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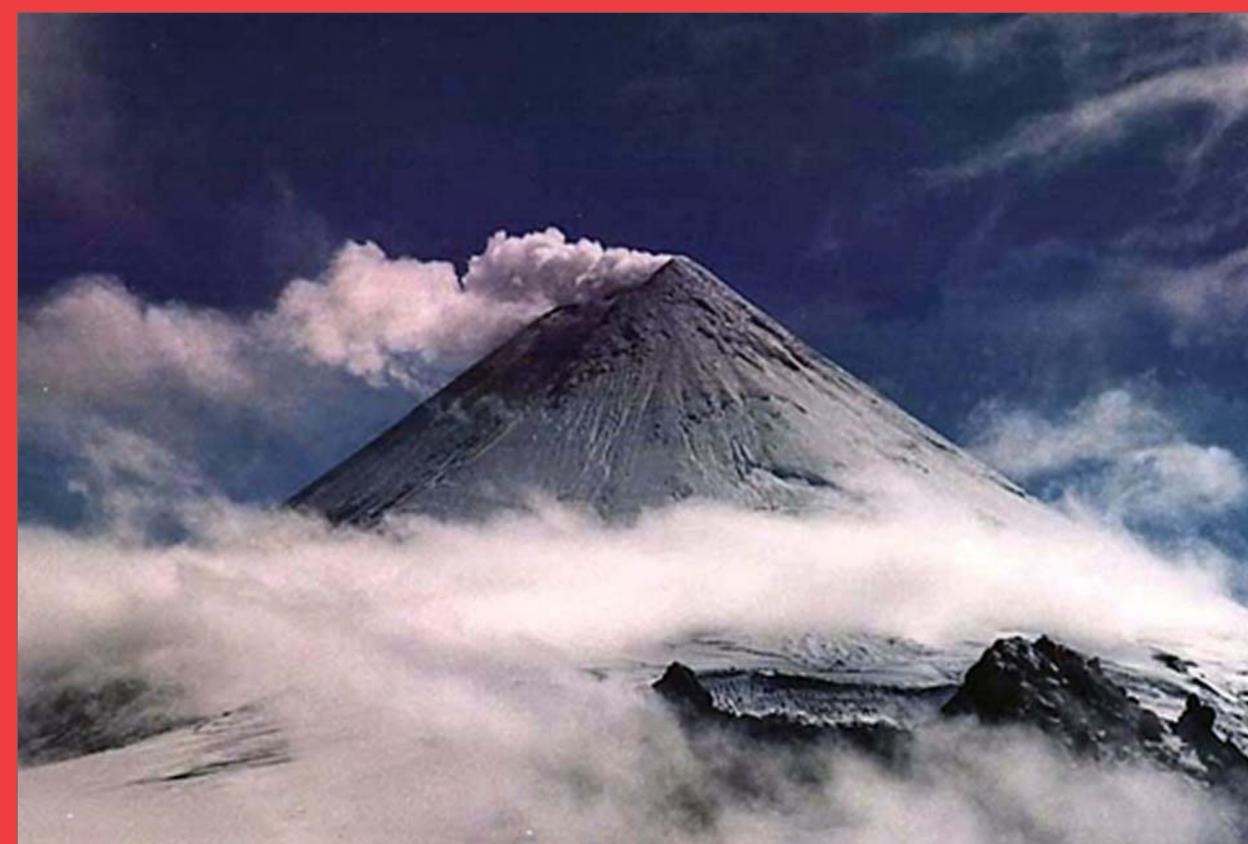
Division of Geological & Geophysical Surveys

Preliminary volcano-hazard assessment for Shishaldin Volcano, Alaska

Report of Investigations 2002-4



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Cover photo: *Shishaldin Volcano from the west. Steam from the summit crater, similar to that shown, is common. The jagged topography in the lower right shows the remains of a previous edifice that was destroyed during the production of a debris avalanche in earliest Holocene time. Photo by Pete Stelling, AVO/UAFGI.*

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Preliminary Volcano-Hazard Assessment for Shishaldin Volcano, Alaska

by J.E. Begét[1], C.J. Nye[2], J.R. Schaefer[2], and P.L. Stelling[3]

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2003

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by J.E. Begét, C.J. Nye, Janet R. Schaefer, and Peter L. Stelling

SUMMARY OF HAZARDS AT SHISHALDIN VOLCANO

Shishaldin Volcano is a 2,857-meter-high stratovolcano on Unimak Island, the most easterly of the Aleutian Islands. It is located about 45 kilometers west of False Pass, a small, permanently inhabited fishing village on Unimak Island that has a summer population of about 100. Shishaldin Volcano is historically one of the most active volcanoes in the Aleutian Islands. Eruptive events have occurred on at least 39 occasions since the late 1700s, when Russian traders and explorers began keeping written records. The most recent eruptive episode occurred from February to July of 1999, when the volcano produced tephra plumes on several occasions and extensive scoria blankets, and lahars on two occasions. The largest explosive eruption, on April 19, 1999, sent ash higher than 16 kilometers above sea level. The ash cloud drifted southward with the wind over the North Pacific Ocean, causing local disruptions in air traffic.

During the last 230 years, most eruptions of Shishaldin Volcano have been explosive, repeatedly producing ash clouds that have risen from 3,000 to 10,000 meters or more above the volcano summit. These ash clouds deposited lapilli and ash on the flanks of the volcano and nearby parts of Unimak Island before drifting hundreds of kilometers downwind. Some of these eruptions deposited small amounts of ash at False Pass and other nearby settlements. In addition, lava flows, lahars, and floods have been produced repeatedly during the relatively small historical eruptions; however, these events have affected only uninhabited areas near the volcano.

Geologic studies show that this volcano has produced frequent explosive eruptions over a period of thousands of years, with some prehistoric eruptions being significantly larger than any recorded in historical time (Begét and Nye, 1998). In addition to eruptions from the summit of Shishaldin Volcano, many of the more than 50 cinder cones, maars, and tuff cones that are found on the flanks of the volcano have produced explosive eruptions in the Holocene. At some cinder cones, effusive lava eruptions followed the explosive phase, with the volume of lava much greater than the volume of the cinder cone.

The largest known eruption of Shishaldin Volcano occurred about 9,500 years ago when the summit of Shishaldin Volcano collapsed to produce the large Cape Lapin debris avalanche. This giant landslide traveled more than 20 kilometers north to the Bering Sea, burying the northwest flank of Shishaldin Volcano and nearby areas of Unimak Island. The modern symmetrical cone of Shishaldin has completely regrown since this collapse event (Begét and others, 1998). Another notable eruption from Shishaldin occurred about 9,000 years ago. This eruption deposited more than 2 meters of pumiceous and scoriaceous tephra near the volcano. Deposits from this eruption are about 3 centimeters thick in Cold Bay, Alaska, about 95 kilometers northeast of the summit vent.

Future eruptions are likely to be similar in size to those of the last few hundred to few thousand years, and the most likely volcanic hazard is the eruption of plumes of volcanic ash that could rise ten kilometers or more into the atmosphere. Such ash plumes would constitute a hazard to aircraft flying long-distance routes over the North Pacific Ocean, as well as those flying more local routes over Unimak Island and the eastern Aleutian Islands. More than 200 flights travel over the region each day (Miller and Casadevall, 2000). Ashfall from eruptions might also affect shipping and fishing activities around Unimak Island. Lava flows, floods, lahars, and small pyroclastic flows and surges may also accompany future eruptions, and would preferentially affect low-lying areas within 10 kilometers of the volcano.

A worst-case scenario would be an eruption similar to those that took place about 9,000–9,500 years ago. Such an eruption might result in the collapse of the summit of Shishaldin Volcano, producing a debris avalanche that could bury large areas on the volcano's flanks. A large debris avalanche could travel far enough to enter the Bering Sea to the north or the Gulf of Alaska to the south, possibly generating tsunami waves. The debris avalanche might also be accompanied by a lateral blast that could travel across topographic barriers and across the sea, devastating areas 25 kilometers or more from the volcano. Thick pumice and ash deposits might bury much of Unimak Island and surrounding areas. Ash clouds associated with such large-scale eruptions could severely impact air traffic across Alaska, Canada, and the continental United

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.

States, and may deposit a significant amount of ash in False Pass and Cold Bay. However, based on the pattern established by the volcano's past behavior, eruptions of this magnitude are very uncommon, and are probably unlikely to recur in the near future.

Volcanic hazards to life and property can be mitigated through public awareness and planning. Volcanic eruptions can vary widely in style and magnitude, and the planning for and response to volcanic emergencies should take into account the unique geologic and geographic characteristics of each volcano. The volcanic processes associated with individual eruptions may be complex. Typical small eruptions of Shishaldin Volcano have been largely explosive, generating plumes of volcanic ash. However, larger eruptions may involve multiple processes, and may be highly destructive over wide areas. Future volcanic hazards at Shishaldin Volcano, ranked approximately by their likelihood of occurrence and importance, are itemized below and shown on sheet 1.

Volcanic ash clouds

Clouds of pumice, lithic material, volcanic ash, and gas that are erupted high into the atmosphere will drift away from the volcano with the wind. Ash clouds produced during eruptions can reach heights of 20 kilometers or more above the volcano. Ash clouds are a hazard to passenger and freight aircraft, as jet engines sometimes stall after ingesting volcanic ash. In some cases avionics and other electronics have been disrupted or have failed as airplanes fly through ash clouds. Ash abrasion has damaged windows, wings, landing gear, and other exposed parts of airplanes. Large ash clouds, in addition to disrupting air travel near the volcano, can maintain their integrity and coherence for days as they drift eastward with prevailing winds, continuing to cause problems for air travel across large areas of Alaska, Canada, and the contiguous United States.

Volcanic ash fallout

Ash fallout from historical eruptions of Shishaldin Volcano has occurred mainly on uninhabited parts of Unimak Island, but accumulations of several millimeters occurred in nearby communities during eruptions in the 19th century. Ash and lapilli deposits from the largest prehistoric eruptions of Shishaldin Volcano are as much as 3.35 meters thick near the volcano.

Small amounts of fine ash fallout may cause respiratory problems in some humans and animals. Heavy ash fallout may interfere with power generation and electrical equipment, damage air filters and gasoline engines, and greatly reduce visibility. Resuspension of ash by wind may prolong the unpleasant effects of ash fallout. Very thick ashfalls may collapse the roofs of buildings.

Lahars and floods

Eruptions of Shishaldin Volcano can melt large volumes of glacier ice and snow, which will produce floods of water and volcanic debris. Hot volcanic ash produced during eruptions may also melt snow and glacier ice on the flanks of the volcano, forming fast-moving slurries of water, mud, rocks, and sand, called lahars, that may travel more than 20 kilometers downslope to the Bering Sea and Pacific Ocean. Lahars may also be generated when thick deposits of proximal ash are eroded rapidly by heavy rainfall. The floods and lahars will tend to follow streams and valleys, but can overflow channels and spread out across flat fans on the lower flanks of the volcano. Lahars produced during the 1999 eruptions at Shishaldin Volcano affected areas as far as 20 kilometers away from the volcano. Future lahars and floods may affect areas along any of the streams that drain Shishaldin Volcano.

Pyroclastic flows and surges

Hot material erupted from the volcano may travel rapidly down slopes as incandescent mixtures of volcanic gas and rock debris called pyroclastic flows and surges. Pyroclastic flows and surges similar to those of the last few thousand years would pose a significant hazard to people within 10 to 15 kilometers of the volcano, possibly reaching the coast on the south side of the volcano. Pyroclastic surges also might be generated by phreatomagmatic eruptions at flank vents, as occurred in the past when eruptions produced two maar craters on the south side of Shishaldin Volcano, and a tuff cone on the north side.

Lava flows

Flows of molten rock (lava) may erupt at the summit or from flank vents around Shishaldin Volcano. These flows will probably move slowly, at rates of only a few meters to tens of meters per hour. Such flows pose little *hazard to humans if a safe distance is maintained. Lava flows can develop steep, blocky fronts and margins, and avalanching of blocks from the flow front or flow side might be hazardous to someone approaching too close to the active lava flow.*

Volcanic gases

Volcanoes can emit gases in concentrations and at temperatures that are harmful to humans. The deep crater at the summit of Shishaldin Volcano contains fumaroles that continually emit steam mixed with gases. These gases include hydrogen sulfide, a gas that can sometimes be smelled at considerable distances from the volcano. During eruptions there may be an increase in the amount of such gases emitted at the volcano. Dangerous, invisible, odorless volcanic gases may collect in the summit crater, making it inadvisable to descend into the crater. It also may be hazardous to approach gas-emitting fumaroles that are associated with active lava flows and lava domes on the volcano's flanks.

Debris avalanche

A debris avalanche is a rapidly moving mass of rock debris produced by a large-scale landslide from the summit areas of a volcano. The 9,500-year-B.P. Cape Lapin debris avalanche from Shishaldin Volcano traveled more than 25 kilometers down the north side of the volcano into the Bering Sea. The potential hazard areas from debris avalanches are the volcano's flanks and the valleys draining Shishaldin Volcano for distances of 30 kilometers from the volcano.

Directed blasts and large pyroclastic flows

A directed blast is a laterally directed explosion of the volcano caused by rapid release of internal pressure. Most directed blasts are caused by a slope failure of newly erupted lava domes or sector collapse of the summit edifice, resulting in a debris avalanche. Directed blasts are rare at active volcanoes, and there is no definitive evidence for a prehistoric directed blast at Shishaldin Volcano. Directed blasts can cause destruction to distances of 25 to 30 kilometers from the volcano. Very large pyroclastic flows can also travel 25 to 30 kilometers or more from the vent. Unless an unusually large eruption occurs, Shishaldin Volcano is unlikely to produce directed blasts and large pyroclastic flows in the near future.

Volcanic tsunamis

Large debris avalanches or pyroclastic flows that travel into the sea may rapidly displace water and initiate volcanic tsunamis. Although no tsunami deposits have been identified, the 9,500-year-B.P. Cape Lapin debris avalanche traveled 20 km from Shishaldin Volcano and reached the Bering Sea. A volcanic tsunami from Shishaldin Volcano would pose a risk to nearby, low-lying coastal areas on Unimak Island, and could affect coastal areas of nearby islands and the westernmost parts of the Alaska Peninsula.

SUGGESTIONS FOR READING THIS REPORT

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

INTRODUCTION

Shishaldin Volcano is a nearly symmetrical, conical 2,857-meter-high stratovolcano on Unimak Island, the easternmost of the Aleutian Islands. It is part of the Aleutian volcanic arc, a chain of at least 42 active volcanoes that extends from the far western end of the Aleutian Islands to the volcanoes of the Cook Inlet area in south-central Alaska (fig. 1). Several eruptions typically occur every year from one or more volcanoes in the Aleutian arc. Over the last several hundred years, Shishaldin Volcano has been one of the most active volcanoes in the Aleutian Islands portion of the Aleutian arc. Its most recent eruptive period occurred in 1999.

Shishaldin Volcano is located 45 kilometers west of the small fishing village of False Pass (population ca. 100), the only permanently inhabited site on Unimak Island (fig. 2). Former Aleut villages at Morzhovoi, Ikatan, Agayadan and other sites around Unimak Island are now abandoned. There have been several occupied installations on southwestern Unimak, including the Scotch Cap Lighthouse (established in 1903, destroyed by a tsunami in 1946, rebuilt and operated into the 1970s, then deactivated), the Cape Sarichef Lighthouse (1904–1979), and a missile defense Distant Early Warning (DEW line) station (1957–1969). Currently, the area around Shishaldin Volcano is visited only by mountain climbers, hikers, fishermen, hunters, biologists, geologists, and archeologists and thus the total number of people near the volcano at any time is small. Shishaldin Volcano is in the federally managed Eastern Aleutians Wildlife Refuge, which virtually precludes any extensive development near the volcano.

There have been two dozen 20th-century eruptions and at least 39 historical eruptions at Shishaldin Volcano since the late 1700s (table 1). During the 20th century the longest interval between eruptions was 15 years. Historical eruptions have occurred mostly from the central vent and have been explosive, with abundant steam, varying amounts of ash, and occasional lahars and floods being generated. Based on the geologic record and the pattern of historical activity, typical explosive eruptions of Shishaldin Volcano produce volcanic ash clouds that rise to 10 kilometers or higher above sea level. The most recent eruptions occurred from March to July of 1999, with the largest eruption occurring on April 19 when an ash cloud reached 16 kilometers above sea level, and caused local disruptions in air traffic over the North Pacific Ocean. Future eruptions of similar ash clouds from Shishaldin Volcano would be hazardous to all aircraft from Asia, Europe, and North America that fly heavily used air routes across the North Pacific Ocean. Historical eruptions of Shishaldin Volcano, including the 1999 event, have also produced dustings of ash in nearby communities, the nearest of which is the village of False Pass, 45 kilometers to the east.

Modern geologic study of Shishaldin Volcano began in the 1930s (Finch, 1934), and continued with intermittent visits by geologists during and after World War II. The first detailed volcanologic study of

Figure 1. *Location of Shishaldin Volcano with respect to other volcanoes in the easternmost Aleutian Islands and the Alaska Peninsula. All of these volcanoes have erupted in late Holocene time and should be considered active and capable of eruptions in the near future. Shishaldin Volcano has been one of the most active volcanoes in the Aleutian Islands during historical time.*

Shishaldin Volcano was done in the 1980s (Fournelle, 1988). The first detailed geologic map of Shishaldin Volcano is currently being produced as a result of field studies, laboratory, and geochronologic work by personnel of the Alaska Volcano Observatory (Begét and others, 1998; Begét and Nye, 1998). This hazards appraisal is the first comprehensive report on the volcanic hazards associated with Shishaldin Volcano, and is partly based on the stratigraphic and geochronologic data obtained during the most recent mapping project.

This report presents an evaluation of a variety of volcanic hazards that may result from different types of eruptions of Shishaldin Volcano and describes hazardous volcanic phenomena that occur near the volcano, as well as the distal effects of eruptions. This report also discusses the present status of monitoring efforts to detect volcanic earthquakes, ash clouds, and elevated surface temperatures, and the procedure for eruption notification and dissemination of information. Also included are maps and illustrations that indicate potential hazard zones, and a glossary of volcanic and geologic terms. This report is designed to provide information useful to government agencies and to private individuals and parties. However, in the event of an eruption, scientists of the Alaska Volcano Observatory will be available for detailed discussions of the actual events occurring at the volcano and specific potential hazards associated with these events.

PHYSICAL SETTING AND THE HISTORICAL RECORD OF SHISHALDIN VOLCANIC ERUPTIONS

Shishaldin Volcano is a 2,857-meter-high active stratovolcano situated near the center of Unimak Island, the largest and easternmost of all the Aleutian Islands (figs. 1, 2). Subduction rates of the Pacific sea floor beneath Unimak Island are high, reaching velocities of about 6.5 centimeters per year. Large, subduction-related earthquakes are common in this area. The present cone of Shishaldin Volcano buries the remnants of an older edifice that is exposed high on the western flank

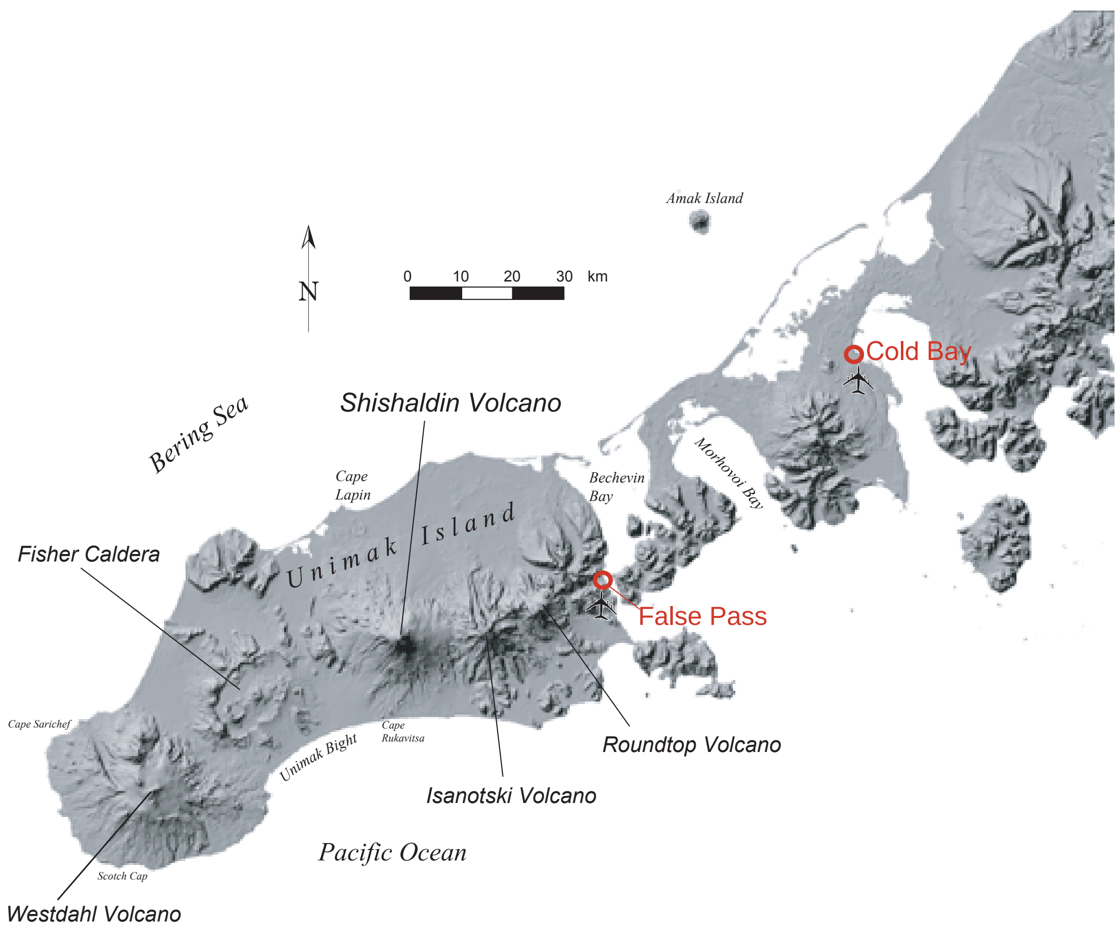

Figure 2. *Location of Shishaldin Volcano and other volcanoes on Unimak Island. Also shown is the location of False Pass, the only inhabited village on Unimak Island.*

Table 1. *Historical activity of Shishaldin Volcano*

Eruption Date	Volcanic Activity	Reference
1775–78	Active; type of activity not specified	Coats, 1950
1790	Smoke	Coats, 1950
1824	Major explosive eruption; smoke; lava flow or plug dome	Coats, 1950
1825	Smoke	Coats, 1950
1826	Lava flow	Simkin and Siebert, 1994
Nov.–Dec., 1830	Major explosive eruption; lava flow or plug dome	Coats, 1950
1838	Minor explosive eruption	Coats, 1950
1842	Minor explosive eruption; lava flow or plug dome	Coats, 1950
1865	Smoke	Coats, 1950
1880–81	Smoke	Coats, 1950
1883	Minor explosive eruption	Coats, 1950
1897	Smoke	Coats, 1950
1898	Minor explosive eruption; lava flow or plug dome	Coats, 1950
1899	Smoke	Coats, 1950
1901	Active; type of activity not specified	Coats, 1950
1912	Smoke	Coats, 1950
1922	Minor explosive activity; lava flow or plug dome; mudflow	Coats, 1950 Simkin and Siebert, 1994
1925	Active; type of activity not specified	Coats, 1950
1928	Minor explosive eruption; smoke	Coats, 1950
May–June 1929	Lava flow or plug dome; some explosive activity; three new craters low on the north side	Coats, 1950 Jaggar, 1932
Feb.–May 1932	Explosive eruption; lava flow; mudflow	Coats, 1950 Jaggar, 1932 Simkin and Siebert, 1994
Aug. 1946–Jan. 1947	Minor Explosive eruption	Coats, 1950
1948	Minor explosive eruption	Coats, 1950
1951	Minor ash emission	Wentworth, 1951
Oct. 4, 1953	Explosive eruption	Simkin and Siebert, 1994
July 1955	Explosive eruption	Simkin and Siebert, 1994
Dec. 28, 1963	Explosive eruption	Simkin and Siebert, 1994
Jan. 28, 1967	Explosive eruption	Simkin and Siebert, 1994
Sep.–Oct. 1975	Ash eruptions[1]	Smithsonian Institution, 1975, v. 1, no. 1.
Jan. 1976	Ash eruptions and small lava flows	Anchorage Times, Jan. 25, 1976, p. 1
Apr.–July 1976	Ash eruptions[2]	Smithsonian Institution, 1976, v. 1, nos. 7, 8, 9, 10
Oct. 1976	Incandescent gas jet; steam-and-ash emissions	Smithsonian Institution, 1976, v. 1, no. 13
Feb. 8, 1978	Minor ash emission	Smithsonian Institution, 1978, v. 3, no. 2
Feb. 1979	Minor ash emission	Smithsonian Institution, 1979, v. 4, no. 2
1981	Steam and ash emissions for several months	Smithsonian Institution, 1981, v. 6, no. 9
Mar. 1986–Feb. 1987	Steam and minor ash	Smithsonian Institution, 1986, v.11, nos. 4, 5, 8, 9, 12; Smithsonian Institution, 1987, v. 12, no. 2

Oct. 28, 1993	Explosive eruption	Simkin and Siebert, 1994
Dec. 1995–May 1996	Steam and ash to as high as 10 km	Neal and McGimsey, 1997
Mar.–July 1999	Ash eruption to 15–20 km; strombolian eruption in April	Smithsonian Institution, 1999, v. 4, nos. 3, 4

[1]Ash sample collected by NOAA's RV Millard Freeman 80 kilometers north of the volcano on September 16, 1975.
[2]Lahar or debris flow from summit to 300-meter elevation seen on April 27, 1976. Flanks of volcano about 70 percent ash covered in late May and early June 1976.

of the volcano and low on the northeast and southern flanks (Fournelle, 1988). The ancestral Shishaldin Volcano was partially destroyed by flank collapse during a large eruption in early Holocene time (Begét and others, 1998). The modern volcanic cone is remarkably symmetrical and uneroded, and small glaciers and snowfields cap its steep summit. The glaciers descend to elevations of 300 to 600 meters above sea level on all sides of the volcano, and together cover about 90 square kilometers (fig. 3). An ice-free crater a few hundred meters across is present at the summit (fig. 4), and is almost constantly steaming, intermittently sending plumes 1,000 to 3,000 meters above the volcano.

Many flank vents surround Shishaldin Volcano. Fifty-four cinder cones and small monogenetic lava cones have been identified, the majority of which are located on the northwest flank of the volcano. A few of the cinder cones may have formed since the 1700s, although most of these vents appear to have formed earlier in the Holocene. Lava flows are associated with many of the cinder cones, and some fresh-appearing unvegetated flows can be traced for more than 5 kilometers downhill from individual cinder cones. Other lava flows emerge from the snow- and ice-covered flanks of Shishaldin Volcano itself, and some of these extend several kilometers from the volcano. A vent at about 1,300 meters elevation on the northeast side of the volcano is the source of a large outpouring of pahoehoe and aa basaltic lava. Recent field investigations (Nye and Begét, unpublished) suggest that this 20-square-kilometer lava flow may have been erupted in 1825 as described by Veniaminov (1840, translated and reprinted in 1984).

Enormous, active fans composed of fluvial and laharic deposits surround much of the volcano. The surfaces of the fans are generally uneroded, although valleys as deep as 40 meters have been eroded by small creeks in the fan on the north side of the volcano. At the Bering Sea coastline, north of the volcano, 4- to 8-meter-high sea cliffs truncate the fan surface. These cliffs may partly reflect recent tectonic uplift of Unimak Island and surrounding areas. Large areas of the surfaces of these fans were buried repeatedly by flood and laharic debris during 20th-century eruptions of Shishaldin Volcano.

Shishaldin Volcano erupts frequently (table 1). A total of 39 eruptive episodes have been recorded at Shishaldin Volcano since 1775, when Russian explorers and traders first began keeping written records of events in the Aleutian, and there have been two dozen 20th-century

Figure 3. *Photo of Shishaldin Volcano, showing the symmetrical cone formed by numerous eruptions in postglacial time. Thin glaciers cover the uppermost parts of the volcano.*

eruptions. Most historical events were relatively small eruptions of ash and steam, although a few were major explosive eruptions, accompanied by lava flows, lahars, and widespread dispersal of volcanic ash. Additional small eruptions during historical time may have gone unrecorded, either because they occurred at times of bad weather when the volcano was obscured from view, or because they were too small to have noticeable effects beyond the volcano's flanks.

The most recent eruptions of Shishaldin Volcano occurred in 1995 and 1999. The December 1995 eruption produced an ash cloud that reached 10.7 kilometers above mean sea level and resulted in a light dusting of ash in the village of Cold Bay, 90 kilometers downwind. From February to July of 1999, the volcano erupted again, and produced ash plumes, scoria falls, and lahars. In February an increase in seismicity was observed, and elevated surface temperatures and small plumes were detected using satellite data. Observers in Cold Bay reported seeing plumes as well. Aerial observations using a thermal-infrared imaging system detected low-level lava fountaining at the summit in April and May. On April 19 the volcano erupted explosively resulting in the highest ash plumes of the 1999 eruption. These plumes rose to over 16 kilometers above sea level and buried the flanks of the volcano with as much as 50 centimeters of ash and mafic lapilli (Smithsonian Institution, 1999). The ash cloud drifted to the south–southeast disrupting air traffic over the North Pacific Ocean. In May, volcanic plumes were at lower altitudes but extended up to 1,000 kilometers to the east, southeast, and south (fig. 5). Trace amounts of ash fell on the village of False Pass, 45 kilometers to the east, but most of the tephra affected only uninhabited areas near the volcano on Unimak Island. A coeval flood originated on the upper north side of Shishaldin Volcano, swept down the glaciated flanks, and eroded a deep channel into the glacier ice where it incorporated sediment from the glacier surface. This flood was more than 30 meters deep where it moved through a narrow valley on the north flank of the volcano. The flood deposited sediment across alluvial fans as far as 20 kilometers to the north, reaching almost to the Bering Sea.

PREHISTORIC ERUPTIVE HISTORY OF SHISHALDIN VOLCANO

Because the written record of volcanism at Shishaldin Volcano goes back only about 230 years, geologic studies of the deposits of prehistoric eruptions were made to reconstruct the eruption history of the volcano and to learn more about the long-term style, magnitude, and frequency of volcanic eruptions and associated hazards. Extensive glaciers covered much of Unimak Island during the Pleistocene ice ages, making it difficult to reconstruct the volcanic history of Shishaldin Volcano prior to the end of the last ice age (about 10,000 years B.P.). Because the products of most ancient eruptions of Shishaldin volcano have been buried by younger volcanic deposits, or removed by erosion, this study concentrates on the record of Holocene activity of Shishaldin Volcano.

Figure 4. *An ice-free crater several hundred meters across is present at the summit of Shishaldin Volcano and is almost constantly steaming, intermittently sending steam plumes 1,000 to 3,000 meters above the volcano.*

The earliest deposits of Shishaldin Volcano that postdate deglaciation are preserved on the north side of the volcano, and record several explosive tephra eruptions. Subsequently, a voluminous debris avalanche buried the northeastern and northern flanks of the volcano. This avalanche traveled at least 20 kilometers from the volcano and today is best exposed in sea cliffs at the shore of the Bering Sea. The summit of Shishaldin Volcano apparently collapsed during this event, as indicated by a truncated rim of lava flows, largely buried by the volcano's modern cone, that can be traced around the western and southern sides of the volcano at an elevation of about 1,500 to 1,800 meters. This feature appears to be part of the rim of a horseshoe-shaped crater left by the summit collapse that resulted in the Cape Lapin debris avalanche.

Within a few hundred years after the debris avalanche a huge explosive eruption occurred at Fisher Caldera, about 30 kilometers to the west, which buried much of the area around Shishaldin Volcano in thick, silicic pumice deposits and a coeval, far-traveled pyroclastic flow (Miller and Smith, 1977).

The discovery of the large debris avalanche from Shishaldin Volcano during this study, and the existence of the slightly younger, thick pumice fall and pyroclastic flow deposit from Fisher Caldera, provided key

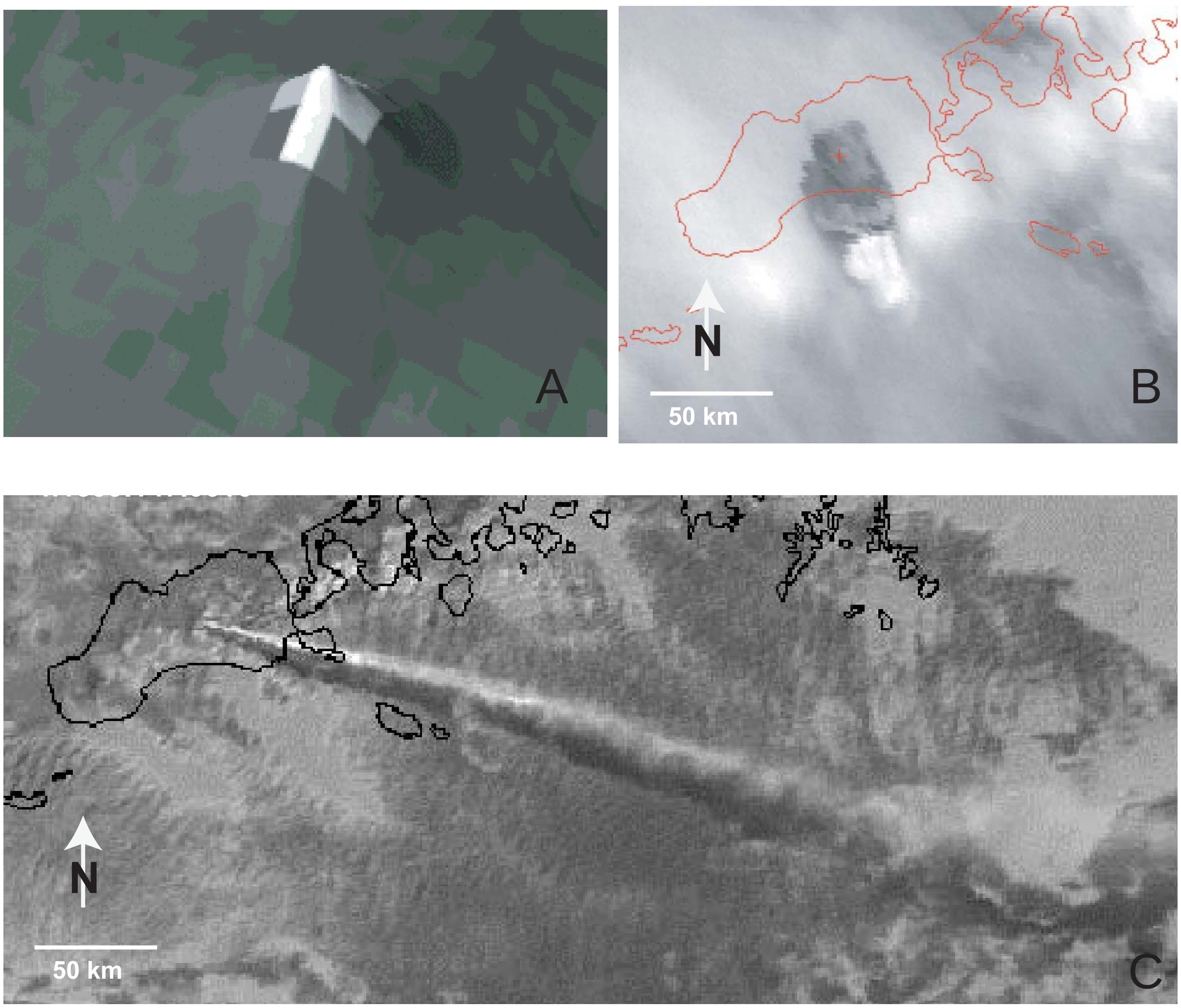

Figure 5. *Satellite images of the 1999 eruption of Shishaldin Volcano. Elevated surface temperatures (A, top left), recorded on March 13 in Advanced Very High Resolution Radiometer (AVHRR) data draped over a digital elevation model. This temperature anomaly may be the result of an early low-level eruption, although there was no visual or seismic confirmation of such an event. Explosive eruptions produced volcanic clouds recorded in Geostationary Orbiting Environmental Satellite (GOES) data on April 19 (B, top right) and AVHRR data on May 27 (C, bottom). Most volcanic clouds from the 1999 eruption blew to the southeast and in May were over 1,000 kilometers long.*

marker horizons during field studies. At sites where these deposits were recognized around Shishaldin Volcano, it was possible to confidently determine which volcaniclastic deposits, lava flows, flank cinder cones, maars, and tuff cones were erupted later in the Holocene.

The most complete record of Shishaldin eruptions that postdate the debris avalanche and the Fisher ignimbrite is found near a large maar crater on the southeast flank of Shishaldin Volcano. At this location, more than 100 volcanic tephra layers, some as much as 5 centimeters thick, are intercalated with eolian silt and alluvium. The thick section of tephra deposits overlies ash correlative with the last major eruption of Fisher Caldera, and is capped by coarse surge deposits and colluvium that form the pyroclastic apron of the nearby maar. These tephra deposits primarily consist of well-sorted, highly vesicular, dark-colored, scoriaceous clasts ranging from a few millimeters to a few centimeters in diameter, and document frequent explosive eruptions of Shishaldin Volcano during the early and middle Holocene. The presence of these tephra layers suggests that explosive eruptions large enough to leave a discrete deposit on the volcano's flanks have occurred, on average, at least once per century through the last 9,000 years of the Holocene (Begét and others, 1998).

Thick deposits that consist of numerous volcanic ash layers are also preserved at other sites on the flanks of the volcano, although most of the volcanic deposits at these sites are younger and contain shorter records of explosive volcanism. A representative sequence of tephra deposits on the north side of Shishaldin Volcano, near the lower limit of modern glaciers, occurs above a young lava flow radiocarbon dated to about 1,000 years B.P. (Begét and others, 1998). At this site, seven coarse tephra layers are preserved above the unglaciated lava top, recording multiple explosive eruptions during the last millennium.

The 1999 eruption provides a useful model for understanding and interpreting deposits of prehistoric eruptions. This explosive eruptive episode produced a new tephra deposit across the south flank of Shishaldin Volcano and a flood deposit on the north flank. The 1999 tephra deposits closely resemble, in grain size and thickness, some of the thicker prehistoric deposits from Shishaldin Volcano. This strongly suggests that the multiple scoria and ash layers preserved at sites around the volcano record numerous prehistoric explosive eruptions. The large explosive eruption on April 19, 1999, sent ash 15 to 20 kilometers above the summit, where strong, northwesterly winds dispersed the ash cloud principally to the southeast (Smithsonian Institution, 1999). Deposits from 3 to 50 centimeters thick accumulated on the south flank of the volcano, but the north and west sides of the volcano received little or no ash, and most of the ashfall was probably deposited over the North Pacific Ocean. By analogy, prehistoric eruptions that produced tephra deposits as much as 50 centimeters thick in areas just downwind of the vent might leave virtually no trace in other areas around the volcano. This indicates that the geologic record tephra falls found at any given site on the flanks of the volcano will provide only a minimum estimate of the total number of explosive eruptions. Unfortunately, widely separated ash deposits often cannot be correlated because the geochemical and physical characteristics of the tephra layers have not varied much through the Holocene. Nonetheless, it is now clear that the record of frequent explosive eruptions during the last 230 years of historical documentation is the latest manifestation of a long-lived pattern of explosive activity that has produced at least 100 significant tephra eruptions over the last 9,000 years (Begét and others, 1998).

The total volume of the 1999 eruption was estimated at 43 million cubic meters by determining the volume of the 1999 ashfall on Unimak Island, and estimating the additional volume of the ash that fell into the sea (Begét and others, 1999). The volume of the numerous prehistoric deposits cannot be precisely estimated, but some of these eruptions appear to have been at least as large as the 1999 eruption. Indeed, it seems probable that any eruption large enough to leave significant ash and scoria deposits at distances of 10 kilometers from the vent would have been large enough to present a hazard to any people near the volcano, or to nearby aircraft. Taken together, the historical and prehistoric records suggest that explosive eruptions as large as that in 1999 occur roughly every 100 to 150 years, while smaller explosive eruptions typically occur at least every 10 to 25 years.

In addition to tephra, the 1999 eruption also produced a flood and lahars that affected the fan surface on the north side of the volcano. Similar geologic deposits at the base of the fan on the north side of the volcano have been dated by radiocarbon techniques at 4,000 years, suggesting that the fans on the north and south flanks of the volcano record numerous 1999-style eruptions over the last 4,000 years. Lahar and flood deposits, possibly produced by small eruptions, are present at low elevations in virtually all streams that drain the volcano. As with the tephra deposits, it is not possible to directly correlate flood and lahar deposits in widely scattered drainages or between the north and south flanks of the volcano.

Some of the prehistoric deposits appear to record lahars larger than that of the 1999 eruption. Thick, prehistoric volcaniclastic alluvium and lahar deposits are exposed in sea cliffs all along the northern shoreline of Unimak Island. In contrast, the 1999 flood deposit did not reach the coastline. In addition to lahar deposits, several thin prehistoric pyroclastic flow and surge deposits are found up to 8 kilometers from the vent on the northeast, north, southeast, and west flanks of Shishaldin Volcano.

Fresh-appearing, unvegetated lava flows extend as far as 18 kilometers from the summit vent on the north side of the volcano, and to the shoreline of the Pacific Ocean, 13 kilometers to the south. The lava flows often bury older, vegetated flows, indicating that lava flows are commonly produced during eruptions of Shishaldin Volcano.

In addition to the central cone, there are numerous flank vents around the volcano. There are two, deep, maar craters on the volcano's south flank, and a tuff cone near the shore of the Bering Sea, 20 kilometers to the north of the volcano. Also, more than 50 cinder cones can be identified on the upper flanks of the volcano. The maars and tuff cone record explosive flank vent eruptions, which were accompanied by hydrovolcanic explosions, surges, and pyroclastic flows. The cinder cones record magmatic explosive eruptions, and are often the source of lava flows. The large numbers of cinder cones and maars show that explosive eruptions at flank vents are common at Shishaldin Volcano.

HAZARDOUS PHENOMENA AT SHISHALDIN VOLCANO

A wide range of volcanic phenomena poses a threat to human life, property, and the environment around volcanoes (Blong, 1984; Scott, 1989). The type and magnitude of volcanic hazards that will affect specific areas around a volcano will depend on the magnitude and style of an eruption. During small eruptions, only areas in the immediate vicinity of the volcano are at risk, while areas at greater distances from the volcano may be affected by the same phenomena during larger eruptions. Some volcanic phenomena will characteristically be dangerous only in areas very near the vent, while hazards associated with other volcanic processes will scale up and affect progressively greater areas during increasingly larger and more energetic eruptions.

Many types of volcanic processes can affect areas within 10 to 20 kilometers of an active vent (fig. 6), but the most hazardous processes are associated with explosive eruptions. These can produce pyroclastic flows and surges that can sweep all areas within a few kilometers of an erupting vent, and result in death or injury to anyone nearby. Once an eruption begins, explosive events can occur without warning, leaving no time to escape. At greater distances from the source, most types of volcanic flows are channeled into low-lying areas, so that conditions may be hazardous along river channels for many kilometers downvalley. Because Shishaldin Volcano lies in an uninhabited part of Unimak Island, only the occasional visitor is currently at risk from proximal volcanic hazards. Probably no more than a few dozen people, including hikers, climbers, hunters and fishermen, visit Shishaldin Volcano each year. No one lives on the flanks of the volcano, although in recent years archeological field parties have surveyed around the volcano, staying for several weeks at an excavation site about 15 kilometers northeast of the central vent.

It is possible that extremely large eruptions, especially those that generate pyroclastic flows and caldera craters, will have severe impacts at distances of 30 kilometers or more from the vent. Other eruption processes, such as the generation of volcanic debris avalanches and lateral blasts, or volcanic tsunamis, can also affect areas at 30 kilometers or more from the volcano. Based on the geologic record at Shishaldin Volcano, such eruptions are extremely rare.

Recently completed geologic mapping of Shishaldin Volcano has delineated the areal extent of volcanic deposits formed during various types of eruptions. Stratigraphic and geochronologic studies have determined the age and magnitude of major eruptions during the last 10,000 years (Begét and Nye, 1998). These studies show that eruptions of Shishaldin Volcano during the last 10,000 years produced ashfalls, pyroclastic flows, lava flows, debris avalanches, lahars, and floods that repeatedly impacted proximal areas within 10 kilometers of the volcano. More rarely, volcanic eruptions occurred that were large enough to impact areas more than 20 kilometers from the volcano.

DETAILS OF VOLCANIC HAZARDS AT SHISHALDIN VOLCANO

Based on written records of volcanic activity in Alaska over the past 230 years, Shishaldin Volcano has been one of the most active volcanoes in the Aleutian Islands. At least 39 eruptive episodes are documented in this historical record. Although little is known about many of the events, several are known to have produced ash plumes several kilometers high that carried ash more than several hundred kilometers downwind (table 1). Recent geologic studies have extended the short historical record of volcanic eruptions back to more than 9,000 years B.P. The geologic data show that Shishaldin Volcano has produced frequent eruptions for thousands of years, indicating that the high frequency of historical eruptions is characteristic of the long-term behavior of this volcano. This strongly suggests that additional eruptions are likely in the near future.

As discussed below, the greatest potential danger from future eruptions of Shishaldin Volcano is likely to result from damage to jet airplanes that encounter ash clouds. However, volcanoes can erupt in a wide variety of ways that may endanger humans and damage infrastructure including machines, roads, and buildings. Many volcanic processes are inherently dangerous, but the hazards from some types of eruptions are mitigated at Shishaldin Volcano because there are very few visitors and no permanently inhabited sites near the volcano. The risks associated with several types of volcanic hazards are discussed in separate sections below, in roughly the order of perceived risk to humans, rather than frequency of occurrence.

Volcanic Ash Clouds

Most historical and prehistoric eruptions of Shishaldin Volcano had an explosive phase that sent ash clouds high into the atmosphere. The material produced during these eruptions ranges from microscopic to several meters in diameter and is collectively called tephra. The coarser volcanic debris rains out near the volcano, while the finer-grained material can rise convectively 10–20 kilometers or higher above the volcano, forming

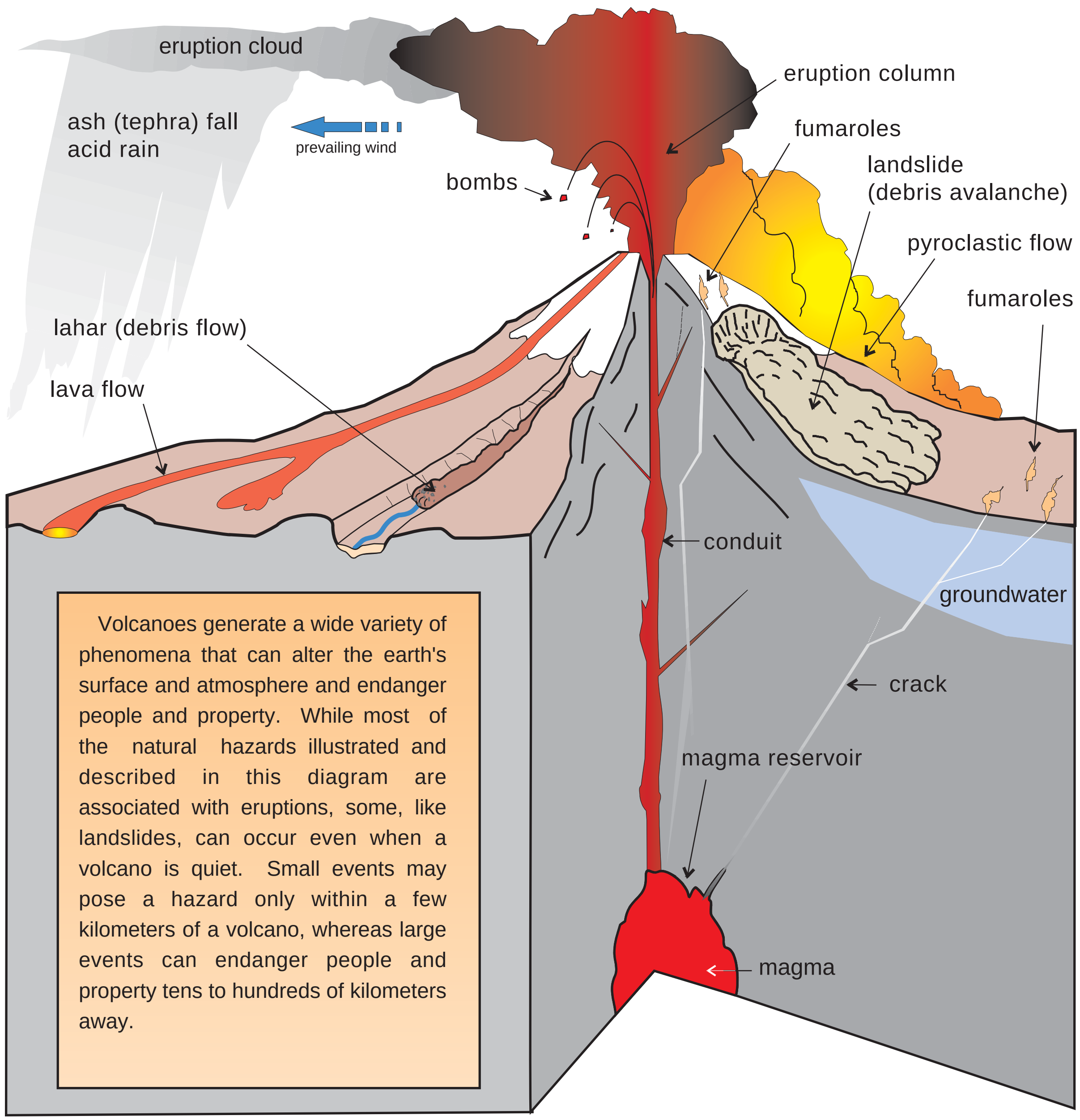

Figure 6. *Simplified sketch of a stratovolcano that illustrates hazardous phenomena that result from typical eruptions.*

an eruption cloud that drifts downwind away from the volcano. Typical ash clouds can travel through the atmosphere for distances of tens to hundreds of kilometers, while ash clouds produced by large eruptions can travel thousands of kilometers over periods of days to months. The glass and aerosol particles in ash clouds are a hazard to any jet aircraft they might encounter, because their physical and geochemical characteristics can damage jet engines and electronics (Swanson and Begét, 1991; Swanson and Begét, 1994; Casadevall, 1994).

The most recent tephra eruption at Shishaldin Volcano, which occurred in 1999, illustrates the type and extent of hazards that are likely to accompany future explosive eruptions. On April 19, 1999, scientists of the Alaska Volcano Observatory detected unusually high levels of seismic activity below Shishaldin Volcano, and a large eruption occurred. Aircraft pilots reported an eruption cloud at an elevation of at least 14 kilometers above sea level. Satellite observations confirmed that an eruption cloud rose high above the volcano and then drifted toward the southeast as it was entrained by strong winds. Because of the eruption monitoring by the Alaska Volcano Observatory and coordination with Federal Aviation Authority staff and private airlines, aircraft were directed away from the ash plume and no mechanical damage to airplanes is known to have occurred.

Probably the greatest risk from ash clouds is to passenger and freight airplanes flying heavily used routes across the North Pacific (fig. 7). For example, on December 15, 1989, a Boeing 747 flying 240 kilometers northeast of Anchorage encountered an ash cloud erupted from Redoubt Volcano and lost power in all four jet engines. The plane, with 231 passengers aboard, lost more than 3,000 meters of elevation before the flight crew was able to restart the engines (Casadevall, 1994). After landing it was determined the airplane had suffered about $80 million in damage (Brantley, 1990). Two jets later encountered the Redoubt ash cloud 5,400 kilometers to the southeast over west Texas. One of these jets suffered a transient engine stoppage, while the other jet's wings were abraded (Waythomas and others, 1998). Altogether, five jet aircraft are known to have sustained abrasion on windshields, wings, landing gear, and other parts of the planes after flying through ash clouds erupted from Alaska volcanoes. The ash clouds travel with high level winds (fig. 8) and typically move east over the Pacific Ocean and Canada. Dilute ash clouds from

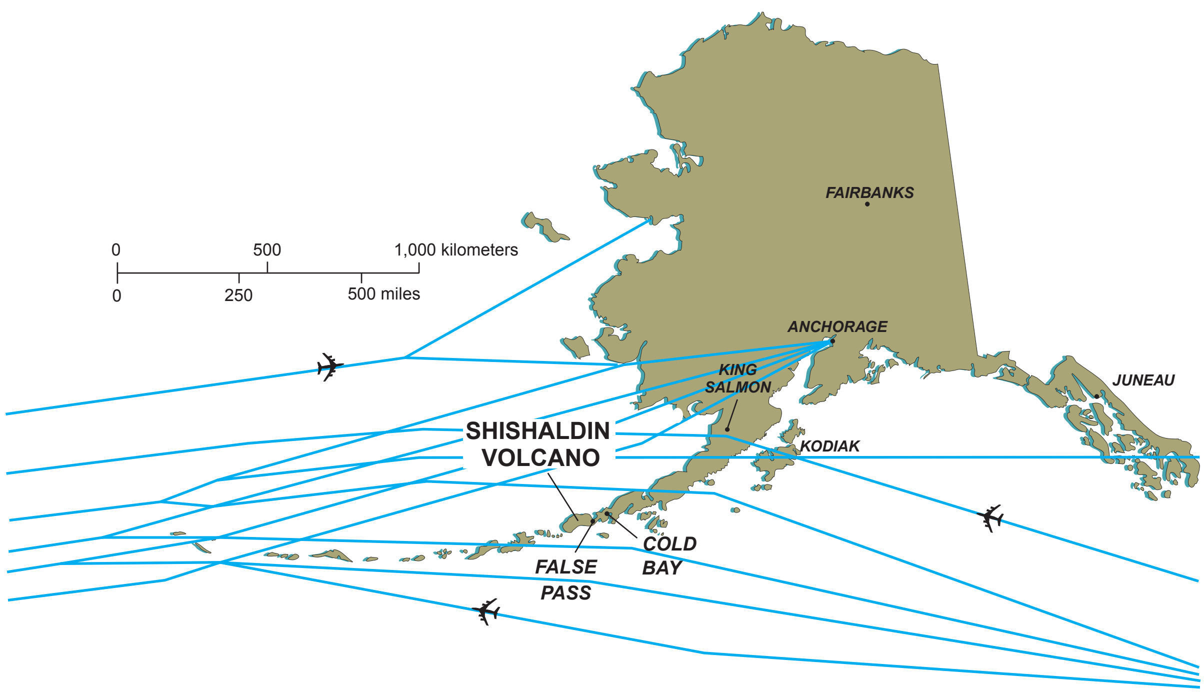

Figure 7. *Typical flight paths of commercial freight and passenger airlines crossing the North Pacific. Future explosive eruptions of Shishaldin Volcano may inject ash as high as 10,000 to 20,000 meters into the atmosphere, causing disruption of trans-Pacific flight schedules. The exact area of ash fallout will depend on synoptic weather conditions and wind directions, but because of prevailing wind patterns ash is most likely to be dispersed east of the volcano. Ashfall during small eruptions will be restricted to the immediate vicinity of the volcano and surrounding parts of Unimak Island, with fallout of large blocks and bombs restricted to areas within 5 kilometers of the vent.*

Alaska volcanoes have been traced as far south as Arizona, and as far east as Virginia.

Airborne ash probability distribution (AAPD) maps have been generated for Shishaldin Volcano (fig. 9; Papp, 2002). This model, based on wind field data, shows the probability of ash distribution at low and high altitudes, both in the summer and winter. In both seasons, the prevailing winds are from the west, and the areas with the highest probability of airborne ash for a hypothetical eruption are from 3 to 8 kilometers above sea level, drifting eastward from the volcano.

The magnitude of the hazards from ash clouds during future eruptions of Shishaldin Volcano will depend on the characteristics of the eruption, including the elevation and rate of ascent of the ash cloud, and the concentration, size, and geochemistry of the ash particles. The regional distribution and long-range transport of the ash clouds will be controlled by meteorological and wind conditions at the time of the eruption, as the cloud will drift with the prevailing high altitude winds. Because prevailing winds at Shishaldin Volcano are usually from the west, eruptions of ash clouds are likely to affect air travel and operations at the regional Cold Bay airport, and are a potential hazard to air traffic over the easternmost Aleutian Islands, Alaska Peninsula, Cook Inlet, and surrounding areas of the North Pacific Ocean.

Volcanic Ash and Bomb Fallout

Explosive eruptions can blast volcanic ash and bombs high into the atmosphere. The bombs will fall near the volcano, while fine-grained volcanic ash will rain out from ash clouds as they drift away with the wind, affecting areas tens or even hundreds of kilometers from the eruption. During ashfalls, the sky typically darkens, and visibility may be reduced to tens of meters, disrupting all types of surface and air transportation. Volcanic ash will accumulate on the roofs of buildings, and the weight of a thick ash layer can cause lightly constructed buildings to collapse. The weight of ash on a roof may be significantly augmented if the falling ash is mixed with rain or snow, or if it rains on the ash after deposition (Blong, 1984).

A wide range of mechanical and electrical systems can be affected by airborne ash during even relatively thin ashfalls of 1 to 2 centimeters. Ash can plug the cooling system and damage the electrical system of automobiles and other internal combustion engines. Equipment in hospitals, power plants, pumping plants, and factories may also be damaged. Ash can cause short circuits, disrupting telephone circuits and other communications systems. Thicker accumulations of ash can clog water and sewer systems (Blong, 1984; Scott, 1989).

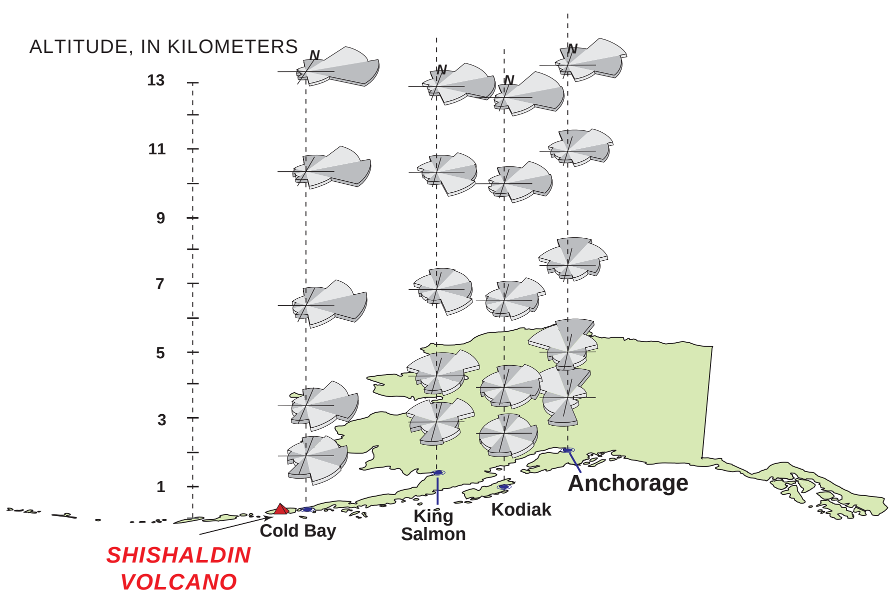

Figure 8. *Average wind direction over the southwestern Alaska Peninsula. During future eruptions of Shishaldin Volcano, volcanic ash will drift with the wind, most likely toward the northeast, east, or southeast. The lengths of the sections on the windrose diagrams are proportional to wind frequency determined by annual percent. Original data are from the National Climatic Data Center, National Oceanic and Atmospheric Administration.*

Ash can cause health problems in humans. People with respiratory problems may experience breathing difficulties during very minor ashfalls. Even healthy people may find prolonged exposure to atmospheric dust during sustained ashfalls irritating to their throat and lungs. At sites near volcanoes the ash may become so thick in the atmosphere that it clogs and blocks breathing passages. It is also possible for volcanic ashfalls to be accompanied by harmful gases, although such incidents are rare.

The health effects of ashfall on humans can be mitigated. People with respiratory problems should stay indoors during ashfalls. Respirators, filters, or even wet cloths over the mouth and nose can help people who must work outdoors. If possible, ash should be removed from roofs and buildings by shoveling before it accumulates to dangerous thicknesses. It can be removed from roads with heavy equipment.

If an eruption is similar in size to typical eruptions of the last approximately 230 years, the areas most likely to be affected by significant ashfall will be restricted to the flanks of the volcano and nearby unpopulated areas of Unimak Island. However, geologic studies show that more powerful eruptions have occurred several times during the last 10,000 years. An ash fallout hazard zone map (fig. 10) illustrates areas that are most likely to be affected in an eruption similar in size to the 1999 eruption.

During explosive eruptions, large volcanic bombs and other rock debris may be blasted from the vent and rain out around the volcano (figs. 6, 11). Typically, large volcanic bombs that weigh as much as tens of kilograms fall no more than a few kilometers from the vent, although in unusually large eruptions bombs may reach areas 10 kilometers or more away. Volcanic bombs are often hot, and may start fires. Because the area around Shishaldin Volcano is uninhabited, the risk from volcanic bombs is low except to humans and low-flying aircraft that might come near the volcano during an eruption.

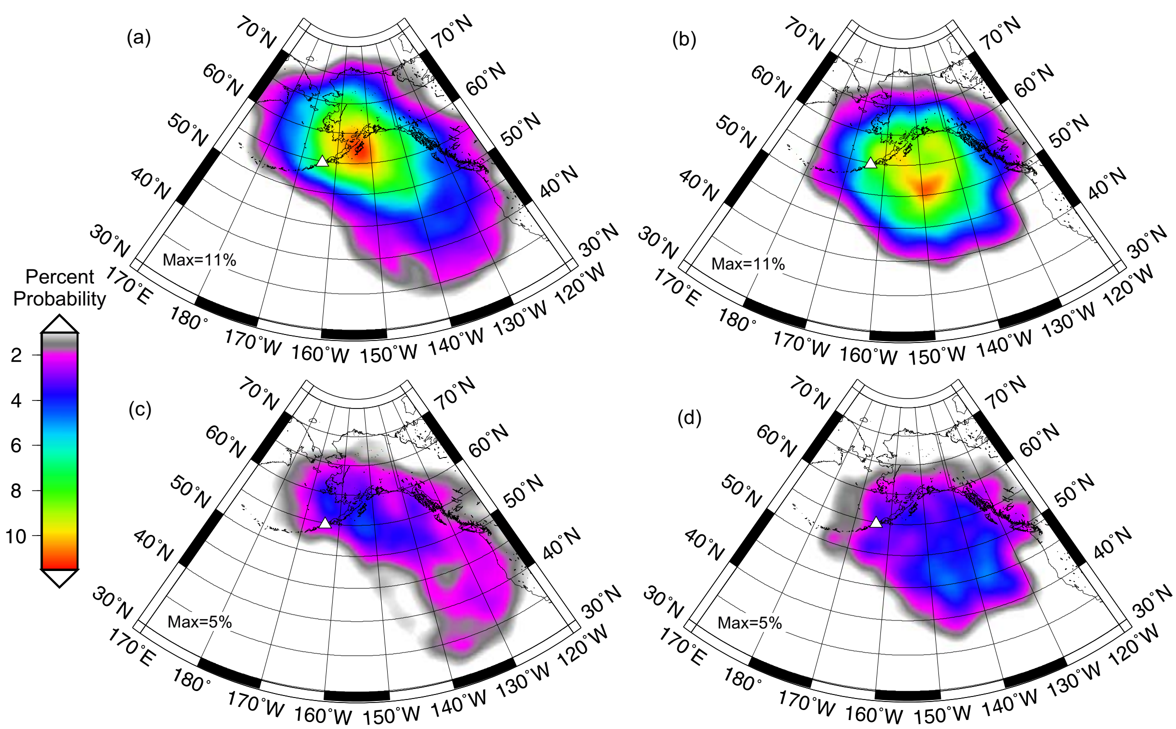

Figure 9. *Twenty-four hour airborne ash probability distribution (AAPD) maps for Shishaldin Volcano. The maps show the regions in the North Pacific most likely to contain airborne ash 24 hours after a hypothetical eruption from the volcano, in winter (October through April) and summer (May through September), both at a low altitude (3 to 8 kilometers above sea level) and at a higher altitude (8 to 12.5 kilometers above sea level). (a) low altitude winter, (b) low altitude summer, (c) high altitude winter, and (d) high altitude summer. Probabilities are based on average wind directions from National Weather Service archives and the PUFF ash dispersion model. Figure from Papp, 2002.*

Lahars and Floods

Vast quantities of glacier ice and snow, which may be melted during volcanic eruptions, can result in floods and volcanic debris flows or lahars. Lahars typically consist of fluid suspensions of boulders, sand, and silt that can travel 20 kilometers or more downvalley at speeds of 10 to 30 kilometers per hour. Lahar deposits have a consistency of wet concrete and can cover floodplains with deposits centimeters to meters thick.

The steep upper slopes of Shishaldin Volcano are mantled by glaciers, and floods and lahars have been produced repeatedly by the interaction of hot material with the glacier ice. During the 1999 eruption, a lahar that traveled more than 20 kilometers downvalley from the north side of the volcano almost reached the coast of the Bering Sea (fig. 12). On the north flank of the volcano, a deep trench was cut into a glacier, while the glacier surface on either side of the trench was swept clean of sediment. Several coeval(?) steep-fronted debris-flow deposits were observed on the uppermost parts of the volcanic cone adjacent to the flood pathway. These observations indicate that the lahar originated as a flood and was transformed into a lahar as it incorporated sediment high on the volcano. The lahar locally exceeded 20 meters in depth where it traveled through a narrow valley. This event deposited a layer of volcanic debris as much as 1.4 meters thick across an area of almost 10 square kilometers. The lahar spread out across a young volcanic fan composed of similar deposits from prehistoric eruptions.

Geologic studies show that floods and lahars from larger past eruptions have reached the coast both to the north and south of the volcano. The greatest hazards

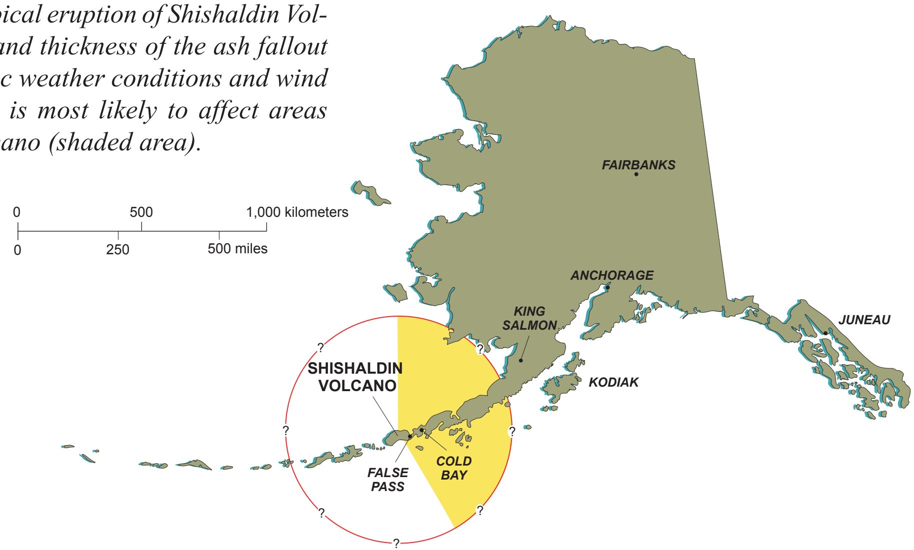

Figure 10. *This map shows areas that might be affected by ash fallout during a typical eruption of Shishaldin Volcano. The exact area and thickness of the ash fallout will depend on synoptic weather conditions and wind directions, but fallout is most likely to affect areas mainly east of the volcano (shaded area).*

Figure 11. *Tephra deposits produced during the 1999 eruptions covered the south flank of Shishaldin volcano to a depth of more than 50 centimeters on the upper flanks of the volcano, but rapidly thinned to only a few centimeters thickness. Note the scoria overlying the snow at the tops of the cliffs.*

Figure 12. *Lahar deposits from the 1999 eruption on the lower flanks of Shishaldin Volcano overtopped a fan of older flood and laharic debris, and reached almost to the shore of the Bering Sea north of the volcano.*

from such flows are in low-lying areas and valley bottoms, extending from the volcano to the ocean on both the north and south flanks. In general, hazards from lahars and floods will be greatest at lower elevations, and will be somewhat less at higher elevations. At the present time, all areas around Shishaldin Volcano, including fluvial channels and fans, are uninhabited and undeveloped.

Pyroclastic Flows and Surges

Pyroclastic flows are hot, dry mixtures of volcanic rock debris and gas that move like a fluid. They typically consist of coarse debris flowing in a basal zone with an accompanying dilute cloud of hot dust above. Pyroclastic flows can begin when masses of hot rock debris are explosively ejected onto the volcano's flanks, or when part of a growing volcanic dome collapses or explodes into rock fragments. The rock debris and intercalated hot gases in pyroclastic flows generally flow downslope under the force of gravity, but can overtop ridges and flow around obstructions. Pyroclastic surges are similar to the upper dust cloud of pyroclastic flows but typically have higher gas contents and are often generated by large volcanic explosions.

Pyroclastic flows and surges constitute an especially severe hazard to human life because of their speed, mobility, and high temperatures (Baxter and others, 1998). Pyroclastic flows and surges have temperatures as high as 700°C to 1,000°C and can travel at speeds of 50 to 150 kilometers per hour. The coarse basal zone of rock debris in pyroclastic flows can bury and incinerate people and buildings, while pyroclastic surges and the dilute clouds of hot ash that form the upper parts of pyroclastic flows can cause asphyxiation and burn skin, throat, and lungs. Also, high-velocity pyroclastic flows and surges can be very energetic, blasting down buildings and carrying sand-sized and larger rock fragments that may cause injury by impact or by their intense heat.

At Shishaldin Volcano, interactions between magma and glacier ice have produced phreatomagmatic explosions and pyroclastic surges on several occasions during the last 4,000 years. Maars and tuff cones on the flanks of the volcano have been additional sources of pyroclastic surges.

Because of their high velocity and mobility, pyroclastic flows and surges can affect areas at considerable distances from the volcano. Pyroclastic flows tend to spread out when they are not channeled down valleys, but when confined by steep valley walls, they might affect areas even further from the volcano. Based on geologic studies of the extent of prehistoric pyroclastic flow and surge deposits erupted from Shishaldin Volcano, nearly all areas within a distance of 10 kilometers from the summit could be affected by pyroclastic flows and surges (fig. 13).

Pyroclastic flows and surges can travel across water, as has been repeatedly observed during the volcanic eruptions that began in 1997 on the island of Montserrat in the Caribbean Sea. During the large caldera-forming eruption of Krakatau Volcano in 1883, pyroclastic flows caused casualties after traveling more than 40 kilometers over water (Carey and others, 1996). While an eruption of comparable size and magnitude seems unlikely to occur at Shishaldin Volcano in the near future, areas farther from the volcano could be at risk if explosive flank eruptions occurred, as has happened on several occasions in postglacial time. For this reason, the hazard zones for pyroclastic flows and surges surrounding Shishaldin Volcano are shown extending out into the Bering Sea on the north side of Unimak Island and into the North Pacific Ocean on the south (fig. 13).

Lava Flows

Shishaldin Volcano and its flank vents have produced lava flows numerous times since the end of the last ice age. Several fresh-appearing lava flows reach more than 18 kilometers from the volcano's north flank, and extend to the Pacific Ocean on the south flank. Shishaldin Volcano lava flows are primarily basaltic andesite to basaltic in composition and can be expected to move downslope at velocities of tens to hundreds of meters per hour. Lava eruptions at Shishaldin Volcano will almost certainly be limited to uninhabited parts of the island, and consequently such eruptions will pose little direct threat to property or people, save those who approach to observe the flow.

Volcanic Gases

Large volumes of volcanic gases, such as carbon dioxide, carbon monoxide, sulfur dioxide, and hydrogen sulfide, are emitted before, during, and immediately after eruptions. These gases can be poisonous in high concentrations, and even when diluted by mixing with air they can irritate the throat and lungs of people who come in contact with them. Hydrogen sulfide has an odor similar to rotten eggs, but carbon monoxide and carbon dioxide are colorless and odorless. Carbon dioxide, which is heavier than air, may collect in low-lying areas, causing suffocation of birds, animals, and humans.

Aerosols and microscopic droplets of sulfuric acid, hydrochloric acid, and hydrofluoric acid may form where volcanic gases interact with water in the atmosphere. Acidic precipitation may result from the mixing of a gas-rich volcanic plume with rain or snow. Clouds of volcanic aerosols or acid rain can cause skin and lung irritation, make plants inedible for local wildlife, and corrode paint, fabric, and metals.

The greatest hazards from volcanic gases and acidic aerosols during eruptions will occur within a few kilometers of active vents—an area that is unpopulated at Shishaldin Volcano. During dormant periods, volcanic gases may build to dangerous levels in low areas that are protected from the wind, such as the summit crater. The gases will be incorporated in steam plumes that intermittently form above the crater and may be carried

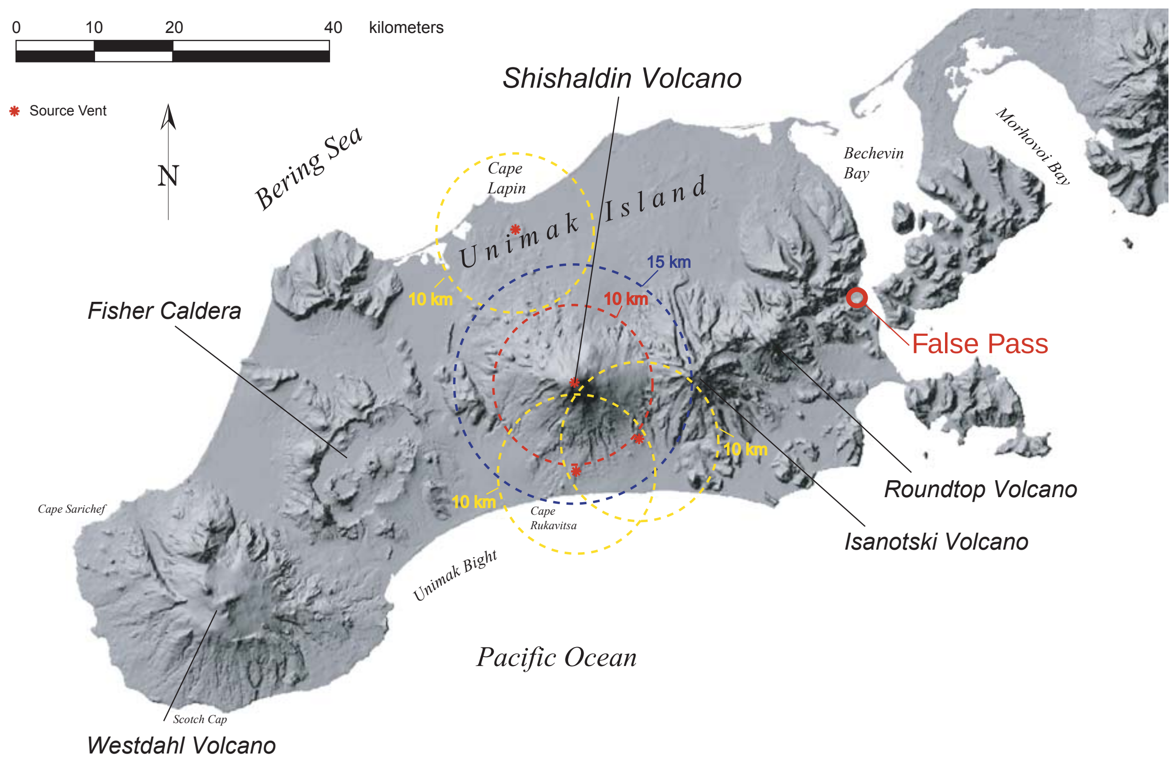

Figure 13. *Areas likely to be affected by pyroclastic flows during small to moderate future eruptions of Shishaldin Volcano are shown by the inner circle (red), while the maximum extent of pyroclastic flows and surges that might occur during a large eruption are shown by the outer circle (blue). Pyroclastic flows are produced only rarely at Shishaldin Volcano. Also, potential hazard zones are shown surrounding postglacial maars and a tuffcone on the flanks of Shishaldin Volcano (yellow). Future flank eruptions at these locations or at new vent sites may produce explosions, pyroclastic flows, and surges.*

by strong winds far downwind from the volcano. The smell of hydrogen sulfide may be noticeable at distances of 10 kilometers or more from the vent, but the gases present are unlikely to present a hazard to people for more than a few kilometers downwind.

Debris Avalanches

Volcanic debris avalanches are giant landslides that form by collapse of the upper parts of volcanoes. Debris avalanches can attain speeds of 30 to 150 kilometers per hour, and may travel 10 kilometers or more from the source volcano, burying everything they encounter beneath many meters of coarse volcanic debris. Volcanic debris avalanches generally occur during eruptions, as occurred during the 1980 eruption of Mount St. Helens in Washington State. More rarely, debris avalanches may occur during non-eruptive periods, especially where hydrothermal alteration associated with fumaroles has weakened the upper parts of a volcanic edifice (Siebert and others, 1995). Unusually large earthquakes that occur along the Aleutian subduction zone may trigger volcanic debris avalanches at volcanoes along the Aleutian arc (Begét and Kienle, 1992).

At Shishaldin Volcano, two thick debris avalanche deposits are present on the northwest and southwest flanks of the volcano. The southwesterly-directed deposit is more than 10,000 years old, has been largely buried by younger volcanic deposits, and is only visible over a small area. In contrast, the deposit on the northwest flank is about 9,500 years old, and forms the modern coastline near Cape Lapin, 25 kilometers from the volcano (figs. 14, 15). This large debris avalanche deposit appears to be similar in magnitude to the event at Mount St. Helens in 1980, although its maximum extent cannot be determined because its most distal parts lie below sea level. The modern summit of Shishaldin Volcano is constructed atop a bench, which appears to be the rim left by the summit collapse that produced the Cape Lapin debris avalanche (fig. 16).

Debris avalanches are uncommon events at Shishaldin Volcano, but still pose a significant hazard because they have the potential to completely obliterate and bury huge areas of the low-lying topography around the volcano (fig. 15). The regrowth of the present cone after the Cape Lapin event suggests that a large debris avalanche could occur in the future. At the present time, all areas around Shishaldin Volcano that might be affected are uninhabited and undeveloped, so only visitors to the area near the volcano would be at risk.

Directed Blasts

A directed blast is a laterally directed explosion caused by dome collapse or by a debris avalanche that uncovers and depressurizes hot magma within a volcano. Deposits from what may have been a directed blast were found associated with the early Holocene Cape Lapin debris avalanche that is exposed at the modern coastline 25 kilometers northwest of the volcano.

It is not possible to directly estimate the extent of any prehistoric directed blast at Shishaldin Volcano because rock and ash from the blast would have traveled north over the Bering Sea for some distance beyond the current coastline. The extent of the hazard from directed blasts at Shishaldin Volcano is therefore based on data from the 1980 eruption of Mount St. Helens Volcano (Moore and Sisson, 1981). This was one of the largest and best-known historical examples of a directed blast and thus provides a realistic model for this hazard.

If a directed blast were to occur at Shishaldin Volcano, it would most likely be associated with a flank collapse and debris avalanche. The blast would affect a broad area downslope from the avalanche scar, in an

Figure 14. *Deposits of the Cape Lapin debris avalanche are exposed along the coast of the Bering Sea at Cape Lapin, about 25 kilometers northwest of Shishaldin Volcano, where they form high sea cliffs that litter the beach with large boulders as they erode. The debris avalanche deposit extends an unknown distance farther to the north into the Bering Sea.*

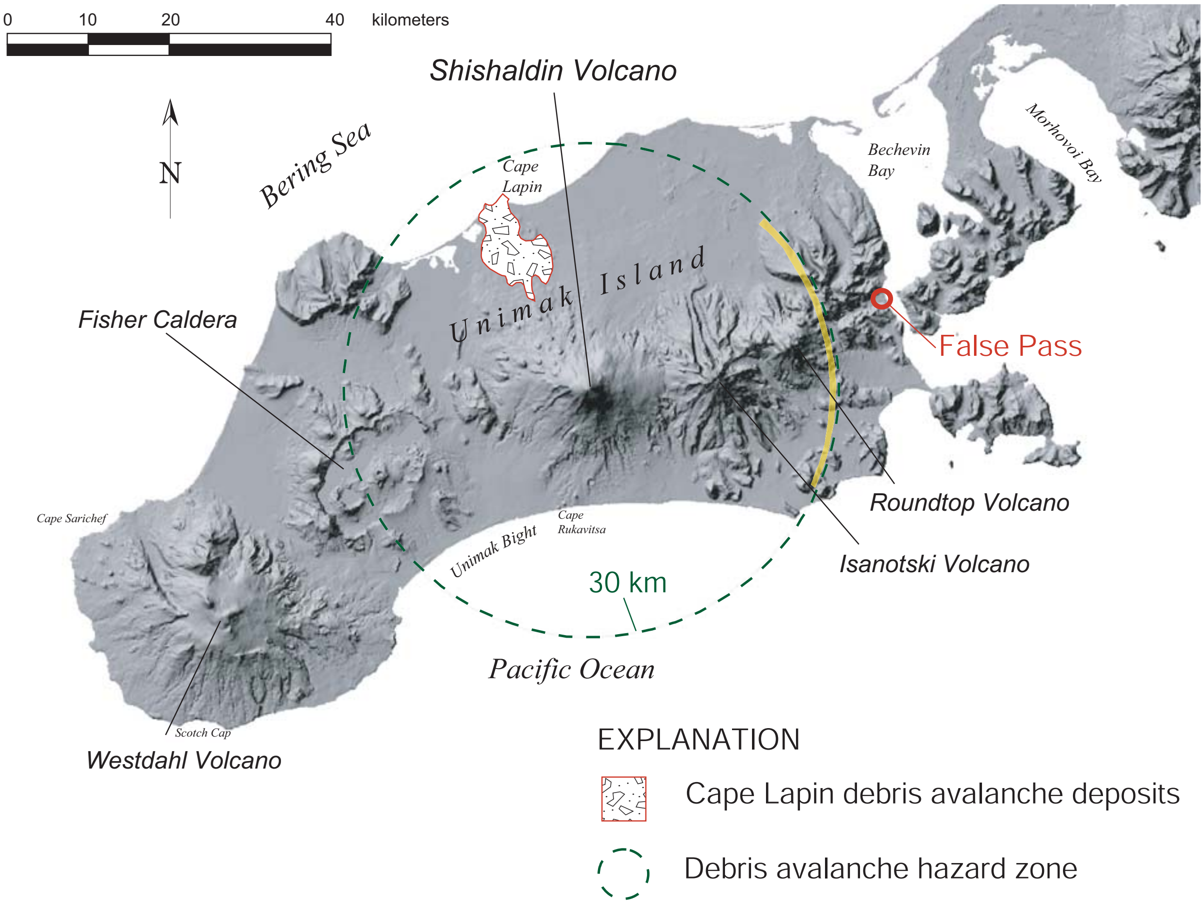

Figure 15. *Maximum likely travel distance of a future large debris avalanche at Shishaldin Volcano, based on the estimated extent of the prehistoric Cape Lapin debris avalanche and other debris avalanches of similar volume generated by volcanoes close to Shishaldin Volcano in size. Deposits from the Cape Lapin debris avalanche that are not covered by younger volcanic debris are shown. Areas east of the volcano (yellow) will be protected by the topographic barrier formed by Isanotski and Roundtop volcanoes.*

Figure 16. *Southwest side of Shishaldin Volcano, showing part of a truncated rim of older lavas buried by the modern volcanic cone. The buried rim appears to be part of a horseshoe-shaped crater rim that most likely formed as a consequence of the destruction of an ancestral Shishaldin cone by the Cape Lapin debris avalanche 9,500 years ago.*

arc that may exceed 180 degrees. The blast might extend about 30 kilometers from the volcano (fig. 17). A directed blast might occur with little warning during the first minutes of a large eruption that involves edifice collapse. The hot, energetic, explosive blast would potentially destroy everything in its path.

Volcanic Tsunamis

Numerous tsunamis, some among the largest and most devastating known in historical time, have been generated during eruptions at volcanoes located near the sea. Most volcanic tsunamis are generated by volcanic explosions or by the displacement of seawater by large masses of volcanic debris entering the ocean (Begét, 2000; Latter, 1991). Voluminous pyroclastic flows and debris avalanches that flow into the sea at high velocity have produced the largest tsunamis, while smaller waves were associated with lahars, lava flows, and surges.

Shishaldin Volcano lies near the center of Unimak Island, only 15 kilometers from the sea at the nearest point on its south flank, and from 22 to 25 kilometers on the north flank. It is possible that during an unusually large eruption, volcanic debris from Shishaldin Volcano could flow into the sea and generate a tsunami. The Cape Lapin debris avalanche that occurred 9,500 years ago, clearly traveled to the modern shore of the Bering Sea, and likely extended farther off shore. However, a flank collapse and debris avalanche of sufficient volume to reach the sea has occurred only once at Shishaldin Volcano during the last 10,000 years, which suggests that it is highly unlikely a hazardous tsunami will be generated in the near future. Nonetheless, because of the proximity of this high volcanic edifice to the sea and its history of debris avalanche formation, the possibility of a volcanic tsunami cannot be ruled out.

Phreatomagmatic Explosions

Contact between hot magma and water can produce violent explosions, the magnitude of which depends on the ratio and total volumes of water and magma involved. Energetic phreatomagmatic explosions can also generate pyroclastic surges (see above). Seismic monitoring of Shishaldin Volcano in January 2000 detected dozens of small explosive events near the summit crater that

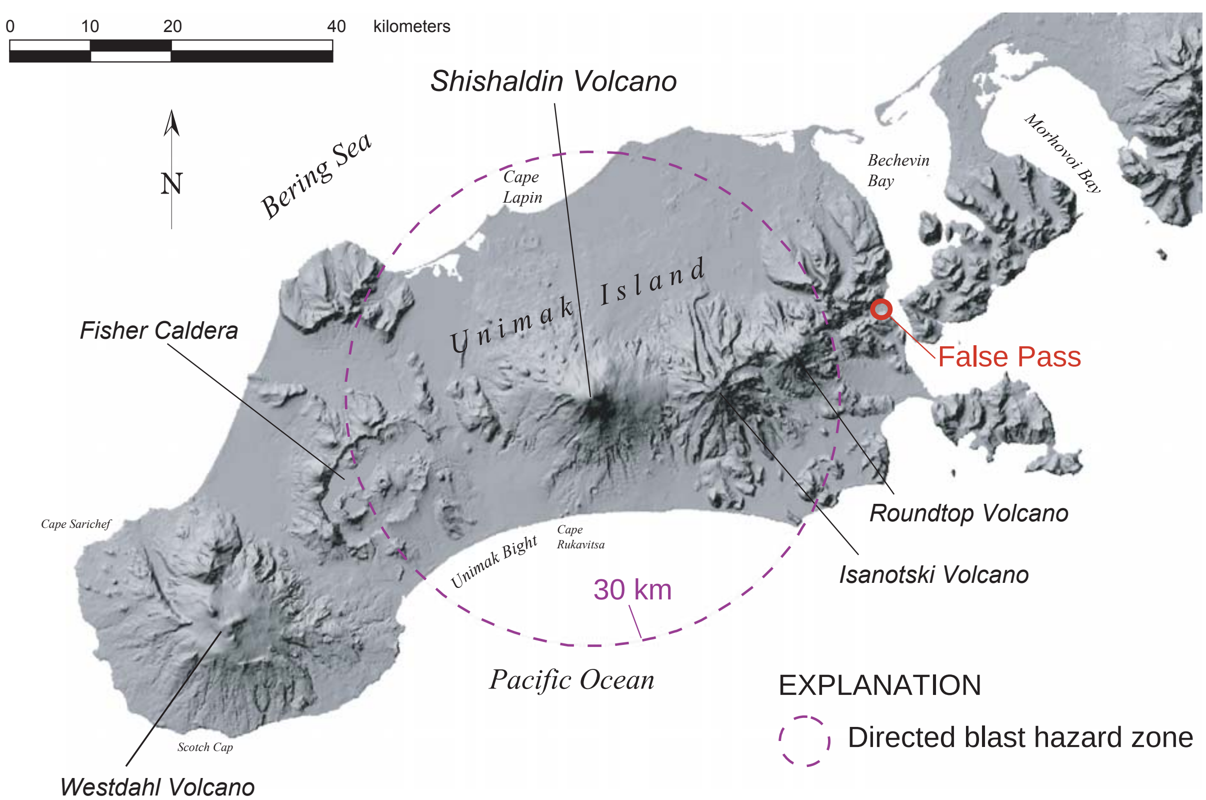

Figure 17. *Directed blast hazard zone at Shishaldin Volcano, assuming the maximum extent of a future blast is comparable to that seen at Mount St. Helens in 1980. Any blast associated with a debris avalanche is likely to be directed broadly in the same direction as the debris avalanche. The extent of hazard shown here is a "worst-case" scenario for a directed blast at Shishaldin Volcano.*

may have been phreatomagmatic in origin. The water source for these phreatomagmatic eruptions may have been from winter snowfall into the hot crater. Glaciers cover the steep upper flanks of Shishaldin Volcano, and provide a voluminous potential source of water for phreatomagmatic explosions. The interior of the steep-sided summit crater is ice-free, but large volumes of water evidently are transmitted through the volcanic edifice to the crater or hot central core of the cone. Intermittent steam clouds, which rise to elevations of 1,000 meters or more above the summit, have been observed throughout the recorded history of the volcano.

Future summit eruptions are likely to produce melting of snow and ice in the summit area and may be accompanied by phreatomagmatic explosions. In addition, lava erupted from fissures on the glacier-covered flanks of Shishaldin Volcano will likely come in contact with ice and meltwater and may result in phreatomagmatic explosions. Cinder cones and tuff cones that protrude through glacier ice at several sites around Shishaldin Volcano provide evidence of past lava–ice interaction.

Phreatomagmatic explosions also have occurred at vents on the lower flanks of Shishaldin Volcano. Two large maar craters, each more than 1,000 meters in diameter, are aligned along a northeasterly-trending fault on the south side of the volcano (fig. 18). These craters were formed as a result of prehistoric phreatomagmatic eruptions during which explosive interactions of magma and groundwater occurred. A large tuff cone almost at sea level near Cape Lapin on the north side of the volcano records phreatomagmatic explosions that occurred almost 20 kilometers from the summit. A second, much smaller tuff cone is present in the saddle between Shishaldin Volcano and Fisher Caldera.

Phreatomagmatic explosions may accompany any future eruption of Shishaldin Volcano. Also, any eruptions on the lower flanks of the volcano in areas where magma comes into contact with groundwater will likely be characterized by repeated phreatomagmatic explosions, ejection of bombs and blocks, and the generation of pyroclastic surges. The frequency of phreatomagmatic explosive eruptions on the lower flanks of the volcano is apparently much lower than the eruption frequency of Shishaldin Volcano itself. Phreatomagmatic eruptions from flank vents on the lower parts of Shishaldin Volcano may last months to a few years and result in the creation of a new maar or tuff cone. Phreatomagmatic explosions are quite dangerous. Falling ballistic ejecta may create a hazard within a few kilometers of the vent, and pyroclastic surges may affect areas 5 to 10 kilometers from the vent.

ERUPTION FREQUENCY AND VOLCANIC RISK AT SHISHALDIN VOLCANO

Evaluations of volcanic hazards require understanding of both the magnitude and style of a potential future eruption, and the likelihood of its occurrence. At Shishaldin Volcano, like most other volcanoes, it is clear that small eruptions occur much more frequently than larger eruptions, but because the historical record is of very short duration, the precise frequency of various types of events is not well known. Also, the historical

Figure 18. *A maar crater blasted deep into older rocks on the southern flank of Shishaldin Volcano by hydromagmatic explosions accompanied by pyroclastic surges and pyroclastic flows.*

record does not include examples of several types of eruptions that are evident in the prehistoric geologic record. To better evaluate the volcanic risk and improve our understanding of the complex relationships between eruption size and probability, we have combined geologic evidence of volcanic behavior at Shishaldin Volcano during the last 9,500 years with the historical data from the last 230 years.

Risks from future eruptions at Shishaldin Volcano fall into three broad categories. First, there are hazards associated with eruptions that are similar in magnitude and style to those seen during the last few hundred years. Such eruptions are relatively small and are likely to occur several times during the next century. Second, there are hazards associated with eruptions that are similar in style to those seen during the last few hundred years, but are somewhat larger and occur less frequently. Finally, we discuss hazards associated with very large eruptions that might resemble the largest known prehistoric event at Shishaldin Volcano about 9,500 years ago.

If Shishaldin Volcano behaves in the near future as it has during the recent past, several eruptions are likely to occur during the 21st century. The primary volcanic hazard during typical eruptions will be from volcanic ash clouds that may drift downwind over False Pass on Unimak Island, over the Alaska Peninsula, and over other parts of Alaska and the North Pacific Ocean. Such ash clouds may interfere with operations of nearby airports at Dutch Harbor and Cold Bay, and may also affect the flight plans of the numerous commercial and passenger jet flights that move daily across the North Pacific between Asia, Europe, and North America. Ash raining out from the tephra clouds could accumulate to thicknesses of a few centimeters in False Pass, the only town on Unimak Island, and to lesser thicknesses at Dutch Harbor and Cold Bay. Such ashfalls may briefly affect air quality, highway travel, and commercial and governmental activities such as the operation of generators or telecommunications equipment.

Thirty-nine eruptive episodes have been recorded at Shishaldin Volcano in the last 230 years (table 1). Most of these eruptions were relatively small, although a few were described as major explosive eruptions, accompanied by lava flows, lahars, steam, and ash. If eruptions occur in the near future at a similar rate, then six to seven eruptions might be expected during the coming century. Most such eruptions are likely to be similar to or smaller in magnitude than the 1999 eruption. They are likely to produce floods, lahars, and perhaps small pyroclastic surges and pyroclastic flows that would be restricted to uninhabited parts of Unimak Island near Shishaldin Volcano.

It is more difficult to evaluate the frequency and risk from larger eruptions, but if the volcano continues to erupt with similar frequencies to those it has maintained since the end of the last ice age, it is possible that an eruption larger than any seen during the 20th century will occur sometime during the 21st century. Geologic field studies show that eruptions larger than any historical event occurred at least 13 times in the last 9,500 years. Such eruptions produced thicker tephra deposits than did any of the historical eruptions, and generated floods and lahars that were more extensive than those of the 1999 eruption. Such eruptions may have lasted longer than historical eruption cycles, and appear to have culminated in explosive eruptions that generated voluminous ash clouds. Such large eruptions might deposit 1 centimeter or more of ash in the towns of Cold Bay or Dutch Harbor and Unalaska. The effects of lava flows, floods, lahars, and coeval pyroclastic flows and surges would be restricted mainly to the uninhabited parts of Unimak Island, although some pyroclastic flows might travel to the shoreline and short distances over the ocean. Floods and lahars could be larger than any seen in the 20th century, and might result in significant sedimentation in river valleys and flood plains around the volcano, as well as prolonged sediment discharge into the waters around Unimak Island.

There is a very small likelihood that a very large eruption might occur in the near future at Shishaldin Volcano. The largest known prehistoric event was the summit collapse that occurred 9,500 years ago. A future eruption of similar magnitude might have serious consequences. A debris avalanche similar in size to that preserved at Cape Lapin could travel as far as 25 to 30 kilometers from the volcano, deeply burying everything in its path. A northward directed debris avalanche might flow into the Bering Sea, while a southward directed avalanche would enter the north Pacific. Large debris avalanches that enter the sea displace ocean water and can sometimes generate destructive tsunamis. The height of the tsunami wave would depend on the velocity and volume of debris entering the ocean, as well as on the bathymetry of the sea floor (Begét, 2000). Tsunamis generated in this fashion at other volcanoes have had initial heights of 5 to 10 meters. Such waves attenuate as they travel away from the debris avalanche but can be locally refocused where they enter bays and run up on shore. Volcanic tsunami waves can cause damage in coastal areas and result in fatalities at distances of 100 kilometers or more away from the source volcano.

There is also a small likelihood that a voluminous pyroclastic flow or large lateral blast might be produced by a very large eruption at Shishaldin Volcano. If a lateral blast or pyroclastic flow were produced coevally with a debris avalanche, it would likely be directed in the same general direction as the debris avalanche. Energetic lateral blasts and pyroclastic flows can destroy areas 25 kilometers or more from the volcano, and could travel across the sea and endanger boats near the shoreline around the volcano. The village of False Pass at the eastern end of Unimak Island is near the approximate travel limit of a lateral blast or very energetic pyroclastic flow from Shishaldin Volcano. However, this village is topographically shielded by Isanotski and Roundtop volcanoes (fig. 2), and therefore is unlikely to be in danger even during a large eruption.

Very large explosive eruptions at Shishaldin volcano could generate ash clouds much more voluminous than any seen in historical time. These ash clouds could result in ash accumulation of 5 to 10 centimeters or more in False Pass and nearby communities. The explosive eruptions might be sustained for a long period of time, and ash clouds might disrupt air travel across the North Pacific for days to weeks.

PRECURSORY ACTIVITY, VOLCANO MONITORING, AND HAZARD MITIGATION

The Alaska Volcano Observatory (AVO) was established in 1988 to evaluate volcano hazards in Alaska, and to issue warnings of imminent volcanic eruptions (Eichelberger and others, 1995). The AVO is a joint facility of the U.S. Geological Survey, the Geophysical Institute of the University of Alaska Fairbanks, and the Division of Geological & Geophysical Surveys of the State of Alaska. In many cases volcanic eruptions are preceded for a period of days to months by earthquakes and by satellite-detected thermal anomalies. These phenomena can provide advance warning of future eruptions. The AVO monitors Shishaldin Volcano with a real-time seismic network (fig. 19) that can automatically signal increases in frequency and magnitude of seismic activity (earthquakes) that typically precede eruptions. Radio-telemetry connects the seismometers around Shishaldin Volcano with relay points in Cold Bay that send the signal on to AVO laboratories in Fairbanks and Anchorage. The seismic network was in place during the 1999 eruption of Shishaldin Volcano, and the

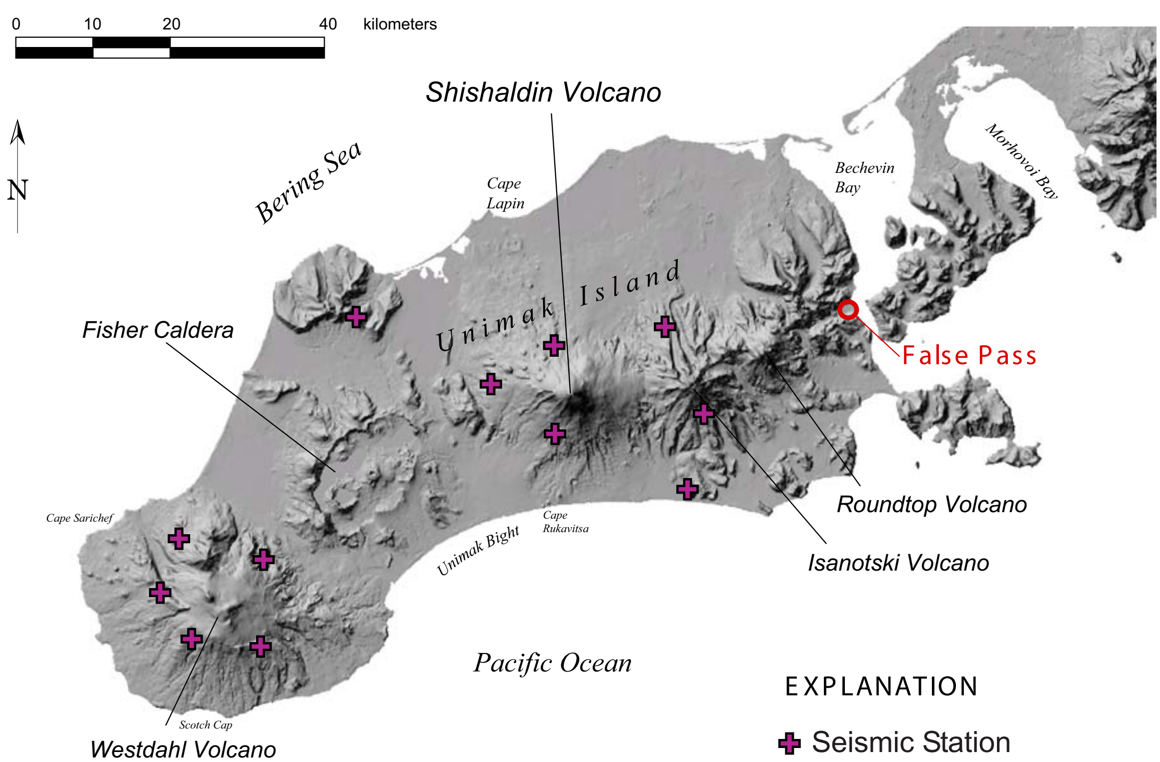

Figure 19. *Location of seismic stations around Shishaldin Volcano. This network is designed to detect small earthquakes beneath the volcano that may signal the onset of a volcanic eruption.*

AVO staff recognized the likelihood of an upcoming eruption several hours before the eruption actually began. Daily observations of satellite imagery allow AVO scientists to detect thermal anomalies and the presence of ash in the atmosphere. The AVO staff is very experienced in recognizing precursory seismic activity and satellite-detected ash and thermal anomalies, and will likely be able to provide warning of future eruptions of Shishaldin Volcano.

Other monitoring techniques may be utilized to better predict the timing and magnitude of a potential eruption. Satellite observations, measurement of changes in volcanic gas flux, remote observation using video cameras or time-lapse cameras, and geodetic surveying using laser theodolites and global positioning satellites have all been successfully applied by AVO scientists to help monitor volcanic unrest and predict eruptions at other Alaska volcanoes.

The AVO posts on its web page (www.avo.alaska.edu), and distributes by fax and e-mail, a weekly newsletter reporting the status of the 24 monitored volcanoes in Alaska, including Shishaldin Volcano. During periods of precursory activity or eruption the AVO frequently updates its reports to keep other government agencies and the public informed about the situation. Copies of the report are sent directly to the Federal Aviation Administration, the National Weather Service, local U.S. military bases and airports, the Governor's office of the State of Alaska, the Alaska Division of Emergency Services, airports and air carriers, and municipal and other civil authorities in the areas around the volcano. Updates are also sent to television and radio stations, newspapers, and newswire services for dissemination to the general public.

The AVO uses a color code system to summarize the status of volcanoes in Alaska (Brantley, 1990). The color code quickly and simply summarizes the level of activity and concern for each monitored volcano (fig. 20). During a volcanic crisis the AVO staff will use the color code to quickly communicate changes in volcanic activity to government agencies, whose staff can then make decisions about governmental response to eruptions.

Although the area around Shishaldin Volcano is currently uninhabited, recreational users including naturalists, fishermen, and mountain climbers regularly visit the area. Volcanologists, biologists, geologists, and other government scientists and land managers sometimes

LEVEL OF CONCERN COLOR CODE

GREEN:	**Volcano is in its normal "dormant" state.**
YELLOW:	**Volcano is restless.** *Seismic activity is elevated. Potential for eruptive activity is increased. A plume of gas and steam may rise several thousand feet above the volcano which may contain minor amounts of ash.*
ORANGE:	**Small ash eruption expected or confirmed.** *Plume(s) not likely to rise above 7,620 meters (25,000 feet) above sea level. Seismic disturbance recorded on local seismic stations, but not recorded at more distant locations.*
RED:	**Large ash eruptions expected or confirmed.** *Plume(s) likely to rise above 7,620 meters (25,000 feet) above sea level. Strong seismic signal recorded on all local and commonly on more distant stations.*

Figure 20. *Alaska Volcano Observatory level-of-concern color code. Color codes are updated based on changing conditions, and are used to quickly indicate the status of Shishaldin Volcano and other Alaska volcanoes. The current code and written explanations and updates are distributed to government agencies, the media, airlines, and the public, and are posted on the AVO web page (http://www.avo.alaska.edu).*

work in the area. A group of archeologists have spent several weeks during the past few summers excavating a site at the coast near Shishaldin Volcano.

If possible, visitors to Shishaldin Volcano should be aware of the possibility of renewed volcanic activity, and should check the latest level-of-concern code released by AVO before making an extended visit to the volcano. If volcanic activity begins suddenly while people are on the volcano or its flanks, they should be aware that low-lying areas along streams that originate on the volcano are at the greatest risk from pyroclastic flows, surges, lahars, and floods. During a small- to moderate-size eruption a risk to human life may quickly develop without warning in areas closer than about 10 to 15 kilometers from the volcano, and access to these areas may be restricted. Planes and helicopters may also be at risk due to dangers from ballistic projectiles and falling ash.

At greater distances from Shishaldin Volcano there is likely to be some warning time to prepare for the effects of an eruption. Interruptions in communications, electrical service, heat, surface transport, and air travel may occur. People (especially children and those with respiratory problems) may be restricted from going outdoors during ashfalls. If the volcanic emergency becomes very severe, evacuation and closure of some areas may be necessary.

This report is an outline of the potential hazards associated with future eruptions of Shishaldin Volcano. It is designed to provide useful information for both government agencies and private individuals and parties. However, in the event of an eruption, scientists of the Alaska Volcano Observatory will be available for detailed discussions of the actual events and developments occurring at the volcano.

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GLOSSARY

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.

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

Cinder cone. A conical hill formed by the accumulation of cinders and other pyroclastic debris around a volcanic vent.

Cinders. Glassy, vesicular, volcanic fragments, ranging in size from 4 to 32 millimeters, that fall to the ground in a solid condition.

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 part of the volcano may become unstable, break away from the volcanic massif, and become an avalanche. Debris avalanches, which may be triggered by an eruption or earthquake, 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. They may be quite voluminous (greater than 10 cubic kilometers) and 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 that results in a rapid drop in the pressure of the intruding magma near the surface of the volcanic edifice. The 1980 eruption of Mount St. Helens was triggered by a massive slope failure and the subsequent laterally directed blast affected a 180-degree 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.

Edifice. The upper part of the volcanic cone, including the vent and summit areas.

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

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

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

Fumarole. Small, vent-like crack or opening with escaping gas and steam.

Holocene epoch. The period of earth history from 10,000 years before present (B.P.) to the present.

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, delivering 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 greater than 750,000 parts per million are not uncommon. Large-volume lahars can travel great distances if they have 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 as far as 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.

Maar. A low-relief broad volcanic crater formed by a shallow explosive eruption. It may contain a lake.

Magma. Molten rock beneath the earth's surface.

Pleistocene epoch. The period of earth history between 1.8 million and 10,000 years before present.

Pumice. Highly vesicular volcanic ejecta; because of 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°C 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 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.

Scoria. Coarsely vesicular pyroclastic rock that is heavier and darker than pumice.

Sulfurous. Sulfur-bearing or rich in sulfur compounds.

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. 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 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.

Tuff cone. A volcanic crater formed by a shallow explosive eruption in an area where surface water is located above the vent. Tuff cones have bedding angles of 20–25° near the rim crests.

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

Vesicular. Characterized by or containing vesicles. Vesicles are small cavities in a glassy igneous rock, formed by the expansion of a bubble of gas or steam as a rock cools and hardens.

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