Alaska Department of Natural Resources
Division of Geological & Geophysical Surveys

Preliminary volcano-hazard assessment for Makushin Volcano, Alaska

Report of Investigations 2000-4

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Preliminary Volcano-Hazard Assessment for Makushin Volcano, Alaska

by J.E. Begét[1], C.J. Nye[1,2], and K.W. Bean[1]

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This DGGS Report of Investigations is a final report of scientific research. It has received technical review and may be cited as an agency publication.

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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.

TABLE

PRELIMINARY VOLCANO-HAZARD ASSESSMENT FOR MAKUSHIN VOLCANO, ALASKA

by J.E. Begét, C.J. Nye, and K.W. Bean

SUMMARY OF HAZARDS AT MAKUSHIN VOLCANO

Makushin Volcano is a 2,036-meter-high stratovolcano on Unalaska Island. The volcano is located 28 kilometers west of the towns of Dutch Harbor and Unalaska, the largest population centers in the Aleutian Islands and the principal fishing, shipping, and air-transportation hub for westernmost Alaska. Explosive eruptions of Makushin Volcano have occurred at least 17 times since the late 1700s, when written records began. These historic eruptions have been relatively small, sending ash 3 to 10 kilometers above the volcano summit and depositing ash mainly on the flanks of the volcano. Geologic studies show that larger explosive eruptions occurred more than two dozen times during the last several thousand years, generating more widespread ash layers. In addition, a series of very large eruptions about 8,800 to 8,000 years ago produced a 4-kilometer-diameter crater at the summit of the volcano and generated not only numerous pyroclastic flows and surges that traveled down valleys to the sea on the east, west, and north flanks of the volcano, but a debris avalanche and lateral blast that entered the sea on the north flank of Makushin Volcano.

If future eruptions are similar in size to those of the last few hundred to few thousand years, the most likely volcanic hazard would be plumes of volcanic ash that could extend several kilometers to 10 kilometers or more into the atmosphere. Such ash plumes would constitute a hazard both to aircraft landing at the Dutch Harbor airport and to passenger and cargo jets that fly over the eastern Aleutian Islands and northern Pacific Ocean on long-distance international air routes. Currently, as many as a hundred flights a day cross above or near Makushin Volcano. Ashfall from future eruptions could also disrupt airport operations, shipping, fishing, and other commercial activities at Dutch Harbor. Such eruptions might be accompanied by floods, mudflows, and small pyroclastic flows and surges that would be dangerous for humans and property within about 10 kilometers of the volcano, particularly in low-lying areas.

If eruptions as large as those of 8,000 years ago were to occur, volcanic ash falls would be much thicker and more extensive than any seen in the area in historic time, and highly mobile pyroclastic flows, surges, or lateral blasts might affect areas tens of kilometers from the volcano, including the towns of Dutch Harbor and Unalaska. Such huge eruptions could also significantly disrupt air travel over the north Pacific area for days and perhaps weeks. However, based on the volcano’s pattern of past behavior, eruptions of this magnitude are very rare, and therefore unlikely to recur in the near future.

The Alaska Volcano Observatory (AVO) currently operates a seismic monitoring network at Makushin Volcano, and is likely to detect signs of precursory volcanic unrest before the next eruption. Volcanic hazards to life and property around the volcano can be mitigated through public awareness and planning. Future volcanic hazards at Makushin Volcano, ranked by their likelihood of occurrence and importance, are itemized below and shown on sheet 1.

Volcanic ash clouds

When clouds of volcanic ash, lithic debris, pumice and gas are erupted high into the atmosphere, they drift away from the volcano with the wind. Ash clouds produced during eruptions can reach heights of 20 kilometers or more above the volcano, although most recent eruptions of Makushin have been smaller. Ash clouds are a hazard to passenger and cargo aircraft because jet engines may fail after ingesting volcanic ash. Ash clouds from recent eruptions of other Alaskan volcanoes have repeatedly interfered with air travel over parts of the North Pacific Ocean and mainland Alaska, and more rarely as far as Canada and the continental United States.

Volcanic ash fallout

Volcanic ash has been repeatedly erupted from Makushin Volcano during the last several hundred to thousand years, sometimes affecting inhabited parts of Unalaska Island. Ash from large prehistoric eruptions is as much as several meters thick near the volcano, and tens of centimeters thick in the community of Unalaska, 28 kilometers to the east. Even 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 ash falls may collapse roofs.

Lahars and floods

Eruptions through the ice-filled summit crater of Makushin Volcano may melt large volumes of ice and produce large floods of water and volcanic debris from the summit area. Hot volcanic debris may also interact with snow and glacier ice on the flanks of the volcano, forming fast-moving slurries of water, mud, rocks, and sand, called lahars. Lahars may also occur when thick deposits of proximal ash are rapidly eroded by heavy rainfall following eruptions. Volcanic mudflows or lahars tend to follow streams and valleys. Lahars and floods may affect areas along all streams draining Makushin Volcano during eruptions.

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

Pyroclastic flows and surges

Hot material erupted from the volcano may travel rapidly down slopes as incandescent flows of volcanic debris called pyroclastic flows and surges. Pyroclastic flows similar to those of the last few thousand years would pose a significant hazard to people within 10 to 15 kilometers of the volcano. Such flows would most likely not reach the coast except on the north flank. If very large eruptions similar to those of the caldera-forming eruptions 8,000 years ago were to occur, they might produce pyroclastic flows and surges capable of traveling 30 kilometers or more from the volcano.

Debris avalanches

A debris avalanche is a rapidly moving mass of rock debris produced by a large-scale landslide from the summit areas of a volcano. Several prehistoric debris avalanches occurred at Makushin Volcano, two of which reached the sea. The direct hazard from debris avalanches is limited to the volcano's flanks and to valleys draining Makushin Volcano for distances of 10 to 15 kilometers from the volcano.

Directed blasts

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 by a sector collapse of the summit edifice, both of which result in a debris avalanche. Directed blasts are rare at active volcanoes, and there is evidence for only one prehistoric directed blast at Makushin Volcano, associated with a debris avalanche on its north side about 8,600 years ago. Directed blasts can cause destruction to distances of about 30 kilometers from the volcano.

Volcanic gases

Some volcanoes emit gases in concentrations that are harmful to humans. A small lake-filled crater and groups of fumaroles currently active at the summit of Makushin Volcano emit gases, including hydrogen sulfide, that can sometimes be smelled at considerable distances from the volcano. Future eruptions may increase the amount of such gases emitted at the volcano. Dangerous invisible, odorless volcanic gases may collect in low-lying areas at the summit, making it inadvisable to descend into craters, caves, or fissures occupied by fumaroles at the summit, or to approach fumaroles associated with active lava flows and domes. Such gases are unlikely to present any hazard to currently populated areas on Unalaska Island.

Lava flows

Flows of molten rock (lava) may erupt in the future at the summit or from flank vents around Makushin Volcano. These flows will probably move slowly, at rates of only a few meters to tens of meters per hour, and pose little hazard to humans. These flows may develop steep, blocky fronts, and avalanching of blocks from the flow could be hazardous to someone close to an active lava flow front. Lava flows may reach the sea, particularly on the north side of the island.

Volcanic tsunamis

Large debris avalanches or pyroclastic flows that travel into the sea may initiate volcanic tsunamis by rapidly displacing water. A volcanic tsunami from Makushin Volcano would pose a risk to low-lying coastal areas around the shores of Unalaska Island and might affect coastal areas of nearby islands. No geologic evidence was found for prehistoric tsunamis, but several debris avalanches and pyroclastic flows from Makushin Volcano have reached the sea in the past.

SUGGESTIONS FOR READING THIS REPORT

Readers who want a brief overview of the hazards at Makushin 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 Makushin Volcano. A glossary of geologic terms is included and additional information about Makushin Volcano may be obtained by consulting the references cited at the end of this report.

INTRODUCTION

Makushin Volcano is part of the Aleutian volcanic arc, a chain of at least 40 historically active volcanoes extending from the far western end of the Aleutian Islands to volcanoes of the Cook Inlet area in south-central Alaska (fig. 1). Eruptions typically occur every year from one or more volcanoes in the Aleutian arc. Over the last several hundred years, Makushin Volcano has been one of the more active volcanoes in the Aleutian arc (Miller and others, 1998). It occupies a large, unnamed peninsula on the north side of Unalaska Island and is separated from the towns of Dutch Harbor and Unalaska by the waters of 10-kilometer-wide Unalaska Bay (fig. 2). Unalaska Island was occupied by large numbers of U.S. Army troops during World War II, who built and then abandoned roads, airstrips, and buildings around Makushin Volcano. The area around the volcano is uninhabited today, and only a few mountain climbers, geologists, fishermen, and hunters visit the volcano each year. Mineral and geothermal exploration has recently occurred along the Makushin Valley on the east side of the volcano, and mining or development of geothermal steam resources may occur in these areas in the future.

On clear days Makushin Volcano can be seen from the towns of Dutch Harbor and Unalaska, the major population, commerce and transportation hubs of the Aleutian Islands, 28 kilometers to the east. The combined population of the two communities is over 4,000, and can exceed 10,000 during the commercial fishing season, making this one of the few localities in the Aleutian arc where thousands of people live and work near an active volcano. Typical eruptions of Makushin Volcano during the last few hundred years have been explosive, producing ash clouds that in some cases rose to 10 kilometers or more above sea level. Eruptions of similar ash clouds from Makushin Volcano in the near future would be hazardous to aircraft flying to the airport at Dutch Harbor, as well as to passenger and cargo jets from Asia, Europe, and North America flying heavily used air routes across the North Pacific Ocean. Several historic eruptions of Makushin Volcano, including a relatively large eruption in 1826, produced ash that fell on Dutch Harbor and Unalaska.

The prehistoric volcanic deposits of Makushin Volcano were first studied and mapped by geologists in the aftermath of World War II (Drewes and others, 1961). Part of the volcano was remapped in detail in the early 1980s as part of a geothermal exploration program (Nye and others, 1984). A detailed map of the entire volcano was recently produced following field studies and laboratory and geochronologic work by personnel of the Alaska Volcano Observatory (McConnell and others, 1997; Bean, 1999). This hazards appraisal is largely based on the results of these recent studies and provides the first comprehensive report on the volcanic hazards that may result from future eruptions of Makushin Volcano. Hazardous volcanic phenomena that occur near the volcano, as well as the distal effects of eruptions, are described. The present status of monitoring efforts to detect volcanic earthquakes and the procedure for eruption notification and dissemination of information are

Figure 1. *Location of Makushin Volcano with respect to other volcanoes in the eastern Aleutian Islands of Alaska. All these volcanoes have erupted in the last 400 years and should be considered active and capable of erupting again.*

also discussed. The report, which includes maps and illustrations that indicate potential hazard zones, concludes with a glossary of volcanic and geologic terms.

PHYSICAL SETTING OF MAKUSHIN VOLCANO AND THE HISTORICAL RECORD OF VOLCANIC ERUPTIONS

Makushin Volcano is a 2,036-meter-high active stratovolcano situated on the north side of Unalaska Island in the eastern Aleutian Islands (figs. 1, 2). The summit of the volcano is a broad, flat, ice-filled caldera about 4 kilometers across (fig. 3). Multiple valley glaciers descend from the summit caldera to elevations of 300 to 600 meters above sea level on all sides of the volcano, and together with the summit icefield cover about 40 square kilometers. An assemblage of pyroclastic-flow deposits as much as 100 meters thick produced during caldera-forming eruptions fills valleys on the east, northeast, north, and west of the volcano. Surge deposits are found both in valley bottoms and mantling ridges and slopes surrounding the volcano. Young, uneroded lava flows, debris-avalanche deposits, and lahar and flood deposits are also found in valley bottoms around the volcano.

Small maars and cinder cones are aligned along a fault on the north side of the volcano. An extensive lava flow, known as the Lava Ramp, covers more than 50 square kilometers on the northeast flank of the volcano, and a large, subsidiary cone (Pakushin Cone) is present on the south. Hot springs and fumaroles are found at the summit and in valleys on the east and southeast sides of the volcano. Numerous cinder cones and lava flows are mapped at distances of up to 20 kilometers around the volcano, particularly on the northeast flank (McConnell and others, 1997).

Makushin Volcano has undergone at least 17 explosive eruptive episodes since the 1700s, when Russian explorers and traders first began keeping written records of events in the Aleutians (Miller and others, 1998). All these were small eruptions, producing only minor ashfall at Unalaska, with the largest recorded in 1826 (table 1). There were probably additional smaller eruptions during this period that were not recorded, either because

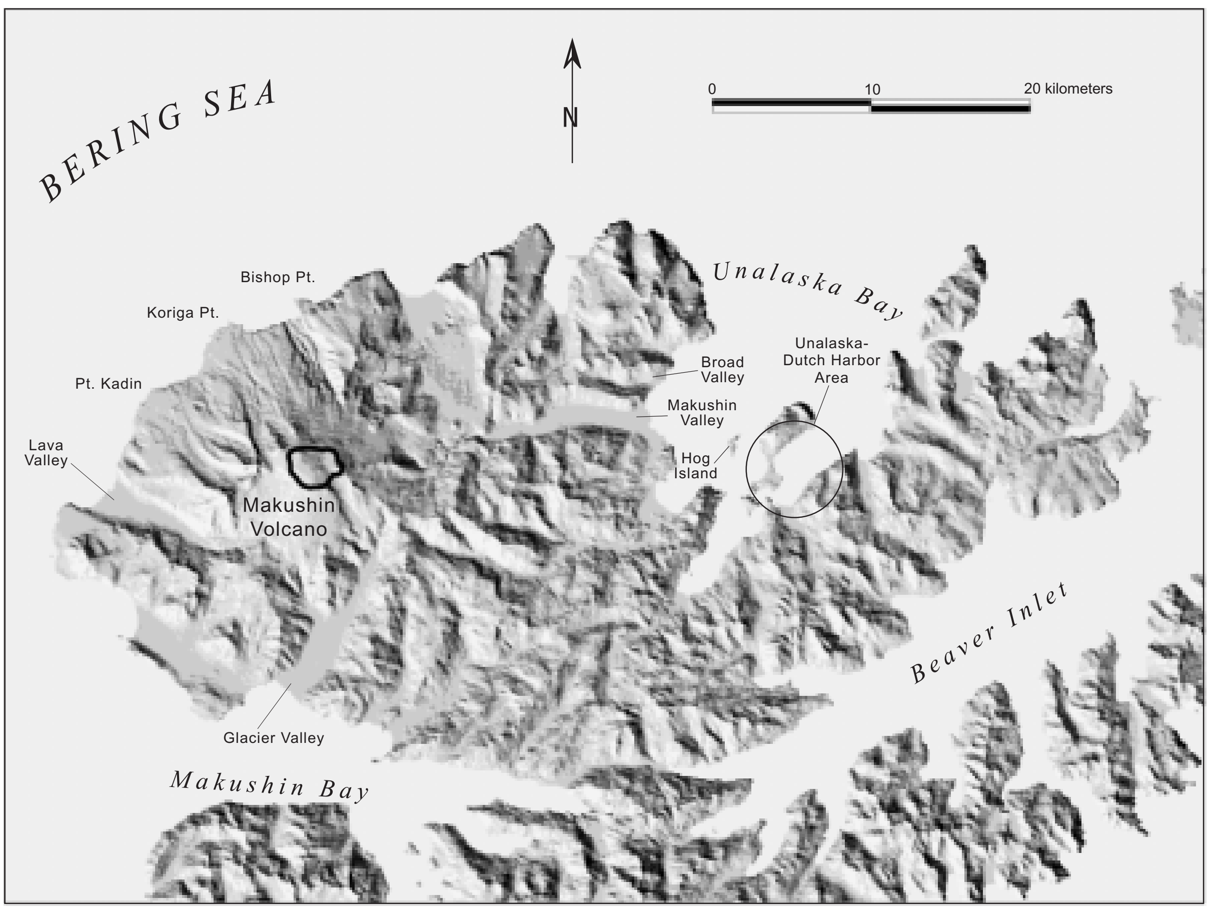


Figure 2. *Location of Makushin Volcano on Unalaska Island. Also shown are the locations of Unalaska and Dutch Harbor, the largest towns in the Aleutian Islands.*

Figure 3. *Oblique photo of the north flank of Makushin Volcano. The flat top of the volcano reflects collapse of part of the summit into a northward-directed debris avalanche about 8,400 years ago, and then further collapse during large caldera-forming eruptions 8,100 to 8,000 years ago. Deep valleys and gullies on the lower flanks of the volcano cut though volcanic ash and pyroclastic flow deposits produced during the caldera-forming event.*

Table 1. *Historic eruptions of Makushin Volcano (Coats, 1950; Powers, 1958; Smithsonian Institution, 1980; Global Volcanism Network, 1995; Miller and others, 1998; Bean, 1999)*

Eruption Date	**Volcanic Activity**
1768-1769	Violent ash eruption
1790-1792(?)	Smoking
1802	Violent ash eruption with earthquakes
1818	Smoking
1826	Violent ash eruption with earthquakes
1827-1838	Smoking
1845	Eruption from unspecified fissure
1865	Smoking
1867	Smoking
1883	Ash eruption
1907	Strong thermal activity along the north wall of the caldera, and a new crater formed between central cone and northern caldera wall
1912	Smoking
1926	Ash eruption with earthquakes
1938	Ash eruption
1951	Phreatic ash eruption
1952	Smoking
1980	Phreatic eruption from parasitic crater
1995	Phreatic ash eruption

they occurred at times of bad weather when the volcano was not observed, or because they were too small to have noticeable effects beyond the volcano's flanks. For instance, in 1983 volcanic explosions were heard by nearby geologists but never correlated with specific deposits, and in 1996 ash deposits found at the summit and on the volcano's flanks were probably produced by previously undocumented eruptions in 1995 (McConnell and others, 1997).

PREHISTORIC ERUPTIVE HISTORY OF MAKUSHIN VOLCANO

Because the written record of volcanism at Makushin Volcano goes back only 230 years, geologic studies of the deposits of prehistoric eruptions are valuable in estimating the long-term style, magnitude, and frequency of volcanic eruptions and associated hazards. Makushin Volcano has been the site of volcanic eruptions for at least a million years, as indicated by radiometric dating of lava flows in deeply eroded cliffs on the flank of the volcano (Nye and others, 1986; Nye, 1990; McConnell and others, 1997). However, most deposits of ancient eruptions of Makushin Volcano have been buried by younger volcanic deposits or removed by glacial erosion, particularly during past ice ages. As a result, a detailed record of volcanic activity at Makushin Volcano can be reconstructed only since the end of the last ice age (that is, during the last 10,000 years).

The oldest deposits of Makushin Volcano that postdate the last ice age record a series of very large eruptions, culminating in the development of a summit caldera (fig. 4). These eruptions began about 8,400 to 8,800 years ago, when a large debris avalanche occurred on the north flank of the volcano and traveled at least 10 kilometers to the coast. On the basis of bathymetry, this avalanche deposit may extend an additional 3 to 5 kilometers offshore. The upper part of the avalanche deposit is gradational into very coarse grained surge deposits that record a lateral blast apparently coincident with the debris avalanche.

Numerous pyroclastic-flow deposits fill valleys on the east, northeast, north, and west of the volcano, and have been dated to about 8,000 to 8,100 years before

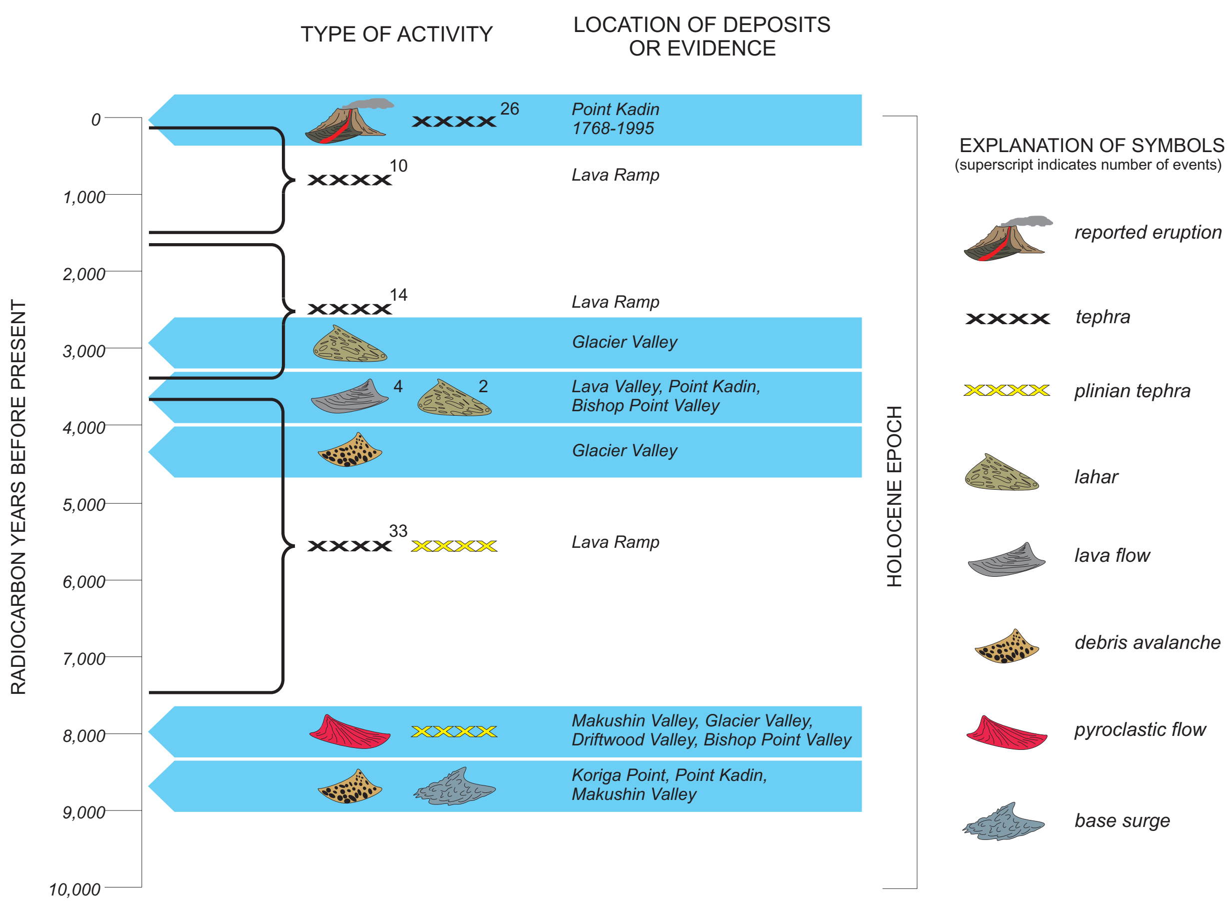


Figure 4. *Prehistoric eruption history of Makushin Volcano, based on geologic mapping (McConnell and others, 1997) and stratigraphic studies (Bean, 1999).*

present (Bean, 1999). The pyroclastic flow deposits are more than 100 meters thick at the head of Makushin Valley and can be traced downvalley 20 kilometers to the shore of Unalaska Bay, where they reach a maximum thickness of 3 meters. Correlative pyroclastic deposits containing incinerated plants occur at Hog Island, 7 kilometers farther to the east across Unalaska Bay, where they are 1 to 2 meters thick. The summit caldera was produced during the pyroclastic flow eruptions 8,000 to 8,100 years ago.

Following the caldera-forming eruptions, frequent but smaller events have occurred up to the present time (fig. 4). The most complete record of Makushin eruptions is found in the upper Makushin Valley, where at least 26 volcanic ash layers, some as much as 5 centimeters thick, are preserved in peat formed on the surface of the valley fill during the last 4,000 years. Several small pyroclastic flow and surge deposits found on the northeast, north, southeast, and west flanks of Makushin Volcano record eruptions that affected the volcano's flanks up to 8 kilometers from the vent. Lahar and flood deposits, possibly produced by small eruptions, are present at low elevations in virtually all streams draining the volcano and can also be traced 8 to 10 kilometers downvalley from the vent. The largest postcaldera volcanic event produced a debris avalanche deposit more than 15 meters thick that inundated a valley on the southeast flank of Makushin Volcano more than 2,500 years ago, traveling more than 10 kilometers from the volcano.

HAZARDOUS PHENOMENA AT MAKUSHIN VOLCANO

A wide range of volcanic phenomena poses potential threats to human life, property, and the environment around volcanoes (Scott, 1989). The specific areas at risk due to volcanic hazards will vary according to the magnitude and style of the eruptions.

Many types of volcanic processes can affect proximal areas within 10 to 20 kilometers of an active vent (fig. 5). Explosive eruptions can produce pyroclastic flows and surges that sweep all areas within a few kilometers of an erupting vent, resulting in death or injury to anyone in the vicinity. Such eruptions may happen with little or no warning, providing insufficient time for people near the volcano to escape. At greater distances most types of volcanic flows become channeled into low-lying areas; thus, hazards would be most severe along the river channels that originate on the slopes of Makushin Volcano. Because the volcano lies in an uninhabited part of Unalaska Island, only the occasional visitor is currently at risk from proximal volcanic hazards. However, both mineral and geothermal exploration has occurred in recent years on the east side of the volcano, and future development of both a mine and a geothermal power facility have been proposed near the head of the Makushin Valley.

Very large volcanic eruptions can cause complete destruction within 20 kilometers of the active vent, and can also affect people and structures that are at greater distances. Generally, volcanic eruptions pose less risk to people at progressively greater distances from the vent because the energy of eruptions dissipates with distance; also there would probably be some advance warning of a major eruption. Nevertheless, extremely large eruptions can cause death and destruction even at distances of 30 kilometers or more, although eruptions of this magnitude occur very rarely. The Alaska Volcano Observatory operates a seismic monitoring network at Makushin Volcano, and would detect signs of precursory volcanic unrest before any large eruption.

A recently completed geologic map of Makushin Volcano (McConnell and others, 1997) shows the areal extent of volcanic deposits formed during prehistoric eruptions, and a stratigraphic study of the volcanic deposits has determined the age and magnitude of major eruptions during the last 10,000 years (Bean, 1999). These studies, which form the basis for this hazard appraisal, show that eruptions of Makushin Volcano produced ash falls, pyroclastic flows, lava flows, debris avalanches, mud flows, and floods that repeatedly impacted proximal areas near the volcano. It is also evident that volcanic ash clouds, ash fallout, and pyroclastic flows and surges have occasionally reached areas more than 20 kilometers from the volcano.

VOLCANIC HAZARDS

Volcanic Ash Clouds

During the last 230 years Makushin Volcano has repeatedly erupted explosively, sending 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 finer grained material can rise convectively to 20 kilometers or more above the volcano, forming an eruption cloud that will drift downwind from the volcano. The ash cloud can travel through the atmosphere for distances of hundreds to thousands of kilometers, over periods of days to months, depending on the size of the eruption. The particles of volcanic glass and other material carried by ash clouds are hazardous to jet aircraft that encounter them (Swanson and Begét, 1994; Casadevall, 1994).

While no large tephra eruptions have occurred at Makushin Volcano in the last few decades, recent eruptions of other Alaskan volcanoes suggest the type and extent of hazards that might accompany future tephra eruptions at Makushin Volcano. During the 1976 eruption of Augustine Volcano, ash clouds reached 12 kilometers above sea level. At least five jet aircraft sustained abrasion on windshields, wings, landing gear, and other parts of the planes after flying through the ash clouds. The ash clouds traveled with high-level winds southeastward over the Pacific Ocean and Canada, and reached as far south as Arizona and as far east as Virginia. In 1986 ash clouds from Augustine Volcano reached at least 12 kilometers on four occasions; one jet aircraft flew through an ash cloud, and air traffic was disrupted at several Alaskan airports for several weeks (Waythomas and Waitt, 1998).

Several explosive eruptions of Redoubt Volcano in 1989-90 sent ash to at least 12 kilometers elevation. On December 15, 1989, a Boeing 747 jet 240 kilometers northeast of Anchorage International Airport, flew into an ash cloud and lost power in all four 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 sustained about $80 million in damage (Brantley, 1990). About 2 days later the Redoubt

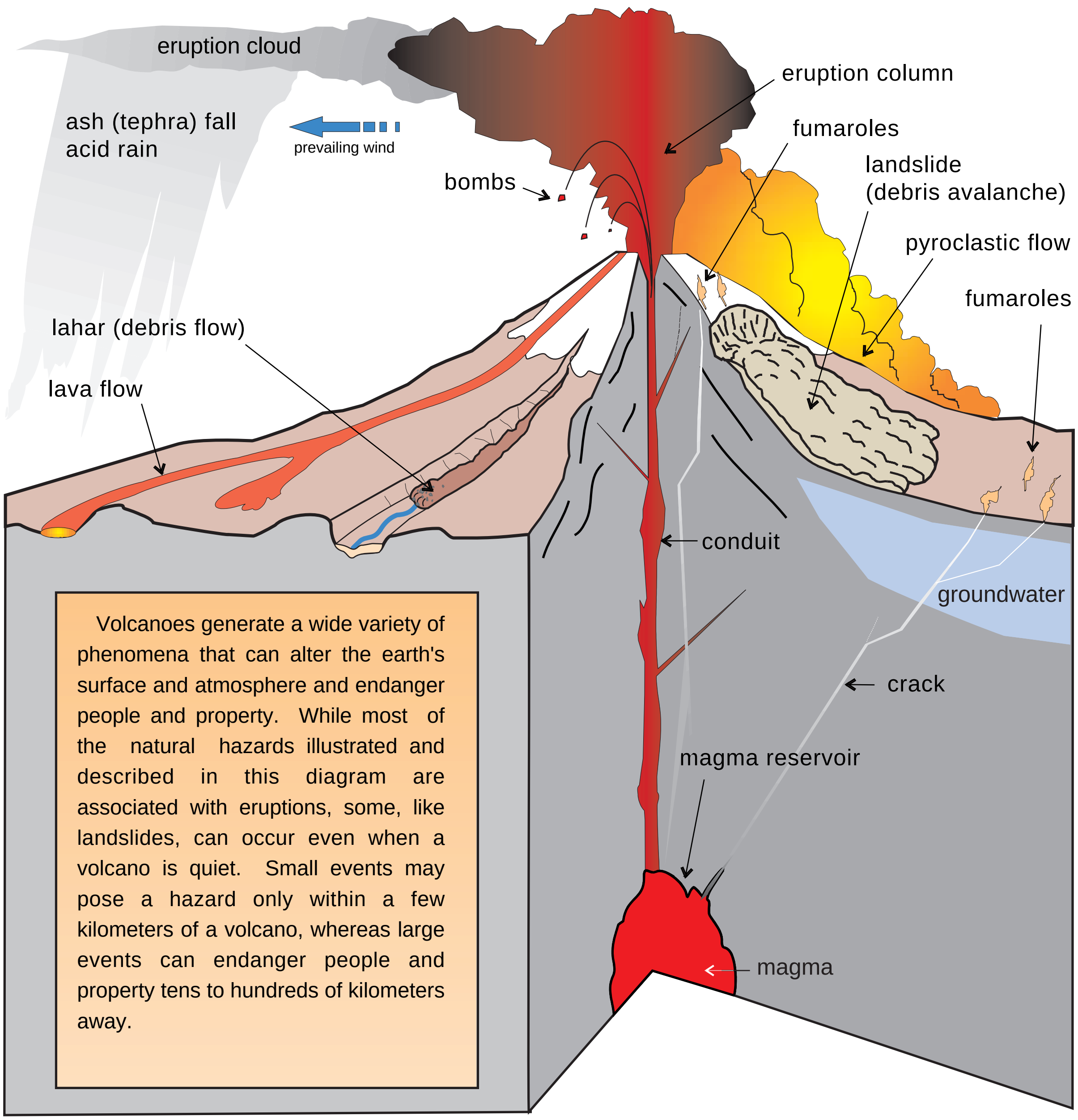


Figure 5. *Simplified sketch of a stratovolcano and associated hazardous phenomena resulting from typical eruptions.*

ash cloud had drifted over 5,400 km to the southeast, where two jets encountered it over west Texas; one of these jets suffered a transient engine stoppage and the other jet's wings were abraded (Waythomas and others, 1998).

The magnitude of the ash-cloud hazard during future eruptions of Makushin Volcano depends on the characteristics of the eruption, including the elevation and rate of ascent of the ash cloud and the volume, concentration, size, and geochemistry of the ash particles. The regional distribution and long-range transport of such ash clouds will be controlled by meteorological conditions at the time of the eruption (fig. 6). In short, even small future eruptions of ash clouds by Makushin Volcano may briefly affect air travel and operations at the Dutch Harbor airport, whereas larger eruptions are potentially hazardous to all air traffic flying over the eastern Aleutian Islands and surrounding areas of the northern Pacific Ocean (figs. 7, 8).

Volcanic Ash and Bomb Fallout

During explosive eruptions, ash, pumice, and large volcanic bombs and rock debris may be blasted from the vent, raining out ballistically around the volcano. Typically, large volcanic bombs fall no more than a few kilometers from the vent, although in unusually large eruptions they may reach areas 10 or more kilometers away. Because the area close to Makushin Volcano is uninhabited, the risk from volcanic bombs is low, except to perhaps low-flying aircraft that might come near the volcano during an eruption.

In contrast, fine-grained volcanic ash falls from ash clouds as they drift away from erupting volcanoes, and can affect inhabited areas tens or even hundreds of kilometers downwind from the eruption (fig. 8). During ashfalls, the sky typically darkens and visibility may be reduced to only tens of meters, disrupting all types of surface and air transportation. Falling volcanic ash accumulates on the roofs of buildings, and the weight of a thick ashfall may cause ceilings or 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). Shoveling ash off structures before it accumulates to a dangerous thickness can mitigate this hazard.

A wide range of mechanical and electrical systems can be affected by airborne ash. Even relatively thin (1 to 2 centimeter) ashfalls can affect the cooling and electri-

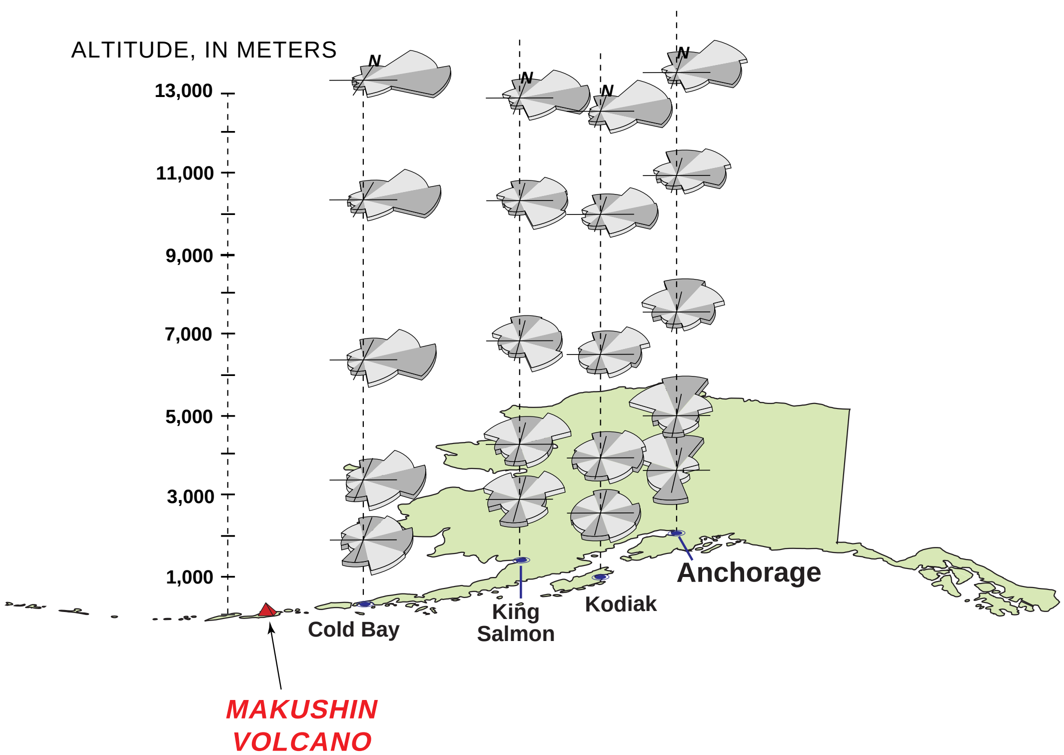
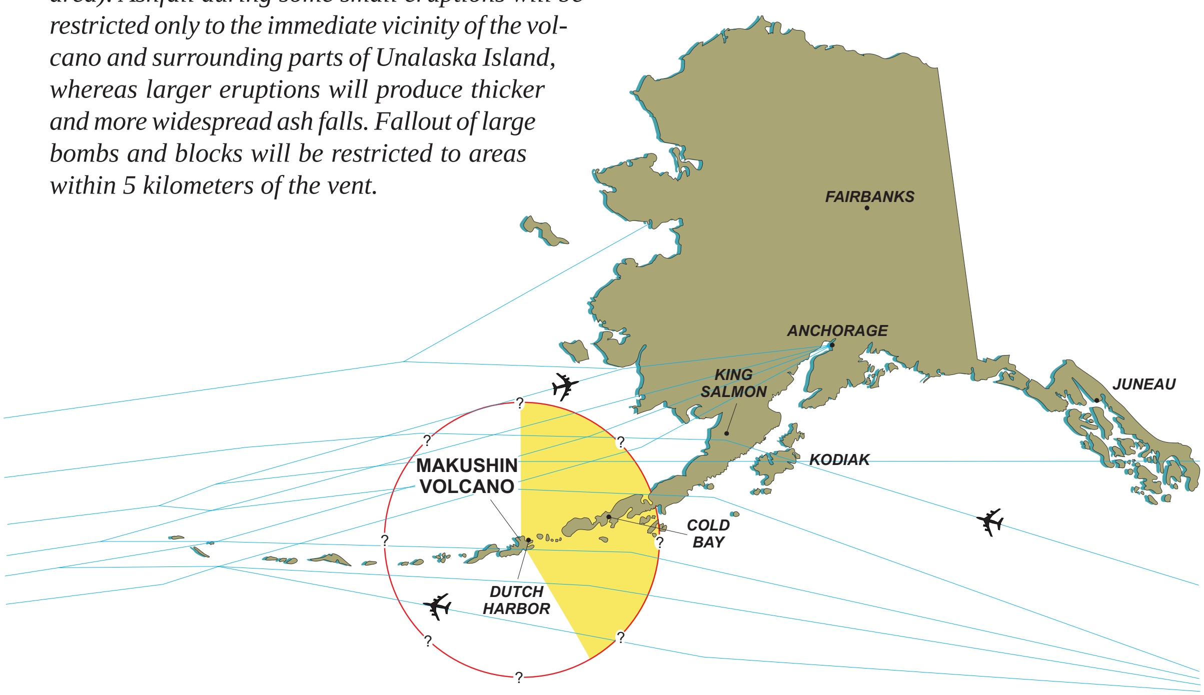


Figure 6. *Average wind direction over southwestern Alaska. Volcanic ash during future eruptions of Makushin Volcano will drift with the wind, most likely toward the northeast, east, or southeast. Windrose-section lengths are proportional to wind frequency determined by annual percent. Original data is from the National Climatic Data Center, National Oceanic and Atmospheric Adminisration.*

Figure 7. *Prehistoric ash deposits exposed near the Dutch Harbor International Airport preserve evidence of multiple explosive eruptions from nearby Makushin Volcano.*

Figure 8. *Flight paths of commercial freight and passenger airlines crossing the North Pacific. Future explosive eruptions of Makushin Volcano may inject ash as high as 20,000 meters into the atmosphere, causing disruption of normal trans-Pacific flight schedules. The circle shows areas in Alaska that might be affected by ash fallout during a typical eruption of Makushin Volcano. The exact area of ash fallout will depend on synoptic weather conditions and wind directions, but it is likely to affect areas mainly east of the volcano (shaded area). Ashfall during some small eruptions will be restricted only to the immediate vicinity of the volcano and surrounding parts of Unalaska Island, whereas larger eruptions will produce thicker and more widespread ash falls. Fallout of large bombs and blocks will be restricted to areas within 5 kilometers of the vent.*



cal systems of automobiles and other internal combustion engines. Equipment in hospitals, power plants, schools, pumping plants, and factories may be damaged. Ashfalls can cause short circuits and disrupt telephone circuits and other communications systems. Thicker ashfalls can clog water and sewer systems (Blong, 1984; Scott, 1989).

Ashfalls can cause health problems in humans. People with respiratory problems can experience breathing difficulties during very minor ashfalls. Even healthy people may be irritated by prolonged exposure to atmospheric dust during sustained ashfalls. Volcanic ashfalls may be associated with harmful gases, although such events are rare. The health effects of ashfall on humans can be mitigated by advising people with respiratory problems to stay indoors during ashfalls, and by recommending the use of respirators, filters, or wet cloths over the mouth and nose for those who must work outdoors.

The areas most likely to be affected by significant ashfall during future eruptions of Makushin Volcano—assuming they are typical of those of the last 230 years—will be restricted to the flanks of the volcano and nearby unpopulated areas of Unalaska Island. However, geologic studies show that more powerful eruptions have occurred repeatedly during the last 10,000 years, in one case depositing pumice and ash more than 100 centimeters thick in areas 20 kilometers from the volcano. In the unlikely case of very powerful, voluminous, caldera-forming eruptions such as those that occurred 8,000 years ago, significant ashfall might occur at distances of 1,000 kilometers or more from Makushin Volcano.

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 in a basal flow zone, accompanied by a dilute, hot dust cloud (fig. 5). Pyroclastic flows form when masses of hot rock debris are explosively ejected onto the volcano's flanks or when part of a growing volcanic dome collapses into rock fragments. The rock debris and intercalated hot gases in pyroclastic flows may have very high initial velocities because of laterally directed explosive eruptions or collapse from high eruption columns. Pyroclastic surges are similar to pyroclastic flows but typically have higher gas content and are always generated by volcanic explosions (Sigurdsson and others, 1987). At Makushin Volcano, explosive interactions between magma and the thick glacier cover on the volcano produced phreatomagmatic explosions and pyroclastic surges on several occasions during the last 4,000 years (Bean, 1999).

Figure 9. *Pyroclastic flow deposits more than 60 meters thick are preserved in Makushin Valley 5 to 10 kilometers east of the volcano, and were produced during caldera-forming eruptions about 8,100 to 8,000 years ago.*

Pyroclastic flows and surges have temperatures of 700°C to 1,000°C and can attain velocities of 150 kilometers per hour. Because of this, pyroclastic flows and surges constitute an especially severe hazard to human life. The basal (coarse) zone of rock debris in pyroclastic flows can bury and incinerate people and buildings, and pyroclastic surges and the dilute clouds of hot ash that form the upper parts of pyroclastic flows can cause burning of the skin, throat and lungs, as well as asphyxiation. Also, high-velocity ash clouds and surges can be very 'energetic,' demolishing buildings and carrying sand-sized and larger rock fragments that may cause injury by impact as well as by their intense heat (Baxter and others, 1998).

Because of their great mobility, pyroclastic flows and surges can affect areas considerable distances from their source. Studies of the extent of prehistoric pyroclastic flow and surge deposits erupted from Makushin Volcano on several occasions during the last 4,000 years indicate that nearly all areas within 10 kilometers of the summit could be affected by pyroclastic flows and surges (figs. 9, 10). Pyroclastic flows are often channeled down steep valleys, and floors of valleys draining Makushin Volcano might be affected for several additional kilometers.

Pyroclastic flows and surges can also 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 (Cole and others, 1998). During the large caldera-forming eruption of Krakatau Volcano in 1883, pyroclastic flows produced casualties on land in southern Sumatra after traveling more than 40 kilometers over water (Carey and others, 1996). The geologic evidence shows that pyroclastic flows produced during the caldera-forming eruption of Makushin Volcano about 8,000 years ago not only reached the sea on

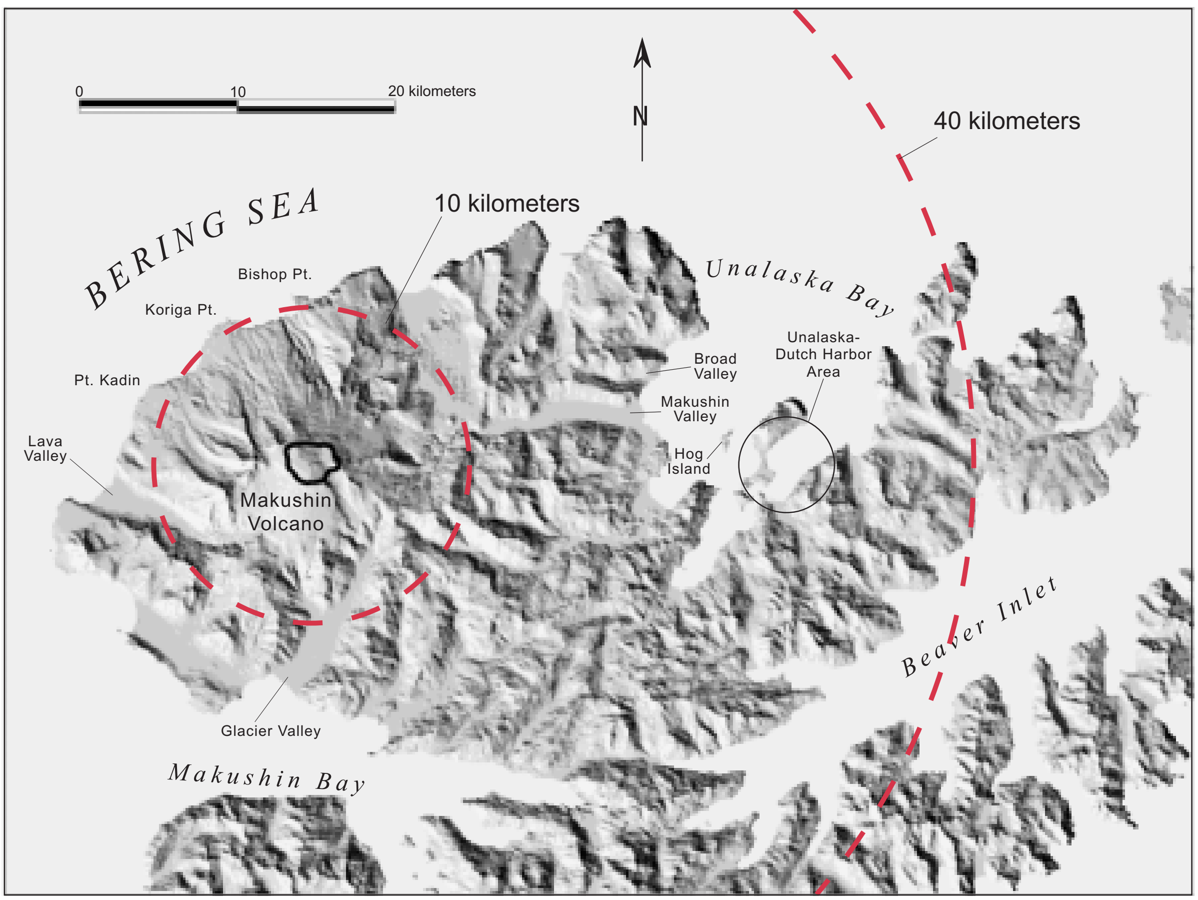


Figure 10. *Areas likely to be affected by pyroclastic flows from typical small to moderate eruptions of Makushin Volcano shown by inner, 10-kilometer-diameter circle, and the maximum extent of pyroclastic flows, surges, and lateral blasts from a very large eruption similar to the caldera-forming eruption which occurred about 8,100 to 8,000 years ago at Makushin Volcano shown by outer, 40-kilometer-diameter circle. Only one caldera-forming eruption has occurred in the last 10,000 years at Makushin Volcano, indicating eruptions of this magnitude are very rare.*

the north and east flanks of the volcano, but traveled at least 10 kilometers across Unalaska Bay to Hog Island (Bean, 1999). On the basis of the well-documented historic extent of pyroclastic flows during caldera-forming eruptions at Krakatau, the maximum hazard zones for pyroclastic flows and surges surrounding Makushin Volcano are set at 40 kilometers from the volcano (fig. 10). A caldera-forming event similar to that which occurred 8,100 to 8,000 years ago will not likely recur in the near future at Makushin Volcano.

Debris Avalanches

Volcanic debris avalanches are giant landslides formed by collapse of the upper parts of volcanoes. They can travel at speeds of 30 to 150 kilometers per hour, and may extend 20 kilometers or more from the volcano, burying landscapes beneath many meters of coarse volcanic debris. Volcanic debris avalanches may occur during eruptions, as was observed during the initiation of the 1980 eruption of Mount St. Helens. Debris avalanches may occur during non-eruptive periods, especially if long-term chemical alteration, usually associated with fumaroles and hot, acidic groundwater, has weakened the upper parts of a volcanic edifice. Volcanic debris avalanches at Alaskan volcanoes may be triggered by the unusually large earthquakes that regularly occur along the Aleutian subduction zone (Begét and Kienle, 1992).

At Makushin Volcano, two thick debris avalanche deposits produced before the main caldera-forming eruptions occurred are present in valley bottoms on the north and west flanks of the volcano (fig. 11). In addition, a small debris avalanche deposit emplaced about 3,000 years ago is preserved on the southeast flank of the volcano (Bean, 1999). Such debris avalanches, although uncommon at Makushin Volcano, have the potential to be a significant hazard because they would completely obliterate and bury anything they encountered in valleys around the volcano. However, all areas around Makushin Volcano that might be affected are now uninhabited and undeveloped (fig. 12).

Directed Blasts

A directed blast is a laterally directed explosion caused by either a dome collapse or a debris avalanche that uncovers and depressurizes hot, magmatic material at a volcano. Deposits of a directed blast associated with an early Holocene debris avalanche at Makushin Volcano are exposed at the modern coastline on the north

Figure 11. *Deposits of the Koriga Point debris avalanche, including a lateral blast sediment facies, are exposed along the coast at Koriga Point, about 8 kilometers from Makushin Volcano. Bathymetry indicates that the debris avalanche deposit continues offshore for at least another 4 kilometers beyond the coastline.*

flank of the volcano (fig. 11). The extent of the prehistoric directed blast at Makushin Volcano cannot be estimated because it was propagated to the north over the Bering Sea for some distance beyond the current coastline.

In the absence of direct evidence of the extent of previous directed blasts at Makushin Volcano, the extent of the hazard from possible future directed blasts at Makushin Volcano is based on data from the directed blast associated with the 1980 eruption of Mount St. Helens (Kieffer, 1981). This is one of the best known historic examples of a directed blast and thus provides a well documented model for this hazard. If a directed blast were to occur at Makushin Volcano, it would most likely be associated with a debris avalanche collapse and would affect a broad area, perhaps exceeding 180 degrees downslope from the avalanche scar, and might extend more than 25 kilometers from the volcano (fig. 13). A directed blast might occur with little warning during the first minutes of a large eruption involving edifice collapse, and the hot, energetic explosive blast would destroy everything it overran.

Lahars and Floods

The summit of Makushin Volcano is mantled with a thick ice cap that fills the summit caldera. Valley glaciers flow from the summit down valleys cut into the flanks of the volcano. During eruptions, large quantities of glacier ice and snow can be melted, and floods and volcanic debris flows or lahars may occur. Lahars typically consist of fluid suspensions of boulders, sand, and silt, which can travel 20 kilometers or more downvalley at speeds up to 30 kilometers per hour. Lahars, which have the consistency of wet concrete, typically cover floodplains with deposits centimeters to meters thick.

Floods and lahars from Makushin Volcano have reached the coast along all drainages leading from the volcano during past eruptions, and might affect low-lying areas in valley bottoms in any of these areas during future eruptions. As previously stated, all valleys head-

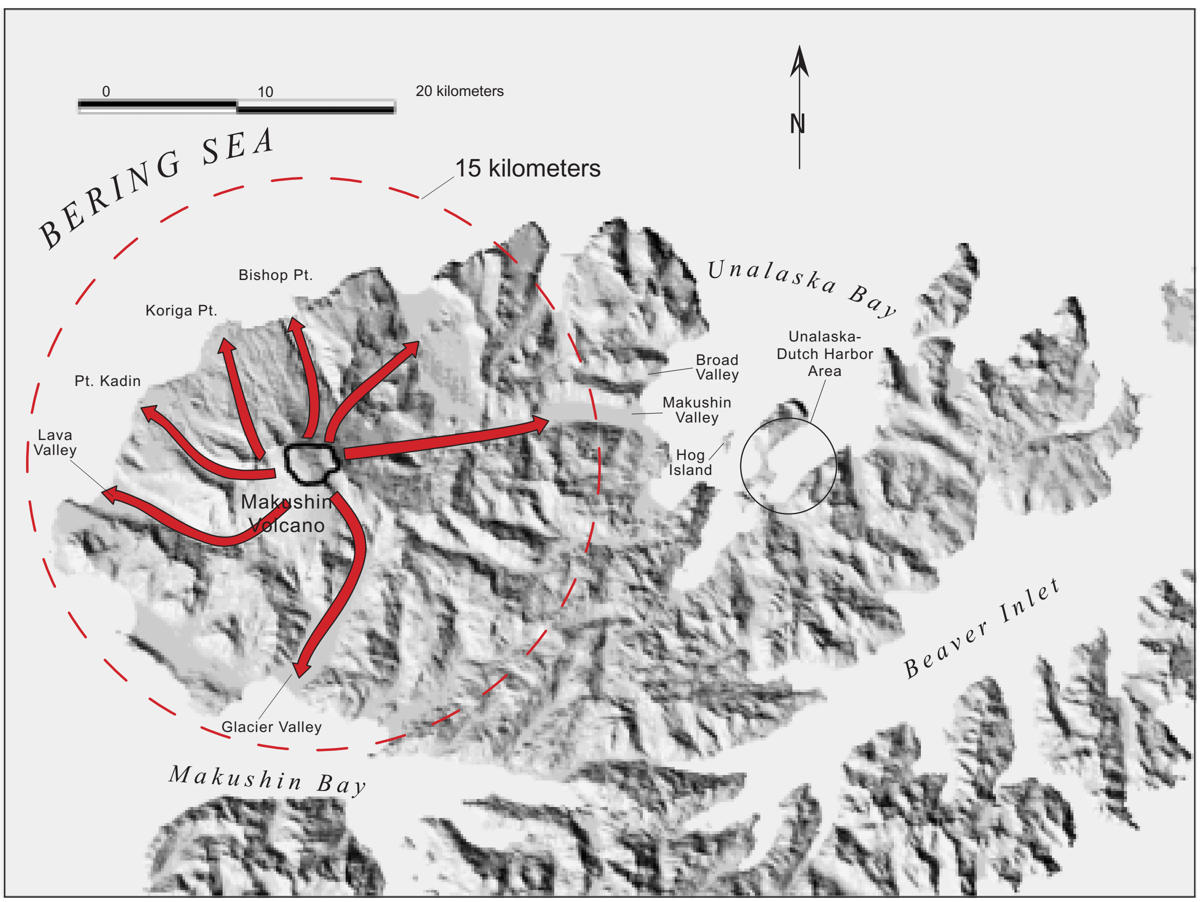


Figure 12. *Maximum likely runout distance of large debris avalanches at Makushin Volcano, based on the extent of the largest debris avalanche of the last 10,000 years is shown by the 15-kilometer-diameter circle. Future debris would be at least partly channelized down valleys, and possible flow paths of debris avalanches during future eruptions of Makushin Volcano are shown by arrows.*

ing on Makushin Volcano are currently uninhabited and undeveloped.

Phreatomagmatic Explosions

Contact between hot magma and water can produce violent explosions when the water flashes to steam and expands. Eruptions through the ice at the summit of Makushin Volcano are very likely to result in phreatomagmatic explosions. A fresh-appearing steep-sided crater about 50 meters across observed at the summit of Makushin Volcano was the source of small eruptions in January of 1995 that produced a thin surge deposit and ashfall that affected only the upper snowfields of the volcano (fig. 14).

Phreatomagmatic explosions have also occurred several times in the past at sites on the flanks of Makushin Volcano. A chain of maar craters, the largest being almost 1,000 meters in diameter, are aligned along a northwest-trending fault on the northwest side of the volcano. These craters were formed during several episodes within the last few thousand years from shallow interactions of magma and groundwater.

Phreatomagmatic explosive eruptions are quite likely to recur in the future, either on the summit or the flanks of Makushin Volcano, probably near the existing chain of maar craters on the northwest side of the volcano. Future phreatomagmatic eruptions will be characterized by repeated explosions, ejection of bombs and blocks, and the generation of pyroclastic surges affecting areas within 5 to 10 kilometers of the vent.

Volcanic Gases

Large volumes of volcanic gases are typically emitted during and immediately after eruptions, with the most common being carbon dioxide, carbon monoxide, sulfur dioxide, and hydrogen sulfide. Hydrogen sulfide has an astringent odor similar to rotten eggs, but carbon monoxide and carbon dioxide are colorless and odorless.

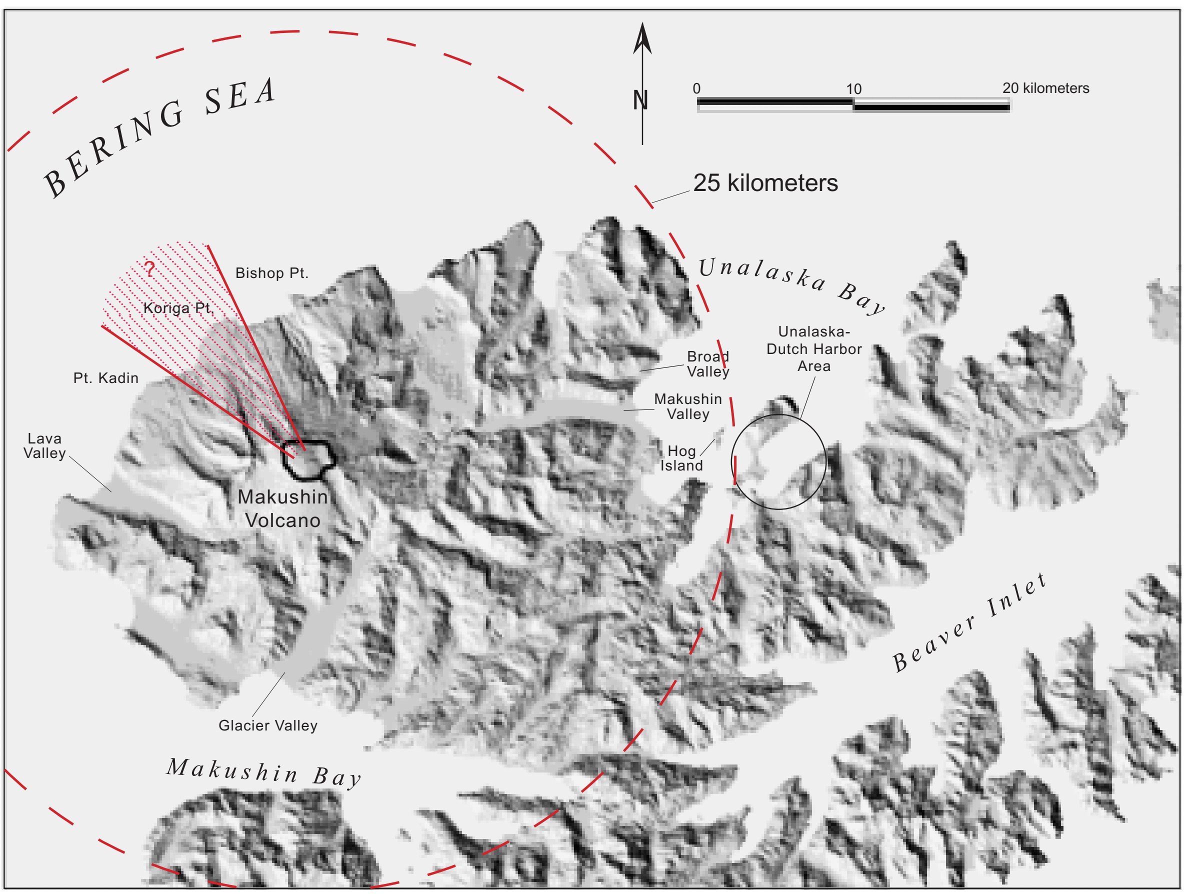


Figure 13. *Lateral blast hazard zone at Makushin Volcano, assuming the extent of a future blast is comparable to that at Mount St. Helens in 1980 (25 kilometers). The shaded sector represents the approximate extent of directed blast deposits in the 8,600 years before present Koriga Point eruption.*

Carbon dioxide, being heavier than air, may collect in low-lying areas, causing suffocation of birds, animals, and humans who go there.

Microscopic droplets and aerosols of sulfuric acid, hydrochloric acid, and hydrofluoric acid may form when volcanic gases encounter water, and highly acidic precipitation may result from the mixing of a gas-rich volcanic plume and rain or snow. Acidic volcanic aerosols can cause skin and lung irritation, and corrode paint, fabric, and metals.

During dormant periods, volcanic gases sometimes build to dangerous levels in basins, in low, protected areas, and in ice caves such as those melted through the summit ice cap of Makushin Volcano by fumaroles. During eruptions the greatest hazards from volcanic gases and acidic aerosols will occur within a few hundred meters to a few kilometers of the active vent. Hydrogen sulfide from the summit vents of Makushin is occasionally carried by strong winds to Dutch Harbor and Unalaska, 28 kilometers to the east, but represents no hazard to people or property at such distance from the volcano.

Lava Flows

Lava flows as long as 5 kilometers have been erupted by Makushin Volcano and its flank vents several times since the end of the last ice age. The flows are primarily basaltic andesite to basalt and probably moved downslope at velocities of a few meters to tens of meters per hour. Future lava eruptions at Makushin will probably be limited to uninhabited parts of Unalaska Island, and pose little direct threat to people or property.

Volcanic Tsunamis

Makushin Volcano occupies a peninsula on the north side of Unalaska Island, and the sea lies only 8 kilometers from the volcano on its north flank, 10 to 15 kilometers on the west and southwest, and 20 kilometers to the east. Numerous tsunamis, some among the largest and most devastating known in historic time, have been generated during eruptions at volcanoes located near the sea (Begét, 1999). In the past 200 years, about 70 percent of the known volcanic tsunamis were generated either by volcanic explosions or by the displacement of

Figure 14. *Summit of Makushin Volcano, showing recently formed summit crater, surrounded by ashfall and surge deposits produced during eruptions in 1995 that sent ash to 2.4 kilometers above the volcano (Smithsonian Institution, 1995). Larger summit eruptions in the future may result in large-scale magma-ice interactions, producing phreatic explosions and eruption of ash clouds to elevations of 5 to 20 kilometers above the volcano. Pyroclastic flows, surges, lahars, and floods may also be produced.*

seawater by large masses of volcanic debris entering the ocean, with another approximately 20 percent attributed to volcanic earthquakes (Latter, 1981). Voluminous pyroclastic flows and debris avalanches that flow into the sea at high velocity have produced the largest tsunamis; smaller waves were associated with lahars, lava flows, and surges.

No tsunamis have been produced at Makushin Volcano during the relatively small eruptions of the last few hundred years, and tsunamis are very unlikely to be produced by typical eruptions of Makushin Volcano in the future. However, if an unusually large eruption, similar to the caldera-forming eruptions of about 8,000 years ago, were to occur again, tsunami waves might be produced. During the prehistoric eruptions, pyroclastic flows and surges traveled from the volcano to the sea, especially on the north flank, where the sea is closest (McConnell and others, 1997). Slightly older debris avalanches also reached the sea on the north flank of Makushin Volcano (Bean, 1999). No geologic deposits of tsunamis produced by eruptions of Makushin were identified during field studies (Bean, 1999). In the unlikely event a volcanic tsunami is generated during a future eruption, it is possible for humans to reduce their risk by climbing to sites at higher elevations.

ERUPTION FREQUENCY AND VOLCANIC RISK AT MAKUSHIN VOLCANO

At Makushin Volcano, like most other volcanoes, small eruptions occur much more frequently than large ones. While the degree of most hazards increases with eruption magnitude, some distal areas are at risk only on those rare occasions when an extremely large eruption occurs. This means that evaluations of volcanic risk and planning to mitigate those risks must take into account complex relationships between eruption size and probability. The future volcanic risk at Makushin Volcano can be divided into two scenarios: (a) hazards associated with the likely recurrence of relatively small eruptions similar to those of the past millennium, and (b) hazards associated with the much less probable recurrence of an eruption similar to that which produced the summit caldera and extensive, voluminous pyroclastic flows about 8,000 years ago.

The historic and geologic records indicate that one or more eruptions of Makushin Volcano, similar to or somewhat larger than the 17 documented during the last 230 years of written history, are likely to occur during this century. The primary volcanic hazard from these eruptions will be from volcanic ash clouds, which may drift over the towns of Unalaska and Dutch Harbor on Unalaska Island or over other parts of the Aleutian Islands, the North Pacific Ocean, or mainland Alaska. Such ash clouds may interfere with operations of the International Airport at Dutch Harbor, as well as the dozens of commercial and passenger jet flights that move between Asia, Europe, and North America across the North Pacific each day. Ash fallout on the nearby towns of Dutch Harbor and Unalaska could be a few millimeters to a few centimeters thick if prevailing winds carried ash clouds eastward. Such ashfalls could interfere with the operation of engines and generators, and would affect commercial and civic activities. These small eruptions might be accompanied by floods, lahars, small surges, and small pyroclastic flows, but the effects of these events would be restricted to uninhabited parts of Unalaska Island near the volcano.

Small eruptions have occurred at least 17 times in the last 230 years at Makushin Volcano, and somewhat larger eruptions at least 26 times in the last 5,000 years (Bean, 1999). If future eruptions were to occur at a rate similar to that indicated by the historic record of the past 230 years and the geologic evidence from the past 5,000 years, then one to five such eruptions might be expected during the next century.

Determining the frequency and risk from significantly larger eruptions—such as the caldera-forming event about 8,000 years ago—is nearly impossible. There is a very small likelihood of such an eruption in the near future. The greatest hazard from such a large, rare eruption would be the generation of highly mobile pyroclastic flows and surges with the potential to travel 40 kilometers or more from the volcano, possibly reaching the vicinity of Dutch Harbor and Unalaska. Such flows can travel across the sea, and might also produce tsunamis. Large debris avalanches have also infrequently been produced by Makushin Volcano, and a future debris avalanche on the north or south flank of the volcano could completely bury the flank of the volcano and travel far enough to flow into the sea. Such large debris avalanches can produce volcanic tsunami waves several meters or more high, and might also be associated with lateral blasts. Explosive eruptions, much larger than those seen during historic time, would also produce much more widespread and lasting ash clouds over the North Pacific air-traffic corridors than those seen in the small eruptions of the 20th century. On the basis of the size of the largest prehistoric tephra eruptions, large explosive eruptions might produce ashfalls near Dutch Harbor 20 centimeters or thicker.

PRECURSORY ACTIVITY, VOLCANO MONITORING, AND HAZARD MITIGATION

The Alaska Volcano Observatory, a joint facility of the U.S. Geological Survey, the Geophysical Institute of the University of Alaska Fairbanks, and the State of Alaska Division of Geological & Geophysical Surveys, was established in 1988 to determine volcano hazards in Alaska and to issue warnings of imminent volcanic eruptions (Eichelberger and others, 1995). Since 1996, the Alaska Volcano Observatory has monitored Makushin Volcano with a real-time seismic network to detect small earthquakes that often precede volcanic eruptions (fig. 15). Radiotelemetry connects the seismometers around Makushin with receiver sites in Dutch Harbor, where the signals are relayed through telephone circuits to Alaska Volcano Observatory laboratories in Fairbanks and Anchorage. Although the seismic network was not in place during prior eruptions of Makushin Volcano, the Alaska Volcano Observatory staff is experienced in recognizing precursory seismic activity, and will likely be able to provide warning of future eruptions of the volcano.

When seismic unrest begins at Makushin Volcano, additional monitoring techniques may be used to more accurately 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 Alaska Volcano Observatory scientists to help monitor volcanic unrest and to predict eruptions at other Alaskan volcanoes.

The Alaska Volcano Observatory distributes by fax and e-mail a weekly report updating the status of more than 20 monitored volcanoes in Alaska, including Makushin Volcano. During periods of precursory activity or eruption, the Alaska Volcano Observatory frequently updates its reports to keep other government agencies and the public informed about the changes. 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

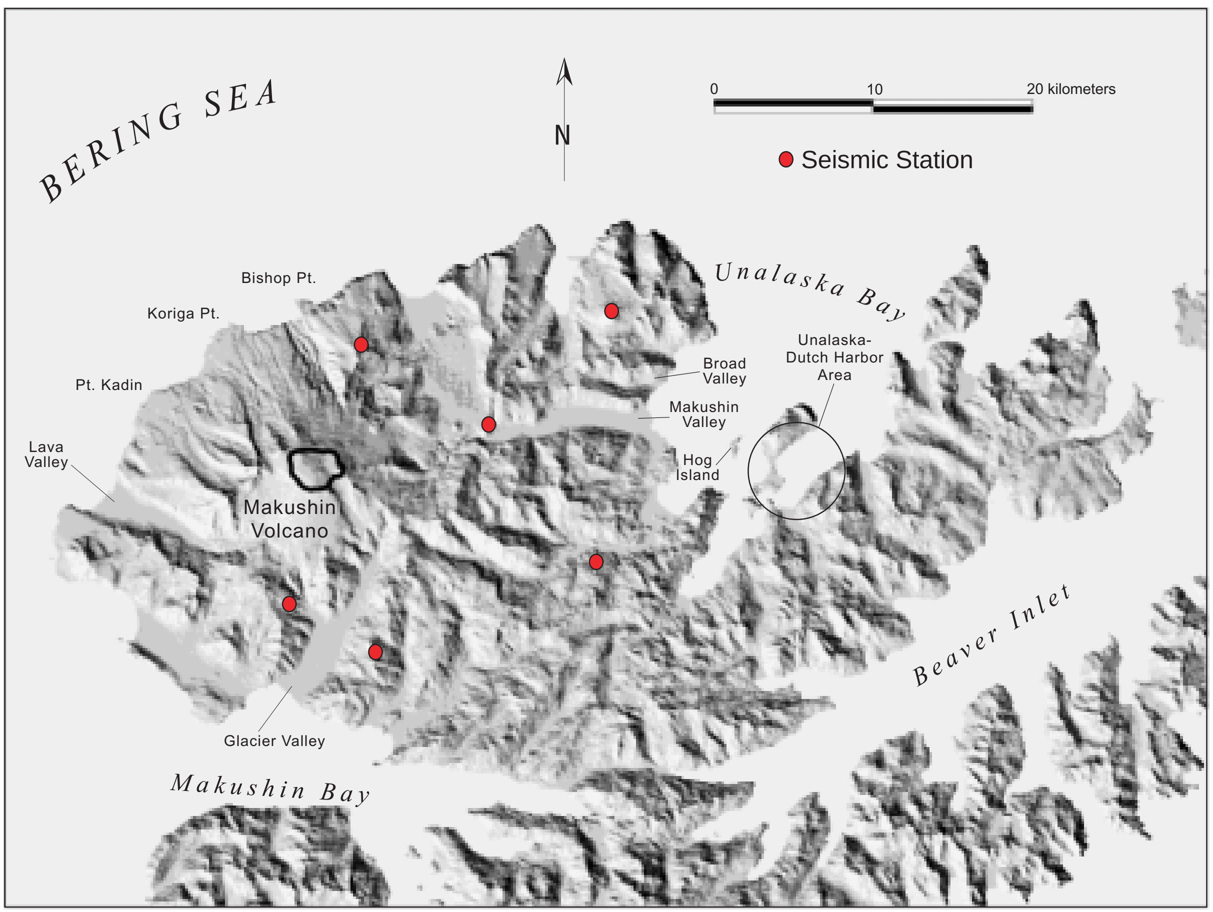


Figure 15. *Location of seismic stations around Makushin Volcano. This network is designed to detect small earthquakes beneath the volcano that may signal the onset of a volcanic eruption.*

Alaska, the Alaska Department 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, news wire services and others for dissemination to the general public. To make this information as widely available as possible in a timely fashion, it is also posted on the Alaska Volcano Observatory web page (http://www.avo.alaska.edu/).

The AVO uses a color code system to summarize the status of volcanoes in Alaska (Brantley, 1990). The color code is used to quickly and simply summarize the level of concern (fig. 16). During a volcanic crisis the Alaska Volcano Observatory staff can use the level-of-concern code to quickly communicate changes in volcanic activity to government agencies, which can then make decisions about governmental response to eruptions.

Although the flanks of Makushin Volcano are currently uninhabited, active mineral and geothermal energy claims exist in areas on the east side of the volcano, and proposals exist for development of geothermal wells and a power plant, a mineral lode mine, and a road to be built near the volcano at some time in the future. Recreational users, including fishermen and mountain climbers, visit Makushin Volcano. All future visitors to Makushin Volcano should check the latest level-of-concern code 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 an eruption, the risk to human life within about 10 to 15 kilometers of the volcano could be great, and access to this area by planes and helicopters should be restricted due to the danger from ballistic projectiles and falling ash.

At greater distances there is likely to be some warning time to prepare for the effects of eruptions. The planning for volcanic emergencies is similar to that for other natural disasters such as flooding, earthquakes, and extreme weather. Interruptions in electrical service, surface transport, and air travel may occur. People (especially those with respiratory problems) and children may be restricted from outdoor activities. If the volcanic emergency becomes very severe, evacuation and closure of some areas may be necessary.

This report is designed to provide an outline of the potential hazards associated with possible future eruptions of Makushin Volcano suitable for use by government agencies and private individuals and parties. Scientists

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 16. *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 Makushin Volcano and other Alaskan 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.*

of the Alaska Volcano Observatory will be available for detailed discussions of any future crises that may occur at Makushin Volcano.

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GLOSSARY

Andesite. A fine-grained volcanic rock made up of feldspars and ferromagnesian minerals; typically has a silicon dioxide (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.

Cohesive. As applied to lahars, any lahar that contains more than about 3 to 5 percent clay in the deposit matrix.

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 Mount 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 that 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 of escaping gas and steam.

Lahar. An Indonesian term for a debris flow containing angular clasts of volcanic material. For 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 an appreciable clay content (greater than 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.

Lahar-runout flow. The downstream or distal component of a lahar. Lahar-runout flows are finer grained and more watery than a typical lahar. Most noncohesive lahars transform to lahar-runout flows as they travel downstream.

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, broad crater excavated into the ground by multiple, shallow, explosive eruptions. It may be filled by water.

Magma. Molten rock beneath the earth's surface.

Noncohesive. As applied to lahars, any lahar that contains less than about 3 to 5 percent clay in the deposit matrix.

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

Plinian. Volcanic eruptions associated with highly explosive ejection of tephra and large-volume emissions of ash. Ash plumes from plinian eruptions usually reach 10,000 meters altitude or higher above the vent.

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.

Sulfurous. Sulfur-bearing or sulfur-rich compounds.

Stratovolcano (also called a 'stratocone' or 'composite cone'). A steep-sided volcano, usually conical, 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' (greater than 64-millimeter-diameter, 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.

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

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