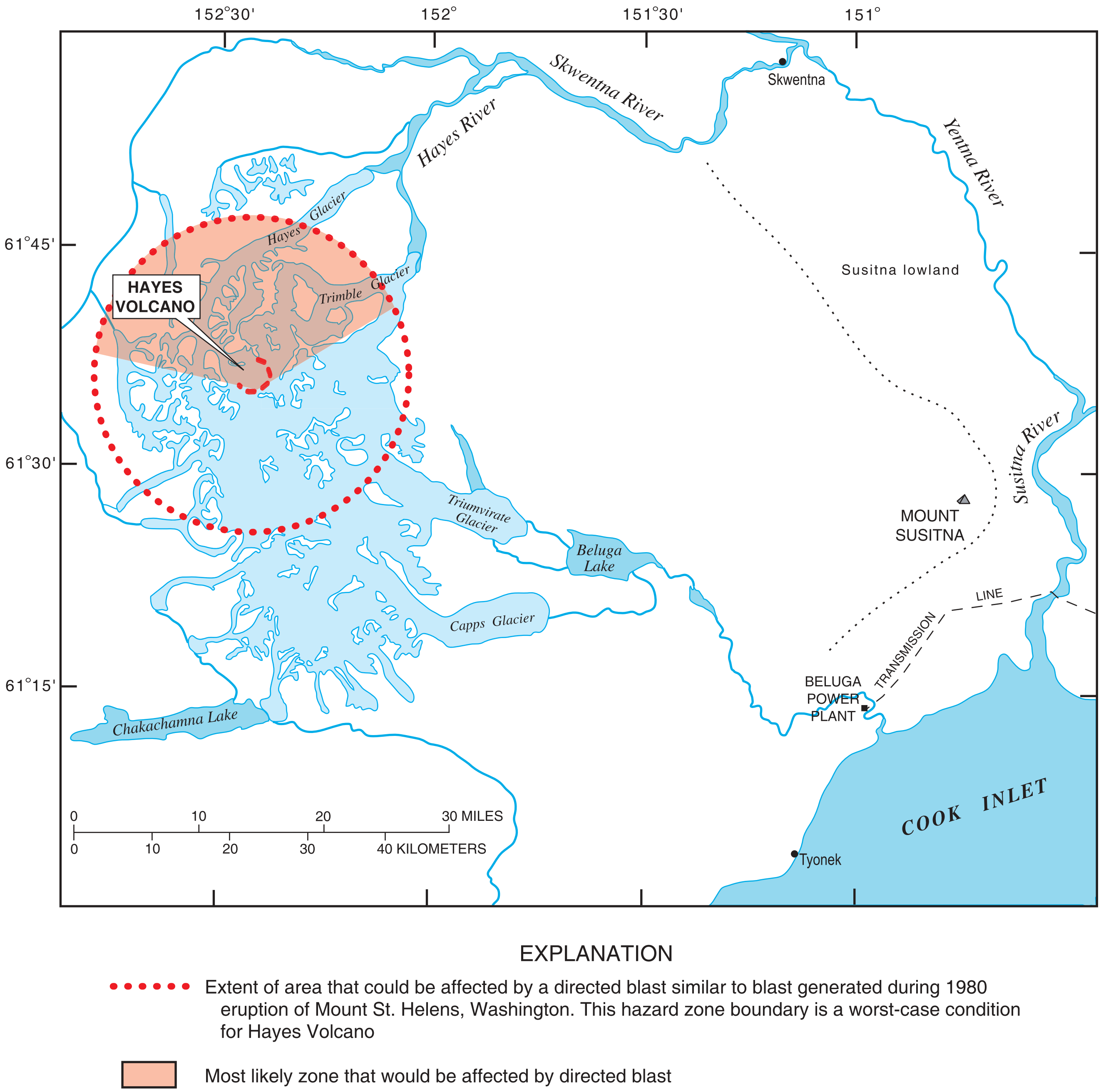


Figure 17. Hazard zonation for directed blasts.

The lava flows are expected 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 erupted from Hayes Volcano may develop steep fronts and could shed hot blocks and debris downslope. Lava flows that reach snow and ice could generate localized flooding and may initiate minor steam explosions.

EVENT FREQUENCY AND RISK AT HAYES VOLCANO

An eruption of Hayes Volcano could occur in the future, but the timing of the next eruption is unknown. The primary proximal hazards during a future eruption will be lahars, lahar-runout flows, floods, ash fall, and pyroclastic flows. Lahars likely will inundate the major drainages on the north side of the volcano, primarily the Hayes, Skwenta, and Yentna Rivers. Watery lahar-runout flows could reach the Susitna River and Cook Inlet but are unlikely to be deep or swift enough to cause damage to facilities or structures near the coast. If a large pyroclastic eruption were to occur, thick accumulations of volcaniclastic sediment in valleys and drainages near the volcano could result, and sediment-laden runoff of volcanic debris could continue for months to years after the eruption.

Because the immediate area around Hayes Volcano is uninhabited and no permanent structures or facilities are present, nothing within about 50 kilometers of the volcano is at risk from future eruptions. During any future eruption, ash could fall on residential areas along the Cook Inlet coastline, such as Skwentna and Tyonek, and at least several millimeters of ash could accumulate downwind from the volcano on the Kenai Peninsula, in Anchorage, in the Matanuska–Susitna valley, and in other areas in south-central Alaska (figs. 10 and 11). In the event of a large explosive eruption, pyroclastic flows could engulf tributary valleys on the volcano, particularly the valley containing Hayes Glacier and the upper Hayes River valley.

Should a sustained explosive eruption occur, clouds of volcanic ash would be generated that could drift thousands of kilometers downwind (fig. 10). All aircraft, some facilities, and living things—including humans—downwind from the volcano are at risk from effects of volcanic-ash clouds and ash fallout. Ash clouds from Hayes Volcano could rise to altitudes of 15,000 meters or more and move into the flight paths of aircraft using Ted Stevens Anchorage International and other airports in south-central and interior Alaska. Drifting clouds of volcanic ash could block local air routes in the vicinity of Hayes Volcano, thereby making access to or from interior Alaska almost impossible. Aircraft using air routes over the North Pacific Ocean and other areas downwind from Hayes Volcano (fig. 18), especially the Gulf of Alaska and Pacific Northwest region, could encounter clouds of volcanic ash. Determining the characteristics of an ash cloud from Hayes Volcano before an eruption occurs is not possible, although it is likely to be similar to those generated by prehistoric eruptions of Hayes Volcano and historical eruptions of other Cook Inlet volcanoes.

HAZARD WARNING AND MITIGATION

Typically, eruptions at Cook Inlet volcanoes are preceded by weeks to months of precursory earthquake activity giving some degree of seismic warning prior to an eruption. However, the Alaska Volcano Observatory (AVO) currently does not monitor earthquake activity at Hayes Volcano with seismic instruments directly on the volcano. Should the volcano become active, volcanic earthquakes might be detected by the seismic network in place on Mount Spurr volcano 35 kilometers to the south. When volcanic unrest is detected, other monitoring techniques, such as observation by airborne and satellite sensors, measurement of volcanic-gas flux, remote observation using 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.

AVO has assessed the geology and potential for eruptive activity of Hayes Volcano with a field-based data-collection program that includes geologic mapping, sampling, and occasional airborne gas measurements. Satellite images of the volcano are analyzed twice daily. Hayes Volcano is part of a very active volcanic belt, and the recent geologic history of the volcano indicates that it is capable of large explosive eruptions. Because the volcano has not erupted historically and shows no signs of unrest, concern about an eruption in the near future is minimal. However, many volcanoes worldwide become active after long periods of dormancy.

One of the primary roles of AVO is to communicate timely warnings of volcanic unrest and potential eruptions (Eichelberger and others, 1995, p. 4). AVO distributes by fax and electronic mail a weekly update of volcanic activity that summarizes the status of the currently monitored volcanoes and some historically active but unmonitored volcanoes along the Aleutian volcanic 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, commercial air carriers, the National Weather Service, the Alaska Department of Emergency Services, local military bases, the Governor's office, various State offices, television and radio stations, newswire services, and others. Updates also are distributed by electronic mail to various volcano-information

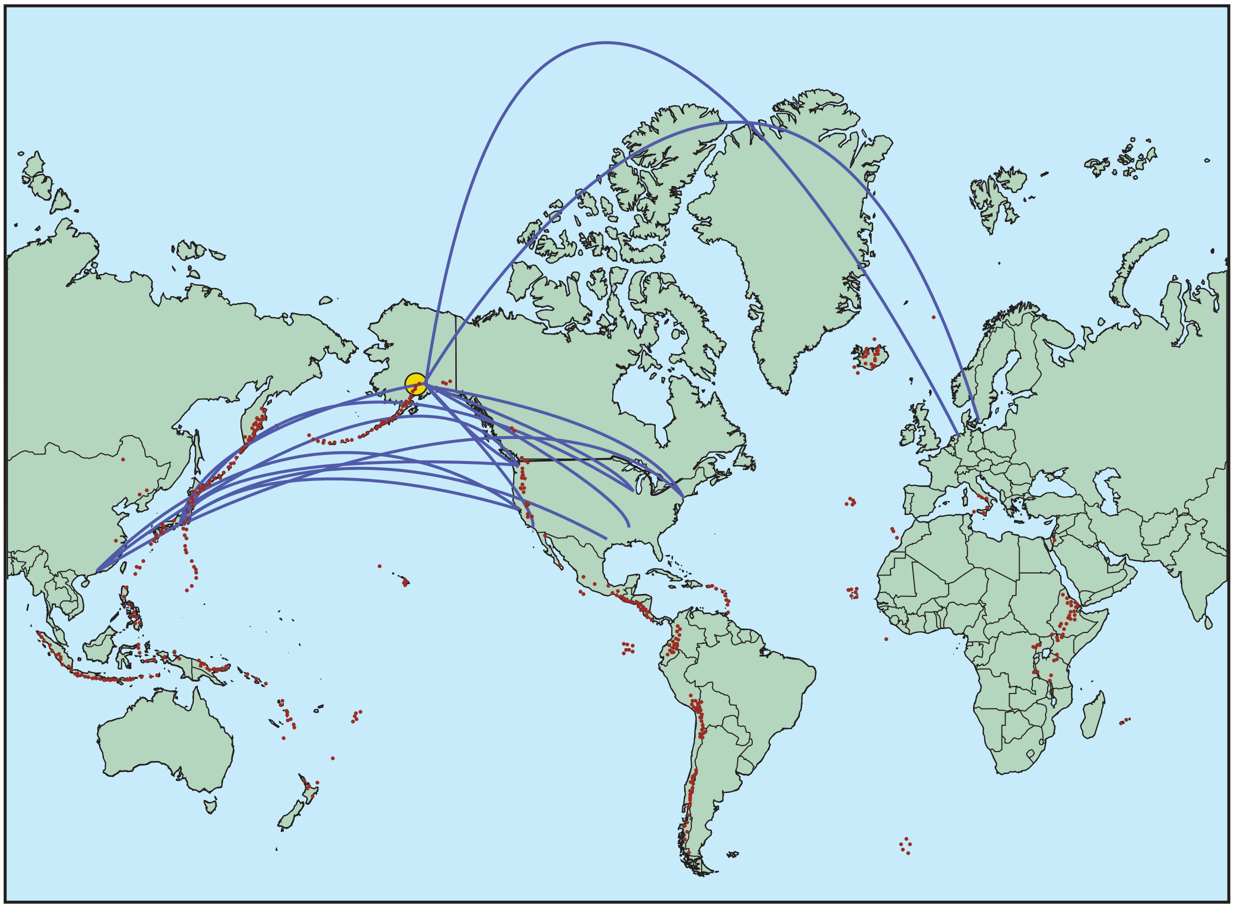


Figure 18. Major air-travel routes in vicinity of Hayes Volcano.

networks and are posted on the AVO web site (URL: <http://www.avo.alaska.edu>).

During the 1989–90 eruptions of Redoubt Volcano, AVO developed a level-of-concern color code (Brantley, 1990; table 1), which provides efficient and simple information about the status of volcanic activity or unrest and conveys AVO's interpretation of that activity or unrest in terms of the potential for an eruption and its likely effects. In the event of a volcanic crisis, various Federal, State, and local officials are contacted by telephone and advised of the situation, and the level of concern color code is established while an update is being prepared. This approach has been used successfully during recent eruptions at monitored volcanoes such as Redoubt Volcano, during 1989–90; Crater Peak, in 1992; Pavlof Volcano, 1996; and Shishaldin Volcano, in 1999.

Minimizing the risks posed by eruptions of Hayes Volcano is possible through understanding potential hazards, adequate warning of eruptive activity, and preparing for an eruption. Areas within about 10 to 30 kilometers of Hayes Volcano are at risk from all hazardous volcanic phenomena. 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 the area around Hayes Volcano should realize that all

Table 1. 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 7,600 meters (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 7,600 meters (25,000 feet) above sea level.

areas within about 30 kilometers of the volcano, as well as all areas downwind from the vent, are subject to tephra and ballistic fallout. Low-lying terrain along glaciers, streams, and gullies that extend toward Hayes Volcano are subject to pyroclastic flow and surge, lahars, lahar-runout flows, floods, and avalanches. Given the present configuration of the volcano, pyroclastic flows and tephra fallout are most likely on the northern and northwestern flanks of the cone. Given the extensive cover of ice and snow on the volcano, an eruption of any size would cause melting and generate lahars, and downstream inundation of the Hayes River valley is likely. During an eruption, access to or escape from areas 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 direction of travel 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 developed and ready prior to the onset of an eruption is useful. The planning for volcanic emergencies is similar to that for other emergencies, such as flooding or extreme weather. Usually the sources of emergency information are the same, and 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

Andesitic. Said of fine-grained volcanic rock made up of feldspars and ferromagnesian minerals and having silica content of 54 to about 62 percent.

Ash. Fine fragments (less than 2 millimeters in diameter) of lava or rock formed in explosive volcanic eruption. Ash particles are typically sharp, angular, and abrasive and are composed of volcanic glass, mineral, and rock fragments.

Block-and-ash flow. Pyroclastic flow that contains blocks of primary volcanic rock in coarse ashy matrix. Block-and-ash flows commonly form from collapsing lava dome.

Cohesive. Said of lahars that contain more than about 3 percent clay in deposit matrix.

Debris avalanche. Rapidly moving, dry flows of disaggregated rock debris, sand, and silt. Volcanic-debris avalanches commonly form by some type of structural collapse of volcano, typically steep front of cooled lava dome or other parts of upper edifice. Large part of volcano may become unstable, break away from volcanic massif, and avalanche. Debris avalanche may be triggered by 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. Typically they are quite voluminous (greater than 10 cubic kilometers) and may run out considerable distances (as much as 85 kilometers) from their source. Resulting debris-avalanche deposit commonly exhibits hummocky surface morphology.

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

Edifice. Upper part of volcanic cone, including vent and summit areas.

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

Eruption column. Vertical part of eruption cloud that rises above volcanic vent.

Fallout. General term for debris that falls to Earth's surface from eruption cloud.

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

Lava. Molten rock that reaches Earth's surface.

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

Magma. Molten rock beneath Earth's surface.

Plinian. Said of volcanic eruptions characterized by highly explosive ejection of tephra and large-volume emissions of ash. Ash plumes from Plinian eruptions commonly reach 10,000 to 45,000 meters in height above vent. Sub-Plinian eruption is similar but total volume of material erupted and maximum height of eruption column are less.

Pumice. Highly vesicular, silica-rich volcanic ejecta; owing to its extremely low density, it commonly floats on water.

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

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

Pyroclastic surge. 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 low, ground-hugging, but highly mobile cloud that can surmount topographic barriers. Surges often affect areas beyond limits of pyroclastic flows.

Quaternary. Last 1.8 million years of Earth history.

Stratovolcano. Steep-sided volcano, typically conical in shape, built of lava flows and fragmental deposits from explosive eruptions. Also called stratocone or composite cone.

Tephra. Any type of rock fragment that is ejected forcibly from volcano during eruption. Tephra may be fine-grained particles or dust, also called volcanic ash (0.0625 to 2 millimeters in diameter, or silt to sand sized); coarser grained particles, also called lapilli (2 to 64 millimeters in diameter, or sand to pebble sized); or large blocks or bombs (greater than 64 millimeters, or cobble to boulder sized). When tephra is airborne, coarsest fraction is deposited close to volcano, but fine fraction may be transported long distances and can stay suspended in atmosphere for many months.

Vent. Opening in Earth's surface through which magma erupts or volcanic gases are emitted.