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Redoubt Volcano, Cook Inlet, Alaska: a hazard assessment based on eruptive activity through 1968

by

Alison B. Till, M. Elizabeth Yount, and J.R. Riehle
U.S.Geological Survey, Anchorage, Alaska

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Abstract

Redoubt Volcano is one of four composite volcanoes on the west side of Cook Inlet, Alaska, which have been active during Holocene time and which pose a hazard to the state's main population center. The volcano, a typical convergent-arc volcano, is composed of about 40 cubic kilometers (km^3) of interbedded lava flows, rubble, and pyroclastic material, which are chiefly of andesitic composition. Minor basaltic and dacitic rocks make up a small part of the volcano. Most of the cone building occurred during middle and late Pleistocene time. At least 30 large tephra-forming eruptions have occurred during the past 10,000 years. Eruptions in 1902, 1966, 1968, and 1989-90 produced ash and generated floods on the Drift River, which drains the north side of the volcano, by melting part of the volcano's extensive glacial cover.

The field work and data analysis on which this report is based were completed before Redoubt erupted in 1989. The report was in final preparation stages at the time of the eruption. Because of this, discussion of events related to the 1989-90 eruption will be included in other reports.

Tephra from future eruptions of Redoubt will probably be carried by prevailing winds to the northeast and could have a substantial impact on human activities as far as several hundred km from the volcano. One-half of the state's population would be affected by such events. In addition, flows or floods in any of several flanking valleys could reach the sparsely inhabited coast of Cook Inlet, where seasonal fishing and recreational use occurs and an oil tanker terminal is located, near the mouth of Drift River. Floods and debris flows large enough to reach the Drift River delta have occurred during historic time; they are thought to have been generated during eruptions. Less likely but potentially more hazardous events than the debris-flows and floods that occurred during historical eruptions are partial cone collapse, prolonged ash-rich emissions, and generation of extremely large-volume debris flows.

A least-likely scenario is highly explosive eruptions of silicic magma that would produce, in addition to the products of the events cited above, fast-moving pyroclastic flows in valley bottoms and (or) a lateral blast, the damaging effects of which could extend as far as 30 or 40 km from the volcano. Such activity is precedented at Redoubt, as the oldest deposits of Redoubt volcano are early Pleistocene dacitic pyroclastic deposits. Eruptions of dacitic material are potentially much more explosive than andesitic eruptions owing to the higher silica content of dacite.

Introduction

Redoubt Volcano, one of four active volcanoes on the west side of upper Cook Inlet in southern Alaska, is 170 kilometers (km) southwest of Anchorage and 80 km west of Kenai (fig. 1); other active volcanoes in the area are Mount Spurr, Mount Iliamna, and Augustine Volcano. Redoubt is an eroded cone-shaped mountain, mostly covered with snow and ice, that rises to a summit height of 3,108 meters (m), some 1,500-1,800 m above the surrounding Chigmit Mountains (fig. 2). The volume of the cone is approximately 40 cubic kilometers (km^3). The volcano is drained on the north by the Drift River, on the east by Redoubt Creek, and on the south by the Crescent River, all of which flow into Cook Inlet. A 1 $^1/_2$-km-wide ice-filled summit crater is breached by a north-flowing glacier (informally known as the Drift glacier; fig. 3). Redoubt is the second most historically active of the Cook Inlet volcanoes, having erupted four times since 1900 (1902, 1966, 1968, 1989-90). The vent active during the 1966, 1968, and 1989-90 eruptions is on the north edge of the summit crater (fig. 1, inset; fig. 3).

Redoubt has erupted at least 30 times during the past 10,000 years. The effects of these eruptions have been recognized as far as 240 km from the volcano. One-half of Alaska's population lives downwind from the volcano in the Cook Inlet area; the distal effects of future tephra eruptions of Redoubt could reach this population readily. Human activity near the volcano is limited. The volcano is located in Lake Clark National Park and is infrequently visited for recreational purposes on a seasonal basis. During the summer fishing season, set-netters work the beaches near Redoubt and boats fish directly offshore. The Drift River terminal, an oil storage and tanker terminal serving offshore oil platforms in western Cook Inlet, approximately 35 km downstream from Redoubt near the mouth of the Drift River, is particularly vulnerable to eruption-related floods (figs. 1,4). Air traffic from Anchorage to communities in southwest Alaska and the Orient passes near the volcano and could be seriously affected during periods of eruptive activity.

No detailed geologic mapping or hazard assessment of Redoubt was done prior to this investigation. Effects of the 1966 and 1968 eruptions on the mass balance of Drift glacier have been studied by Sturm and others (1983, 1986). Riehle and Emmel (1980) and Riehle and others (1981) recognized 3,500-year-old volcanic debris-flow deposits (lahars) in seacliff exposures southeast of the volcano. In a study of ash deposited in the upper Cook Inlet region within the past 10,000 years, Riehle (1985) identified at least 30 ash layers that were produced by eruptions of Redoubt. Forbes and others (1969) and Pulpan and Kienle (1979, 1980) published chemical analyses of volcanic rock collected during reconnaissance work.

The field work and data analysis on which this report is based were completed before Redoubt erupted in late 1989. The report was in final preparation stages at the time of the eruption. Because of this, little discussion of events related to the 1989-90 eruption is included. Detailed discussion of the 1989-90 eruption will be included in other reports.

Mapping of Redoubt's cone and the valleys that drain it provides the basis for reconstructing its geologic history and for assessing the volcanic hazards associated with future eruptions. In assessing hazards to life and property we considered the range of past eruptive behavior at Redoubt as well as that at other volcanoes of similar type and eruptive style. The past eruptive behavior of Redoubt, as indicated by the type, age, and volume of deposits, is a specific analog for its future behavior, although a change in eruptive style is possible. Also, the types of past eruptions of similar volcanoes can be used as analogs, in a generalized sense, to aid in identifying types or magnitudes of unprecedented eruptions that might occur at Redoubt.

The geologic history of Redoubt is briefly outlined here because it has not been described elsewhere. An assessment of potential hazards from future eruptions follows. A description of volcanic processes and resulting deposits is included in the "Appendix".

Geologic History

Introduction

The geologic history of Redoubt Volcano can be divided into four eruptive periods: an early explosive period recorded by hot pyroclastic flow deposits and shallow intrusive rocks, an early cone-building period recorded by thin lava flows and interlayers of volcanic rubble, a late cone-building period recorded by thick lava flows and voluminous pyroclastic deposits, and the latest period recorded by voluminous debris-flow deposits and widespread tephra deposits. Each period encompasses many individual eruptions that are characterized by a similarity in style and general lava composition. Volcanic activity at Redoubt probably began more than 400,000 years ago, but most of the cone has been built in the past 200,000 years. Volcanic products of the early explosive period are largely dacitic (62-68% SiO_2). Basalt and basaltic andesite (49-59.5% SiO_2) erupted during the early cone-building period around 190,000 years ago (J. VonEssen, written commun., 1988); later cone-building flows and pyroclastic deposits are andesitic in composition (54-62% SiO_2). Holocene tephra deposits of Redoubt are silicic andesite (59-61.5% SiO_2). After the early cone-building period, average magma composition has generally become more silicic with time (fig. 5).

Pleistocene History

Deposits of the early explosive period crop out low on the north, south, and southeast flanks of the volcano. They consist of debris-flow and glacial deposits containing dacitic pumice, dacitic pyroclastic deposits, and a dacitic rock mass that may be a shallow intrusion or dome. The magma extruded during these eruptions was the most silicic in Redoubt's history (fig. 5), implying that these may have been Redoubt's most explosive eruptions.

The present cone began forming during the succeeding early cone-building period, during which numerous basalt and basaltic andesite lava flows containing tephra and rubble erupted. Exposures of these thin flows (each less than 6 m thick) have distinctive color-bands: the flows are gray to black, and the tephra and rubble are red. The banded sequences are exposed on all sides of the volcano and provide a marker horizon for determining relative ages of deposits (fig. 6).

Andesitic lava flows and a voluminous apron of pyroclastic debris erupted during the late cone-building period. These thick (30-60 m) columnar-jointed lava flows form the upper edifice of the volcano, and also occur low on the north flank (fig. 7). The pyroclastic apron consists of unconsolidated, poorly sorted deposits that interfinger with the lava flows and dominate the southern slope of Redoubt (fig. 8). The deposits are sand-sized tephra to boulder-sized blocks of andesitic lava. Many of the blocks are radially fractured (fig. 9); such fractures indicate that they were transported while hot, in avalanches shed from lava flows or pyroclastic flows.

Holocene History

The eruptive history of Redoubt Volcano during Holocene time (the past 10,000 years) is summarized in figure 10. The prehistoric eruption record was inferred from the examination and dating of Holocene tephra deposits identified at 31 localities in the Cook Inlet region (Riehle, 1985). Locations at which Redoubt tephra was identified are shown in figure 11. At least 30 tephra layers from Holocene eruptions of Redoubt were identified within 22 km of the volcano. Tephra deposits correlative with Redoubt Volcano on the basis of chemical and mineralogic similarity to one or more proximal Redoubt deposits are identifiable at least as far as Tyonek (112 km northeast), and perhaps as far as Anchorage and Talkeetna (as far as 240 km away)(figs. 1,11). The 1966 and 1968 eruptions of Redoubt did not produce enough tephra to be identified at the sites studied by Riehle; this absence indicates that the Holocene tephra record includes only deposits larger than those produced during the 1966 and 1968 eruptions. Eruptions of a size sufficient to impact human activity also may not be large enough to produce deposits in the stratigraphic record. Therefore, during Holocene time there may have been many more than 30 eruptions of sufficient size to have affected human activity.

Many more eruptions occurred during the Holocene than the 30 eruptions documented in the tephra stratigraphy. Such minor eruptions produced several very thin tephra deposits as far as 160 km east of the volcano on the Kenai Peninsula. These deposits are difficult to adequately sample for identification, but they are generally similar in composition to Redoubt tephra deposits. The deposits probably represent several eruptions of Redoubt Volcano during the past one to two thousand years (Douglas Reger, written commun., 1986; dating based on proximity of the deposits to archeological horizons). Although no data exist on the distribution of Holocene tephra to the west or south, wind data indicate that most tephra deposits are likely to be found in the northeast quadrant (fig. 11).

Eruptions of the size represented by tephra in the stratigraphy likely produced numerous pyroclastic flows and (or) debris flows, by analogy with other volcanoes. Deposits from these events may exist on Redoubt but are indistinguishable from older deposits owing to similarity or extensive reworking. Indirect estimation of the likely size of the deposits related to the large Holocene eruptions is hampered by the lack of thickness and distribution data for specific tephra beds in the regional stratigraphy.

Approximately 0.5 km^3 of volcanic debris was deposited in the Crescent River valley about 3,500 years ago. These debris-flow deposits contain abundant material derived from the south slopes of Redoubt. The debris-flows reached Cook Inlet 32 km away (where deposits are 2-5 m thick) and filled the valley from Squarehead Cove on Tuxedni Bay to Polly Creek (pl. 1, map A). Part of the deposit forms the natural dam that contains Crescent Lake (Riehle and others, 1981). Riehle and others (1981) interpreted these deposits to be the result of a cone-destructive eruption of Redoubt and suggested that the hummocky topography of the natural dam at Crescent Lake might have been formed by a debris avalanche. It is unclear from their study what the temperature of emplacement of the debris-flow deposits might have been, and no specific evidence relating the deposits to an eruption has been found. Theirs is not, however, an unreasonable hypothesis.

After 3,500 years ago, no major debris flows were deposited in the Crescent River valley. Activity moved to the Drift River valley, possibly as the result of a shift in location of the volcano's vent. Debris-flow deposits in the Drift River valley are younger and smaller in volume than those in the Crescent River valley, and they have been generated fairly frequently. Four to six debris-flows were deposited on the Drift River after about 2,000 years ago and probably within the past 200-400 years. Drift River deposits are composed largely of sand in contrast to the bimodal, boulder-in-clay composition common in those of the Crescent River (fig. 12). Clasts in the Drift River debris-flow deposits are dominated by a single lithology. Material carried in the Drift River debris-flows was probably derived from ejection of hot pyroclastic material onto snow and ice or mobilization of unconsolidated deposits on the cone by large amounts of water. Drift River debris flows apparently had a higher ratio of water to rock debris than the Crescent River debris flows when deposited; the Drift River flows were mapped 32 km downstream from the volcano (pl. 1, map A). Some of these debris flows deposited boulders with mean diameters of 0.5-2 m as far as 19 km downstream from the volcano (13 km upstream from the Drift River terminal site)(fig. 13). Ice rafting may have transported the few anomalously large boulders observed on the lower reaches of Drift River. The debris-flow deposits grade into flood deposits farther down the drainage.

Lake deposits occur at one locality in the Drift River valley immediately upstream from the Drift glacier (pl. 1, map A). There, tan, planar-laminated, locally ripple-cross-bedded fine sand is interlayered with gray, coarse sand- to pebble-sized tephra layers (fig. 14). The deposit is a minimum of 1.5 m thick, and it may have formed when the river was dammed either by volcanic debris or by the advance of the Drift glacier. In either case, subsequent catastrophic failure of the unstable dam (a common occurrence in glacier- and debris-dammed lakes) would have caused flooding on Drift River. However, there is no direct evidence that debris-flow deposits downstream from the glacier formed in this manner.

An area of altered rock is present on the east flank of Redoubt (pl. 1, map A). Although the age and origin of these rocks are not known, they are important in assessing volcanic hazards, because they may constitute a weakened part of the cone. Lava flows and pyroclastic deposits within this area are orange, rust, mustard, and locally green from weathering or alteration. The varicolored stains coat clasts and fractures and are locally dispersed through the matrix of pyroclastic deposits. Phenocrysts in lava flows are altered to clays; silicified material occurs locally. Unlike typical volcanic deposits, bedding of these altered flows dips uniformly toward the summit of the volcano. The bedding orientation is probably not related to an adjacent volcanic edifice east of Redoubt, inasmuch as no associated deposits have been found. The strata on the east flank of the mountain were hydrothermally altered and probably slid as a coherent block (like a large landslide) down that flank at some time during the past 10,000 years.

Pumice fragments were found sitting on and intergrown with mats of vegetation on ridges east, south, southwest, and north of Redoubt. The presence of the pumice indicates that eruptions of Redoubt during the last 1,000-2,000 years have produced more than fine ash.

Historical Record

Records of volcanic activity in the Cook Inlet region before the late 19th century are found in notes and diaries of explorers. Volcanoes were often observed to be "smoking," but in most cases the smoke was probably water vapor rather than tephra. Captain James Cook in 1778 observed that Redoubt was "emitting a white smoke but no fire" (Beaglehole, 1967, p. 370). In 1794, George Vancouver saw Redoubt but apparently did not note any "smoke" (Lamb, 1984). In an 1850 compilation of volcanic phenomena in Alaska, Grewingk attributed to Baron von Wrangell the observation that Redoubt "had been smoking since 1819" (Petroff, 1884) or "in 1819 the Redoubt Volcano of Cook's Inlet smoked" (Dall, 1870, p. 499). In our opinion, these early reports are not accounts of actual eruptions.

In 1902, explosive eruptions of Redoubt deposited tephra from Lake Clark to the Skwentna valley (Martin and Katz, 1912). Tephra fell on the settlement of Hope, on the Kenai

Peninsula (fig. 1), January 22 and repeated explosions were heard there February 17 and 18 (The Alaskan, Sitka, March 29, 1902). An English tourist reported that "at Kenai and Kussiloff [Kasilof] * * * [tephra] lay on the ground several inches thick in places" (Cane, 1903). This is probably an exaggeration, because there is no sign of 1902 tephra in terrestrial sites or in lake cores near Kasilof or Kenai (Thomas Ager, written commun., 1985). Tephra deposits from this eruption have been recognized elsewhere, however, and an analysis of tephra from this eruption was published by Pulpan and Kienle (1979).

Following an earthquake in May 1933, Redoubt was observed "belching smoke," which was unusual since it "had never been known to emit anything more than a slight wisp of smoke" (Fairbanks Daily News-Miner, May 25, 1933). The report does not mention tephra or that the smoke was dark in color. Hence, it seems likely that the activity was water-vapor emissions rather than an eruption.

In January and February of 1965, pilots reported that five fissures had opened on the southeast wall of Redoubt and were emitting water vapor and hot gases (Anchorage Daily News, January 29 and 30, 1965, Fairbanks Daily News-Miner, February 4, 1965). One year later on January 24, 1966, Redoubt erupted. "Giant black puffs" of tephra rising 6,000 m above the summit and tephra falling over a 24-km radius were reported (Anchorage Daily News, January 25, 1966). A 22-man seismic crew camping and working along the lower Drift River was evacuated following flooding of the river as a result of the eruption. According to their account (Anchorage Daily News, January 26, 1966), the ice-bound river broke up suddenly and water rose 1 to 1.2 m in 15 minutes, carrying chunks of ice "the size of a D-7 cat". The flood crested and returned to normal within about 30 minutes. During this flood, boulders with mean diameters of 1-2 m were deposited within approximately 3-5 km of the volcano. Other smaller floods occurred through February and March (Sturm and others, 1986).

Infrasonic waves attributed to explosive eruptions of Redoubt were recorded 550 km away at College, Alaska, during two periods: six explosions from January 24 to February 20, 1966, and five explosions from December 7, 1967, to April 28, 1968 (Wilson and Forbes, 1969). Wilson and Forbes also reported "another series of clouds" erupted from January 1 to 15, 1967, that reached altitudes of 6,000 m, but no accompanying infrasonic waves were recorded.

Sturm and others (1986), in a study of long-term effects of the eruptions on the Drift glacier that drains the summit crater, estimated that 60,000,000 m^3 (.06 km^3) of ice were "blasted, melted, scoured, or washed away by the cumulative events of 1966-68". When parts of the glacier that were separated by the eruption reconnected, a dramatic thickening of the lower glacier occurred and the surface speed increased by a factor of ten. This surge apparently culminated in 1986 without causing a damming of the Drift River.

In mid-December 1989, anomalous seismic activity developed under Redoubt and on December 14 the volcano started a series of ash-rich eruptions (Alaska Volcano Observatory, 1990). During late December and January, dome building alternated with explosive activity. A large flood inundated the Drift River drainage and reached as far as Cook Inlet (Alaska Volcano Observatory, 1990). Ash clouds generated during explosive events caused damage to aircraft and interrupted air traffic. Oil production in Cook Inlet was temporarily curtailed because of the flood and hazards associated with the ongoing eruption (Alaska Volcano Observatory, 1990).

Summary

Initial activity of Redoubt Volcano in early Pleistocene time included explosive eruptions of dacitic material. The composition of the subsequent cone-building deposits, which included both air-fall debris and lava flows, evolved from basalt and low-silica andesite in the early period to andesite in the late period. Holocene eruptions have produced andesitic and dacitic airfall debris and lava domes. but no lava flows; some destruction of the cone has occurred. Large debris flows and floods have inundated major valleys that drain the volcano, a result of closely coupled glacial and volcanic processes. At least 30 eruptions of Redoubt have produced enough tephra to be recorded in the stratigraphy of upper Cook Inlet in the past 10,000 years. Approximately 3,500 years ago, debris flows and possibly a debris avalanche deposited abundant material in the Crescent River valley. These deposits may have resulted from an eruption. Since then, minor eruptions have produced debris flows originating in drainages on the north side of the volcano, domes at the vent, and lapilli-sized tephra fragments. In the Drift River valley, coupling of volcanic and glacial processes *may* have resulted in formation and subsequent collapse of ice or debris dams, creating floods downstream up to 20 years after an eruption.

Volcanic Hazards

The fundamental assumption made in this assessment is that Redoubt's past eruptive style indicates its future eruptive style, an assumption proven reasonable for other volcanoes, such as Mount St. Helens (Crandell and Mullineaux, 1975, 1978). However, another factor to be considered is that eruptions of a type or magnitude unprecedented in Redoubt's past but like those that have occurred at similar volcanoes may also occur in the future.

Life- and property-threatening effects of volcanic eruptions decrease in severity with distance from a volcano. The "safe distance" from the volcano depends on the magnitude and explosivity of the eruption and the nature of the eruptive products.

Explosivity depends chiefly on viscosity and volatile content of the magma or erupted material. Low-silica basaltic lava is fluid (has low viscosity) and allows easy escape of gases, and is therefore not explosive. Gases trapped by pasty, viscous magma escape violently upon eruption. The higher the silica content, and (or) the lower the temperature of the magma, the higher the viscosity and the greater the potential explosivity of the eruption.

Explosive activity can also be caused by factors independent of magma composition, viscosity, and volatile content. Rapid heating of large volumes of ground water and surface water can lead to highly explosive hydromagmatic eruptions. Therefore, magma rising into a ground-water system or water circulating into a magma system may erupt explosively, independent of its composition and gas content.

To judge the potential effects of an eruption, the types of events likely to occur are also an important factor. For instance, debris avalanches, debris flows, floods, and large pyroclastic flows generally travel farther and faster from their source than lava flows. Lateral blasts may affect large areas and may be unimpeded by topographic barriers. The "safe distance," therefore, is strongly dependent on the type of events associated with an eruption. Moreover, eruptive effects are interrelated; hot tephra fall or pyroclastic flows mixed with snow and ice can generate debris flows and floods.

Finally, the size of the eruption is critical in determining its potential hazard. Products from small eruptions may be flowage deposits limited to drainages immediately around the volcano and a small tephra deposit; large eruptions may affect both valleys and highlands in a sizable area around the volcano. Large tephra plumes, or a large volume of tephra erupted over a prolonged period, can affect large areas at great distances from the volcano.

The 1966-68 eruptions of Redoubt produced material containing 59 - 61.5 percent silica (fig. 5). Products of future eruptions will likely be of material similar to or slightly more silica-rich than the recent products, that is, silica-rich andesite or possibly dacite. If the magma produced has a high silica content, it will be viscous and contain more volatiles. Future eruptions, therefore, are likely to be explosive, regardless of their size and duration.

The size of eruptions is difficult to predict. The 1966-68 eruptions produced minor tephra deposits and floods that are probably typical of the least intense and the most frequent type of eruption Redoubt. The 1966-68 events are useful as a model for high-frequency, low-volume debris flows and floods on the Drift River, but they are not representative of larger eruptions such as the 30 significant tephra-forming eruptions observed in the Holocene stratigraphy of the Cook Inlet basin.

Importantly, the fact that floods reached the Drift River delta as a result of historic eruptions indicates that eruptions need not be as large as the 30 recorded in Holocene stratigraphy to have an impact on the population in south-central Alaska. Smaller eruptions could certainly have a noticeable effect on human activities in upper Cook Inlet if tephra dispersal were directed toward population centers. The eruptions of Redoubt in 1966-68 and Augustine Volcano in 1976 and 1986, for example, are not considered "significant" in volume of tephra produced, and yet the Augustine eruptions did impact human activities (Yount and others, 1987).

Some hazardous events can occur without an eruption. Crandell (1971) described a debris-flow deposit that extends 35 km from Mount Rainier and formed at a time for which there is no evidence of an eruption. The debris-flow deposit is clay-rich and originated in an area of altered lava flows on the flank of the mountain. A debris flow or debris avalanche could originate on the east flank of Redoubt in a similar fashion, without an associated eruption. However, Crandell (1971) noted that such flows or avalanches are most commonly triggered by earthquake or volcanic activity.

Large eruptions of Redoubt might result in catastrophic failure of the volcano's flank. A lateral blast, debris avalanche, and (or) large-volume debris flow might occur. Blockage of major drainages around the volcano and movement of large debris flows as far as tidewater are possible and precedented at Redoubt. Pyroclastic flows, domes, and lava flows on the cone could trigger landslides and debris flows. Large volumes of tephra, from single or repeated eruption events, could be directed toward the upper Cook Inlet area by the prevailing winds, and would affect population centers.

Although the duration of an eruption of a circum-Pacific volcano can range from several hours to many years, most eruptions last no longer than several months, with their most violent phases lasting several days. For example, the 1986 eruption of Augustine Volcano consisted of three explosive phases, each 5-10 days long, spanning a 5 month period. Within each of the three phases, the intensity of explosive activity fluctuated considerably (Yount and others, 1987). Accounts by Wilson and Forbes (1969) suggested similar fluctuations occurred during the 1966 and 1968 eruptions of Redoubt.

The Hazard Map

The area around the volcano was divided into four hazard zones on the basis of hazards that arise from different types of eruptive activity as well as different sizes of eruption (plate 2). Certain zone boundaries can be located precisely due to the overriding influence of topography on distribution of debris flows, pyroclastic flows, and lava flows. Other zone boundaries are approximate, and their placement is more arbitrary, as discussed below. For any future eruptions, the violence and duration of the eruption and the position of the vent will influence the location and extent of the hazards created; therefore, the hazard zones shown on plate 2 should be considered guides, rather than rigid predictions.

Hazard zones were differentiated by types of deposits (plate 2). Zones A and B are "flowage-hazard zones", delineating hazards created by eruption products flowing down valleys. The extent of zones A and B is limited by the topography, the nature of the eruptive products, and the size of the eruption. Zones A and B delineate hazard zones due to lava flows, pyroclastic flows, debris avalanches, debris flows, and floods. Zones A_1 and A_2 are most likely to be impacted by debris flows and floods generated by the present vent or any vent in the summit crater. Zone A_1 is likely to be affected by products of any eruption, including eruptions similar to or smaller in magnitude than the 1966 and 1968 events. During a single small eruption, the zone might be repeatedly inundated. Zone A_2 is likely to be affected by short periods of flooding during a small eruption from the summit crater or inundated by one or several large-volume debris flows during a larger eruption. Both zones A_1 and A_2 could be affected by outburst flooding as a result of damming of Drift River by pyroclastic flows, glacial advances, or avalanches. Zone B delineates areas that, in addition to A_1 and A_2, are likely to be affected by debris avalanches, debris flows, floods, pyroclastic flows and related ash-cloud surges and or lava flows during an eruption larger than those in 1966 and 1968. Portions of zone B could also be affected by eruptions of any size from a vent outside the summit crater.

Zone C and zone D (in the inset) represent areas that may be affected by hot tephra clouds and lateral blasts; these areas are hard to define precisely due to the extreme mobility of clouds and blasts. The size and direction of travel of those clouds and blasts will determine the extent of the area affected. We have arbitrarily drawn the boundary of zone C at the ridge crest closest to Redoubt to represent the likely distribution of hot gas and tephra clouds in a moderate to large eruption. It is common for clouds or blasts to overtop ridges; the divide at the edge of zone C varies considerably in height along its length. Large blasts and clouds will likely travel outside the boundaries of zone C, especially where the divide is low. The 35-km radius indicated in the inset as zone D shows the largest area likely to be affected by a large lateral blast (Crandell and Hoblitt, 1986). At Mount St. Helens, the lateral blast of the May 18, 1980 eruption leveled trees as far as 29 km away (U.S. Geological Survey, 1981).

Once the location of the vent is known for a given eruption, the areas in zones A and B most likely to be affected can be better delineated. The amount of ice and loose rock debris directly around the vent controls the supply of material to debris flows and floods. The particular drainage affected by debris flows or floods depends on the location of the vent. The most likely vent position during the next eruption is near or at the site of the vent active in 1966, 1968, and 1989-90, on the north side at the head of the Drift glacier.

The north and the south sides of the cone contain different amounts of ice and unconsolidated material. The large volume of ice and small amount of unconsolidated material on the north side indicates that floods are more likely than debris flows in the Drift River drainage as a result of a small eruption. The south flank of the volcano is underlain by a large fan of unconsolidated pyroclastic deposits that could easily be mobilized by meltwater to produce large debris flows during a small eruption. Depending on the location of the vent, an eruption could produce large debris flows and floods on any side of the volcano.

Sturm and others (1983, 1986) attributed the destruction of upper Drift glacier during the 1966 eruption to both melting and explosive disruption. They hypothesized that the large burst of water that formed the first 1966 flood was derived from subglacially ponded meltwater, produced as the vent heated before the eruption and released by the eruption. The accumulation area for the Drift glacier is the summit crater; the outlet from the crater is the site of the most recent vent (figs. 3,15). Heating of rocks in the vent area may melt a large quantity of ice before any other manifestations of an eruption are evident. In addition, the mass of the glacier extending immediately down-drainage from the vent and glaciers on the north flank are likely to be melted by hot eruptive debris. These two sources of water may combine to produce a large volume of water that would be released into the Drift River valley during the course of an eruption (fig. 16).

Sturm and others (1986) showed that eruptions may result in surges of the Drift glacier that could dam the Drift River. Their data show that surges occur as the glacier attempts to reestablish equilibrium after its upper reaches have been altered or destroyed by an eruption. Associated advance of the glacier could temporarily block the Drift River and create a lake on the upstream side. Failure of the ice dam would result in flooding of the river and possibly endanger the oil terminal at the coast. Flood hazard created by glacial damming of Drift River could culminate as long as 10-20 years after the eruption. However, surging of the Drift glacier *without* damming of the Drift River was documented after the 1966-68 eruptions (Sturm and others, 1986), indicating that there is not a necessary relationship between ice damming and eruptive activity.

A large eruption of Redoubt could result in a lateral blast, caused by catastrophic failure of a side of the cone as magma moved up into it. Lateral blasts have occurred several times at Mount St. Helens and Lassen Peak (Crandell and Hoblitt, 1986). In general, blasts occur infrequently and are smaller than the lateral blast from Mount St. Helens in 1980 (Crandell and Hoblitt, 1986). A lateral blast can occur on any side of a volcano, but weakened rock provides a preferred pathway for magma entering the cone. The presence of a large volume of altered rock on the east side of Redoubt suggests that side of the cone may be structurally weak (pl. 1, map A). If this is the case, the east flank of the mountain would provide a pathway for eruption of gas, lava, or a lateral blast in the future.

Tephra Distribution

Tephra dispersal is likely to have the greatest impact on human activity in the Cook Inlet area. None of the hazard zones shown on plate 2 indicate the distribution of tephra that could be expected from future eruptions of Redoubt because the distribution can be expected to extend beyond the area of the plate. Factors that affect the distribution of tephra are the altitude reached by the tephra-laden eruption column, the speed and direction of winds at altitudes reached by the column, the size and density of the contained particles, the amount of precipitation during the eruption, and the length and continuity of the eruption.

In February 1966, an explosion at Redoubt sent tephra to 13,700 m (Wilson and others, 1966). Small eruptions such as those that occurred in 1966 and 1968 from Redoubt's most recently active vent at an elevation of 2,500 m can be expected to propel tephra as far as 12,000 m above the vent. Larger eruptions can be expected to produce larger and higher eruption columns. The dramatic May 18, 1980 eruption of Mount St. Helens propelled tephra more than 25,000 m into the atmosphere (Sarna-Wojcicki and others, 1981). Scheduled and private air traffic from Anchorage to other points in Alaska and the Orient passes near Redoubt; an eruption column reaching 12,000 m would intersect both high- and low-level flight routes used daily by commercial and private aircraft.

Summaries of upper-air wind data for Anchorage and King Salmon were compiled to characterize the prevailing wind conditions in the region (fig. 17). Data for Anchorage should more accurately reflect winds at Redoubt inasmuch as the volcano is on the east side of the Alaska Range and closer to Anchorage. Winds 3,000 m and higher above Anchorage more commonly blow toward the north and east rather than the south and west. Thus, it is highly likely that an eruption of Redoubt would result in tephra fall on the upper Cook Inlet region and the south flank of the Alaska Range. If winds were more typical of King Salmon, tephra might be distributed in a northeast or southeast direction, depending on the season.

Any future eruptions of Redoubt Volcano can be expected to send tephra at least tens of thousands of meters into the atmosphere; most often, prevailing winds would blow tephra toward the north and east. Heavier concentrations of tephra will be deposited directly downwind from the volcano following more violent explosions. If an eruption is prolonged, the direction of tephra transport would vary as wind direction changes. It is likely that small amounts of tephra would be distributed over a wide area south of the Alaska Range and east of the Chigmit Mountains (fig. 18). If heavy precipitation occurs during an eruption, tephra would be washed from the air more rapidly than it would otherwise settle to the ground, and therefore would be less widely distributed.

Summary

The 1966 and 1968 eruptions provide a good model for the smallest type of eruption that occurs at Redoubt. Any future eruption of Redoubt has a high probability of being at least as large as those small events and is likely to produce floods, debris flows, pyroclastic flows, and possibly lava flows and domes (see plate 2, zones A and B). Floods and debris flows on the Drift or Crescent Rivers (depending on vent position) and tephra fall are the events likely to occur during a small eruption that would threaten human activity. Duration of the eruption, size of the eruption column and wind speed and direction would determine whether tephra fall reaches population centers on Cook Inlet. If an eruption results in severing of the Drift glacier, a surge of the glacier could be triggered 10-20 years after the eruption (Sturm and others, 1986).

A large-volume eruption of Redoubt is less probable than a small event. A large eruption may produce tephra fall, pyroclastic flows, debris flows, debris avalanches, floods, lava flows, and possibly a lava dome or lateral blast (plate 2). For such events, the position of the vent is important in determining the nature and distribution of the products. The east flank of the mountain in particular may be more prone to destruction by lateral blast.

A large eruption from a vent located on the south side could trigger voluminous debris flows in the Crescent River drainage, as has occurred in the past (Riehle and others, 1981). Eruptions from a vent located on the north side would most likely produce water-rich debris flows or floods on the Drift River. The most harmful effect of any eruption would be tephra distributed in the Cook Inlet region.

APPENDIX I - Typical Events and Products Associated With Volcanic Eruptions

Events associated with the eruption of composite volcanoes such as Redoubt range from those that throw material many kilometers into the atmosphere to those that slowly squeeze material out of the vent; airborne particles may travel great distances from the volcano, whereas lava oozing out of the vent may move a very short distance.

Tephra Fall

Material thrown into the air during explosive eruptions can vary in size from dust to large blocks and can consist of pulverized rock from the existing cone, from other rocks underneath the volcano, or from molten lava supplying the volcano. Tephra refers to particles of all sizes explosively emitted during an eruption. Explosive fragments smaller than 2 millimeters (mm) are called ash. Vapor emissions accompanied by minor amounts of ash are commonly among the first manifestations of an impending eruption. Explosive eruptions of composite volcanoes are commonly characterized by vigorous tephra-and-vapor plumes and periodic tephra-rich explosions.

Tephra is the most widely distributed product from eruption of volcanoes similar to Redoubt. The area covered by tephra deposits depends on the height to which the tephra is injected into the atmosphere, the direction and speed of the wind, the size of the particles erupted, and the violence and duration of the eruption. This area can be very large, up to tens of thousands of square kilometers. Small to moderate-sized eruptions commonly produce explosive eruption columns that may rise at speeds from 8 to 30 m per second as high as altitudes of 29 km (Blong, 1984). Winds at different levels in the atmosphere commonly blow in different directions, sometimes in direct opposition to each other, and thus increase the area of tephra dispersal. Tephra from small eruptions can be blown tens to hundreds of kilometers from the volcano.

Harmful effects of tephra are due to its abrasive and corrosive characteristics or to its low melting temperature. Wilcox (1959) documented the effects of tephra fall with emphasis on Alaskan volcanoes. Eyes and nasal passages of humans and animals may be irritated by tephra. Grazing animals may suffer tooth abrasion or gastric irritation by ingesting tephra-covered foliage. As was discovered during the 1980 eruptions of Mount St. Helens, tephra can have detrimental effects on transportation of goods and people, generation of electricity, communication, operation of computers, and of any other activity dependant on machinery. The effects on jet turbines can be particularly serious, because their operating temperatures are similar to the melting temperatures of tephra. Tephra drawn into a jet engine can melt and coat engine components with volcanic glass; this may cause overheating and automatic shutdown of the engine. Blong (1984) cited two incidents of jets inadvertently flying through tephra plumes over Indonesia and having engine failure; in both cases the pilots were able to restart their engines. Damage to aircraft was also reported during the 1976 and 1986 eruptions of Augustine Volcano and the 1989 erupion of Redoubt (Kienle and Shaw, 1979; Yount and others, 1987; Alaska Volcano Observatory, 1990; Kienle and others, 1990).

Other effects of tephra are due to its weight and acidity (Wilcox, 1959). Acidity and turbidity of water supplies may temporarily increase. Buildings may not be able to support the weight of a thick accumulation of tephra. Sewage systems may become clogged. Plants may be smothered. Cloth and (or) other susceptible materials may be damaged by exposure to mildly acidic conditions caused by the mixing of tephra and moisture.

Debris Avalanches, Debris Flows and Floods

A debris avalanche results from a massive failure of the flank of a volcano. Debris avalanche deposits are characterized by hummocky topography consisting of small hills and closed depressions. Longitudinal and transverse ridges may occur. The deposits are dry compared to debris flows and floods and commonly occur in areas of the cone that have been weakened by faulting, hydrothermal alteration, or both.

Debris flows are moving masses of rock, soil, and water. As the proportion of rock to water decreases, debris flows grade into floods. Debris flows and floods are common during eruptions of ice-covered volcanoes such as Redoubt, because the hot eruptive material melts the snow and ice. Debris flows and floods are highly mobile and capable of traveling many kilometers down valleys draining the volcano. The Osceola debris flow moved 100 km from Washington's Mt. Rainier to the city of Puyallup, within 9.5 km of Tacoma (Crandell and Waldron, 1956). The volume and rate of flow govern the size of the material that can be transported downstream. In larger flows, boulders several meters in diameter can be transported.

Lateral Blasts

An explosive eruption may occur as a vertical column or as a lateral blast. During a lateral blast, the thrust of the eruption is directed horizontally from the vent rather than vertically. A lateral blast results from catastrophic failure of a flank area weakened by cracking, faulting, or alteration. When gaseous (highly explosive) magma is injected into the cone, it takes the weakest pathway to the surface; if the flank is weaker than the summit area, a lateral blast will occur. When one occurs, material from the failed portion of the cone as well as the invading magma body move in part as a density current, in the form of a debris avalanche or pyroclastic flow, and in part as an inflated gas-and-tephra cloud. The volume of the material moving as an avalanche or flow and the local topography will partially control or influence the area of impact. The gas-and-tephra cloud rapidly travels great distances from the volcano, generally unimpeded by topography, and will be the biggest influence on the area of impact. The May 18, 1980 eruption of Mount St. Helens produced a lateral blast that leveled trees in a broad area as far as 29 km from the vent (U.S. Geological Survey, 1981; Crandell and Hoblitt, 1986).

Pyroclastic Flows and Surges

Pyroclastic flows are fast-moving, dry, turbulent mixtures of eruptive particles of all sizes that are buoyed up by hot, rapidly expanding gases. They are of higher temperature and travel faster than debris flows, and they are commonly generated during explosive eruptions as the debris in the eruptive column falls back to earth and flows down the volcano's flank. As pyroclastic flows travel, rapid expansion of internal gases lifts finer tephra or ash particles upward into a billowing cloud called an ash-cloud surge or glowing cloud (fig. 19).

Pyroclastic flows may move at speeds of greater than 225 km per hour on steep slopes (Moore and Melson, 1969), and internal temperatures of flows commonly exceed 590^{o}C. Associated ash clouds may outdistance flows, thereby extending the danger zone. In 1902, nearly 30,000 people in the town of St. Pierre, Martinique, died from the blast of a hot ash cloud associated with pyroclastic flows from an eruption of Mt. Pelee (Fisher and others, 1980). The blast leveled most structures in its path and upset, sank, or burned ships anchored in the harbor (Macdonald, 1972).

Although pyroclastic flows and surges can surmount topographic barriers and travel tens of kilometers if their speed, gas inflation, and volume are great enough, smaller flows are usually confined or strongly influenced by topography. The area affected by ash-cloud surges is determined by the size of the associated pyroclastic flow, the height of the cloud above the flow, and the wind direction and strength (Crandell, 1980). The main hazard zones from pyroclastic flows are the valleys leading from the volcano; the area threatened by associated ash-cloud surges extends up valley walls as well and is influenced by wind direction.

Because of the heat contained in pyroclastic flows and surges, they may generate debris flows and floods when they occur on snow- and ice-covered volcanoes.

Lava flows and lava domes

Lava flows and domes result when magma oozes from the vent. If the magma is viscous, it will mound up around the vent, to create a dome. If magma is more fluid, it will flow away from the vent under the influence of gravity. Viscosity and slope angle control the speed at which the lava moves; the rate at which the lava is extruded may influence the size of the flow.

The path of a lava flow, more so than other volcanic phenomena, is determined by topography. However, lava flows are not always erupted from the summit of the volcano and may erupt from vents on the side of the cone. Composite volcanoes similar to Redoubt tend to produce high-viscosity lava flows that do not travel much beyond the base of the cone, unless they are of unusually large volume. Lava flows move more slowly than pyroclastic flows and surges, debris avalanches, debris flows, or floods, and they pose less of a threat to life; nevertheless, they totally devastate property in their path.

Eruptions that produce volcanic domes are commonly accompanied by explosions and small pyroclastic flows. Volcanic domes are usually extruded after early, gas-rich explosive activity and may grow intermittently over several months or years.

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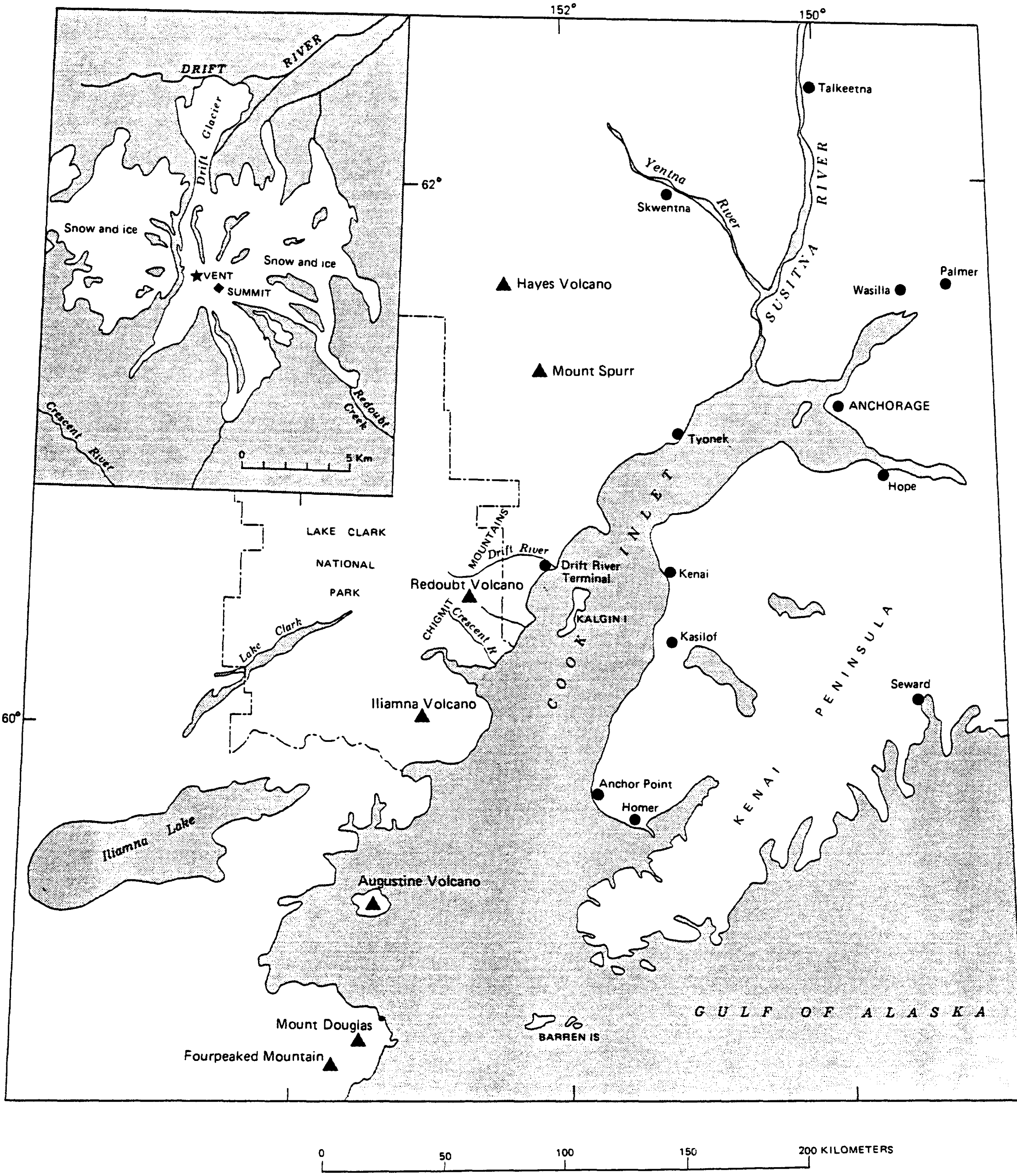


Figure 1. Geographic features of Cook Inlet region with inset showing extent of snow and ice cover on Redoubt Volcano.

Figure 2. Redoubt Volcano and surrounding Chigmit Mountains, (view from the east); Cook Inlet in foreground.

Figure 3. Summit crater of Redoubt Volcano (view from the north-northwest); true summit is on left (east) side. Drift glacier drains northward past 1966-68 vent (shown by circle).

Figure 4. View across Drift River delta toward river mouth. Buildings are Drift River terminal, a storage and shipment point for oil produced in Cook Inlet.

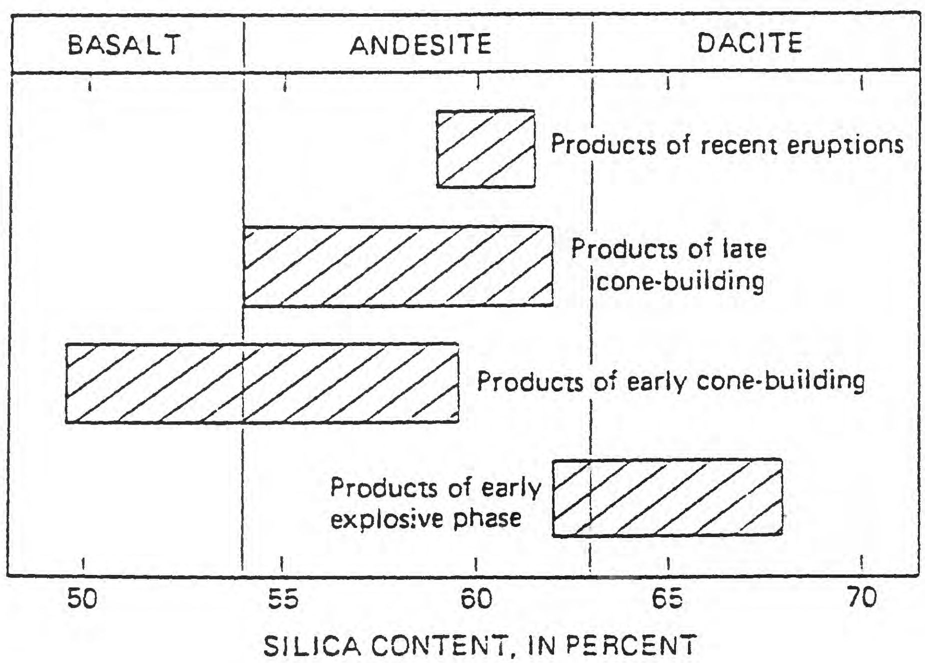


Figure 5. Silica content of products erupted during the four periods of Redoubt Volcano's history. "Recent" phase represents analyses of lithic fragments collected from thin air-fall deposits that mantle ridges on north and east sides of volcano and may have erupted as recently as 1966 or 1968.

Figure 6. A 200-m-high cliff on west side of canyon of Drift glacier exposes early cone-building deposits; light bands are thin lava flows, dark layers are rubble and ash.

Figure 7. Late cone-building columnar-jointed andesite flows tens of meters thick exposed on south flank of mountain.

Figure 8. View west along southwest flank of Redoubt Volcano showing deposits of pyroclastic apron erupted during late cone-building period; width of view approximately 0.8 km.

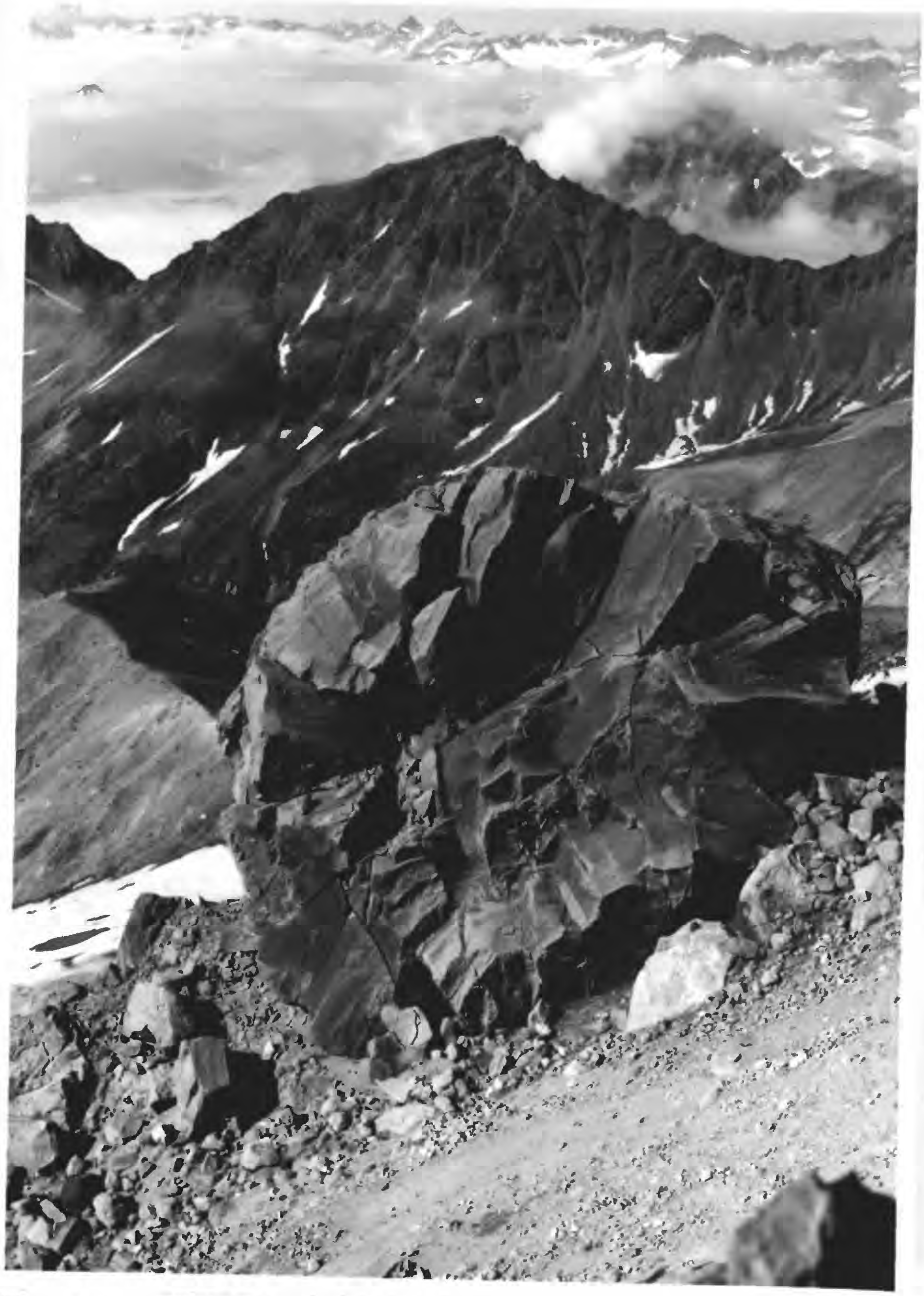
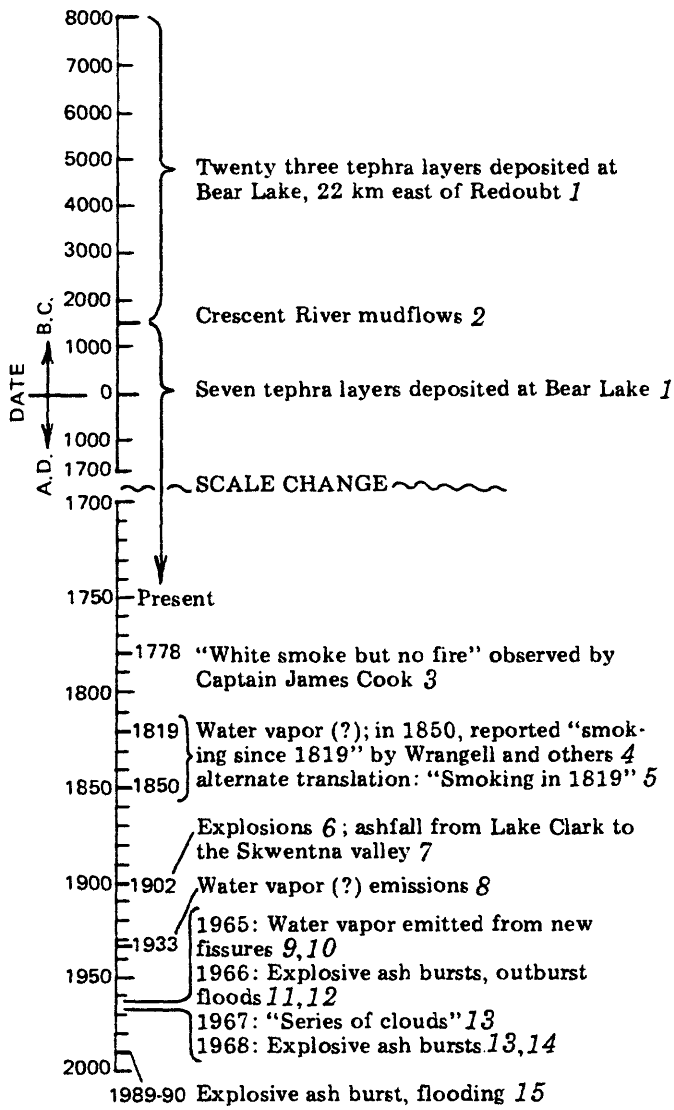


Figure 9. Radially fractured block, 3 m in diameter, exposed on south flank of the Redoubt Volcano. Fracturing indicates that block was deposited hot and cooled in place; otherwise it would likely have disintegrated during transport.



1 Riehle, 1985
2 Riehle & others, 1981
3 Beaglehole, 1967
4 Petroff, 1884
5 Dall, 1870
6 The Alaskan (Sitka) March 29, 1902
7 Martin & Katz, 1912
8 Anchorage Daily Times, May 23, 1933
9 Anchorage, Daily News, Jan. 29-30, 1965
10 Fairbanks News-Miner, Feb. 4, 1965
11 Anchorage Daily News, Jan. 25-29, 1966
12 Sturm & others, 1986
13 Wilson & Forbes, 1969
14 Anchorage Daily News, Jan. 7, 1968
15 Alaska Volcano Observatory, 1990

Figure 10. Volcanic activity at Redoubt Volcano during the past 10,000 yrs.

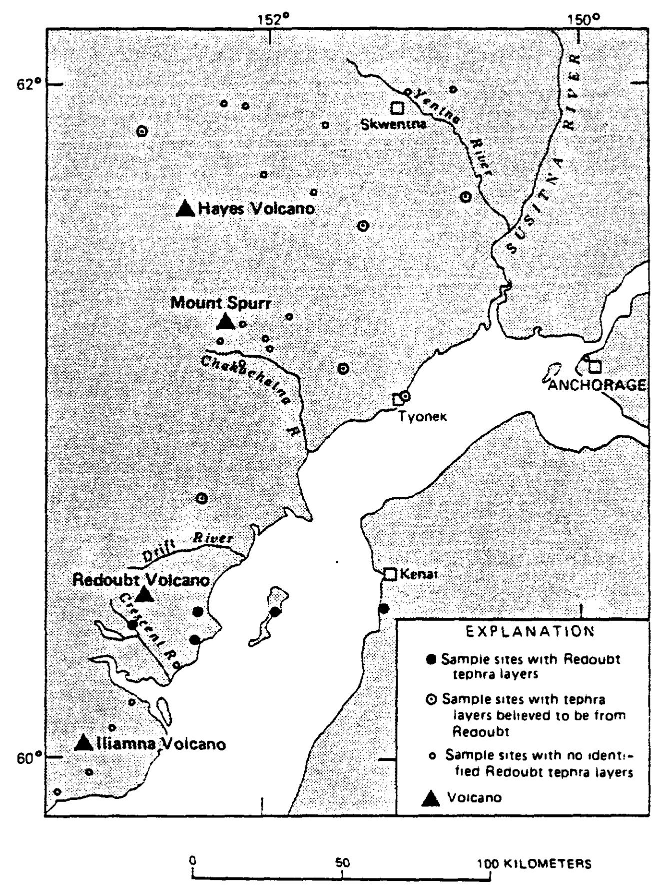


Figure 11. Upper Cook Inlet and occurrence of tephra deposits correlated to Redoubt Volcano (modified from Riehle, 1985). Samples of tephra layers from Christianson Lake near Talkeetna and Circle Lake near Homer (see fig. 1), beyond the limits of this figure, may also be from Redoubt (Riehle, unpub. data, 1985; samples provided by Thomas Ager).

Figure 12. Debris-flow deposits greater than 10 m thick in Drift River Canyon adjacent to toe of Drift glacier.

Figure 13. View up Drift River canyon showing surface of debris-flow deposits; large boulders on left were deposited by 1966 debris flows. Photo taken approximately 9 km from Drift glacier terminus.

Figure 14. Finely laminated, ripple-cross-bedded fine sand just upstream from Drift glacier interpreted to be lake deposits (see pl. 1 for location). Pencil for scale.

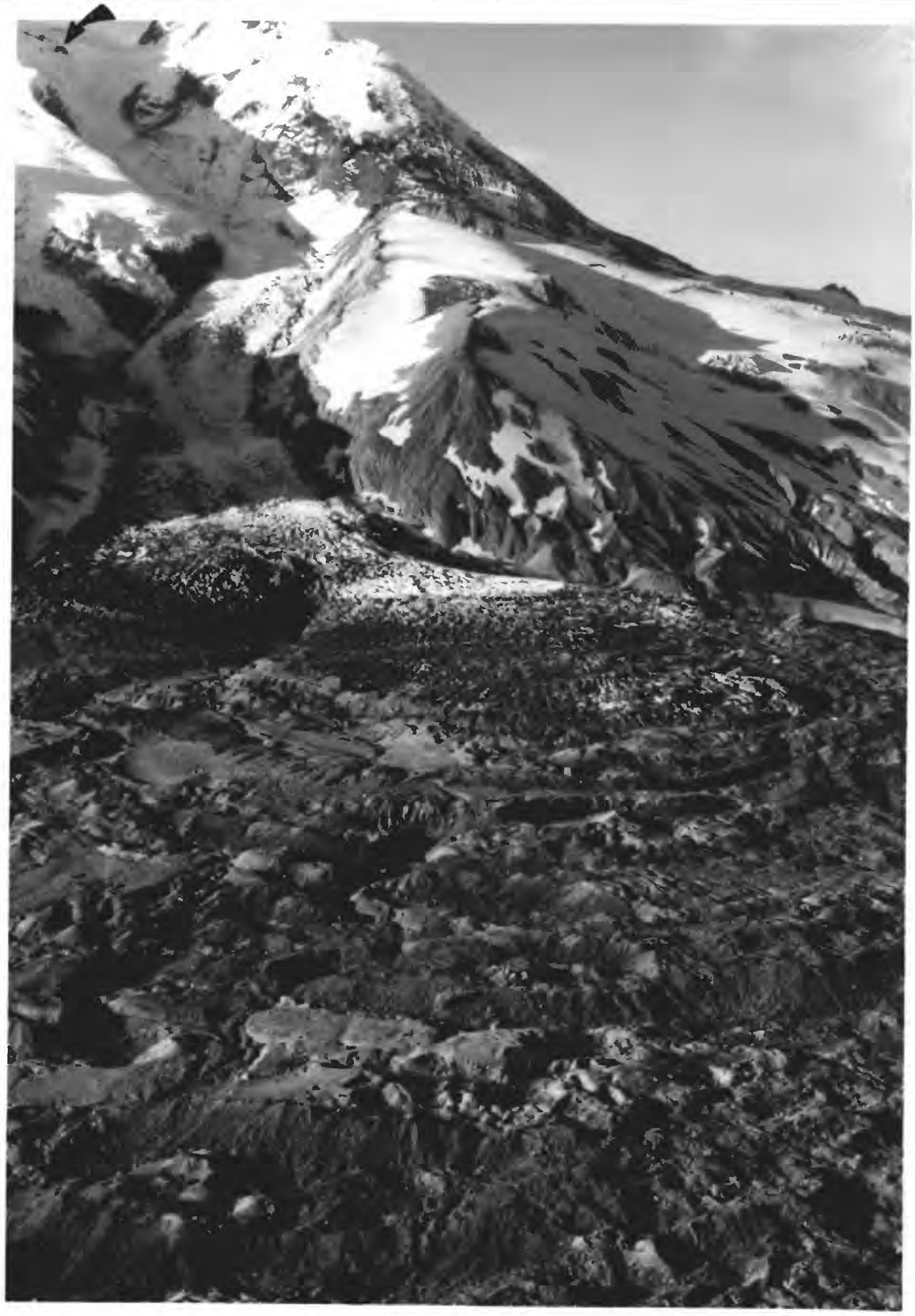


Figure 15. View up Drift glacier toward summit of Redoubt Volcano; glacier surface in foreground is covered with deposits from 1966-68 debris flows; arrow marks site of 1966-68 vent.

Figure 16. View down Drift River valley across lower Drift glacier (foreground). Glacier confines Drift River against north wall of valley. Volcano is to right of field of view. Oil terminal is 35 km downstream, out of sight to right.

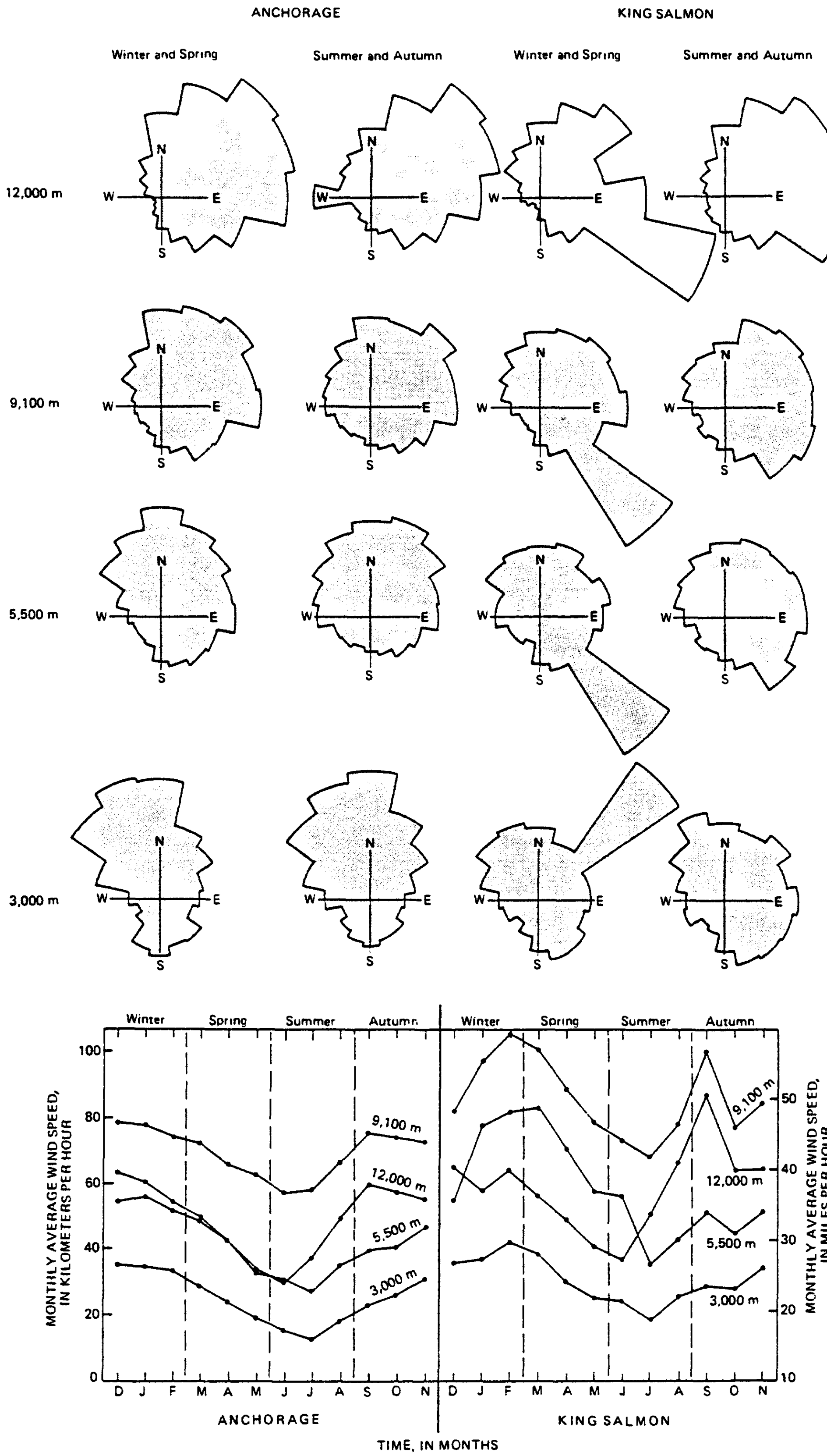


Figure 17. Average wind direction and speed for four levels in atmosphere above Anchorage and King Salmon, Alaska. Data from National Climatic Data Center, Asheville, North Carolina. Anchorage data cover period 1948-72; King Salmon data cover period 1953-60. Compass roses depict percentage of time winds blew toward a given direction.

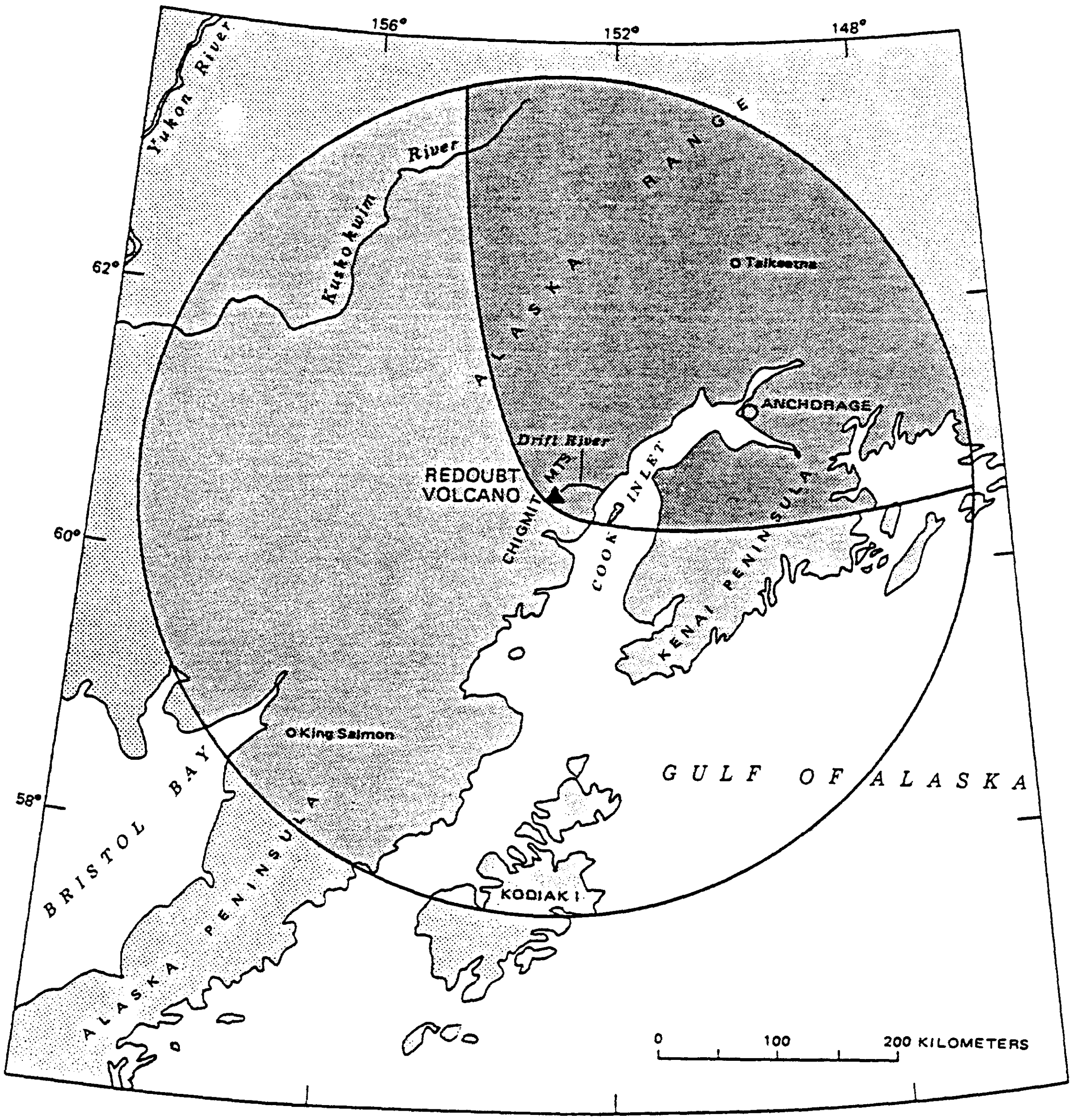


Figure 18. Approximate areas likely to receive noticeable tephra fall from explosive eruptions of Redoubt Volcano. Area denoted by parabola most likely to be affected because of prevailing winds; area outside of parabola would receive ashfall if wind direction were unusual. Thickness of tephra deposited will decrease with distance from Redoubt.

Figure 19. Small pyroclastic flow descending north flank of Augustine Volcano on March 30, 1986. Billowing ash cloud rising from flow is an ash-cloud surge; width of view approximately 600m.