THE ERUPTION OF REDOUBT VOLCANO, ALASKA

December 14, 1989 - August 31, 1990

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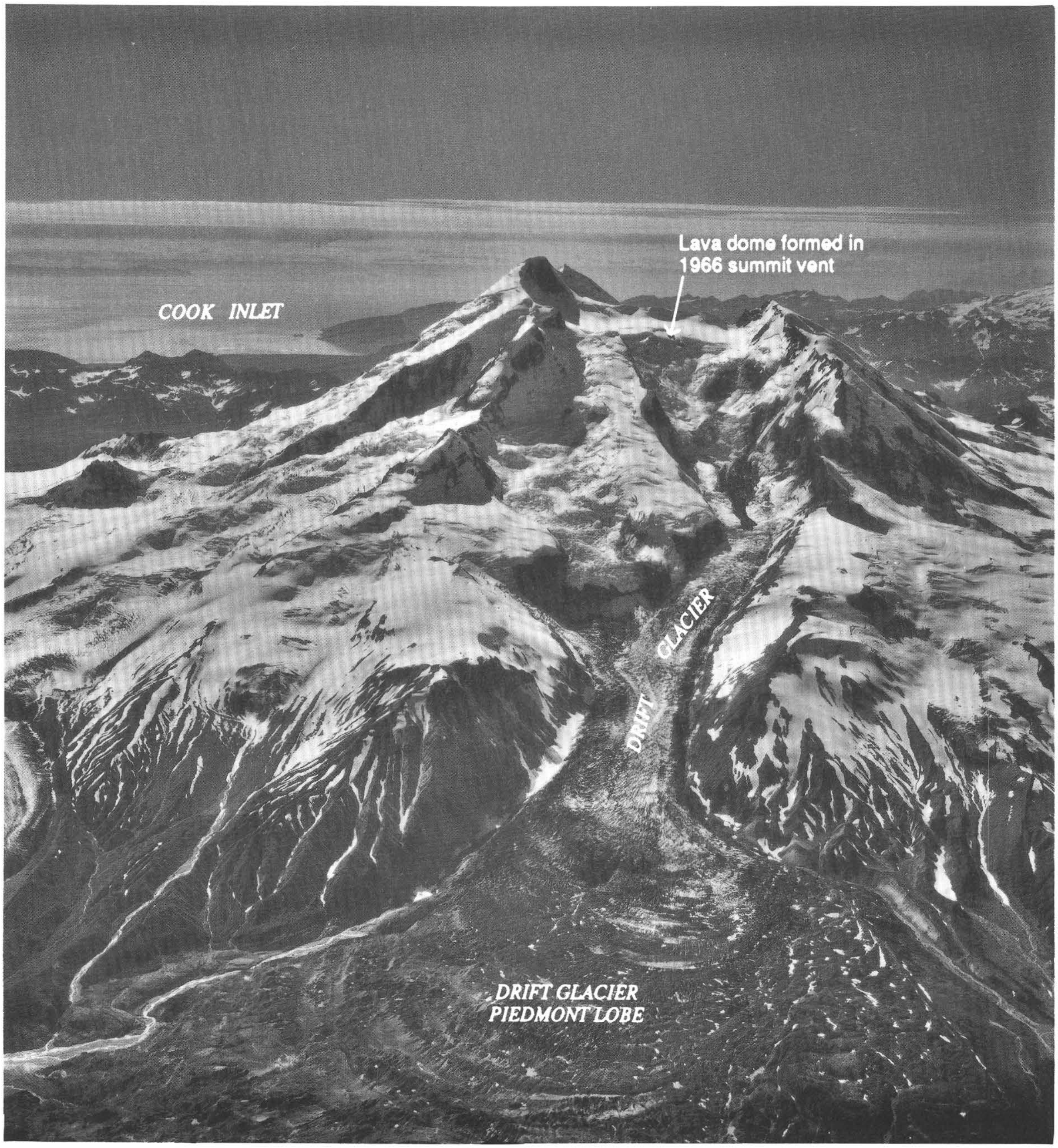
THE ERUPTION OF REDOUBT VOLCANO, ALASKA, DECEMBER 14, 1989–AUGUST 31, 1990



Frontispiece. Aerial photograph of north flank of Redoubt Volcano. Drift glacier descends from the breached summit crater down the north flank. Arrow marks location of lava dome that formed in 1966. Photograph by Austin Post on August 27, 1987. (Photograph identification no. 87R3-095).

The Eruption of Redoubt Volcano, Alaska, December 14, 1989–August 31, 1990

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Cover. Redoubt Volcano emits a vigorous plume consisting mostly of water vapor (steam), sulfur dioxide, and carbon dioxide. Plume is drifting to the west. View is to the north. Photograph by Steven R. Brantley on January 22, 1990.

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GLOSSARY

Accretionary lapilli. More or less spherical masses of loosely aggregated ash, mostly between 1 mm and 1 cm in diameter.

Andesite. A volcanic rock consisting of 53–63 percent silica; has a moderate viscosity when in a molten state.

Ash. Fragments of lava or rock less than 2 mm in diameter that are blasted into the atmosphere by volcanic explosions.

Basalt. A volcanic rock consisting of less than 53 percent silica; has a low viscosity when in a molten state.

Caldera. A large volcanic depression, usually circular in map view.

Composite volcano. A steep-sided volcano composed of layers of volcanic rock, usually of high-viscosity lava, and unconsolidated material such as debris-flow and pyroclastic deposits.

Dacite. A volcanic rock composed of 63–68 percent silica; has a high viscosity when in a molten state.

Debris flow. A flowing mixture of water and rock debris. Volcanic debris flows are sometimes referred to as volcanic mudflows or lahars (an Indonesian word).

Dome. A steep-sided mound that forms when highly viscous lava piles up near a volcanic vent. Domes are formed by andesite, dacite, and rhyolite lavas.

Earthquake. A sudden motion or trembling in the Earth caused by the abrupt release of accumulated strain in rocks.

Lava flow. Molten rock that erupts from a vent or fissure and flows downhill.

Magma. Molten rock, which contains dissolved gas and crystals, formed deep within the Earth. When magma reaches the Earth's surface, it is called lava.

Phreatic eruption. A steam explosion that occurs when water comes in contact with hot rocks or ash near a volcanic vent.

Piedmont. A flat or low-angle slope, area, glacier, or other feature at the base of a mountain.

Pumice. A light-colored volcanic rock containing abundant trapped gas bubbles formed by the explosive eruption of magma. Because of its numerous vesicles, or bubbles, pumice commonly floats on water.

Pyroclastic flow. A hot, fast-moving, and high-density mixture of ash, pumice, rock fragments, and gas that flows downhill during explosive eruptions.

Seismicity. The phenomenon of earthquakes or earth vibrations.

Silica. A molecule formed of silicon and oxygen (SiO_2) that is the basic building block of volcanic rocks and the most important factor controlling the viscosity of magma. The higher a magma's silica content, the greater its viscosity.

Silicosis. Fibrosis of the lungs caused by long-term inhalation of silica dust and resulting in a chronic shortness of breath.

Tephra. A general term for airborne rock fragments ejected during explosive eruptions. Tephra consisting of fragments less than 2 mm in diameter is called ash.

Tremor. In relation to volcanoes, a type of seismicity characterized by continuous vibration of the ground. The vibration is related to the transport of fluids and gas within or beneath a volcano.

Volcanic landslide. The downslope movement of soil, rock debris, and sometimes glacial ice, with or without water, from the flank of a volcano.

Volcano. A vent on the surface of the Earth through which magma erupts, and also the landform that is produced by the erupted material.

The Eruption of Redoubt Volcano, Alaska, December 14, 1989–August 31, 1990

Steven R. Brantley, *Editor*

SUMMARY

The 1989–90 eruption of Redoubt Volcano, 177 km southwest of Anchorage, Alaska, began on December 14, 1989, less than 24 hours after a swarm of earthquakes struck beneath the volcano. A huge cloud of ash heralded the volcano's fourth and most damaging eruption of this century. Volcanic ash generated by numerous explosive episodes from December 1989 through April 1990 caused significant damage to aircraft, severely disrupted air traffic above southern Alaska, and resulted in local power outages and school closures. The explosions produced hot, fast-moving clouds of ash, rock debris, and gas (pyroclastic flows) that swept across Redoubt's heavily glaciated north flank. These events triggered massive debris flows in Drift River valley that threatened an oil tanker terminal near the river's mouth. Partial flooding of the terminal compound on two occasions forced authorities to modify its operating procedures, which temporarily curtailed oil production from 10 platforms in Cook Inlet. The damage and loss of revenue from ash and debris flows are estimated to total more than $100 million, which makes this the second most costly volcanic eruption in the history of the United States, exceeded only by the 1980 eruption of Mount St. Helens in Washington.

The eruption not only focused public attention on the hazards posed by Redoubt Volcano and other volcanoes in the Cook Inlet region, but also demonstrated the value of monitoring volcanoes and the capability of providing forecasts of impending eruptions. The recently established Alaska Volcano Observatory (AVO) monitors the active volcanoes west of Cook Inlet in order to detect signs of volcanic unrest that may lead to an eruption and conducts geologic studies to assess the hazards the volcanoes pose to life and property. A seismic network centered on Redoubt became fully operational in October 1989 as part of the AVO monitoring program, and a detailed assessment of hazards from Redoubt (Till and others, 1990) was nearly finished when the volcano began showing signs of renewed activity in mid-December. These measures—plus the experience gained by scientists monitoring eruptions in the 1980's at Mount St. Helens in Washington, Nevado del Ruiz in Colombia, and Augustine Volcano in Alaska—enabled AVO to provide accurate information about Redoubt's activity and to issue advance warnings for several explosive episodes.

This report summarizes the Alaska Volcano Observatory's observations during the first nine months of the 1989–90 eruption of Redoubt Volcano and discusses the hazards and effects of the eruption sequence.

Highlights of the Eruption and Monitoring

The activity of Redoubt during the first nine months of the 1989–90 eruption was not as violent—and did not produce as much erupted material—as some other eruptions in the world in this century; nor were effects of this activity unexpected. Nevertheless, monitoring the volcano's activity provided valuable lessons for mitigating volcanic hazards in the future, not only in Alaska but elsewhere in the United States and the world. Principal observations include the following:

- The explosive onset of the eruption on December 14 was preceded by only about 24 hours of intense seismic activity. Because the volcano was being monitored, this was sufficient time for AVO to warn officials and the public of Redoubt's restlessness, and for AVO and other Federal, State, and local government agencies to activate emergency plans before eruptive activity began.
- Increases in the rate of seismicity beneath the volcano were the basis for short-term warnings issued by AVO before major explosive episodes on December 14 and January 2 and before moderate explosive episodes on March 23 and April 6. AVO monitored the seismic activity beneath Redoubt 24 hours a day in order to enable scientists both to alert aviation and public officials of the increased potential for ash and debris flows and to determine when such events were in progress, especially at night and when the volcano was obscured by clouds. Not all significant explosive episodes were forecast, however, because a seismic station on the volcano was destroyed early in the eruption sequence and also because some of the smaller explosions were not preceded by detectable changes in seismicity.
- The size and type of volcanic activity that occurred during the Redoubt eruption were typical of the volcano's past activity as inferred from the geologic record (Till and others, 1990). Analyses of hazards based on a

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volcano's eruptive history can be used in long-term planning of land use and investment in volcanic areas to help minimize the damaging effects of future eruptions. The Drift River Terminal was built in 1967, before such a hazard assessment was initiated.

- Volcanic ash is the most common and widespread volcanic hazard in Alaska; it is especially dangerous to aircraft. At least four commercial jet aircraft suffered damage from encounters with airborne ash during the first three months of the eruption. The most serious occurred on December 15 when a Boeing 747 jetliner carrying 231 passengers entered an ash cloud 240 km northeast of Redoubt. The jet lost power in all four engines and dropped about 4,000 m in altitude before the pilot succeeded in restarting the engines. The plane landed safely in Anchorage, but sustained an estimated $80 million in damage (Steenblik, 1990). Although existing technology cannot always track the movement of ash away from a volcano in real time, this near-tragic incident prompted AVO and other government agencies to search for ways to provide better information to the airline industry regarding forecast wind direction and speed and eruptive activity.
- Numerous floods of water, ice, and volcanic-rock debris (debris flows) inundated the Drift River valley when explosive activity disturbed portions of the volcano's extensive cover of snow and ice. Pyroclastic flows swept across Drift glacier and eroded and melted several hundred million cubic meters of snow and glacial ice, generating water that combined with sediment to cause massive debris flows. The largest debris flows, on January 2 and February 15, entered the Drift River Terminal from Rust Slough and damaged its logistical support facilities. No oil, however, was spilled. Although the likelihood of flooding in the Drift River valley was recognized before the 1989–90 eruption, uncertainties in estimating various contributing factors prevented scientists from predicting the magnitude of the debris flows. These uncertainties included the type and magnitude of volcanic activity, the volume and rate of snowmelt and icemelt during different types of volcanic activity, and the volume of sediment that could be incorporated, transported, and deposited along the Drift River channel during a single flood event.
- Recently developed seismic data acquisition and analysis systems using relatively low cost personal computers (PC's) proved extremely effective in monitoring seismicity beneath Redoubt during the eruption. These systems permitted scientists both to quantify the volcano's seismic activity on a minute-by-minute basis and to detect subtle changes in the character of the seismicity before some eruptions. Since these PC-based systems are easily portable, it will be possible to install similar seismic systems quickly during future volcanic crises.
- New experimental systems were effective in detecting large ash plumes and volcanic debris flows. Lightning discharges associated with several large plumes of ash were detected with a system designed for locating cloud-to-ground strikes, and debris flows in the upper Drift River valley were detected by an array of seismometers especially sensitive to high-frequency vibrations of the ground.

INTRODUCTION

Redoubt Volcano lies near the northeast end of the Aleutian volcanic arc, an active chain of volcanoes that extends 2,500 km from near Anchorage southwest along the Alaska Peninsula to the western Aleutian Islands (fig. 1). At least one volcano in the chain erupts, on average, each year (Simkin and others, 1981). Scientists have identified more than 40 historically active volcanic centers along the chain, and they are particularly concerned about volcanoes whose eruptions could affect the Cook Inlet region, where 60 percent of Alaska's population resides and which is the State's major supply, business, and financial center (fig. 2). Three volcanoes west of Cook Inlet—Mount Spurr, Redoubt, and Augustine—have erupted ash over Cook Inlet population centers seven times since 1900. Recently, geologists identified about 90 different layers of volcanic ash in the upper Cook Inlet region that formed during the past 10,000 years (Riehle, 1985). These layers record only a small percentage of the eruptions thought by scientists to have occurred during this time. At least 30 of the layers are attributed to eruptions of Redoubt Volcano, and 35 layers are attributed to the Crater Peak vent on nearby Mount Spurr.

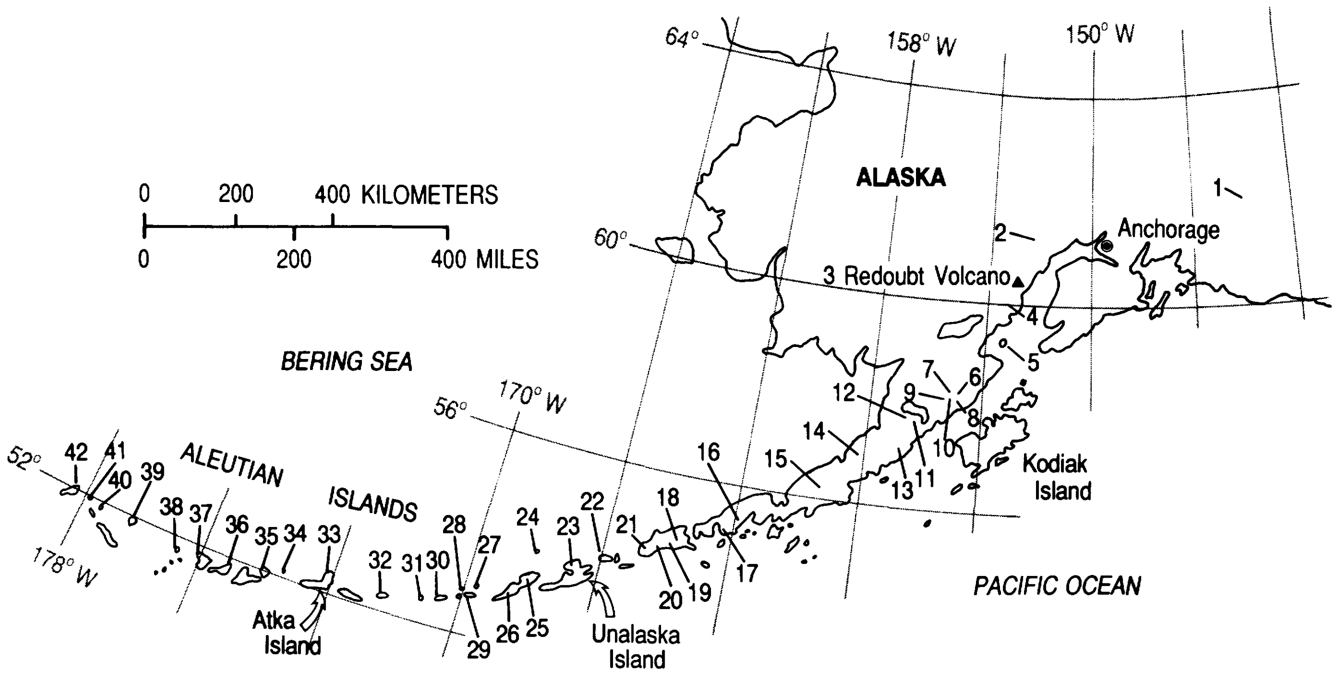
The potential for future hazardous eruptions near Cook Inlet led Congress to support an expanded Alaska volcano monitoring program in 1988. The Alaska Volcano Observatory (AVO) was formally established in 1988 to better monitor unrest at active volcanoes in Alaska and to assess the hazards they pose to life and property. AVO is a cooperative program consisting of scientists and facilities of the U.S. Geological Survey (USGS) in Anchorage, Alaska, Vancouver, Wash., Menlo Park, Calif., and Hawaii; the Geophysical Institute of the University of Alaska in Fairbanks (UAGI); and the Alaska Division of Geological and Geophysical Surveys (ADGGS) in Fairbanks (fig. 3). Although its participants are widely dispersed, the observatory serves as a coordination center for the study of Alaskan volcanoes and the dissemination of volcanic-hazard information. The goals of AVO are as follows:

- to assess the nature, likelihood, and timing of volcanic activity
- to evaluate potential volcanic hazards associated with future eruptions, including the types of activity, effects, and areas at risk
- to provide timely and accurate information on volcanic hazards, and warnings of impending dangerous activity to local, State, and Federal officials and the public

Redoubt Volcano

Redoubt Volcano is a large steep-sided composite volcano 3,108 m high. It is constructed of alternating layers of lava and ash and other fragmented volcanic rock debris formed by explosive eruptions over the past several hundred thousand years. Ten glaciers radiate from its summit region, which includes an ice-filled crater 1.8 km in diameter (see frontispiece). Breached to the north, the crater is the source of Redoubt's longest glacier, informally named Drift glacier. The glacier extends 8 km down a canyon incised in the volcano's north flank and across the Drift River valley to within 50 m of the north valley wall, forming a broad, rounded piedmont lobe. The volcano is drained to the north by Drift River, to the east by Redoubt Creek, and to the south by the Crescent River, all of which flow into Cook Inlet (fig. 4).

Redoubt Volcano lies within the rugged Lake Clark National Park and Preserve and is visited infrequently, mostly by outdoor enthusiasts and scientists. The closest facility with year-round residents is an oil-storage terminal built in 1967 at the mouth of Drift River, 35 km downstream from the volcano, where the river flows across a broad delta (fig. 5). Oil is pumped from 10 oil-well platforms in western Cook Inlet via a buried pipeline to the storage terminal, then onto tankers at a loading platform just offshore. The terminal can store a total of 1.9 million barrels (83.6 million gallons) of oil in seven tanks. Prior to the eruption, the terminal was bordered on the north and east by an L-shaped levee 3.6 m tall that was designed to divert



EXPLANATION

1 Mt. Wrangell
2 Mt. Spurr
3 Redoubt Volcano
4 Iliamna Volcano
5 Augustine Volcano
6 Mt. Katmai
7 Novarupta
8 Mt. Trident
9 Mt. Mageik
10 Mt. Martin
11 Mt. Peulik
12 Ukinrek maars
13 Mt. Chiginagak
14 Aniakchak caldera
15 Mt. Veniaminof
16 Pavlof Volcano
17 Mt. Dutton
18 Isanotski Peaks
19 Shishaldin Volcano
20 Fisher Caldera
21 Westdahl Peak
22 Akutan Peak
23 Makushin Volcano
24 Bogoslof Island volcano
25 Okmok Caldera
26 Mt. Vsevidof
27 Kagamil Island volcano
28 Carlisle Island volcano
29 Mt. Cleveland
30 Yunaska Island volcano
31 Amukta Island volcano
32 Seguam volcano (Pyre Peak)
33 Korovin Volcano
34 Kasatochi Island volcano
35 Great Sitkin Volcano
36 Kanaga Volcano
37 Tanaga Volcano
38 Mt. Gareloi
39 Mt. Cerberus
40 Little Sitkin caldera
41 Segula Peak
42 Kiska Volcano

Figure 1. Historically active volcanoes in Alaska.

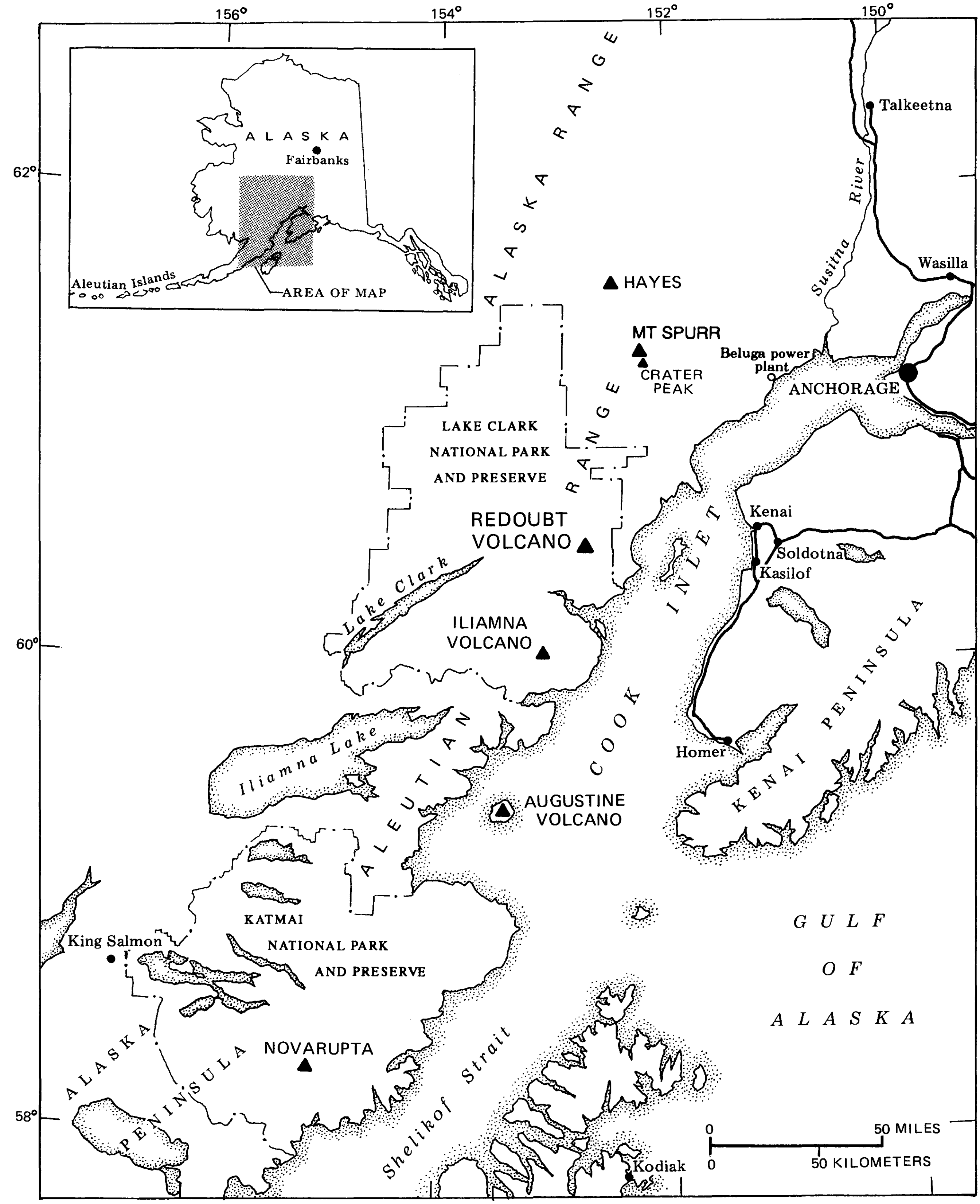


Figure 2. Geographic features of Cook Inlet region. Solid triangles are volcanoes.

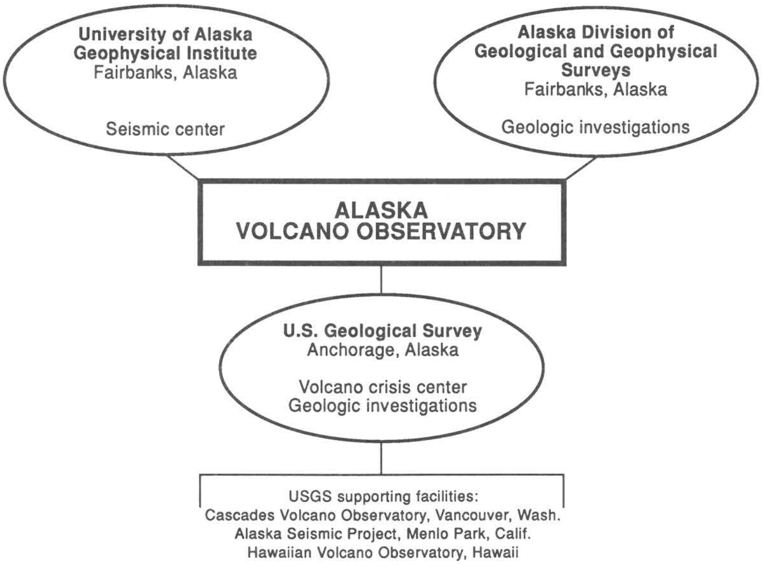


Figure 3. Institutional components of the Alaska Volcano Observatory (AVO).

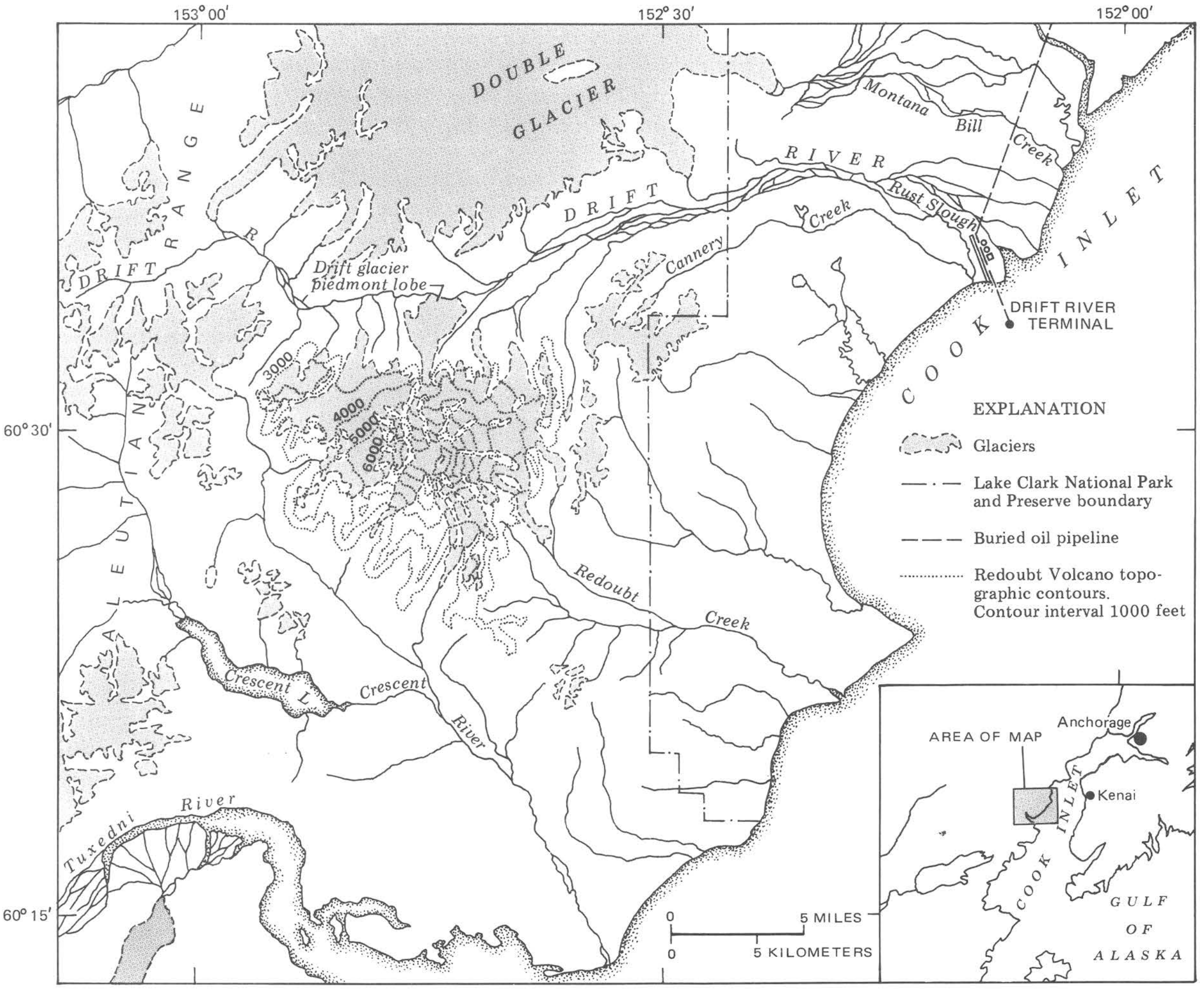


Figure 4. Topography of Redoubt Volcano and location of drainages and the Drift River Terminal.

high-water flows of the Drift River away from the facility. Individual storage tanks are surrounded by 2.4-m-tall berms designed to contain oil in the event of a leak. In addition to the tanks, the Drift River Terminal includes an airstrip and several buildings for living quarters and maintenance and operational support.

Eruptive History

Volcanism at Redoubt began as early as about 900,000 years ago, but the bulk of the cone was formed in the past 200,000 years (Till and others, 1990). An early cone-building period is marked by numerous thin (less than 6 m) basalt and basaltic-andesite lava flows, and layers of ash and coarser fragmented volcanic debris. The volcano's upper cone consists of thick (30 to 60 m) andesite lava flows and a voluminous apron of pyroclastic debris. Redoubt has a history of intermittent explosive eruptions accompanied by pyroclastic flows and debris flows, some much larger than those that were generated during the 1989–90 eruption (Till and others, 1990; Riehle and others, 1981). These larger pyroclastic flows, however, occurred during the early history of the volcano when the composition of the magma was dacite, which tends to produce more explosive activity and more voluminous pyroclastic flows than the andesite magma that is currently being erupted. The recent history of the volcano suggests that a return to highly explosive eruptions and extensive pyroclastic flows is not very likely during the present activity.

Before the current eruption, the largest known debris flows at Redoubt were those that swept down Crescent River valley all the way to Cook Inlet (see fig. 4) about 3,500 years ago and deposited rock debris that dammed Crescent Lake (Riehle and others, 1981). Numerous small mounds near the lake are remarkably similar to mounds of the volcanic landslide deposit that formed during the eruption of Mount St. Helens on May 18, 1980. This similarity suggests that the debris flows probably accompanied a large landslide or partial collapse of Redoubt's south flank (J.R. Riehle, oral commun., 1990). Sedimentary deposits also suggest that at least four and possibly six major debris flows flowed through Drift River valley to Cook Inlet during the past 200 to 400 years (Till and others, 1990).

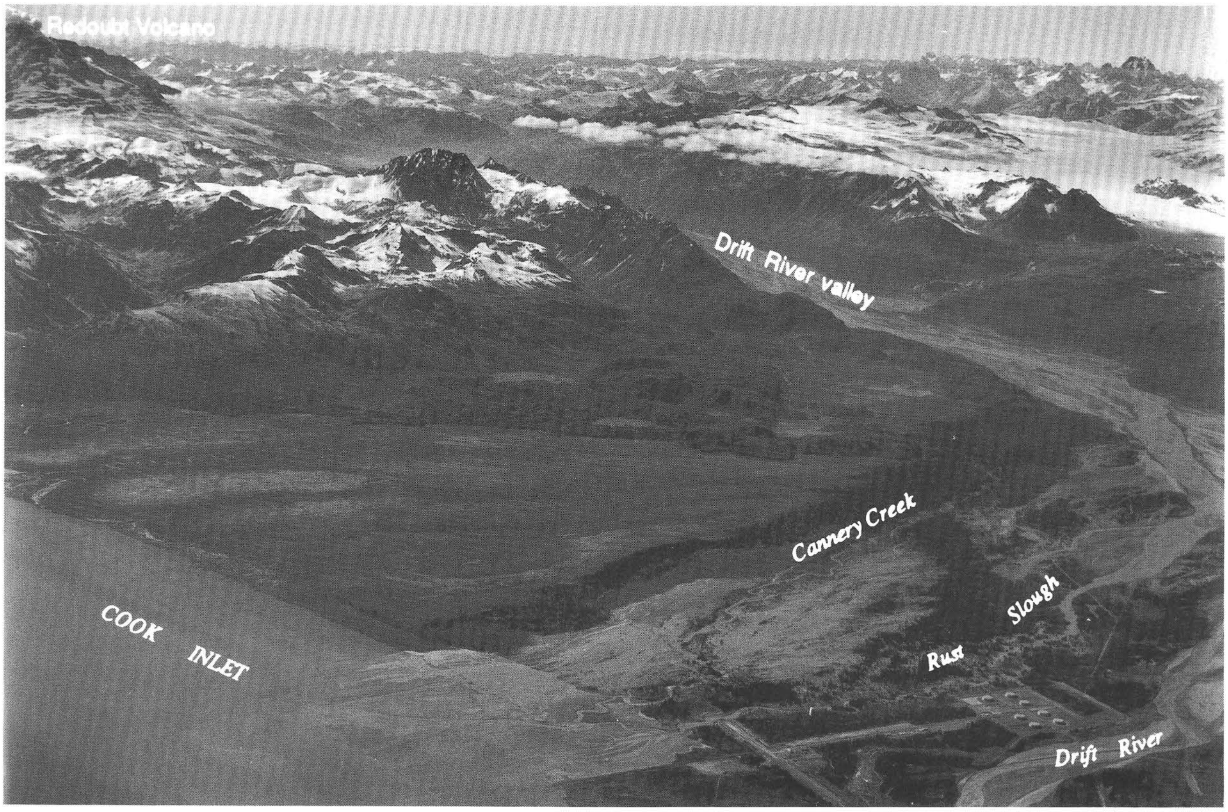


Figure 5. Aerial photograph of Redoubt Volcano, Drift River valley, Rust Slough, Cannery Creek, and Drift River Terminal (between Rust Slough and Drift River). View to west. Photograph by Steven R. Brantley on April 27, 1990.

More recently, during eruptive activity in January 1966, a debris flow swept down Drift River valley to Cook Inlet and inundated the site where the oil terminal was subsequently located. A seismic-exploration crew trapped near the site had to be rescued.

Regional Geologic Setting

In recent decades, scientists have learned that the earth's crust is divided into many large "plates" that move relative to one another. An average of 80 km thick, these rigid plates are spreading apart from, sliding past, or colliding with each other in slow motion on top of the Earth's hot pliable interior. The volcanoes of southern Alaska, including Redoubt Volcano, lie just landward of the boundary between the Pacific and North American plates. Here the Pacific plate is thrust beneath the North American plate at a rate of about 6 to 8 cm per year along a gently dipping geologic fault which forms the Aleutian trench and which extends in an arc from south-central Alaska to the west end of the Aleutian Islands (fig. 6). As the Pacific plate is thrust beneath the continent and the Aleutian Islands, it bends downward. Earthquakes, which accompany the downward movement of the Pacific plate, mark the top of the relatively cold, brittle downgoing plate (fig. 7). As the Pacific plate descends, rock in the overlying plate is partially melted. Some of this newly formed magma rises toward the Earth's surface to form the volcanoes west of Cook Inlet.

CHRONOLOGY OF THE 1989–90 ERUPTION

Pre-Eruption, November 20–December 13, 1989

The first report of unusual activity at Redoubt was received by AVO late on the afternoon of December 8, 1989, when a steam plume rising from high on Redoubt's north flank was visible from Anchorage. Seismicity at this time was at a low level, and scientists interpreted the plume to reflect a slight increase of geothermal heat in the summit crater. Clouds completely obscured the volcano between December 9 and 14, preventing scientists from making observations of the summit crater until after the eruption began on December 14. Scientists at AVO later learned that a pilot flying less than 1 km southwest of Redoubt on November 20 had noticed a small steam "cloud" rising a few hundred meters above the summit crater and a strong sulfur odor downwind from the volcano. Another pilot observed a small steam plume on December 3.

Elevated levels of seismicity were first observed on December 13, and the seismicity rapidly developed into an intense swarm of earthquakes. More than 4,000 earthquakes smaller than magnitude 2 were recorded in the 24 hours before the first eruption on December 14. The rapidly increasing seismicity beneath Redoubt prompted AVO to notify the Department of Emergency Services, the Federal Aviation Administration, the National Weather Service, the Drift River Terminal, and the news media of the increased volcanic hazard (fig. 8). A statement was issued late in the afternoon on

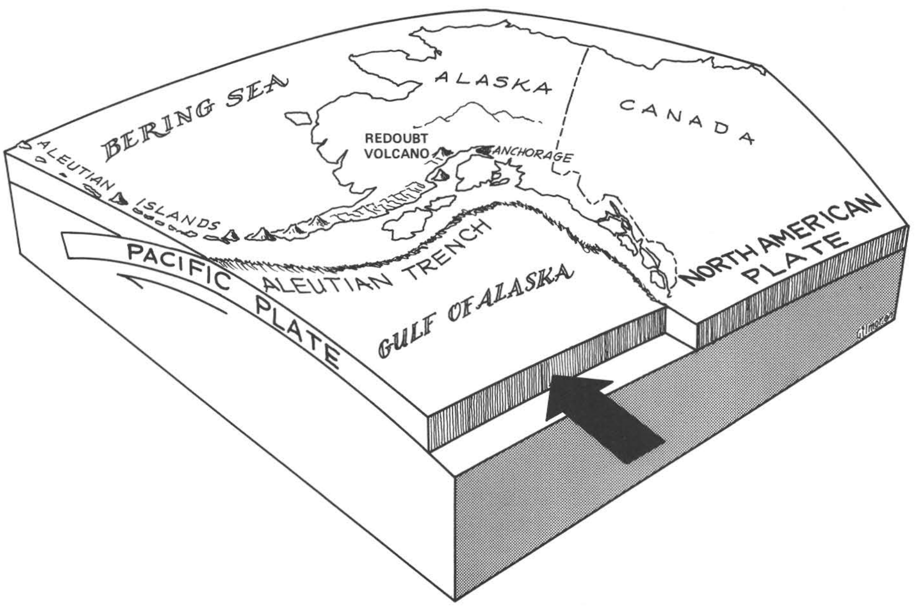


Figure 6. The Pacific plate being thrust beneath the North American plate along the Aleutian trench. Sketch by Robert F. Gilmore.

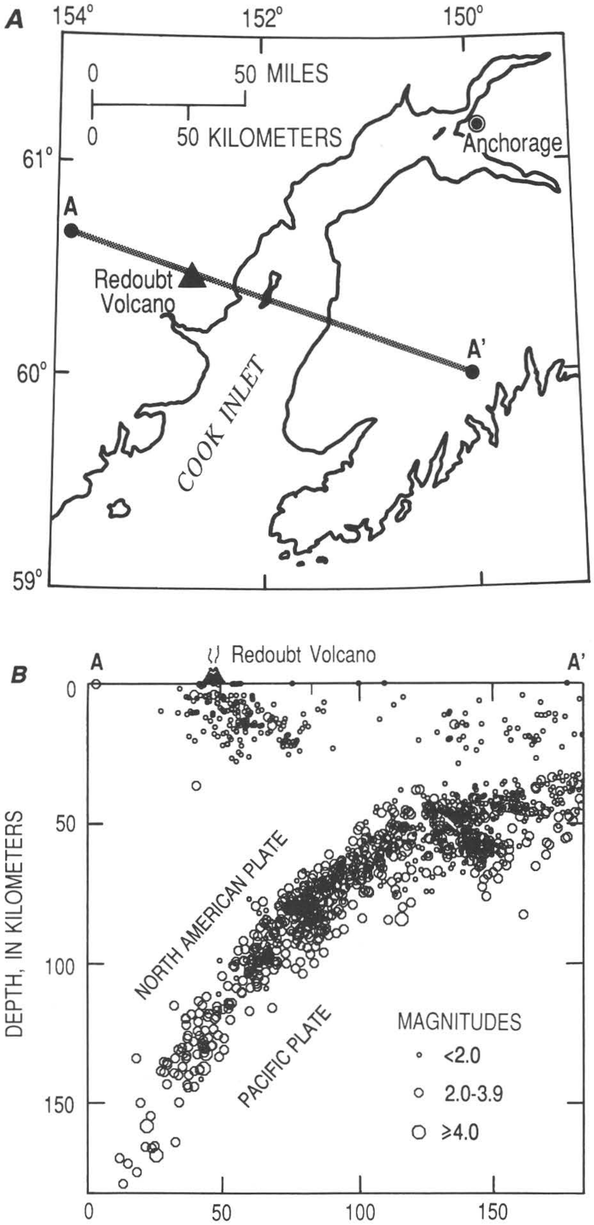


Figure 7. Location of earthquakes beneath Cook Inlet region between January 1980 and November 1989. *A*, Map showing location of cross section A-A', which lies above the boundary between the Pacific and North American plates. *B*, Vertical section through the Earth showing the location of earthquakes within 50 km of cross section A-A'. Most of the earthquakes occurred in a landward-dipping zone that lies in the upper part of the descending Pacific plate. A zone of shallow earthquakes lies beneath the line of active volcanoes on the west side of Cook Inlet.

December 13 that noted, "It is impossible to state at this time whether the seismic activity is a precursor to a volcanic eruption, but that is a possibility of some concern."

Most of the earthquakes were located at depths less than 1 to 2 km beneath the crater and consisted of low-frequency events, one of two main types of earthquakes usually associated with volcanoes (fig. 9*A*). (The second type consists of high-frequency events at greater depths, fig. 9*B*, and will be discussed later). This intense seismicity was likely caused by the rise of magma (molten rock) inside the volcano and the magma's interaction with ground water to produce highly pressurized water and volcanic gases, predominantly steam. As the magma and gases moved through existing fractures and caused new fractures to form, the upper part of the volcanic cone was weakened, and a pathway for the magma was created.

December 14–December 21, 1989

A major explosive eruption on December 14 at 9:47 a.m. AST (Alaska standard time) was the first of several explosive episodes that opened a new vent in the summit crater and repeatedly spread tephra throughout south-central Alaska (figs. 10 and 11). Tephra refers to all airborne products of an eruption which fall from a volcanic plume, including ash-size (less than 2mm in diameter) and larger rock fragments. During the next 5 days, intermittent tephra plumes carried by strong winds blanketed south-central Alaska with thin layers of gritty ash. The explosive activity also generated large debris flows in Drift River valley that swept past the Drift River Terminal. Though the terminal was not flooded, its vulnerability to larger debris flows was clearly demonstrated, and crews were evacuated on December 14.

In the first 25 hours of the eruption, four explosive episodes produced giant columns of tephra as high as 12,000 m above sea level, where strong winds blew the tephra several hundred kilometers to the northeast (table 1). Initially, the tephra consisted primarily of shattered rock and mineral fragments derived from preexisting rocks within the volcano. But by the morning of December 15, the character of the tephra changed: it became rich in fresh glass shards and pumice fragments, which form when new gas-rich magma is explosively expelled (fig. 12). This change indicated opening of a vent in the summit crater; the vent had been cleared of older rocks, and magma was now escaping through it to the surface. The majority of pumice was erupted during the most energetic episode, which began at 10:15 a.m. on December 15. Within 20 minutes,

Figure 8. Seismic center at the University of Alaska Geophysical Institute in Fairbanks. Seismic data are recorded digitally on a mainframe and personal computer and displayed on seismographs shown in foreground. AVO's warnings of eruptive activity at Redoubt Volcano were based on seismicity beneath the volcano. Photograph by James Coccia, University of Alaska Geophysical Institute.

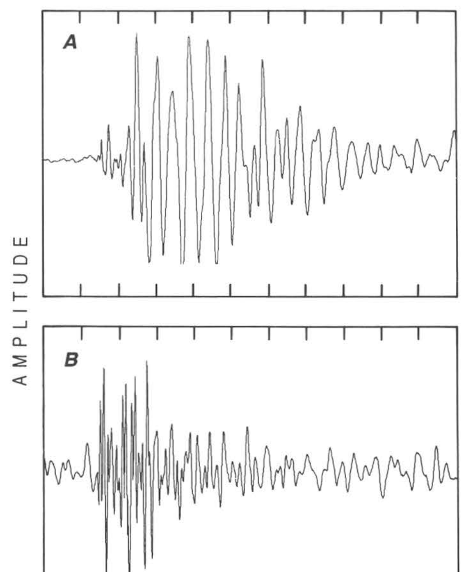


Figure 9. Typical seismograms illustrating the two main types of seismic events recorded at Redoubt Volcano. A seismogram is a graphical representation of the motion of the ground at the location of a seismometer—an instrument that measures ground motion. The amplitude of the ground shaking is represented by the vertical deviations of the peaks and troughs from the normal baseline. Time is recorded in the horizontal direction. These seismograms are from seismic station RDN on the north flank of Redoubt (see fig. 34). *A*, Low-frequency event originating near the summit of the volcano. *B*, High-frequency event occurring at a depth of several kilometers beneath the volcano. The frequency of the seismic signal is expressed in terms of the number of peaks or troughs that occur during one second of time. Note that for a given interval of time there are more peaks in the bottom seismogram; in other words, it is characterized by a higher dominant frequency. In this figure, the frequencies (number of peaks per second, or hertz) are about 2.3 and 5.0 hertz (Hz) for the upper and lower seismograms, respectively.

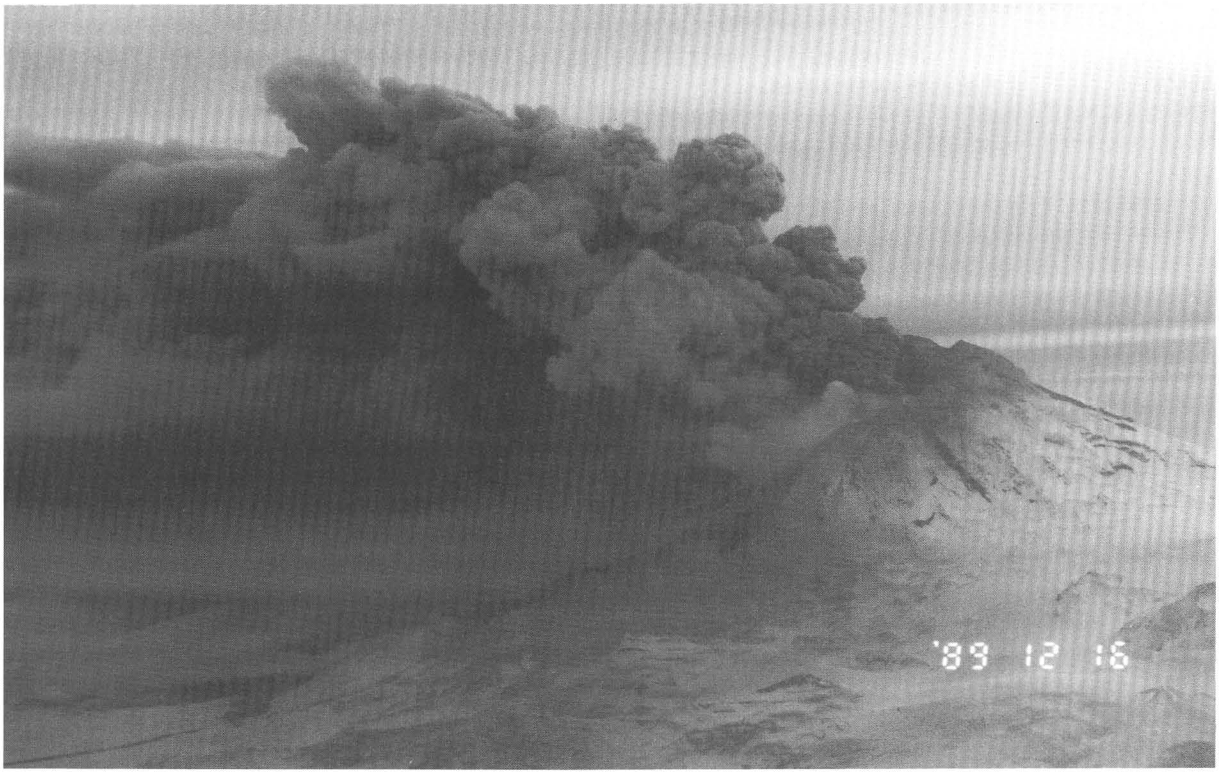


Figure 10. Tephra plume rising from Redoubt's crater to about 5,000 m above sea level and drifting to the northeast on December 16, 1989. Photograph by Hollis Twitchell, National Park Service.

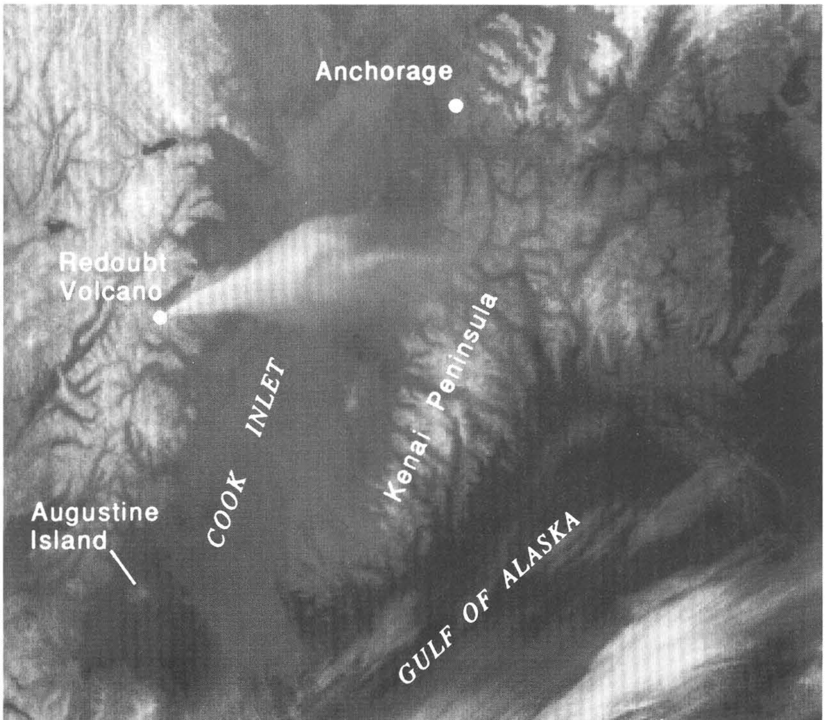


Figure 11. Nighttime Advanced Very High Resolution Radiometer image from a National Oceanic and Atmospheric Administration (NOAA) satellite of Redoubt Volcano in eruption at 3:17 a.m. AST (Alaska standard time) on December 16, 1989. The tephra plume extends downwind from Redoubt across Cook Inlet and over the Kenai Peninsula. Compare to figure 2. Snow, clouds, and plume are white; land and water are shades of gray to black. The image was processed by the EROS Alaska Field Office (U.S. Geological Survey) in Anchorage, Alaska.

Table 1. Chronology of the 1989-90 eruption of Redoubt Volcano

[X, volcanic activity occurred; na, not applicable; ?, volcanic activity uncertain]

		Type of volcanic activity				
Day	Time[1]	Explosion[2]	Dome collapse	Debris flow	Plume height, azimuth[3]	Remarks
December 1989						
14	9:47 am	X(17)	na	X	>10 km, NE	First major explosive episode.
15	1:40 am	X(12)	na	?	?	Seismicity consists of tremor, probably
	3:48 am	X(10)	na	?	?	accompanied by explosive activity.
	10:15 am	X(40)	na	X	>12 km, NNE	Major explosive episode generates pyroclastic flow and avalanche of snow, ice, and rock down Drift glacier. Debris flow crests 3 m below top of levee at Drift River Terminal.
16-18		X	na	?	<7 km, NE/SE	Nearly continuous ejection of tephra from crater.
19	6:30 am	X(9)	na	X	>9 km, ?	
January 1990						
2	5:48 pm	X(26)	X	X	>12 km, NNE	Explosions accompanied by collapse of
	7:27 pm	X(61)	X	X	>12 km, NNE	lava dome down north flank; debris flow causes flooding at Drift River Terminal.
8	10:09 am	X(15)	X	X	>12 km, ESE	No precursory seismicity detected.
11	10:01 am	X(5)	?	?	>9 km, ?	
	1:42 pm	X(12)	?	?	?	
16	10:48 pm	X(13)	?	X	>11 km, NNE	Minor debris flow in upper Drift River.
February 1990						
15	4:10 am	X(20)	X	X	>10 km, SE	Pyroclastic flow travels about 12 km NE of crater.
21	12:32 am	X(6)	X	X	9 km, ENE	
24	5:05 am	X(4)	X	X	9 km, NE	
28	9:47 am	X(5)	X	X	8 km, ?	
March 1990						
4	8:39 pm	X(8)	X	X	12 km, NNE	Drift River flows into Cannery Creek for the first time.
9	9:51 am	X(10)	X	X	10 km, WSW	
14	9:47 am	X(14)	X	X	12 km, NE	
23	4:04 am	X(8)	X	X	>10 km, NE	
29	10:33 am	X(7)	X	?	?, NNE	Vigorous "steam plume" reported by pilots above 15 km.
April 1990						
6	5:23 pm	X(7)	X	X	9 km, E	
15	2:49 pm	X(8)	X	X	>10 km, NW	
21	6:11 pm	X(4)	X	X	>8 km, NNW	

[1]Alaska Standard Time.

[2]Numbers in parentheses indicate explosive activity in minutes, based on duration of seismicity recorded at seismic stations on Mt. Spurr (see figs. 2 and 22).

[3]Estimated plume height above sea level; azimuth from Redoubt Volcano.

pumice fragments as large as 10 cm across were falling about 40 km downwind of Redoubt.

The initial explosive episodes also triggered several debris flows consisting of water, ice, and rock debris in Drift River that swept past the oil terminal and into Cook Inlet. The largest debris flow crested about 8 m above the river channel near the Drift River Terminal, 3 m below the top of the outer protection levee that borders the storage tanks. Blocks of ice probably covered the surface of the debris flow, for when the crews returned to the terminal on December 17 the channel was littered with ice blocks as large as 10 m across and lined with ice levees 3 m tall. These levees partly protected the terminal because they confined the debris flow to the main channel. The largest debris flow was most likely triggered by the explosive episode at 10:15 a.m. on December 15, which was the most energetic of the early explosive episodes.

The triggering mechanisms of these debris flows are not well understood because the precise timing of the debris flows relative to specific eruptive episodes is not known. However, the debris flows were probably caused by fast-moving pyroclastic flows (avalanches of hot pumice, ash, rock debris, and gas) that swept down Redoubt's north flank and across Drift glacier and melted massive volumes of snow and ice. When geologists investigated the upper Drift River valley at the base of Redoubt on December 26, they discovered a multi-layered deposit as thick as 10 m consisting of snow, blocks of glacial ice as large as 2.5 m across, rock debris, and some pumice. The deposit extended at least 4 km downstream from the Drift glacier piedmont lobe. Field evidence indicates that some layers were wet when they formed and were overridden and partly eroded by subsequent flows of water. The complex deposit was probably the result of several avalanches of snow, ice, and rock debris that were triggered by pyroclastic flows moving down the upper flanks of the volcano.

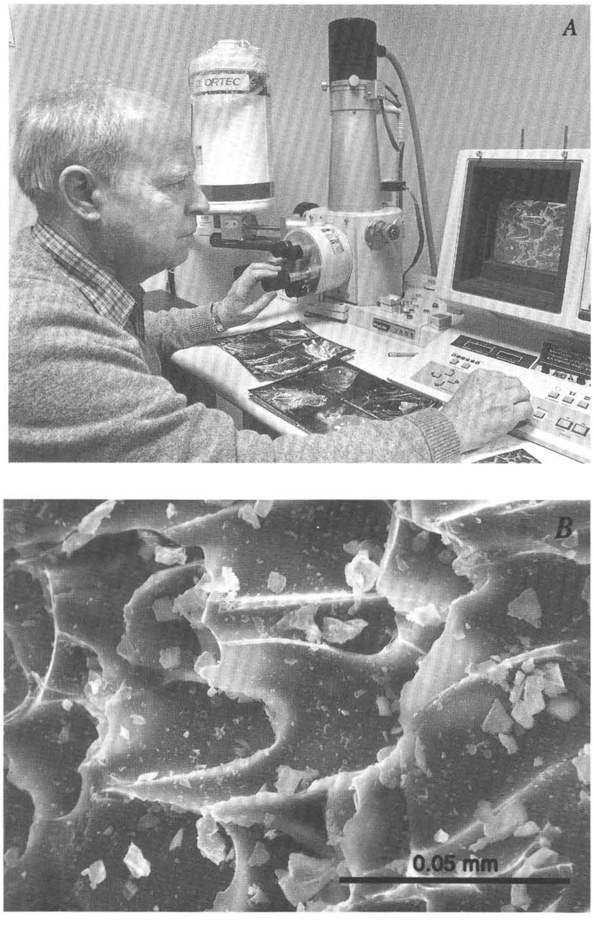


Figure 12. *A*, Scanning electron microscope (SEM) reveals the shape and type of ash particles erupted from Redoubt Volcano on December 15, 1989. Copyrighted photograph by Bill Roth, Anchorage Daily News, reprinted by permission. *B*, SEM view of volcanic glass with many elongate, thin, delicate walls between vesicles (bubbles). SEM view by Maurice Lynch, Minerals Management Service, Anchorage, Alaska.

Seismicity was highly variable from December 14 to 21. It consisted of periods of quiet, periods of tremor, and periods of intense seismicity associated with explosive activity. (Tremor is a continuous and rhythmic signal associated with the movement of fluids—magma and water—or gas within a volcano.) The initial explosive episodes were preceded and accompanied by shallow earthquakes of a low-frequency type discussed earlier (fig. 9*A*). These earthquakes were followed on December 16 by deeper earthquakes between 4 and 10 km beneath the crater (fig. 13). The deeper earthquakes consisted chiefly of a high-frequency type that is related to the brittle fracture of rock beneath a volcano (fig. 9*B*). They were likely associated with readjustment of stress in the rocks surrounding the magma conduit system as magma moved upward from deeper levels.

December 22, 1989–January 2, 1990

The character of the eruption changed on about December 22 from intermittent explosive activity to the extrusion of viscous lava. The lava gradually formed a steep-sided mound, called a lava dome, over the vent (fig. 14). Such domes are common features at composite volcanoes where lava extruded from a vent is too viscous to flow very far; lava of the Redoubt dome is andesite with a silica (SiO_2) composition ranging from about 58 to 63 percent (see examples in table 2, p. 21). Its relatively high silica content makes andesite a moderately viscous type of lava. Seismicity indicates that this first dome likely began growing as early as December 22, though it was not seen by scientists until December 26. Small plumes of ash accompanied frequent rockfalls that swept down the steep north side of the dome. By January 1, the dome was perched precariously above Drift glacier and had an estimated volume of about 25 million m^3 (Alaska Volcano Observatory Staff, 1990).

Seismicity during growth of the first lava dome was similar to seismicity observed during the extrusion of viscous magma at other volcanoes, notably Mount St. Helens in Washington, Augustine Volcano in Alaska, and Usu volcano in Japan. At the station

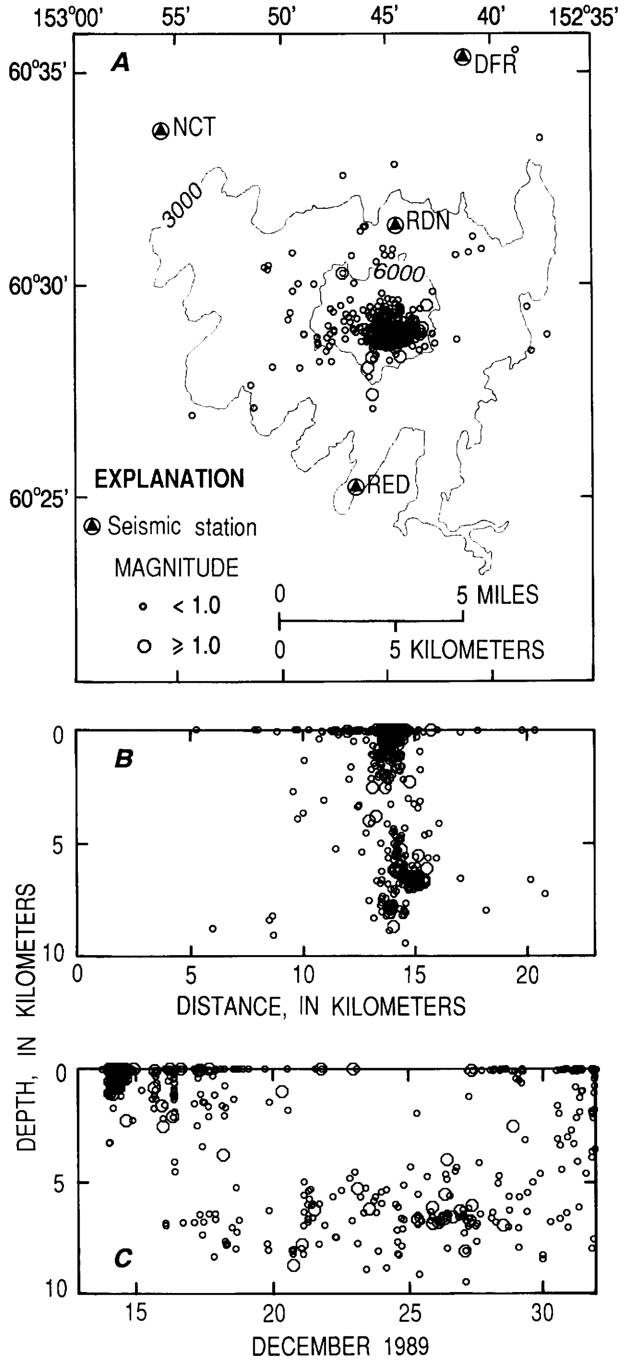


Figure 13. Seismicity at Redoubt Volcano, December 13–31, 1989. *A*, Spatial distribution of seismic events beneath Redoubt Volcano. Light lines are topographic contours, in feet. A fifth seismic station, RDT, is located east of this map (see fig. 34). *B*, Vertical cross section beneath Redoubt showing depth of seismic events shown in *A*. *C*, Diagram showing how depth of seismic events varied over time, from December 13–31. Note beginning of seismic events deeper than 4 km on December 16.

closest to the crater, small shallow earthquakes dominated the seismic record during extrusion. The number of seismic events began increasing steadily about December 28, and the seismicity again changed character with the return of low-frequency events on December 29 (fig. 9*A*). Scientists interpreted these changes as indications that the magma system beneath the dome was becoming increasingly pressurized, perhaps because of a "capping effect" of the growing dome. Accelerating seismic activity and the precarious position of the dome prompted AVO to issue warnings on January 1 and 2 of the possibility of "moderate to strong explosive activity" associated with collapse of the dome. On January 2 at 3:50 p.m., after discussions with AVO scientists, the Cook Inlet Pipeline Company evacuated its crews from the Drift River Terminal.

January 2, 1990

AVO's warnings were on the mark. Two powerful explosions at 5:48 p.m. and 7:27 p.m. on January 2 sent tephra plumes to heights of more than 12,000 m and destroyed more than 80 percent of the dome. A few minutes after the first explosion began, a pilot 65 km south of Redoubt described the activity as an intermittent "orange flame shooting straight up from the summit like a cannon" (Captain Jerry Friz, oral commun., 1990). Lightning from the eruption damaged the only seismic station then located on the volcano (station RDN on fig. 34), which impaired seismic monitoring until the station was repaired on January 9.

Both explosions were accompanied by partial collapse of the dome that generated fast-moving avalanches of hot blocks and ash down the north flank of

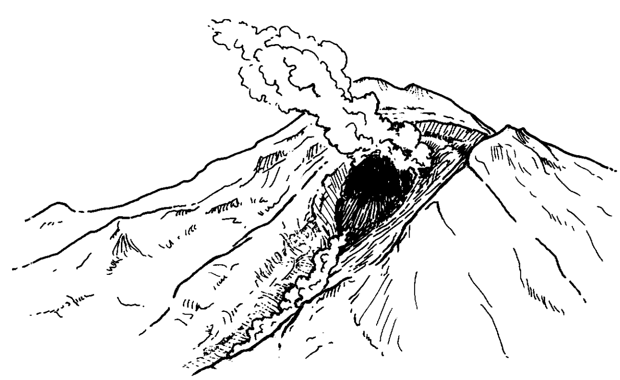


Figure 14. Sketch of the eruption's first lava dome, which formed in Redoubt's summit crater between about December 22, 1989, and January 2, 1990. Steam rising from bottom of canyon below dome was caused by stream of hot water melted from Drift glacier. Most of the dome was destroyed on January 2. Sketch by Bobbie Meyers.

Redoubt and across Drift glacier. The avalanches scoured and melted ice and snow from the glacier and caused the largest debris flow of the eruption (fig. 15). Field evidence indicates that the debris flow consisted of at least two pulses. Unlike earlier events, this debris flow contained a large proportion of hot rock debris from the dome, and it completely filled the 2-km-wide valley floor. Some rocks were as large as 8 m across. Trees as large as 0.8 m in diameter were toppled and whittled by the flowing debris into downstream-pointing bayonet-like shapes. The peak discharge of the debris flow about 22 km downstream from the crater was estimated to be 30,000–50,000 m^3/s, which is comparable to the peak discharge of the 1985 volcanic debris flow that destroyed Armero, Colombia (Alaska Volcano Observatory Staff, 1990), and slightly more than the average discharge of the Mississippi River.

Because of the deposition of debris, the main channel of the Drift River became clogged with sediment about 8 km upstream from Cook Inlet, forcing most of the debris flow into adjacent Rust Slough (fig. 16). Muddy water from Rust Slough entered the oil terminal from the west and south, inundating some buildings with water as deep as about 75 cm and disabling the facility's power generators. Flooding of the terminal forced the Cook Inlet Pipeline Company to temporarily curtail its operation in order to repair damaged equipment and to reassess its operating procedures.

Tephra from the explosions spread northeast from the volcano but resulted in only light ash fall at the Beluga power plant west of Anchorage and in Anchorage itself (fig. 2). However, the ash fall was sufficient to cause airlines to cancel flights. Near the volcano, the tephra deposit was as thick as 10 cm and consisted of tiny aggregate balls of wet ash, known as accretionary lapilli. These lapilli form when moisture and electrical charges develop within an expanding tephra plume. The tephra deposit did not contain pumice, and dense rock fragments were no larger than a few millimeters in diameter. The size of the tephra and the absence of fragments embedded in snow on the volcano argue against the dome being blasted apart by a series of explosions. These characteristics and the distribution of large dome rocks throughout the Drift River valley suggest that most or all of the dome was destroyed by catastrophic collapse and avalanche down the volcano's north flank.

January 8–February 14, 1990

Removal of most of the lava dome from the summit crater on January 2 left an open vent that provided an unobstructed pathway for magma to rise with relative ease, and seismicity declined to the lowest levels since the eruption began in December. On January 8, with no seismic warning, a sudden explosion destroyed the remainder of the dome. A mushroom-shaped column of tephra quickly formed above the volcano and spread east over the Kenai Peninsula within about 1 hour (fig. 17), turning day into night (fig. 18). Hot avalanches again swept down Drift glacier and triggered a relatively small debris flow containing dome rocks (fig. 19) and few ice fragments. The debris flow diminished in size within a few kilometers of the volcano, and no flooding occurred in the lower valley.

Two small explosive episodes on January 11 and 16 were followed by renewed extrusion of lava that

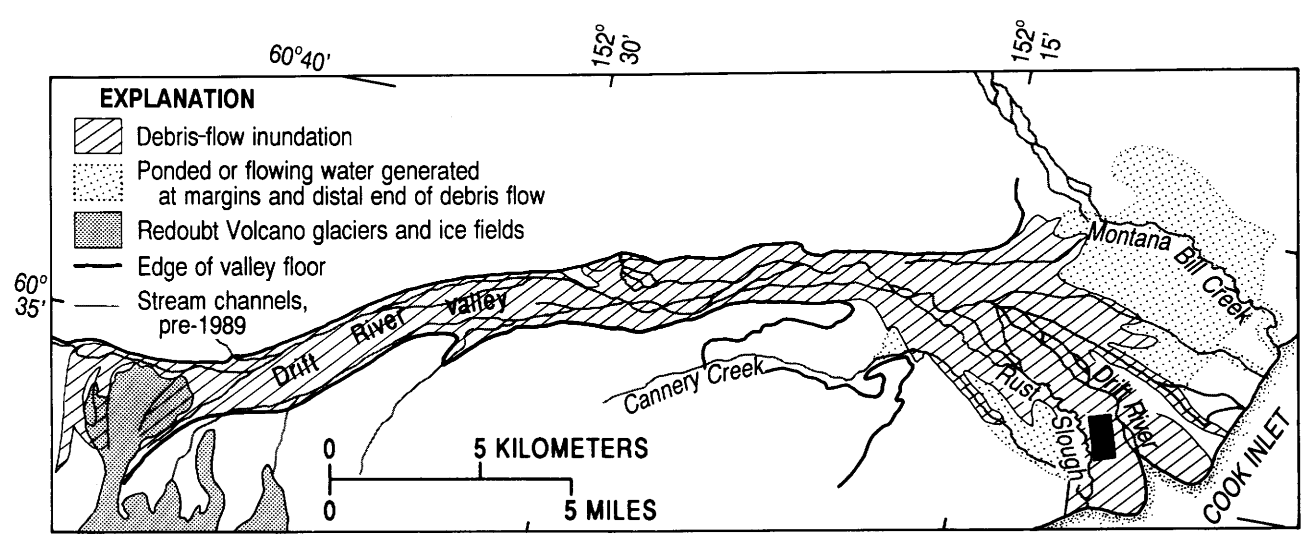


Figure 15. Approximate boundaries of area inundated by debris flow in Drift River valley on January 2, 1990. Some buildings in Drift River Terminal (black rectangle) were flooded with water as deep as about 75 cm.

built a new lava dome, which attained about one-third the volume of the first dome. No explosive events accompanied growth of the dome, but numerous rockfalls down its steep flanks generated ash-rich plumes a few hundred meters high. Seismicity consisted primarily of small shallow earthquakes.

By mid-January, more than 100 million m³ of ice had been removed from Drift glacier (Alaska Volcano Observatory, 1990). Pyroclastic flows and avalanches of hot debris from the dome eroded hundreds of gullies and enlarged crevasses on the glacier, forming a network of steep-walled channels tens of meters deep. Many of these merged with a narrow canyon that was carved along the axis of the glacier from the crater down to the piedmont lobe. Nearly all of the ice in the canyon was removed to bedrock; only vestiges of glacial ice remained on the canyon floor.

February 15, 1990

A weak increase in seismicity preceded by about 4 days a large explosion and the collapse of the second dome on February 15 at 4:10 a.m. Because the increase was much less dramatic than those preceding the December 14 and January 2 explosions, seismologists overlooked its significance and no warning of an impending eruption was issued. About 75 percent of the dome was removed in an avalanche of hot blocks and ash that swept down the north flank of Redoubt and across Drift glacier. A fast-moving ash cloud swept across Drift River valley and climbed 700 m up the north valley wall, which faces the volcano. This hot mixture of gas, ash, and gravel-sized rock debris burned and abraded small willow trees on the north valley wall and drove willow branches endwise into the snow at least 1 m. The ash cloud was diverted eastward by the valley wall at least 4 km, and it deposited ash along the way. On Redoubt, the ash cloud spread across slopes to the east and west of Drift glacier that had been unaffected in earlier eruptions, causing numerous snow avalanches and again destroying the critical seismic station that was struck by lightning on January 2.

The hot avalanche that swept across Drift glacier severely eroded its surface and generated a debris flow in Drift River that flowed to Cook Inlet. When geologists visited the glacier 10 hours after the event, the sandy deposits on the glacier still had a temperature of at least 230 °C, and the glacier surface was visibly more irregular and incised than it had been after the January 8 episode (fig. 20). Many large ice blocks were partly detached from gully walls. The debris flow rafted hot

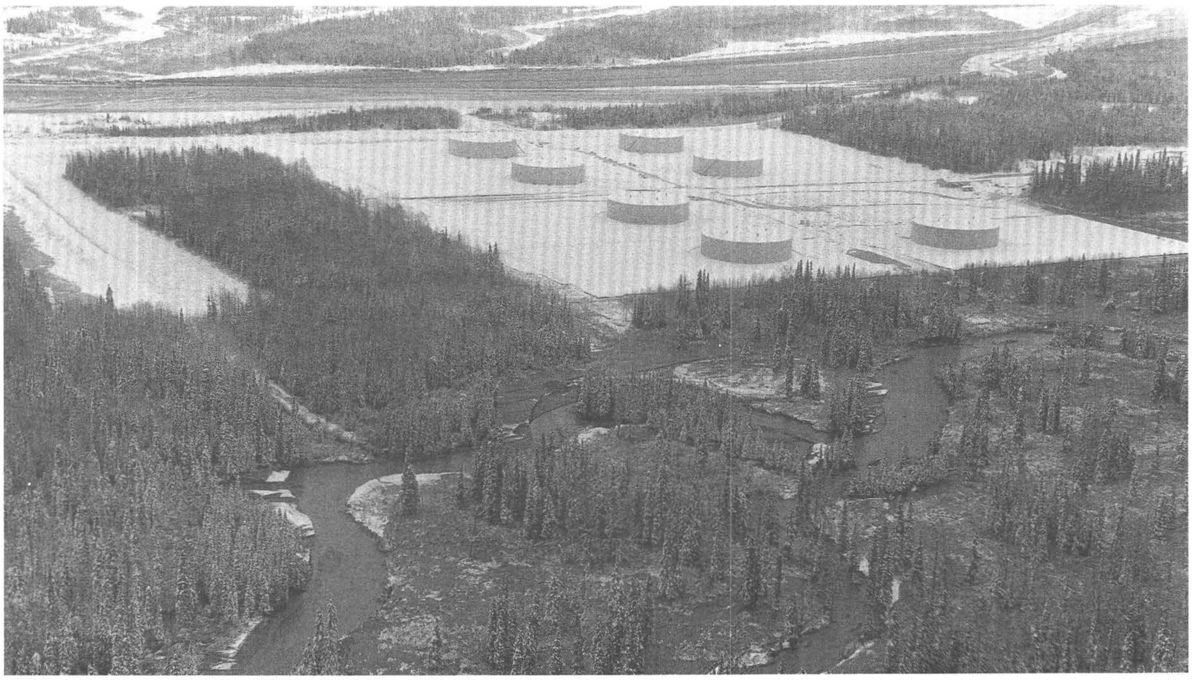


Figure 16. Storage tanks of Drift River Terminal between Rust Slough (foreground) and main channel of Drift River. The debris flow on January 2 diverted Drift River south into Rust Slough. The tanks can store about 1.9 billion barrels of oil; when the eruption began on December 14, 1989, about 830,000 barrels were stored in the tanks. View to east. Copyrighted photograph by Erik Hill, Anchorage Daily News, January 8, 1990; reprinted by permission.

Figure 17. Huge, eerie, anvil-shaped ash cloud moving toward the Kenai Peninsula from Redoubt Volcano on January 8, 1990. View to west. Copyrighted photograph by Roy Shapley, reprinted by permission.

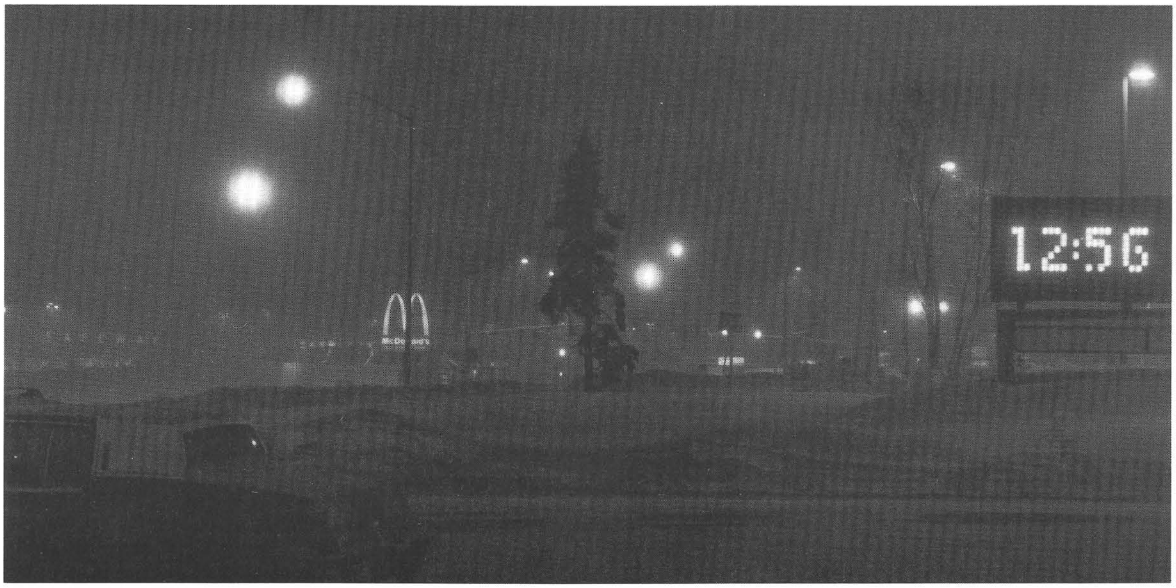


Figure 18. Daytime darkness in downtown Soldotna on the Kenai Peninsula at 12:56 p.m. during an ash fall from Redoubt Volcano. Copyrighted photograph by Thomas Weaver on January 8, 1990, reprinted by permission.

dome rocks, as large as 1 m across, and blocks of ice and snow down the Drift River valley. Field measurements made after the event suggest the debris flow had a velocity of about 60 km/hr at the base of the glacier and about 30 km/hr midway down the valley. Most of the debris flow went down Rust Slough, and muddy water inundated part of the oil terminal's runway. For the first and only time, water and debris topped the inner containment berm surrounding the tank closest to Rust Slough. No oil was spilled.

February 21–April 20, 1990

During the next two months, lava was extruded almost continuously to form a succession of domes that were mostly destroyed by explosions every 4 to 8 days. The explosions produced tephra plumes as high as 12,000 m (fig. 21) and hot avalanches of dome blocks and ash that triggered relatively small debris flows in Drift River valley. The avalanches continued to ravage the surface of Drift glacier, and the debris flows transported significant quantities of sediment to the upper Drift River. On the delta, the river changed its course several times between Rust Slough, Cannery Creek, and its original channel (fig. 4). Tephra was blown in almost every direction from the volcano between February and April (table 1), but only traces of ash were deposited in Anchorage and on the Kenai Peninsula. Earthquakes continued beneath the volcano at depths less than 10 km at approximately the same rate that had characterized the activity since mid-December.

The explosive episodes during this period were

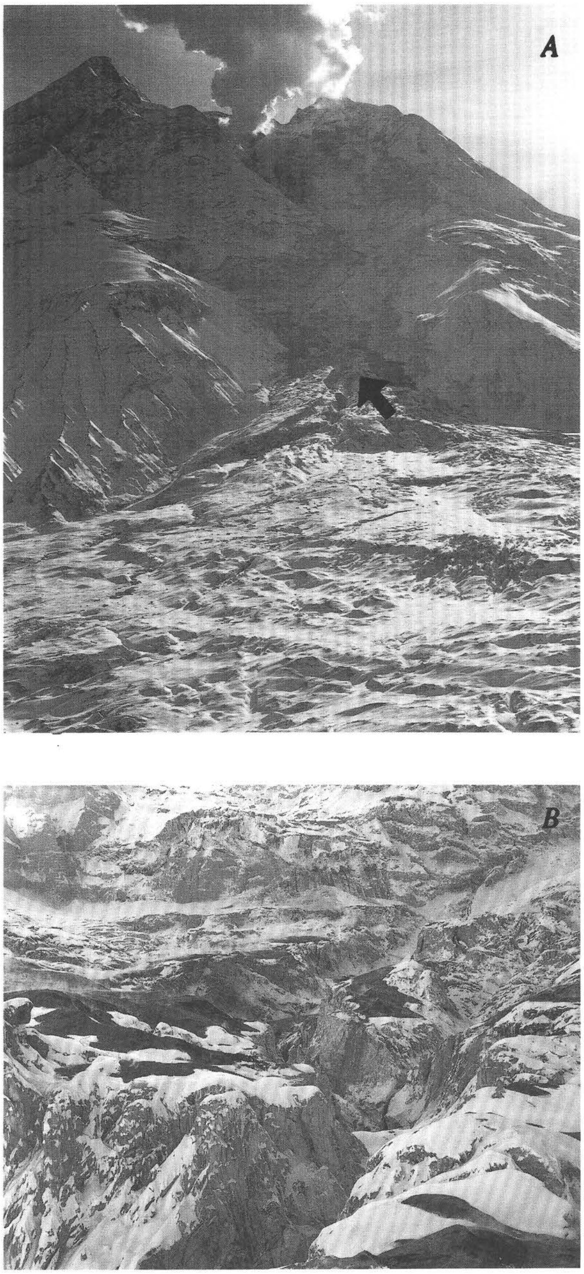


Figure 20. *A*, North flank of Redoubt Volcano looking across Drift glacier piedmont lobe (see fig. 4). Note channels eroded in Drift glacier. Dark areas on glacier are pyroclastic-flow deposits. *B*, Close view of channels in Drift glacier looking in direction indicated by arrow in *A*. The highly irregular surface of Drift glacier was eroded and melted by repeated pyroclastic flows generated by dome collapses in the summit crater. Photographs by Richard B. Waitt on March 4, 1990.

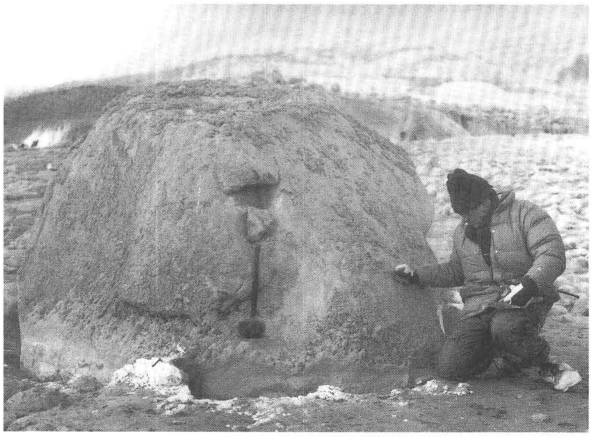


Figure 19. Block of the first lava dome, deposited in Drift River valley 5 km downstream from Redoubt Volcano. The block was transported downstream by a debris flow caused by an explosive episode on January 8, 1990. When measured 6 days later, the temperature of the rock was still 145 °C. Photograph by C. Dan Miller on January 14, 1990.

less energetic and of shorter duration than earlier explosive events and followed one another with remarkable regularity, averaging about 4.5 days apart until March 14, and 8 days apart through April (fig. 22). Between February 15 and March 4, there were no seismic stations operating on the cone of the volcano, which precluded the detection of precursory changes in seismicity during this interval. After a new station was established on the volcano, however, clear seismic precursors prompted AVO to issue advance warning before the explosions on March 23 and April 6. In addition to patterns of seismic activity, AVO scientists used the regularity of eruptions after February 15 to define time intervals within which explosions were most likely to occur. This statistical forecasting method was only partially successful. On this basis, advance warning was provided for an explosion on April 15, which occurred within a 3½-day forecast window announced by AVO on April 12; no seismic precursors were detected prior to this explosion. However, no explosion occurred during a similar forecast window between April 22 and 26.

While the eruption of Redoubt settled into a familiar pattern of recurrent dome growth and partial destruction, geologists took advantage of longer daylight hours to spend more time investigating volcanic deposits on Drift glacier. By March 1, the glacier's surface had become highly irregular, marked by deep gullies, closed basins, and isolated ice buttes. A gully as much as 30 m deep and 25 m wide formed a central ice canyon along the east side of the glacier (fig. 23). Both sides of this deep canyon were covered with hot pyroclastic-flow deposits as thick as 10 m (fig. 24). The deposits contained dome rocks as large as 1 m in diameter in a loose sandy matrix and retained their heat for several months; temperatures as high as 400 °C were measured in these deposits in August. As some of the loose material slid into the canyon, temporarily damming the channel, clouds of hot ash rose several hundred meters above the gorge. When the dams failed, small floods scoured the canyon floor. On April 10, a series of explosions at the 890-m level of Drift glacier formed an elongate crater in the deposits about 300 m long and sent an ash and steam plume as high as 1,000 m. Similar events sometimes resulted in reports of eruptive activity from passing pilots and residents on the Kenai Peninsula. The explosions were probably caused by the interaction between the hot deposits and water flowing on the glacier surface.

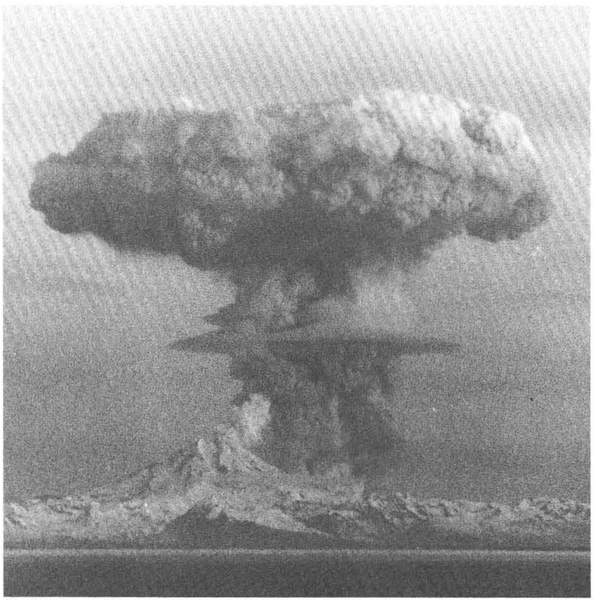


Figure 21. Redoubt Volcano during a moderate explosive episode on April 21, 1990. The mushroom-shaped tephra plume rises from a pyroclastic flow that swept down the volcano's north flank. A smaller, light-toned plume rises from the summit crater. View is northwest across Cook Inlet. Copyrighted photograph by Robert J. Clucas, reprinted by permission.

April 21–August 31, 1990

A small explosion on April 21 destroyed the latest dome; a new lava dome was observed in the crater five days later and continued to grow through early June (fig. 25). The new dome's north flank quickly became oversteepened and was the source of several rockfalls that generated ash-laden clouds a few thousand meters above the volcano's north flank; the largest rockfalls

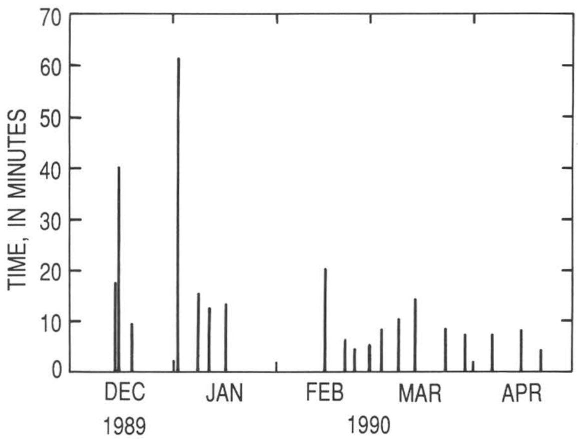


Figure 22. Duration of Redoubt's explosive episodes determined by the duration of seismic signals recorded by seismic station SPU, located on Mount Spurr about 100 km north of Redoubt Volcano (see fig. 2). The relative size of each eruptive episode generally corresponds to the duration of the seismicity that accompanied each episode.

occurred on April 26 and May 26. The dome has remained intact as of the time of this writing (October 1990) and is estimated to be the third-largest dome in the current eruption sequence. Seismic activity declined between June and August to the lowest levels observed since the eruption started, but scientists still characterized the volcano's status as restless (color-code yellow in table 3).

EFFECTS OF THE 1989–90 ERUPTION

Introduction

The eruption of Redoubt affected the Cook Inlet region by significantly interrupting air traffic, causing ash fall over populated areas, and triggering debris flows down Drift River valley. Downwind from the volcano, ash fall produced darkness during daylight hours and caused local power outages (fig. 26) and school closures. Sports and cultural events normally held in winter were canceled, including an invitational collegiate ice-hockey tournament in Anchorage, and industries and communities were forced to face the possibility of sudden ash fall throughout the spring and summer of 1990. Downstream from Redoubt, debris flows spread over the floor of Drift River valley, inundated part of Drift River Terminal, and raised channel beds, diverting the river from its original course to Rust Slough, Cannery Creek, and Montana Bill Creek (fig. 4). Oil production in Cook Inlet was severely reduced for several weeks. These effects were temporary and no lives were lost, but preliminary estimates of damage to property and loss of revenue attributed to the eruption exceed $100 million. Protective measures at the Drift River Terminal alone cost the Cook Inlet Pipeline Company more than $20 million.

Tephra

Explosive eruptions blast shattered fragments of magma (molten rock) and old rock into the air. Collectively, these airborne fragments are called tephra; they range in size from particles larger than 5 cm in diameter to fragments of crystals and rapidly quenched

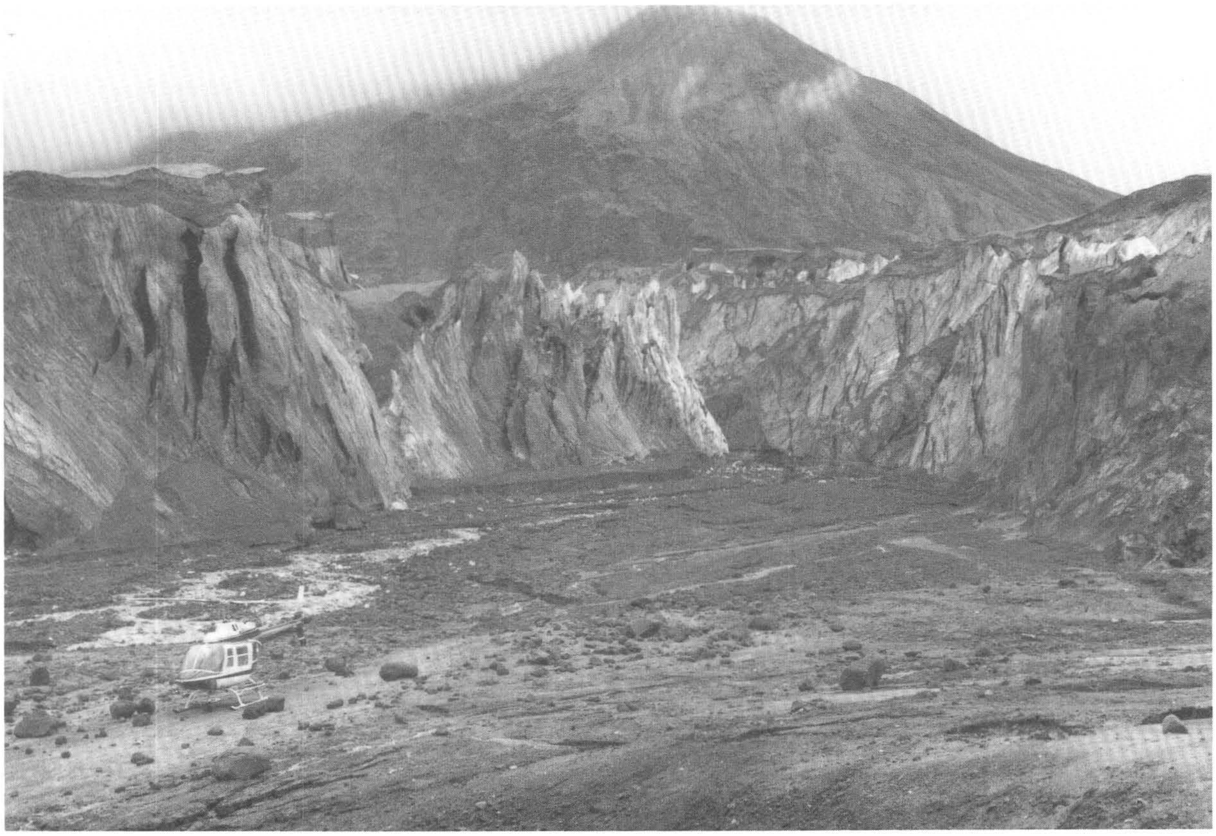


Figure 23. Ice canyon eroded into Drift glacier by pyroclastic flows generated by dome collapses. Glacier is mantled with pyroclastic-flow deposits. Note helicopter in foreground for scale. Photograph by Thomas P. Miller on June 19, 1990.

Figure 24. Pyroclastic-flow deposits atop Drift glacier. These two layers were deposited during different eruptive episodes when domes collapsed down the north flank of Redoubt as hot, fast-moving avalanches of rock debris, or pyroclastic flows. Deposits in this view are about 2 m thick; other flow deposits were as much as 10 m thick. Photograph by Cynthia A. Gardner on May 24, 1990.

Figure 25. Third-largest dome of the eruption, which formed after the explosive episode on April 21, 1990. The dome stopped growing in June. Below the dome, the upper part of Drift glacier has been completely removed down to bedrock. View to southeast. Photograph by David E. Wieprecht on July 17, 1990.

fragments of volcanic glass less than 0.01 mm in length. Tephra consisting of particles less than 2 mm in diameter is called ash. During a major explosive eruption, tephra can be carried more than 20,000 m into the air and fall over very large areas. For example, the area covered by tephra from the eruption of Mount St. Helens on May 18, 1980, was about 150,000 km². For comparison, the area covered by tephra from the eruption of Redoubt on December 15, 1989, was estimated as less than 20,000 km². The composition of tephra varies with each volcano and sometimes during an eruption sequence (table 2).

With increasing distance downwind from Redoubt, both the size of the tephra fragments (fig. 27) and the thickness of the resulting deposits generally decreased. Communities bordering Cook Inlet on the Kenai Peninsula were the hardest hit by ash fall during the eruption. The ash was more of a disruption and nuisance than a danger to public health, but during brief periods of heavy ash fall, as a precautionary measure, officials closed schools and encouraged people to stay indoors or to wear dust filter masks. Researchers studying the health effects of ash from the eruption of Mount St. Helens concluded that ash is an irritant at low to moderate concentrations, but exposures experienced downwind of Mount St. Helens were too low to pose a serious threat for the development of silicosis (a chronic lung disease) (Buist and others, 1986). The volume and duration of ash fall resulting from the eruption of Redoubt was much less than that resulting from the eruption of Mount St. Helens. The layers of ash that blanketed the Kenai Peninsula were less than 1 cm thick, and they were covered with snow within hours to days of each eruptive episode. The snow cover significantly reduced or eliminated the concentration of airborne ash particles. However, when the snow began to melt in April, residents and health officials reported unusually high dust levels that may have been related to the ash (Rinehart, 1990). At the Beluga power plant (fig. 2), the main power source for Anchorage, a brief period of heavy ash fall on February 24 forced all but one of the gas turbines to be shut down as a precautionary measure.

Following several of Redoubt's explosive episodes in December and early January, domestic and international airline traffic above south-central Alaska was brought to a standstill. Hundreds of scheduled flights were canceled, most of them during the Christmas holiday season (fig. 28), and many international flights were routed around the State. The Anchorage International Airport (AIA) is a major hub of domestic and

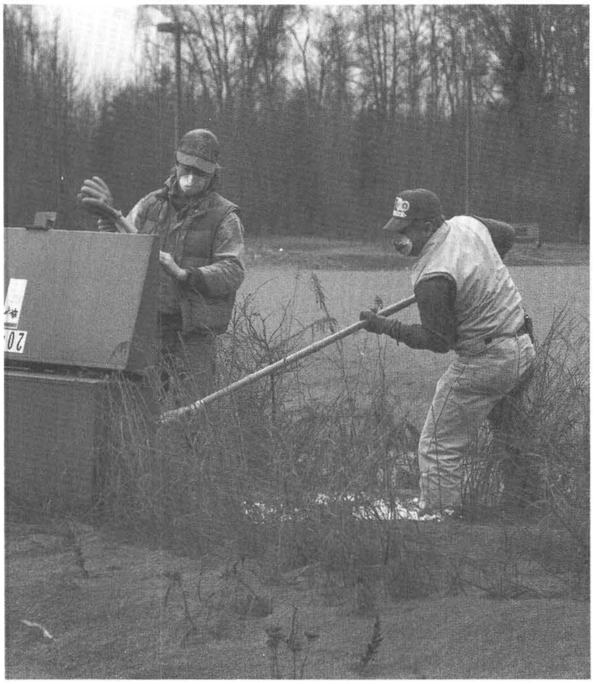


Figure 26. Workers repair an electric transformer that short-circuited because of ash fall in Soldotna on December 16, 1989. Snow is covered by ash in foreground. Copyrighted photograph by Roy Shapley, reprinted by permission.

Table 2. Chemical composition, in percent, of rock samples from several recent eruptions in Alaska

[-- , not reported]

Volcano	Redoubt[1]	Redoubt[2]	Mt.Spurr[3]	Augustine[4]
Eruption date . .	12/15/89	1/2/90	7/9/53	4/3/86
SiO_2	60.22	62.14	55.2	64.5
Al_2O_3	18.22	17.31	17.2	10.2
Fe_2O_3	--	--	3.1	1.5
FeO	5.35	4.58	4.2	2.0
MgO	2.08	1.73	3.7	2.1
CaO	6.60	5.68	7.4	3.0
Na_2O	4.08	4.09	3.4	3.6
K_2O	1.48	1.65	1.0	1.2
H_2O-	--	--	.24	.14
H_2O+	--	--	.93	.19
TiO_2	.52	--	.74	.55
P_2O_5	.21	.18	.30	.29
MnO	.14	.13	.16	.09
S	--	--	.60	--
Cl	--	--	--	.10

[1]Pumice sample.

[2]Lava sample.

[3]Wilcox, R.E., 1959, Some effects of recent volcanic ash falls, with especial reference to Alaska: U.S. Geological Survey Bulletin 1028-N, p. 409-476.

[4]Yount, M.E., Miller, T.P., Gamble, B.M., 1987, The 1986 eruptions of Augustine Volcano, Alaska--Hazards and effects, *in* Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 4-13.

international air traffic (fig. 29), and as the eruption of Redoubt demonstrated, flights within the State and between the Orient and Europe are susceptible to disruption by eruptions that produce significant tephra plumes. In December 1989 and January 1990, AIA experienced an estimated revenue shortfall of $2.62 million (Ken Burdette, written commun., 1990) because of canceled flights into the airport. Between December and February, four commercial jet aircraft encountered ash downwind of the volcano (Steenblik, 1990). The abrasive quality of the ash "sandblasted" the cockpit windshields and the leading edges of wings; the windows had to be replaced and the wings polished. All of the engines required thorough inspection.

The most serious incident occurred on December 15 when a Boeing 747 enroute from Amsterdam and carrying 231 passengers and 13 crew members began its descent into Anchorage. Though the pilot was following the path taken by another Boeing 747 only 20 minutes earlier, the plane encountered a cloud of volcanic ash 240 km downwind from Redoubt at an altitude of about 7,500 m. The volcano had erupted 90 minutes earlier. As the pilot attempted to climb out of the cloud, ash particles melted by the heat of the engines began to solidify and formed a glassy coating in parts of the turbine section of the engine, which restricted the engines' intake of air. All four engines shut down. For the next 8 minutes, the plane glided steeply, losing 4,000 m of altitude before the pilot succeeded in restarting the engines with less than 2,000 m of clearance between the plane and the ground. The cold Alaska air and repeated attempts to restart the engines

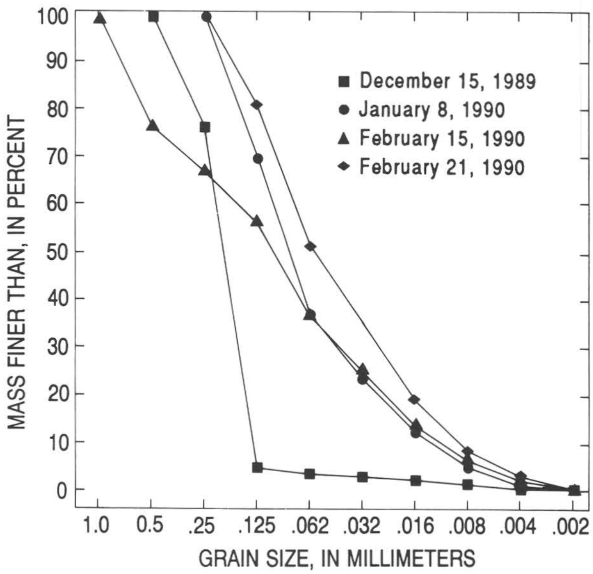


Figure 27. Particle-size distribution of ash that fell downwind of Redoubt Volcano. Locations where ash samples were collected for particle-size analysis are as follows: Dec. 15, 1989, 115 km north of Anchorage along Highway 3; Jan. 8, 1990, 30 km southwest of Soldotna along Highway 1; Feb. 15, 1990, 45 km southwest of Soldotna along Highway 1; Feb. 21, 1990, 15 km southeast of Anchorage along Highway 1.

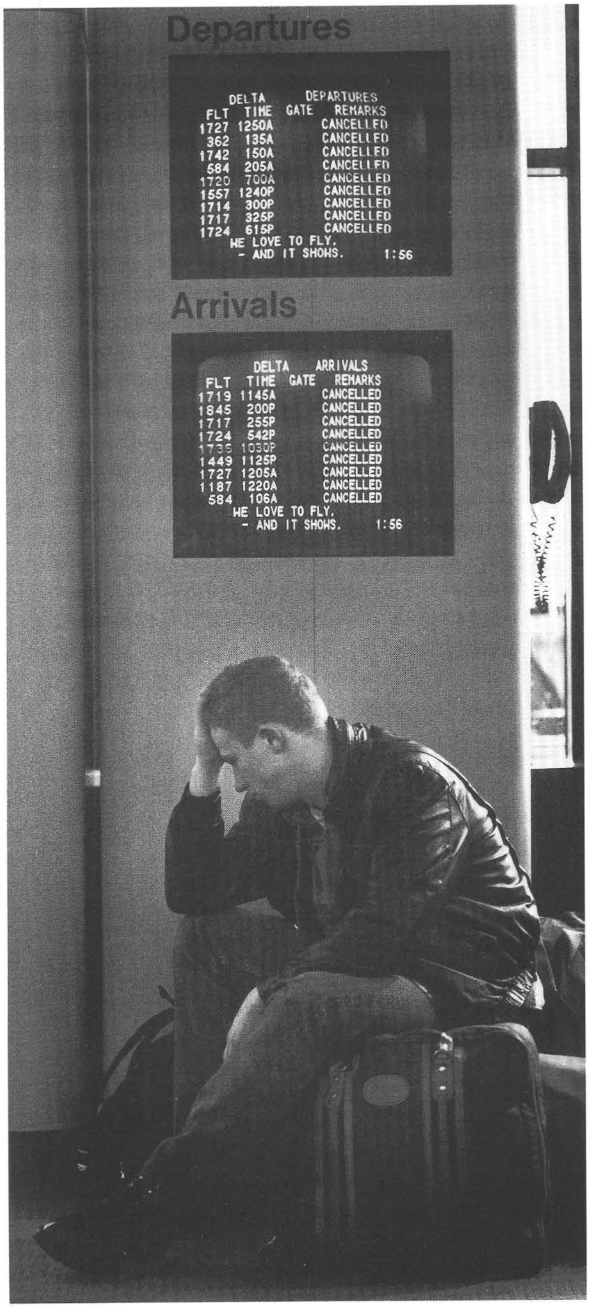


Figure 28. Numerous explosive episodes of Redoubt Volcano resulted in hundreds of canceled flights during the busy Christmas holiday season. Copyrighted photograph by Michael Dinneen, Anchorage Times, reprinted by permission.

resulted in a partial breakup of the glass coating, and the plane landed safely in Anchorage about 38 minutes after the incident began. All four engines had to be replaced (fig. 30), as well as the electrical and avionics systems, and the entire aircraft had to be thoroughly cleaned of fine ash. These repairs cost an estimated $80 million (Steenblik, 1990).

This near-tragic encounter underscored the importance of notifying pilots of wind conditions and volcanic eruptions that generate significant tephra plumes only minutes after they occur. Such notification requires quick, reliable communication between AVO, the Federal Aviation Administration, the National Weather Service, airline officials, and pilots during eruptive activity. In an effort to better characterize the volcano's activity, AVO adopted a color-code scheme (see below) in February, and several airlines developed emergency plans that specified a certain response for each color. Beginning in early January, AVO provided airline officials with maps predicting the paths along which an ash cloud would move away from Redoubt at different altitudes and times (fig. 32). In order to more accurately measure wind speed and direction, the National Weather Service installed a state-of-the-art Wind Profiler radar system near Homer during the summer and has developed plans for additional installations in south-central Alaska in 1991.

Figure 30. Crew examines one of the Boeing 747 jet engines that suffered extensive damage when the jet encountered an ash cloud on December 15, 1989. Copyrighted photograph by Bob Hamilton, Anchorage Daily News, reprinted by permission.

Figure 29. Anchorage International Airport. The geographic location of Anchorage makes it an ideal fueling and distribution center for flights between the Orient and Europe. In 1989, the total landed cargo weight was 3.63 million metric tonnes (8 billion pounds), the highest in North America and more than that handled by John F. Kennedy International Airport (New York) and Los Angeles International Airport combined. View to east. Photograph by Mark Skok, Anchorage International Airport; reprinted by permission of the Alaska International Airport System.

Debris Flows

Debris flows, rapidly flowing mixtures of water and rock debris, are commonly produced at steep-sided, snow- and ice-covered volcanoes. Debris flows vary considerably in the concentration of water and rock debris, ranging from very water-rich flows containing less than 20 percent sediment by volume to sediment-rich flows containing more than 60 percent sediment. Volcanic debris flows are generated when large volumes of water mix with loose material on a volcano or in river valleys that drain the volcano. This mixing can occur during the explosive ejection of water from a crater lake, during the erosion of volcanic rock debris by heavy rain, or during the rapid melting of snow and ice by hot volcanic debris. Some of the world's most destructive debris flows result from eruptions of volcanoes mantled by snow and ice—the 1985 eruption of Nevado del Ruiz in Colombia, for example, generated debris flows that claimed at least 22,000 lives (Naranjo and others, 1986).

The largest debris flow of the Redoubt eruption was triggered by the major explosions and dome collapse on January 2. The debris flow flooded part of the Drift River Terminal, and the Alaska Department of Environmental Conservation (DEC) issued an emergency order on January 5 calling for a reduction in the amount of oil stored at the terminal to 150,000 barrels (Petroleum Information, 1990a). Later, the U.S. Coast Guard requested that this limit be reduced to 50,000 barrels, which led industry officials to suspend tanker loadings because of the increased danger of a spill resulting from longer loading times. Additional debris flows in subsequent episodes prompted the Cook Inlet Pipeline Company and DEC to suspend operations at the terminal on March 17, to remove most of the oil from the terminal, and to develop alternative plans for its future long-term operation.

Meanwhile, 10 platforms in Cook Inlet that supplied oil to the terminal were forced to suspend production, which totaled about 30,000 barrels of oil a day before the eruption (Petroleum Information, 1990b). On the basis of November 1989 royalty figures, the halt in production cost the State about $39,000 a day. The economic consequences of a long-term shutdown of oil production in western Cook Inlet would be serious, especially to the Kenai Peninsula. For example, the total revenue from Cook Inlet oil in 1989 was $168.5 million or about $14 million a month, and royalty payments to the State averaged $1.7 million per month. About 500 industry jobs with an estimated payroll of $27.5 million are tied to oil production in western Cook Inlet (Wayne Haerer, written commun., 1990).

In order to protect the storage tanks from future volcanic debris flows and floods, the Cook Inlet Pipeline Company constructed new levees 6 m tall around much of the terminal and raised critical electrical equipment at least 1 m above the ground. For the protection of its crews, a safe house was built atop an enormous platform 3 m above the ground. These measures cost about $20 million (Harold Mouser, oral commun., 1990). Under an interim agreement with the DEC, the levees will permit the company to store up to 338,000 barrels of oil at the terminal as long as Redoubt Volcano remains active.

Deposition of sediment in Drift River valley and on the delta at its mouth during the 1989–90 eruption upset the normal course of the river, forcing the river south into Rust Slough and Cannery Creek and north into Montana Bill Creek. During the summer, the river changed its course frequently, sometimes flowing back in its original channel on the north side of the terminal. Significantly increased water flow in Rust Slough caused severe bank erosion near the terminal. To monitor future changes in the river system, the U.S. Geological Survey initiated a surveillance program in the spring of 1990. Surveillance now includes repeated surveys of the river channel, aerial photography, detailed mapping of the delta area, and water and sediment discharge measurements.

HAZARD INFORMATION PROVIDED BY ALASKA VOLCANO OBSERVATORY

Introduction

The emergency caused by the eruption of Redoubt created an enormous demand for volcano information that quickly overwhelmed AVO's small staff. Scientists from other facilities of the USGS were brought to Anchorage and Fairbanks to help monitor and interpret the volcano's activity and to disseminate information as needed, and a Public Information Scientist was identified to facilitate the release of information to the news media and public. Also, many scientists from the UAGI and ADGGS (fig. 3) were diverted from their normal tasks to aid in the response. Hazard information was disseminated by AVO through the immediate notification of key government and industry officials (for example, officials of the Department of Emergency Services and the Federal Aviation Administration) when warranted by volcanic activity, through printed volcano updates, and through briefings. Briefings were given to (1) representatives of private industry; Federal, State, and local government agencies; and congressional committees; (2) the Governor of Alaska; (3) Senators and their staffs; (4) news media; and (5) groups of citizens. Before key officials were notified of a volcanic event, scientists at the crisis center in Anchorage and the seismic center in Fairbanks first confirmed the nature of the event that was occurring at the volcano.

Volcano Update

Seven days after the eruption started, AVO began releasing a printed "Redoubt Volcano Update" one or more times each day which described eruptions, earthquake activity, important observations, and noteworthy events during the preceding 24 hours; beginning on July 6, the updates were issued once a week. The updates also included a general summary of potential volcanic hazards over a period of days to weeks and, when possible, specific predictions about future events (fig. 31). This information was also provided on a recorded phone message that was continually updated.

Color Code

In early February, a scheme of color codes was developed to represent the level of concern based on the seismic activity beneath Redoubt or confirmed by visual observations by AVO field crews or the airline industry (table 3). This system was implemented in order to more consistently describe the status of the volcano when a potentially hazardous event was in progress or was expected. Four colors were chosen to represent different levels of activity that were either presently occurring or expected to occur at the volcano. Green, for example, meant the volcano was in a "dormant" state. Red indicated either the occurrence or the imminence of a large explosion or series of explosions likely to send ash higher than about 8 km above sea level. (In practice, many of the episodes in March and April that produced plumes between 8 and 10 km high were characterized as "orange.")

REDOUBT VOLCANO UPDATE
Thursday, March 22, 1990; 11:15 AST

Level of concern about the state of the volcano

Current level is: ORANGE	At this level since: March 22, 1990 Last level was YELLOW For definitions see update of 2/23/90

Seismic activity at stations nearest the summit has steadily increased during the last 12 hours, and is presently at a higher level than it has been in the last few days. We have upgraded the level of concern color code to ORANGE. Based on projected wind data below 50,000 feet, we would expect a plume, if emitted today, to move to the west and northwest of the volcano.

An AVO field crew yesterday noted a continuous steam plume emanating from the dome, but this plume seldom reached elevations higher than the summit of the mountain. The crew had a clear look at the dome and it appeared to have grown since Sunday. Gases from the steam plume were analyzed during an overflight of the mountain.

Given the current level of seismic activity, continued dome-building or explosive activity remain likely over the next few days or weeks. AVO will continue to monitor the volcano 24 hours a day looking for any subtle changes in the character of the seismicity which may be indicative of increased activity. The level of concern color code will be updated as appropriate.

Figure 31. Text of Redoubt Volcano Update, March 22, 1990.

Forecast Plume Trajectory

In early January, AVO arranged with the National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA) to receive forecast wind data above south-central Alaska from which potential ashfall areas downwind from Redoubt could be determined (Miller and others, 1981). The predicted paths of parcels of air originating at the volcano at various times and altitudes were plotted on maps of Alaska and the Cook Inlet region (fig. 32). The maps were used by various agencies and private industries, especially the Alaska Department of Emergency Services and both domestic and international airlines, to anticipate probable ash-fall-hazard zones following an eruption.

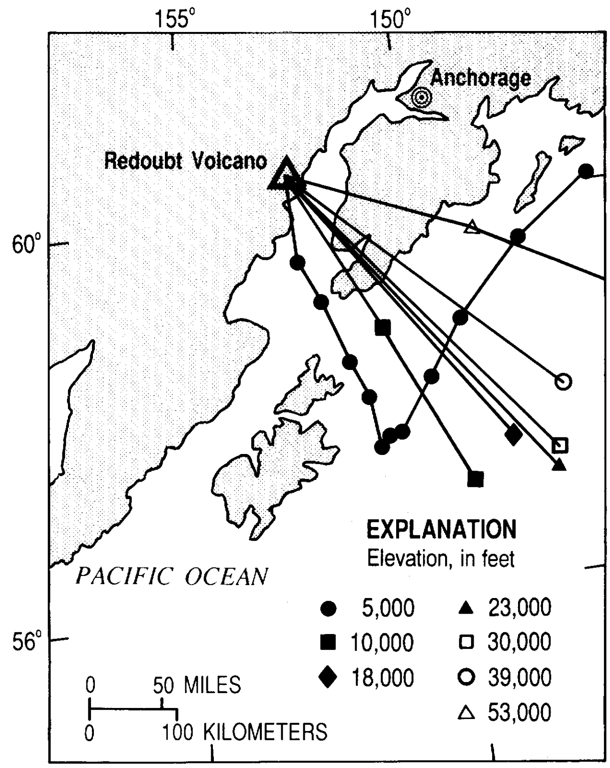


Figure 32. Plume trajectory forecast for 3:00 a.m. on February 15, 1990. Symbols represent the location of parcels of air originating above Redoubt Volcano at successive 3-hour intervals for specific altitudes. An explosive episode at 4:10 a.m. generated a tephra plume that blew from Redoubt to the southeast, as predicted by this forecast.

Table 3. Color-code scheme developed by Alaska Volcano Observatory to characterize eruptive status of Redoubt

Color	Description
Green	Volcano is in its normal "dormant" state.
Yellow	Volcano is restless. Earthquake activity is elevated, and a plume of gas and steam may be rising a few km above the crater. Activity may include extrusion of lava and emplacement of a lava dome.
Orange	Small ash eruptions are expected or confirmed. Plume(s) not likely to rise above 8 km (25,000 ft) above sea level. Minor flooding on the Drift River is possible. Seismic disturbance recorded on Redoubt seismic stations but not recorded at more distant locations.
Red	Large ash eruptions are expected or confirmed. Plume likely to rise above 8 km (25,000 ft) above sea level. Significant flooding in Drift River possible; flooding in the Crescent River also possible but less likely. Strong seismic signal recorded on all Redoubt stations and commonly on more distant stations.

MONITORING THE 1989–90 ERUPTION

Introduction

Volcano monitoring is undertaken to assess the current status and near-term eruptive potential of a volcano and to document the occurrence and character of eruptions. Volcano monitoring involves a variety of measurements and observations designed to detect changes at a volcano that reflect increasing stress caused by the movement of magma within or beneath the volcanic cone (fig. 33). Experience gained at well-monitored volcanoes indicates that most eruptions are preceded by measurable changes in the state of the volcano. The challenge faced by scientists is not only to recognize the signs of restlessness that may foretell possible eruptive activity but also to interpret the monitoring information in order to specify a time window within which an eruption is likely to occur. Not all signs of unrest lead to an eruption. An even more difficult task that scientists face is to determine when an eruption is over so that people can resume their normal activities. Volcano monitoring also involves detecting the onset of eruptive activity and determining the type and magnitude of volcanic events during an eruption, including the speed and areal extent of tephra plumes, lava flows, debris flows, and pyroclastic flows.

Monitoring Redoubt Volcano during the winter was extremely difficult. Visual observations of eruptive activity, investigation of the resulting deposits, and installation and repair of monitoring instruments were limited by the generally poor weather conditions, short daylight (less than 6 hours per day in December), and long travel times between Anchorage and the volcano (1 hour by helicopter). Snowfall obscured the details of pyroclastic- and debris-flow deposits, and extremely cold temperatures caused deposits containing water to freeze, making them difficult to examine and interpret. In one regard, the winter weather aided researchers: snowfall temporarily preserved tephra-fall deposits for further study and made it possible to map areas covered with thin tephra layers from an airplane.

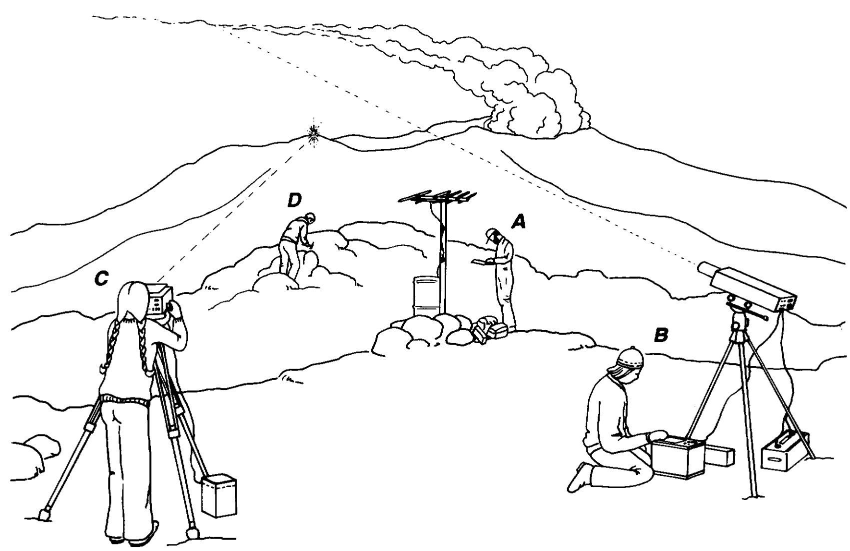


Figure 33. Scientific methods used to monitor volcanoes. *A*, Seismic station detects vibration of the ground caused by earthquakes and volcanic activity, and transmits data by radio to a volcano observatory. *B*, Correlation spectrometer (COSPEC) measures sulfur-dioxide emission and is used either from the ground or an airplane. *C*, Precise surveying instruments measure a volcano's changing shape caused by magma rising into its cone. *D*, Geologists observe volcanic deposits to understand eruptive processes, and collect lava and tephra samples to determine their chemical composition. Sketch by Bobbie Meyers.

Seismicity

Seismic monitoring is the primary means of volcano surveillance, and it provided the basis for warnings issued by AVO during the Redoubt crisis. The Redoubt experience clearly demonstrates the tremendous value of maintaining seismic networks consisting of several seismometers within 10 to 20 km of historically active volcanoes, including one or more located on each volcano. In October 1989, just two months before Redoubt began to erupt on December 14, a five-station seismic array (fig. 34) centered on Redoubt became fully operational. This array provided critical information for gauging the status of the volcano and for providing warnings of impending eruptions. During most of the eruption sequence, earthquake activity beneath the volcano changed constantly, requiring seismologists to work 24 hours a day to detect subtle variations in the type and intensity of seismic activity and to determine when a potentially hazardous eruptive episode was occurring. The network of seismometers around Redoubt and new seismic-recording and seismic-analysis systems that run on small, powerful personal computers (Lee and others, 1989; Rogers, 1989; Murray and Endo, 1989) were critical for accurate and timely interpretations of the seismicity. The computers record the seismic data in digital form and perform several different analyses every few minutes.

An essential tool for monitoring the overall level of seismicity during the Redoubt crisis was the Real-time Seismic Amplitude Measurement system (RSAM).

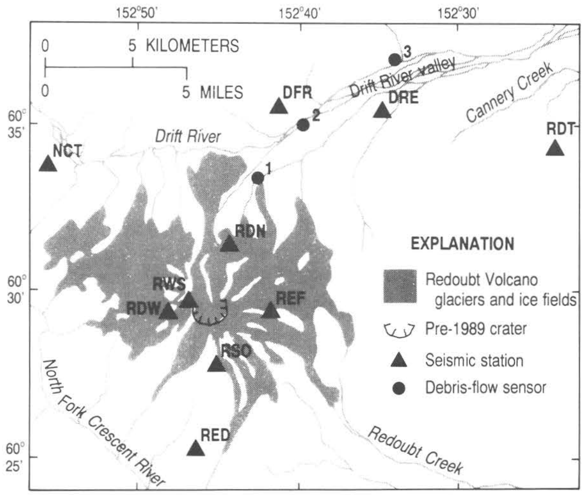


Figure 34. Location of seismic stations and debris-flow sensors around Redoubt Volcano. Seismic stations DFR, NCT, RDN, RDT, and RED became fully operational in October 1989. The other stations and sensors were installed at various times after the eruption began.

The RSAM was developed by the Cascades Volcano Observatory of the USGS in 1985 for monitoring seismicity at Mount St. Helens, Washington (Murray and Endo, 1989). Unlike other seismic data acquisition systems, which continuously record the oscillation of the ground at a seismic station, the RSAM system computes and stores the average amplitude of the ground oscillation over 10-minute intervals. As either the magnitude or number of earthquakes increases, and as volcanic tremor increases, the average amplitude of ground oscillation also increases. A small increase in the number of earthquakes, however, has only a small effect on the RSAM averages because the averages are computed over 10-minute intervals. The RSAM averages must be interpreted in conjunction with standard seismograms since ground shaking can be caused by different processes, including earthquakes, wind, volcanic explosions, or debris flows.

The advantage of the RSAM system is its ability to continuously measure the level of seismicity during intense activity, especially during eruptions and volcanic tremor, and when earthquakes are so numerous that individual events cannot be distinguished and counted. The pronounced increases in the rate and amplitude of seismic events at Redoubt that prompted AVO's warnings of possible eruptive activity before December 14, 1989 (fig. 35), and January 2, 1990 (fig. 36), are clearly demonstrated in the RSAM data. In the last few hours leading up to these eruptive episodes, seismologists could not recognize and count individual earthquakes, and they relied on the RSAM system to quantify the level of seismic activity at Redoubt.

Recently, seismologists have developed a new system for continuously monitoring both the amplitude and frequency of a seismic signal. The seismic signal corresponds to vibrations of the ground and consists of a series of waves that vary in amplitude and frequency, measured in cycles per second (hertz, abbreviated Hz), as a function of time (fig. 9). The Seismic Spectral Amplitude Measurement (SSAM) system measures the relative amplitude of the seismic signal in specific frequency bands, permitting seismologists to determine which frequencies dominate a signal from each seismometer. Different types of seismic events generate signals with different characteristics. By examining the frequency of a signal, seismologists can infer its possible origin, or classes of origin.

The SSAM system aided AVO seismologists in recognizing patterns of subtle seismic changes before several moderately explosive episodes in March and April; these subtle patterns were not always apparent on standard seismic records. Beginning as many as 27 hours before an eruption, seismologists observed seismic signals dominated by frequencies between 1.9 and 3 Hz at stations on the volcano (fig. 37). The SSAM system played an increasingly important role in forecasting explosive episodes as the eruption sequence continued. Between March 5 and April 21, when at least one seismometer was operating within 3 km of the crater, clear signals preceded five of the eight moderate explosive episodes that occurred during this time period. On the basis of these signals, the level-of-concern color code was elevated from yellow to orange several hours before the onset of eruptive episodes on March 23 (fig. 31) and April 6.

Field Observation

Visual observations of Redoubt's eruptive activity and investigation of volcanic deposits both on the volcano and in Drift River valley were essential for assessing the volcano's activity and the hazards associated with it. As the eruption progressed, field observations provided critical information needed for relating the character of the seismicity to the volcano's actual eruptive activity. Geologic observation of debris-flow deposits was critical for interpreting the signals from sensors of the debris-flow detection system (see below) and for advising State officials about flood hazards at the Drift River Terminal. As often as weather permitted, geologists made observation flights over the volcano and Drift River valley, evaluated growth and stability of the lava dome, mapped volcanic deposits from the volcano to Cook Inlet, and documented changes occurring on Drift glacier.

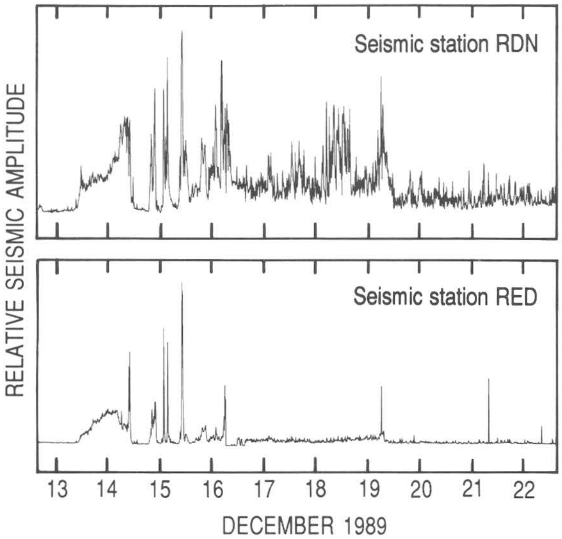


Figure 35. Seismicity at Redoubt Volcano between December 13 and 22, 1989, expressed in average amplitude values (RSAM) for seismic stations RDN and RED (see fig. 34 for station locations). Note increase in amplitude beginning late on December 13 before the first explosive event at 9:47 a.m. AST on December 14. Peaks in amplitude correspond generally to explosive episodes (see table 1).

Sulfur-Dioxide Emission

Redoubt Volcano continuously emits volcanic gas from its summit crater and lava dome. Most of the gas is water vapor, but emissions also include sulfur dioxide, carbon dioxide, hydrogen, and lesser amounts of other gases such as carbon monoxide and hydrogen chloride. The concentration of volcanic gases is difficult to measure, and during eruptions, gas is extremely dangerous to collect. Scientists have learned, however, that the emission rate of sulfur dioxide gas generally reflects the total gas release from an active volcano. Sulfur dioxide gas can be measured safely from an airplane using an instrument originally designed for pollution studies. The correlation spectrometer (COSPEC) measures the amount of solar ultraviolet light absorbed by sulfur dioxide and compares it to an internal standard. Several traverses are made beneath the plume at right angles to the plume path to calculate an average daily emission rate.

Sulfur dioxide emission rates since March 20 ranged from about 800 to 6,600 metric tonnes per day (fig. 38). Measurements could not be made before March because of the low angle of the sun above Alaska during winter. Emission rates decreased beginning in late May and remained relatively low through August, which corresponds generally to the time period during which new magma was not rising into the dome. The relationship between emission rates and eruptive episodes is not clear. Before the March 23 episode, emission rates decreased from 4,600 to 1,600 tonnes per day at a time when the number of small seismic events was increasing. Such a decrease may reflect the sealing of the dome

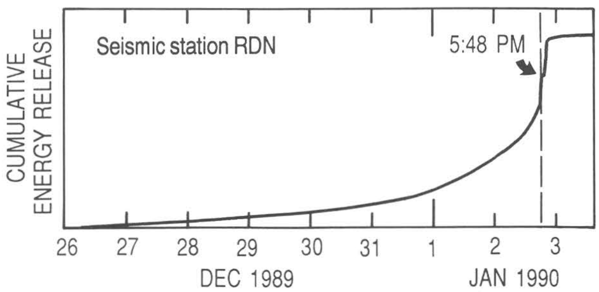


Figure 36. Cumulative energy release recorded by seismic station RDN, December 26, 1989–January 3, 1990, calculated from RSAM values (see fig. 34 for station location). The rapid upturn in the curve reflects the accelerating seismic activity beneath the volcano prior to the January 2 explosions and was the basis for warnings issued by AVO before the explosions occurred.

to gas loss. As the magma system beneath the dome became pressurized, seismicity increased until the dome was ruptured by explosive activity or collapsed down Redoubt's north flank. A similar decrease in emission rates, however, was not measured before the subsequent eruptive episodes.

Slow-Scan Video Monitor

Within 48 hours of the first explosive episode on December 14, a video camera was installed at Kasilof (fig. 2), 80 km east of Redoubt on the Kenai Peninsula, to provide images of the volcano during clear weather for scientists at the seismic center in Fairbanks. The camera is nearly 3,500 times more sensitive to light than most commercial home-video cameras, and thus it can record images of the volcano at night. An image is transmitted every 35 seconds to the seismic center and displayed on a black-and-white television monitor. This video system helped seismologists to correlate seismic events with volcanic activity. Five explosive episodes (two of which occurred at night), lightning, and brief periods of incandescence were successfully observed. Clouds prevented observations of most of the explosive episodes.

Lightning-Detection System

Spectacular lightning displays were observed during Redoubt's explosive episodes, even from places as far away as Homer, 120 km to the southeast. The cause of eruption lightning is uncertain, but it may result from friction between tephra particles and steam and other gases within a tephra plume. Eruption lightning discharges include both cloud-to-ground and cloud-to-cloud strikes. During a large seismic event when the volcano is not visible, the presence of lightning dispels the uncertainty in interpreting the seismicity—a tephra plume is almost certainly present when sustained seismic signals and lightning occur together. AVO requested the help of the Bureau of Land Management's Alaska Fire Service to deploy a lightning-detection

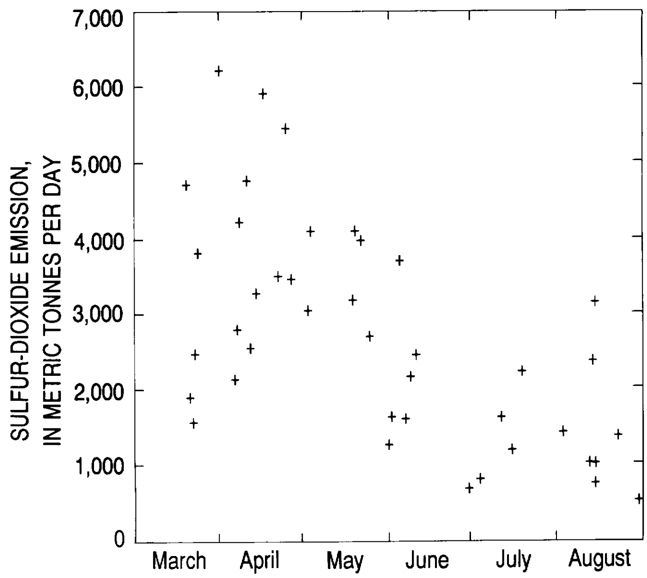


Figure 38. Daily sulfur-dioxide emission rates of Redoubt Volcano.

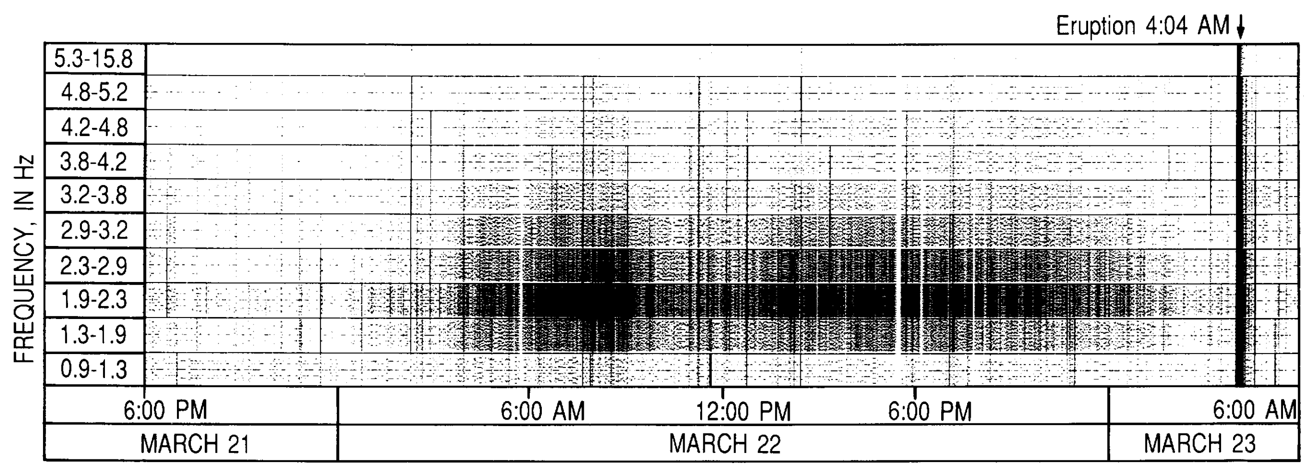


Figure 37. Record from Seismic Spectral Amplitude Measurement system (SSAM) showing signature of a swarm of low-frequency events that preceded the moderate explosion on March 23, 1990. On the basis of this signature, AVO issued a warning of future eruptive activity by upgrading the color code from yellow to orange (see fig. 31 and table 3) 17 hours before the explosion. The record shows the relative strength of the ground motion in specific frequency bands for seismic station RSO (see fig. 34 for station location). The strength of the motion is represented by the relative darkness of the dot pattern and, in this record, is most intense in the 1.9–2.3 hertz (Hz) frequency band. The precursory seismic activity began at about 1 a.m. on March 22 and continued until about 2 a.m. on March 23.

network around Redoubt as an experiment. The Alaska Fire Service maintains a lightning-detection network in Alaska during summer months to help locate and prevent the spread of lightning-caused forest fires. A network capable of both detecting and locating cloud-to-ground lightning strikes was set up around Redoubt and became operational on February 13. The results are promising: lightning was detected every time an explosive episode formed a tephra plume. For some episodes, scientists were able to conclude within minutes that a tephra plume was forming above the volcano even though the plume could not be seen (fig. 39). The results also suggest that the number of lightning strikes detected is proportional to the size of a plume. Because of these promising results, AVO will soon install a permanent network to detect and locate eruption lightning at Redoubt and other volcanoes on the west side of Cook Inlet.

Debris-Flow Detection System

During almost every eruptive episode, debris flows were generated in Drift River valley by the melting of snow and ice by pyroclastic flows and dome collapses. Many of the debris flows traveled all the way to Cook Inlet. This repetitive activity was ideal for testing an experimental flow-detection system designed to track debris flows down river valleys. The flow-detection system consists of three stations located adjacent to Drift River at increasing distances from the volcano (fig. 34). Each station consists of a seismometer sensitive to high-frequency (10–300 Hz) ground vibrations caused by flowing mixtures of water and rock debris, and a radio to send the data to AVO facilities in Anchorage. The signals are separated into frequency ranges and continuously analyzed by a small computer. Flow events can be detected on the basis of their high-frequency character even during volcanic activity and earthquakes (fig. 40). When the flow-detection system was operating, all debris flows triggered by volcanic activity were detected. In the future, this system could provide important information on the speed and size of debris flows

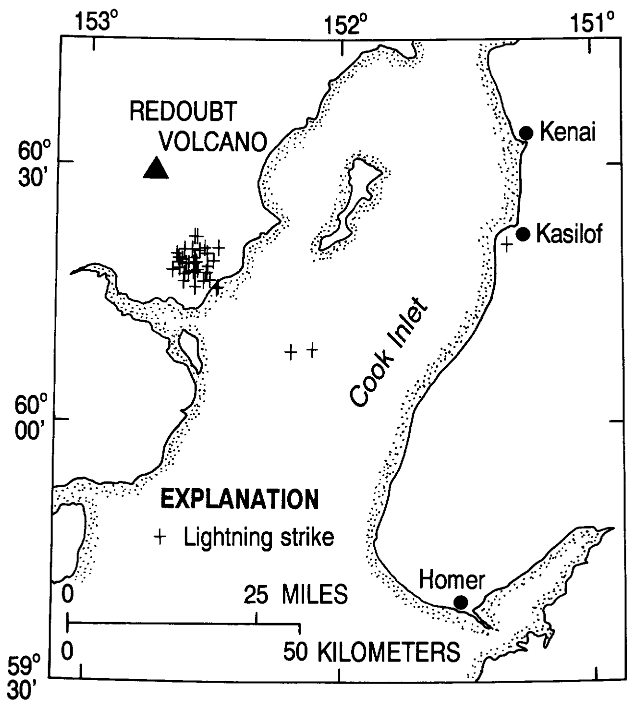


Figure 39. Location of lightning strikes during the February 15, 1990, explosive episode.

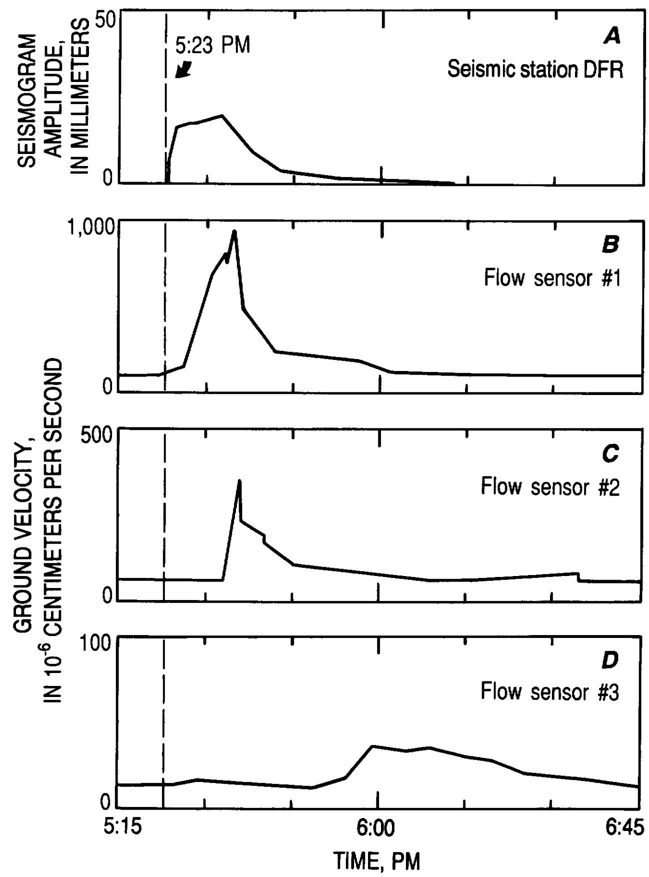


Figure 40. A debris-flow detection system using seismometers proved effective in detecting and tracking debris flows during the eruption of Redoubt. The debris flow triggered by an explosive episode at 5:23 p.m. on April 6, 1990, was detected as shown here (see fig. 34 for location of seismic station and flow sensors). *A*, Amplitude of the seismic signal that accompanied the explosive episode, measured from seismogram recorded at seismic station DFR. *B-D*, Ground velocity of signals from flow sensors 1-3. (Amplitude and ground velocity are two different measures of ground motion.) The time delay between peak ground velocities recorded by the flow sensors can be used to calculate the speed of the flow, and the ground velocities can be used to evaluate relative size of the flow with increasing distance from the volcano. Note change in scale in *B-D*.

and could be used to warn people downstream of an advancing debris flow.

FUTURE ERUPTIONS IN ALASKA

The long history of frequent eruptions in Alaska and the State's geologic setting clearly imply that future eruptions are inevitable. In the past 10,000 years, nearly 10 percent of the Earth's eruptions occurred in Alaska (Simkin and others, 1981). Although scientists cannot predict which of Alaska's volcanoes will erupt next, the types of volcanic activity that can be expected from future eruptions are well known (Scott, 1989; UNDRO, 1985; Blong, 1984) and enable us to construct the following list of hazardous volcanic events that can be produced by Alaskan eruptions: debris flows, lateral blasts, lava flows and domes, pyroclastic flows and surges, tephra, tsunamis, volcanic gases, and volcanic landslides. Since 1800, most eruptions in Alaska have generated little cause for concern, but like the 1989–90 eruption of Redoubt, some have had direct and dramatic effects on the lives of people and communities surrounding Cook Inlet. Historical eruptions demonstrate that tephra is the most common and widespread volcanic hazard in Alaska, followed to a lesser extent by debris flows, pyroclastic flows, and tsunamis (giant sea waves). Future eruptions are certain to produce tephra that will affect Alaska in ways similar to the recent activity at Redoubt. Larger eruptions could deposit considerably more ash in a downwind direction, which in the Cook Inlet area varies generally between north and southeast (fig. 41).

Alaskan volcanoes are capable of producing extremely large eruptions. The largest eruption on Earth this century occurred in 1912 at Novarupta in Katmai National Park on the Alaska Peninsula (fig. 2). This awesome eruption expelled an estimated 12–15 km^3 of magma (Hildreth, 1987), about 30 times the volume erupted by Mount St. Helens, Washington, in 1980. Pyroclastic flows buried a river valley with as much as 200 m of debris to produce the famous Valley of Ten Thousand Smokes. A huge tephra plume deposited most of its material in the sea, but about 25 cm of tephra fell at Kodiak village 160 km to the southeast, severely damaging many buildings. Some ash also fell in the Cook Inlet region. So much magma and old rock was expelled from beneath the Novarupta vent that a large depression called a caldera was created. The caldera was subsequently filled with volcanic debris (Hildreth, 1987). The eruption apparently triggered the collapse of Mount Katmai volcano 10 km away, which also formed a caldera. At least 20 similar catastrophic caldera-forming eruptions have occurred in Alaska during the past 10,000 years, averaging one every 500 years (Miller and Smith, 1987).

Since 1988, AVO has improved seismic monitoring of Mount Spurr and Augustine and Redoubt Volcanoes by installing new seismometers and by upgrading the computer recording and analysis systems at the University of Alaska seismic center in Fairbanks. Other types of monitoring activities were also initiated at Augustine Volcano, and several geologic mapping studies are underway to decipher the eruptive history of Alaskan volcanoes (table 4).

CONCLUSION

To date, the 1989–90 eruption of Redoubt Volcano has cost more than $100 million in damage to aircraft and loss of oil-production revenue, making it the most costly of Redoubt's four eruptions this century. Numerous explosive episodes sent ash plumes higher than 8,000 m above sea level, and wind carried the ash across air-traffic routes. The ash clouds severely disrupted domestic and international air service and resulted in the near-tragic encounter of a Boeing 747 jet with ash 90 minutes after a major explosive episode on December 15, 1989. The explosive episodes also caused massive debris flows in Drift River valley when hot,

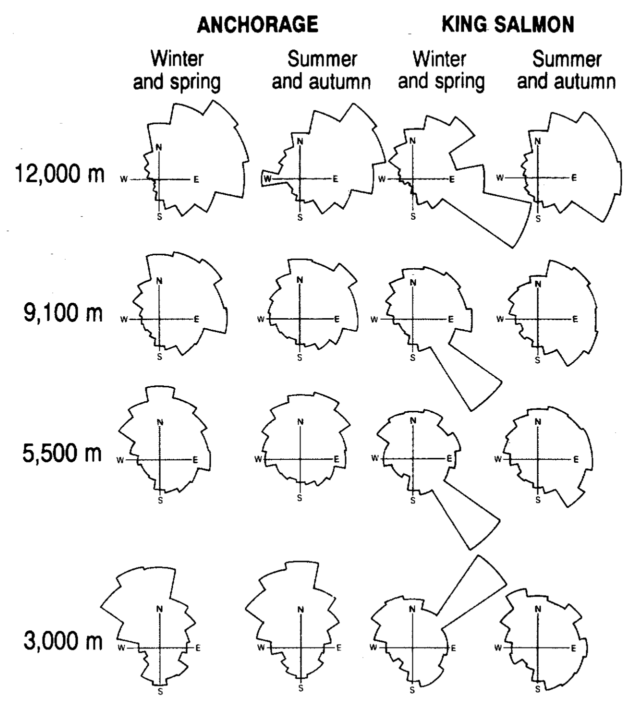


Figure 41. Average wind direction at four altitudes above Anchorage and King Salmon, Alaska (see fig. 2). Data from National Climatic Data Center, Asheville, North Carolina. Anchorage data cover period 1948–72; King Salmon data cover period 1953–60. Compass-rose diagrams show percentage of time winds blew toward a given direction. Modified from Till and others (1990).

Table 4. Status of monitoring and geologic studies at Alaskan volcanoes

Volcano	Scale of geologic map	Hazard assessment	Monitoring		
			Seismic	Geodetic	Gas
		Cook Inlet			
Hayes	No map	No	No	No	No
Mt. Spurr	1:63,360[1]	In progress	Yes	No	No
Redoubt	1:63,360[1]	Yes	Yes	Planned	Yes
Iliamna	1:63,360[1]	No	No	No	No
Augustine	1:24,000[1]	Preliminary	Yes	Yes	Yes
		Alaska Peninsula			
Katmai group[2]	1:250,000	No	Yes	No	No
Ugashik caldera-Mt. Peulik	1:63,360[3]	No	No	No	No
Yantarni-Mt. Chiginagak	1:63,360[4]	No	No	No	No
Aniakchak caldera	1:125,000[1]	No	No	No	No
Black Peak	1:63,360[3]	No	No	No	No
Mt. Veniaminof	1:125,000[4]	No	No	No	No
Mt. Dana	1:63,360[4]	No	No	No	No
Emmons Lake caldera-Pavlof	1:125,000[4]	No	Yes	No	No
Mt. Dutton	1:63,360[4]	No	Yes	No	No
		Aleutian Islands			
Reconnaissance geologic maps exist for about one-third of the Aleutian volcanoes, but these lack the details necessary for deciphering eruptive history. Only a few monitoring and geologic studies have been made of Aleutian volcanoes.					

[1]Begun.
[2]Includes Novarupta and Mounts Katmai, Martin, Mageik, and Trident. No studies of individual volcanoes.
[3]Compiled.
[4]Completed.

pyroclastic flows and debris from dome collapses cascaded down the north flank of Redoubt and melted snow and ice on Drift glacier. The largest debris flows, on January 2 and February 15, invaded the Drift River Terminal near the mouth of the river, but no oil was spilled. These floods and the continued activity of Redoubt prompted State and industry officials to modify the operating procedures of the oil terminal, which led to the temporary shutdown of 10 oil platforms in Cook Inlet.

The Alaska Volcano Observatory, established in 1988 to improve monitoring of volcanoes near Cook Inlet, issued warnings of potential eruptive activity at Redoubt Volcano before several eruptive episodes, including those on December 14, 1989, and January 2, March 23, and April 6, 1990. These warnings were based on seismicity beneath the volcano, and they demonstrate the benefits of maintaining a seismic monitoring system on active volcanoes. Experimental systems for detecting significant ash plumes and debris flows also proved effective during the eruption sequence.

Most volcanic eruptions are preceded by measurable changes in the state of the volcano. The explosive episode that marked the beginning of the 1989–90 eruption of Redoubt was preceded by only about 24 hours of intense seismicity. This period of time was sufficient for AVO to warn officials and the public about the volcano's potential for eruptive activity. Emergency response plans, however, require far more time to prepare. The briefness of the seismicity that preceded Redoubt's eruption underscores the importance of planning for future volcanic emergencies before the first signs of restlessness appear.

The size and type of volcanic activity that occurred during this eruption were anticipated on the basis of an analysis of the volcano's eruptive history. Similar analyses are underway at Mount Spurr and at Augustine, Iliamna, and Hayes Volcanoes. Hazard assessments resulting from such geologic investigations show areas around volcanoes where there are risks to life and property, and discuss the character of volcanic hazards.

ACKNOWLEDGMENTS

This report draws upon the work of many individuals who participated in the response to the eruption through their documentation of volcanic deposits, interpretation of seismicity, analyses of eruptive products, installation and maintenance of instruments and computers, and communication of hazard information to the public and government and industry officials. Also, many members of the Branch of Alaskan Geology, U.S. Geological Survey, and students of the University of Alaska in Fairbanks spent long hours on 24-hour watches. In addition to those who contributed directly to the writing of this report (listed on title page), the following individuals contributed indirectly through their work, informal reviews, and preparation of illustrations.

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