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Glacier Peak, Washington: A Potentially Hazardous Cascade Volcano

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ABSTRACT / Recent field studies of postglacial volcanic deposits at Glacier Peak indicate the volcano has erupted more often, more voluminously, and more recently than previously thought. These past eruptions produced pyroclastic flows, extensive lahars, and widely distributed tephra falls. Analysis of the magnitude of past eruptions and the distribution of volcanic sediments indicates that future eruptions at Glacier Peak as large as those of the last several thousand years would dramatically affect people and property downstream and downwind from the volcano. Pyroclastic flows and lateral blasts would primarily affect uninhabited valleys within a few tens of kilometers of the volcano. Lahars and floods constitute the major hazard to populated areas from future eruptions, and could affect areas at low elevation along valley floors and in the Puget lowland as far as 100 km downvalley west of the volcano. Air-fall tephra from future eruptions will probably be deposited primarily east of Glacier Peak because of prevailing westerly winds.

Introduction

The recent eruptions at Mount St. Helens provide a dramatic and tragic example of the dangers associated with eruptions of Cascade volcanoes. Mitigation of hazards from eruptions of other Cascade volcanoes requires recognition of the types and magnitudes of volcanic eruptions most likely to occur in the future. One approach to this problem is to study deposits of recent past eruptions, on the premise that future eruptions will most likely resemble those of the last several eruptive cycles. Similarly, the distribution of volcanic deposits from past eruptions of the last several millenia may show which areas are most likely to be at risk during different sorts of eruptions in the future (Crandell and others, 1975, 1979). While future eruptions may include events unprecedented in the geologic record, an assessment of hazards based on past eruptive activity constitutes a practical approach which is demonstrably useful for local land-use planning (Miller and others, 1981).

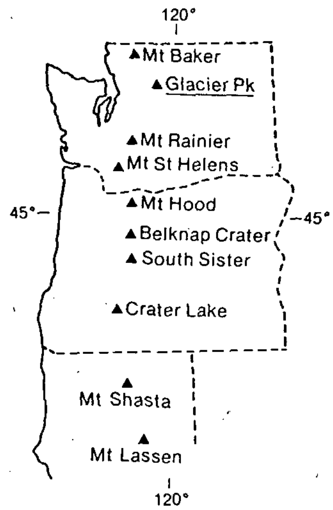

Figure 1. Index map of Glacier Peak and other major cascade volcanoes.

Glacier Peak (3,214 m) is a glaciated dacitic stratovolcano in the North Cascade Range of Washington State. Although previously thought to have been dormant or extinct throughout the Holocene (Tabor and Crowder, 1969; Harris, 1976), recent studies have shown that the volcano has erupted intermittently in the last several thousand years (Beget 1981, 1982). It is located about 100 km northeast of Seattle and 110 km south of the International Boundary with Canada (Fig. 1).

Glacier Peak is drained on the east and north by short tributaries of the Suiattle River. Drainage on the west and southwest flows into the White Chuck River. Both the White Chuck and Suiattle drain into the Sauk River, which today is a major tributary of the Skagit River (Fig. 2). The lower parts of the Sauk and Skagit rivers, and the Stillaguamish River valley are currently largely rural, with several small logging and agricultural towns.

Evidence of historic volcanic activity at Glacier Peak is scanty. Glacier Peak was dormant during the nineteenth century, when several other Cascade volcanoes, including Mount Baker, Mount Rainier, Mount St. Helens, and Mount Hood erupted small amounts of steam and ash (Harris, 1976). Indians reported eruptions of Glacier Peak during the seventeenth and eighteenth century (Majors, 1980), but it apparently has remained inactive throughout the period of European exploration and colonization of the Pacific Northwest.

No modern fumaroles are known at Glacier Peak. The only evidence of lingering volcanic heat are three small hot springs which occur around the flanks of the volcano (Tabor and Crowder, 1969). An eroded crater, filled with snow and ice, lies just north of the summit. Rocks north of the crater are stained yellow and red, possibly as a result of previous solfataric activity. Areas of hydrothermally altered rocks have also been reported at the head of the Kennedy Glacier and above the Sitkum Glacier (Tabor and Crowder, 1969.).

Glacier Peak was first explored and studied by I. C. Russell of the U.S. Geological Survey in 1899 (Russell, 1900). Russell

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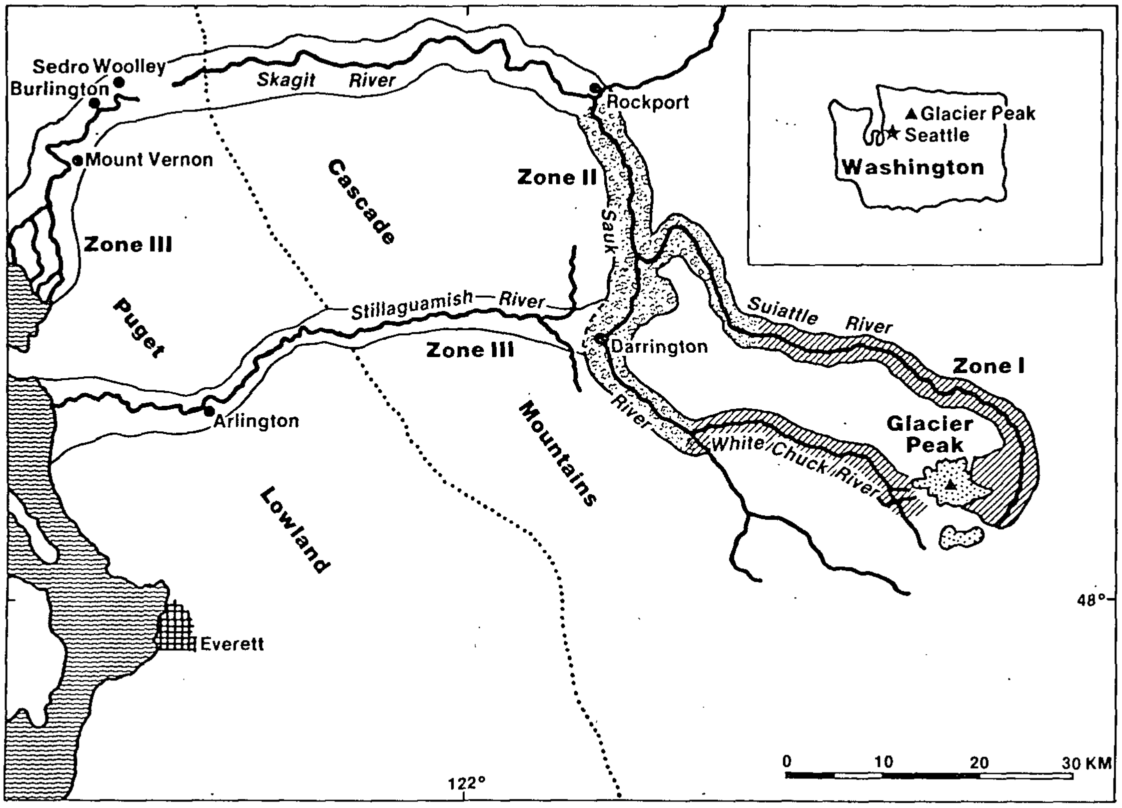

Figure 2. Regional geography and flowage-hazard zones for possible future eruptions of Glacier Peak. Potential hazards are greatest in zone I and decrease in zones II and III. Hazards decrease downstream within each zone and with altitude above the valley floor.

considered the volcano to be a large cinder cone. The next geologic study was not undertaken until the 1950s, when A. B. Ford (1959) described Glacier Peak as a stratovolcano flanked by fans of pyroclastic debris. A detailed study of the geology of the Glacier Peak area was completed by the U.S. Geological Survey in the late 1960s. This study concluded that "there is no evidence of eruptions of Glacier Peak more recent than 12,000 yrs. B.P." (Tabor and Crowder, 1969, p. 28).

Several recent studies have concentrated on the stratigraphy and chronology of the well-known late Pleistocene Glacier Peak ash deposits. Wilcox (1969) suggested that the eruption that produced the Glacier Peak tephra actually consisted of two separate eruptions, which were closely spaced in time. More recently, Porter (1978) subdivided the tephra deposits into nine separate layers. Mehringer, Blinman, and Petersen (1977) showed that tephra layer B, the youngest of Porter's nine layers, is about 11,250 radiocarbon years old. The oldest tephra layer (G) has recently been dated at 11,180 ± 150 yr B.P. (Mehringer and Sheppard, 1983).

Eruptive History of Glacier Peak

Study of postglacial volcanic deposits at Glacier Peak indicates that the volcano has frequently been active during postglacial time (Beget 1979, 1980, 1981, 1982.) These eruptions may be divided into two main groups. Shortly after glaciers retreated at the end of the last glaciation, Glacier Peak produced the well-known and widespread tephra layers, as well as voluminous pyroclastic-flow deposits. Radiocarbon dating indicates the pyroclastic flows were produced during eruptions between about 11,250 to 11,700 years ago (Table 1.). At least nine tephra layers, named G, F, N, C, M, T_1, T_2, T_3, and B, were erupted between about 11,500 (?) and 11,250 yr B.P. (Porter, 1978; Mehringer and Shepard, 1983).

The late Pleistocene eruptions began when a debris flow consisting of hydrothermally altered volcanic rocks traveled 20 km down the White Chuck River (Fig. 3) Subsequent pumiceous pyroclastic flows produced during this period also extended down valleys as far as 20 km and at least one flow is locally welded. Lahars and alluvium consisting entirely of reworked pyroclastic debris were deposited contemporaneously in the Sauk and Stillaguamish valleys as far as 100 km downstream. During this eruption cycle a thick sedimentary fan of lahars and volcanic alluvium was deposited in the upper Stillaguamish River valley. The Sauk River was diverted north into the Skagit River drainage at this time. (Vance, 1957; Beget, 1981).

Following the late Pleistocene eruptions, Glacier Peak was

Table 1. Postglacial volcanic events and deposits on various sides of Glacier Peak.

Time scale years B.P.	Tephra erupted at Glacier Peak: Layer or net name	Tephra erupted at Glacier Peak: Description[a]	West and southwest sides: Valleys of Kennedy and Baekos creeks and White Chuck River	East side: Valleys of Dusty and Chocolate creeks and Suiattle River
200	X	Pumice, contains hb, hy, au, ox. Scattered isolated lapilli on northeast flank of volcano.	Outburst floods moved >5 km. Rock avalanche moved 1 km down Kennedy Creek valley.	Outburst floods moved >8 km. Lahars moved >3 km down Dusty Creek valley.
		Ash, gray to white, contains hb, hy, au, ox. Contains isolated lapilli, as thick as 30 cm, on north and northeast flanks of volcano.	A single lahar and flood gravels extended at least 30 km down the White Chuck River valley.[b]	
1,000			At least five lahars moved >30 km.[b] Possible formation of dacite dome.[b]	At least two lahars moved >2 km down Dusty Creek valley. Lahars and pyroclastic flows moved down Chocolate Creek valley.
	A	Dacite lithic fragments, black to gray, contains hy, hb, ox, as thick as 10 cm, lapilli and small bombs, occurs on north and northeast flanks of volcano.[b]	One lahar extended 30 km.[b] At least three lahars extended >15 km down the White Chuck River valley.	Possible formation of dacite dome. One lahar moved 2 km down Chocolate Creek valley.[b]
2,500			At least three lahars extended >15 km down the White Chuck River valley. Possible formation of dacite dome.	At least three pyroclastic flows and lahars of hot rock debris moved >4 km down Chocolate Creek valley.
5,000	D	Several fine layers, ash and fine lapilli, olive brown to bluish gray, hy, hb, 15 cm thick, occurs on all flanks of the volcano. Extends to the east.	Formation of dacite dome(s). Many pyroclastic flows and lahars moved down Kennedy Creek. Some lahars extended >100 km.	Formation of dacite dome(s). Many pyroclastic flows and lahars moved down Chocolate and Dusty Creek. Some lahars extended 70 km down the Suiattle River.[b]
6,000			One or more lahars extended >10 km[b]	One lahar extended >3 km.[b]
Dormant Interval				
11,000	B	Pumice, gray to grayish white, contains hy, hb; 200 cm thick, occurs on all flanks of the volcano, extends to southeast.	Possible formation of dacite dome.[b] Ten or more pyroclastic flows and many lahars moved down the White Chuck River. Some lahars moved >100 km.	At least one lahar extended as far as 50 km downstream in the White Chuck River valley.
	F,N,C,M,T	Several layers, light gray, contains hy, hb; 50 cm thick, lapilli and ash, occurs on all flanks of the volcano, extends to southeast and east.[b]		
	G	Pumice, grayish yellow, contains hy, hb, 200 cm thick, occurs on all flanks of the volcano, extends to southeast.[b]	A single lahar moved >35 km down the White Chuck River valley.[b]	
13,000				

[a]Heavy minerals in tephra: ox, oxyhornblende; hb, hornblende; au, augite; and hy, hypersthene.
[b]Dates of event are not well known except within wide limits.

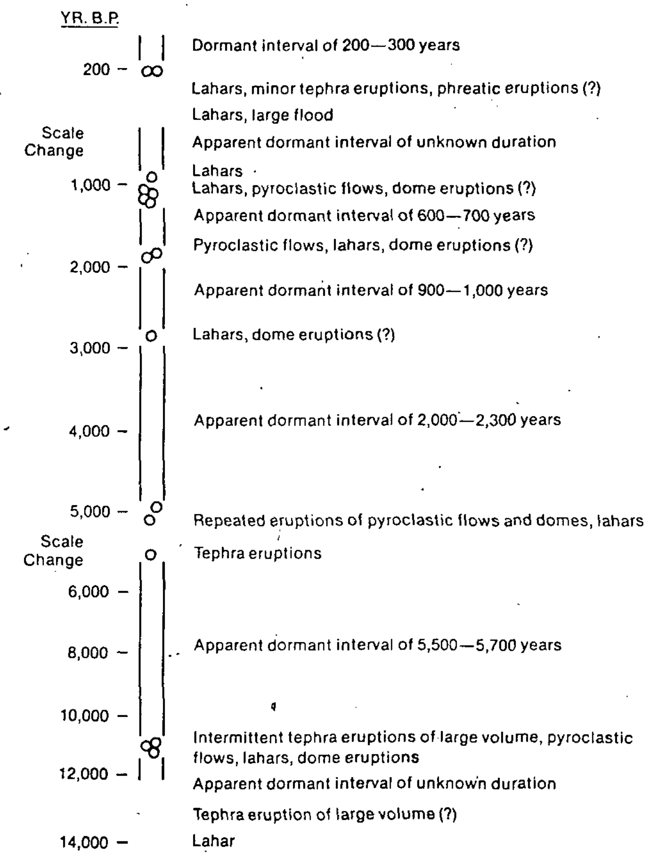

Figure 3. Eruptions and dormant intervals at Glacier Peak in postglacial time. The circles represent specific eruptions that have been dated or closely bracketed by radiocarbon age determinations; the vertical boxes represent inferred dormant intervals.

apparently dormant for about 5,700 years. There may have been small eruptions during this period which were not large enough to leave recognizable deposits. Soil development occurred on late Pleistocene volcanic deposits, and streams incised deep canyons in the 100–300-meter-thick unconsolidated valley fills of pyroclastic debris that flanked the volcano.

Pyroclastic eruptions resumed about 5,500 years ago (Table 2). Mudflows, consisting largely of hydrothermally altered rock debris, were produced early in this eruptive cycle and traveled several kilometers down valleys east and west of the volcano. The mudflow deposits are buried by several cubic kilometers of lithic pyroclastic debris, recording the growth of domes high on the summit of the volcano. Radiocarbon dating suggests that these eruptions continued intermittently until at least as recently as 5,100 years ago. During this period of time thin tephra layers, collectively named tephra set D, were deposited as far as 25 km east of Glacier Peak. Near the volcano, block-and-ash flows and ash-cloud deposits buried valleys both east and west of the volcano beneath 200–300 m of debris. Lahars associated with the eruptions extended far downstream in the Sauk, Suiattle, and Skagit River valleys.

Another apparently dormant interval occurred between 5,100 and 2,800 years ago. About 2,800 years ago several lahars travelled as far as 30 km downvalley in the White Chuck drainage. These lahars consist of fresh lithic debris. They have resulted from pyroclastic eruptions at Glacier Peak, or from the emplacement of a dome near the volcano's summit. Also sometime during this interval thin deposits of poorly sorted lithic dacitic tephra were locally deposited north and northeast of the volcano, possibly during steam explosions.

Another dormant interval occurred between about 2,800 and 1,700–1,800 years ago. Pyroclastic-flow deposits and lahars erupted about 1,800 yr B.P. formed a thick-fill in the Chocolate Creek valley. At about the same time, lahars extended at least 15 km down the White Chuck River valley. The lahars in the White Chuck consist of fresh lithic debris and appear to have resulted from reworking of freshly erupted pyroclastic material. Contemporaneous deposits in the White Chuck River and Chocolate Creek valleys probably were formed during the same series of eruptions, and record the emplacement of one or more domes near the volcano's summit.

Some time after 1,800 years ago, a large lahar consisting almost entirely of oxyhornblende-dacite debris travelled at least 30 km down the White Chuck River. This debris flow may have originated as a large landslide from an oxyhornblende-bearing dome on the south flanks of Glacier Peak named Disappointment Peak (Tabor and Crowder, 1969). It is not known if this lahar originated during an eruption.

Approximately 1,000–1,100 years ago, clayey lahars as well as pyroclastic flows and lahars of fresh rock debris were deposited in two valleys east of Glacier Peak. All these deposits were probably formed during a single eruptive period, and record another cycle of dome growth. At about the same time a 20-meter-thick lahar assemblage consisting of fresh lithic debris partly filled the White Chuck River valley for a distance of at least 30 km downstream to the west of the volcano. The lahars in this assemblage are not radiocarbon dated, but stratigraphic relations with older and younger dated deposits indicate that the assemblage was also probably produced during the eruptive episode about 1,100 years ago.

At least one younger lahar and a very large flood are recorded in sediments that extend to the confluence of the White Chuck and Sauk rivers, some 30 km from Glacier Peak. Trees growing on the deposits indicate that they were emplaced more than 300 years ago. It is possible that the large flood and the lahar were produced by eruptions at Glacier Peak, although no unequivocal evidence of eruptive activity during this time interval has been recognized.

About 200–300 years ago, small tephra eruptions deposited isolated pumice lapilli and ash east of Glacier Peak. These

Table 2. Average Wind Speeds, in Knots, at Various Altitudes.[a,b]

From Toward	N S	NNE SSW	NE SW	ENE WSW	E W	ESE WNW	SE NW	SSE NNW	S N	SSW NNE	SW NE	WSW ENE	W E	WNW ESE	NW SE	NNW SSE
Approximate altitude (m)																
3,000	18.6	16.3	14.8	11.5	11.6	12.4	13.8	18.1	24.2	25.7	25.4	24.2	23.5	21.8	22.4	21.2
4,300	26.7	21.7	18.7	15.1	13.7	15.5	18.2	21.5	27.2	30.7	31.3	31.1	31.0	29.4	29.6	28.5
5,000	33.2	27.8	27.9	18.5	17.6	16.8	20.8	22.9	32.2	36.6	38.6	38.3	38.4	37.3	35.7	36.9
9,100	48.6	43.8	36.5	29.9	30.2	26.4	32.2	38.0	46.8	52.5	55.9	55.4	56.2	50.8	51.6	53.9
12,200	40.9	31.5	30.3	14.9	19.7	16.9	18.8	28.0	35.8	43.8	48.5	50.3	50.9	46.2	46.3	45.4
16,200	20.1	12.4	11.3	6.3	6.4	9.0	9.7	13.9	15.5	21.1	23.7	25.8	26.2	25.1	23.7	21.4
Average wind speed	31.4	25.6	23.2	16.0	16.5	16.2	18.9	23.7	30.3	35.1	37.2	37.5	37.7	35.1	34.9	34.6

[a]One knot = 1.15 m/hr or 1.85 km/hr. Based on 20-year record (1950–70) at Quillayute, Washington. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Federal Building, Asheville, N.C. 28860.)
[b]Data from Hyde and Crandell (1978).

deposits, formerly called the "grassroots ash" (Carithers, 1946), are collectively referred to as layer X. The ash deposits, which are locally present on moraines estimated to be about 350 years old (Beget, 1981), may be the products of small pyroclastic or phreato-magmatic eruptions at Glacier Peak, similar to those at Mount St. Helens that predated the May 18 eruption. Also at about this time, lahars were deposited in several valleys east of Glacier Peak. It is possible that Indians observed these eruptions, since they told pioneer naturalist George Cribbs that Glacier Peak had been active in the recent past (i.e., the seventeenth and eighteenth centuries) (Majors, 1980). No volcanic activity has been observed during the last 150 years, during which time historic exploration and settlement has occurred.

This newly discovered eruption history indicates that Glacier Peak has erupted on the average every 900–1,100 years during the last 5,500 years. During the last 1,800 years, at least three and possibly four eruptive events have occurred, two of which (1,800 and 1,100 yr B.P.) involved the formation of multiple pyroclastic flows and the deposition of thick lahar assemblages for distances of ten of kilometers downvalley from the volcano. It is possible that additional small eruptions occurred that did not leave a recognizable trace. This history of intermittent eruptions, which has continued to within a few hundred years ago, indicates Glacier Peak, although it has been dormant throughout historic times (i.e., the last 150–300 years) has remained intermittently active through much of the Holocene, and will probably be active again.

Potential Geologic Hazards

Past dormant intervals at Cascade volcanoes typically have lasted several hundred to a few thousand years (Crandell and Mullineaux, 1975). Glacier Peak remained dormant in the nineteenth century, when several other Cascade volcanoes were the sites of minor eruptions (Harris, 1976). There is no way to predict when or how the current dormant period at Glacier Peak will end.

This evaluation of potential volcanic hazards at Glacier Peak, following the technique of Crandell and others (1975, 1978, 1979), assumes that future eruptions will be similar in type and scale to those of postglacial time. Potentially hazardous events that have occurred at Glacier Peak in postglacial time include eruptions of tephra, emplacement of domes, eruption of pyroclastic flows and incandescent ash clouds, and formation of large avalanches of altered volcanic rocks, lahars, and floods. Lateral blasts and steam blasts may also have occurred.

Air-Fall Tephra Hazard Zones

Potential hazards from plinian air-fall tephra eruptions depend on the volume, rate, vent orientation, and duration of the eruptions, and on the chemistry of the volcanic deposits and any associated volcanic gases. The regional distribution of tephra is controlled by the strength and direction of the wind at the time of the eruption (Wilcox, 1959); ash and fine lapilli can be dispersed for tens or even hundreds of kilometers downwind. As demonstrated in the May 1980 eruptions of Mount St. Helens, even small amounts of lapilli and ash may damage or kill vegetation, contaminate surface water and change soil chemistry, and affect machinery and highway and aerial traffic at great distances downwind from the volcano (Schuster, 1981; McKnight and others, 1981; Gough and others, 1981). Coarse lapilli and large volcanic bombs thrown on ballistic trajectories constitute a serious danger only relatively near the vent. Toxic fumes from the volcano or from tephra may affect vegetation as well as the eyes and respiratory systems of people downwind from the volcano (Winner and Mooney, 1983).

Glacier Peak produced large volumes of air-fall tephra in early postglacial time, between about 11,500 and 11,250

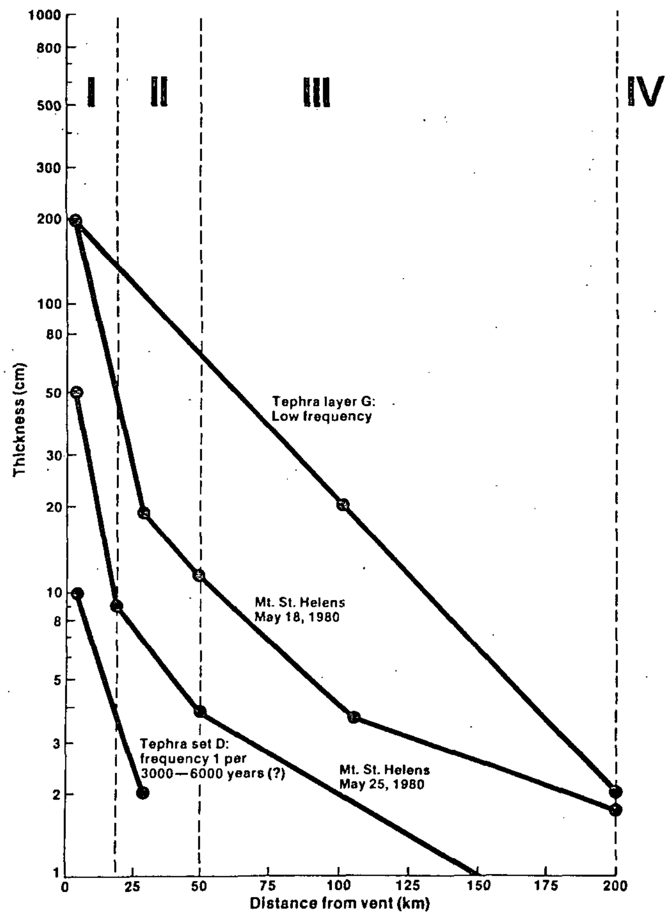

Figure 4. Thicknesses of representative tephra deposits downwind from Glacier Peak along the axis of each tephra lobe. Tephra deposits G, M, and D are shown because their thicknesses are relatively well known. These deposits are estimated to have volumes on the order of 1 km^3, 0.1 km^3, and 0.001 km^3, respectively. Data in part from Porter (1978). Areas covered by tephra-hazard zones I, II, and III are shown in Figure 5. Future tephra eruptions, if similar in magnitude to those that produced tephra set D, should have little or no effect on human health beyond zone II.

radiocarbon years ago. Tephra layers B and G erupted at this time had estimated volumes of 2.5–2.2 km^3, respectively (Porter, 1978). At least seven other tephra layers erupted from Glacier Peak at this time each had volumes on the order of 0.01–0.1 km^3. Since late Pleistocene time, Glacier Peak has erupted tephra at least three more times. These recent eruptions, all of which have occurred during the last 7,000 years, have each involved volumes of only a few hundred thousand to tens of millions of cubic meters.

These tephra deposits suggest a range of volumes that might reasonably be expected to result from future tephra eruptions at Glacier Peak. The thicknesses of tephra can be estimated by plotting data from representative tephra deposits. These are shown in Figure 4 together with mapped thicknesses of two recent eruptions from Mount St. Helens. Although definitive prediction is impossible, tephra has been a very minor component of the most recent sequence of eruptions at Glacier Peak during the last 7,000 years, and it seems likely that future tephra eruptions will also be comparably small in volume. Tephra thicknesses deposited during a small eruption might resemble those of tephra set D (Fig. 4.) Tephra eruptions of this size are unlikely to constitute a significant danger to people at distances greater than 20 km from Glacier Peak. However, by analogy with the several small tephra eruptions of Mount St. Helens that have followed the major May 18 eruption, considerable short-time inconvenience and damage, principally to automobiles, could result at distances of 100–200 km or more downwind (Schuster, 1981). Glacier Peak has not erupted large (i.e., >1 km^3) amounts of tephra in more than 11,000 years. Nonetheless, its past history indicates that such eruptions are possible. Such eruptions would be comparable to or larger than the May 18 eruptions of Mount St. Helens.

The mapped distribution of tephra deposits produced during previous eruptions suggests that the wind has generally blown from the west during the recent geologic past (Porter, 1978; Beget, 1981). Modern wind direction and wind speed data compiled at Quillayute, Washington, a weather station 70 km west of Glacier Peak, indicate that winds at all levels of the atmosphere today are also from the west. The wind blows from the east less than 10% of the time, suggesting that tephra from future eruptions of Glacier Peak will most likely be deposited east of the volcano, away from large cities and populated areas in the Puget lowland (Tables 2 and 3).

Tephra-hazard zones (Fig. 5) are based on the thickness and distribution of previous Glacier Peak tephra deposits and the observed effects of the Mount St. Helens eruptions, as well as on the recent records of wind directions and speeds in northwest Washington. East of Glacier Peak the boundaries of tephra-hazard zones in Figure 5 have been placed at 20, 50, and 200 km. Most small future eruptions of tephra at Glacier Peak will probably have little or no permanent effect outside of zone 1, although temporary dislocations of automotive and aerial traffic at greater distances are possible. Very large and violent eruptions, similar to those of 11,000–12,000 years ago, would have significant effects well beyond the limits of zone III, much as the tephra fall of the May 18 Mount St. Helens eruption caused problems in communities as much as 1,000 km downwind. Tephra thicknesses should decrease away from the volcano in a uniform manner, similar to that shown in Figure 4, although rainstorms during transport, variable local winds, and other factors may cause local variations.

Table 3. Average Percentage of Wind Directions, by Month, at Altitudes of About 3,000–16,000 m, Average.[a,b]

From Toward	N S	NNE SSW	NE SW	ENE WSW	E W	ESE WNW	SE NW	SSE NNW	S N	SSW NNE	SW NE	WSW ENE	W E	WNW ESE	NW SE	NNW SSE
Jan.	3.4	1.4	0.7	0.5	0.5	0.2	0.5	1.8	2.7	6.8	12.5	16.9	18.4	15.2	11.9	7.0
Feb.	3.9	1.9	1.3	.6	.8	1.1	2.0	1.8	1.7	6.5	10.8	14.2	16.4	15.2	12.3	7.4
Mar.	4.5	2.1	1.1	.5	.9	.9	.9	1.5	4.3	8.4	12.2	14.2	15.5	12.7	12.8	7.6
Apr.	4.2	2.7	2.1	1.4	1.2	1.3	1.6	2.5	4.8	7.0	11.9	13.4	14.8	12.2	11.3	7.6
May	4.4	2.2	1.6	1.0	1.0	1.6	3.0	3.9	6.9	8.6	13.6	15.0	13.0	10.1	7.7	6.0
June	3.7	2.8	2.3	1.7	1.4	1.5	1.7	2.8	6.0	9.0	13.9	14.9	13.4	10.0	8.6	6.2
July	3.1	1.9	1.4	1.0	.9	.9	1.1	2.2	4.0	8.6	18.9	19.8	13.8	9.4	1.6	5.7
Aug.	3.1	2.3	1.5	1.0	1.0	1.2	1.6	2.6	5.1	9.0	15.8	17.6	14.7	10.0	8.1	5.4
Sept.	5.3	2.4	1.6	1.1	1.2	.8	1.2	2.2	3.2	7.9	12.2	12.7	14.7	14.7	11.3	7.7
Oct.	2.2	1.4	.7	.4	.2	.2	.5	1.1	3.8	8.7	16.6	19.9	19.2	12.5	7.8	4.6
Nov.	3.3	1.4	.5	.2	.4	.4	.8	1.7	3.5	8.1	13.9	17.0	20.2	14.0	11.3	5.1
Dec.	3.1	1.2	.4	.3	.3	.3	.5	.9	3.2	8.8	14.4	17.4	18.5	14.4	10.5	6.0
Average	3.7	2.0	1.3	0.8	0.8	0.9	1.3	2.0	4.3	8.1	13.9	16.1	16.1	12.5	10.1	6.4

[a]Based on 20-year record (1950–70) at Quillayute, Washington. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Federal Building, Asheville, N.C. 28860.)
[b]Data from Hyde and Crandell (1978).

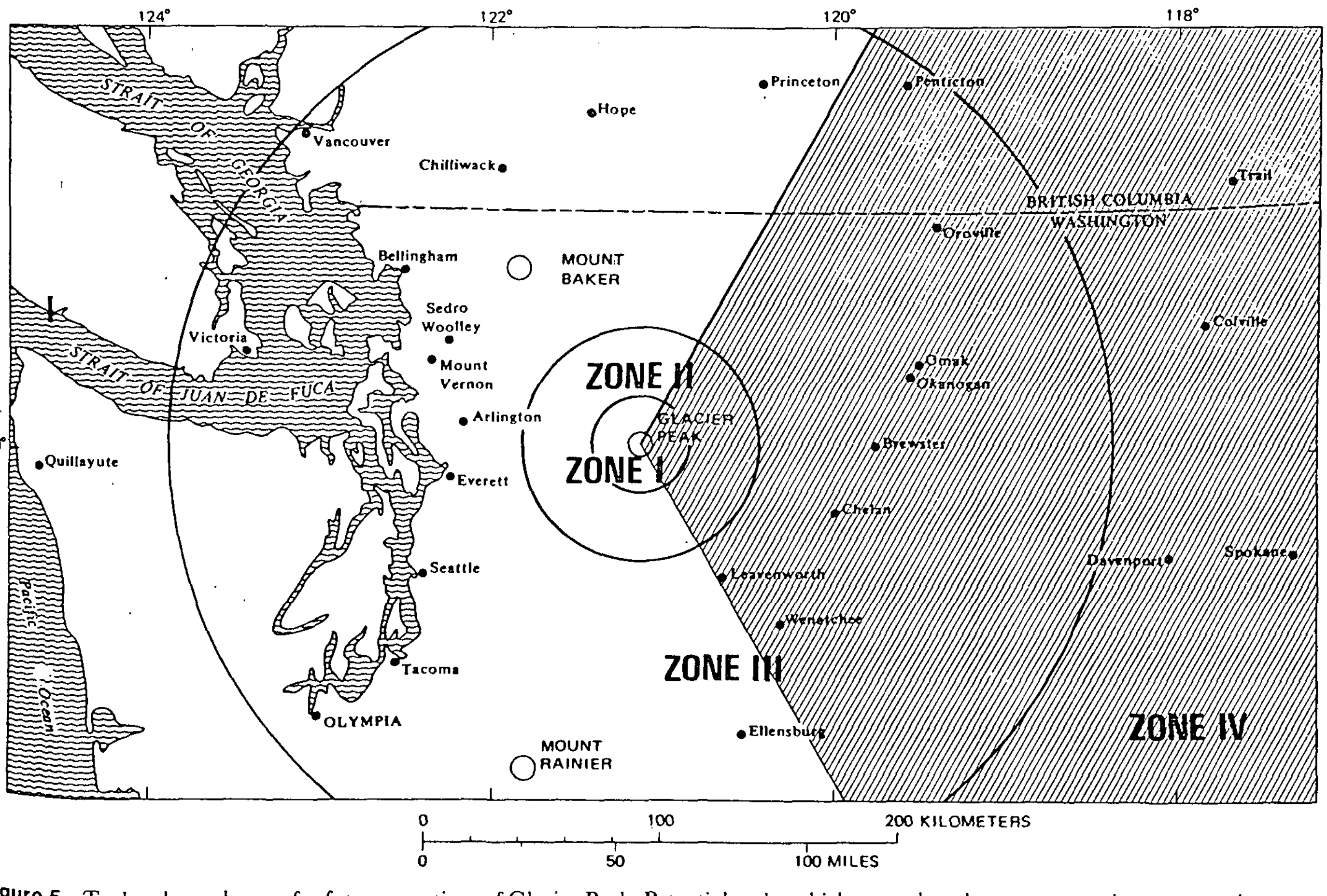

Figure 5. Tephra-hazard zones for future eruptions of Glacier Peak. Potential tephra thicknesses, based on representative past eruptions, are greatest in zone I and decrease progressively away from the volcano across zones II and III. Tephra is significantly more likely to fall in the shaded portions of zones I, II, and III, because winds blow to the east approximately 80% of the time (Tables 2 and 3). Future tephra eruptions, if similar to those of the last 7,000 years, probably would have little or no direct effect on human health outside of tephra-hazard zones I and II. Eruptions similar to those of late Pleistocene time could significantly affect areas beyond the limit of zone III.

Phreatomagmatic eruptions and lateral blasts similar to that of May 18, 1980, at Mount St. Helens appear to constitute a particular hazard at glaciated stratovolcanoes, where an abundant supply of water is available to be heated to steam by ascending magma or a "cryptodome" (Christiansen and Peterson, 1981; Christiansen, 1980). Similar eruptions had previously occurred at Bezymianny volcano (Gorshkov, 1959) and at Shiveluch volcano (Gorshkov and Dubik, 1970) on the Kamchatka Penninsula. Slow intrusion of a dome into the glaciated summit of Glacier Peak would probably also create a hazard of phreatomagmatic eruptions and steam explosions. The May 18 lateral blast at Mount St. Helens was restricted to within 20 km from the volcano, and the Bezymianny eruption to 25 km. Similar lateral-blast eruptions at Glacier Peak would probably be restricted within tephra hazard zone I. The existence of the Glacier Peak Wilderness Area around the volcano mitigates hazards to property and humans from such an eruption, which would probably be preceded by many precursory tremors.

Steam blasts, or phreatic explosions, may occur at active volcanoes without warning, and without accompanying fresh magmatic ejection (Williams and McBirney, 1979). Layer A, a thin, poorly sorted layer of non-vesicular dacite found on the east and north sides of the volcano, may record such an event at Glacier Peak. While hazardous to individuals on the flanks of the volcano (Tsyua, 1933), such an event would have no effects beyond zone I.

Flowage-Hazard Zones

The flowage-hazard zones (Fig. 2) are based on the frequency, total number, and extents of lava flows, pyroclastic flows, ash-cloud deposits, and lahars that have occurred during late glacial and postglacial time. While laymen assume lava flows constitute the greatest hazard from volcanic eruptions, flows are quite limited in extent at Cascade stratovolcanoes. No postglacial lava flows have been recognized on the lower slopes of Glacier Peak, although very viscous postglacial lava flows and domes are preserved at the volcano's summit.

The record of eruptions over the last 5,500 years suggests that future eruptions at Glacier Peak would most likely begin with the extrusion of a sililic dome (or intrusion of a cryptodome) near the summit of Glacier Peak. The early stages of a new eruptive cycle might be expected to be similar to the first few months of activity at Mount St. Helens, and include precursory earthquakes, steam emissions, and the creation of a volcanic crater or bulge on the volcano. Landslides and debris flows of hydrothermally altered debris and glacier-outburst floods might also occur.

Any dome will probably be restricted to the summit or flanks of the volcano. More extensive hazards are associated with accompanying generation of pyroclastic flows and lahars. In the past, the very largest late Pleistocene pyroclastic flows from Glacier Peak have not travelled beyond the boundary of zone I, about 30 km from the volcano (Fig. 2), and this probably is a very conservative maximum limit for future pyroclastic flows. In comparison, prehistoric pyroclastic flows at Mount St. Helens are known to have travelled about 15 km from the cone (Hyde, 1975), and the pyroclastic flows from the May 18 eruptions travelled about 8 km downvalley from the vent (Rowley and others, 1981).

Lahars and debris flows produced during past eruptions of Glacier Peak have travelled much farther than the pyroclastic flows. Catastrophic debris flows of hydrothermally altered lithic debris have extended as far as 30 km down the White Chuck River (Fig. 4) and lahars are found more than 20 km away. By comparison, the large May 18 avalanche-debris flow down the North Fork of the Toutle River from Mount St. Helens extended about 22 km (Voight and others, 1982).

Most lahars from Glacier Peak have consisted exclusively of fresh, reworked pyroclastic debris. These mudflows probably originated when Merapi-type domes shed large volumes of fresh, hot debris on snowfields, glaciers, and valleys surrounding the volcano. The lithic material was reworked into large mudflows, which travelled tens of kilometers downvalley. Large floods were probably accompanied with lahars.

Areas within flowage-hazard zone I, which includes Glacier Peak itself and the upper portions of valleys heading on the volcano, have been affected by volcanic events at least as often as once every 1,000–3,000 years over the last 6,000 years. These individual volcanic events have included the eruption and deposition of multiple pyroclastic flows and lahars. Within zone I, those areas nearest to Glacier Peak are most likely to be affected most often and most severely, while the potential hazard generally decreases with distance from the volcano.

Zone II consists of areas known to have been affected by lahars in postglacial time, lying beyond the mapped extent of the largest pyroclastic flows. Potential hazards in zone II also generally decrease with distance downvalley from Glacier Peak. This is because areas within zone II that are nearer to Glacier Peak have been affected by lahars in the past more often and more severely than areas farther downvalley. Because lahars will travel downstream from Glacier Peak along valley floors, areas at greater heights above flood plains are, in general, less hazardous than areas at lower elevations. Lahars have been deposited in areas designated as hazard zone II several times in the last 3,000–6,000 years. Some areas within zone II probably have also been affected by floods caused by volcanism.

Flowage-hazard zone III includes downvalley areas affected

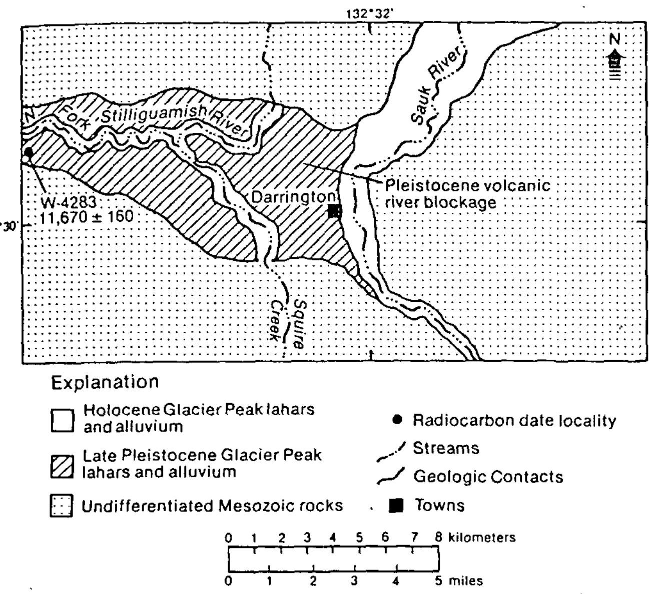

Figure 6. Generalized geologic map of the Darrington area, Washington, showing the extent of the Pleistocene laharic valley fill in the upper Stilliguamish River valley.

at least once in postglacial time by lahars originating at Glacier Peak. Deposition of lahars in the lower Stillaguamish River valley occurred during late Pleistocene time. The Skagit River valley at least as far west as the town of Burlington and possibly all the way to Puget Sound has been affected at least once by lahars during the last 6,000 years. During all but the largest future eruptions, floods are the most likely hazard in zone III. The depths and extents of future volcanically generated floods cannot be accurately predicted, but if floods caused by eruption coincided with seasonal periods of high water, the resulting floods could be higher than normal floods.

In addition to floods, areas in zone III could be affected by drainage changes that might result from a very large future eruption. Lahars and alluvium deposited during the late Pleistocene eruptions at Glacier Peak now bury and block the upper portions of the Stillaguamish valley. This natural dam in the upper Stillaguamish valley diverts the Sauk and Suiattle rivers from draining westward to Puget Sound by the most direct route (Fig. 6), and the rivers today flow north through a narrow bedrock canyon to join the Skagit River.

During a large eruption resulting in about 10 m of river aggradation by lahars and floods, this blockage would be overtopped, and the Sauk and Suiattle rivers might again change their courses and resume their former courses west down the valley of the Stillaguamish past Darrington. If this happened, floods and lahars would move down the Stillaguamish River valley as well as down the Suak and Skagit River valleys, increasing the area of potential damage, and causing a major realignment of drainage in the Stillaguamish and Skagit River valleys.

Discussion of Potential Hazards

This review of potential hazards from future eruptions of Glacier Peak has dealt with possible consequences of future eruptions. The location of a volcano with respect to local population centers and land-use patterns constitutes a very significant factor in an analysis of potential hazards. The administrative status of the Glacier Peak Wilderness Area surrounding the volcano excludes permanent habitations within tens of kilometers of the volcano. At most a few hundred recreational visitors may be near the volcano during the summer months. This fact, combined with an absence of roads near the volcano and the tragic example of the Mount St. Helens eruptions, would expedite closure of the volcano area and its immediate vicinity in the event of signs of imminent eruptions (seismic activity, steam emissions, ground-tilt, etc.) and reduce hazards to human life. The major hazard to populated areas will be lahars and floods in the Suiattle, White Chuck, Sauk, and Skagit drainages far downstream from the volcano. During past eruptions, individual lahars and floods have deposited as much as several meters of debris in areas 70 km and more downstream, suggesting that a threat to buildings and other property in floodplains may extend as far as Puget Sound.

Intermittent dome extrusion and pyroclastic eruptions have occurred repeatedly during the last 5,500 years. Glacier Peak should be considered a dangerous volcano and should be monitored to detect precursors of future eruptions. Potential volcanic hazards should be considered in land-use planning for floodplains and valleys downstream from the volcano to reduce urbanization in areas susceptible to mudflows and floods during future eruptions.

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