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Postglacial Volcanic Deposits at Glacier Peak, Washington, and Potential Hazards from Future Eruptions

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Postglacial Volcanic Deposits at Glacier Peak, Washington, and Potential Hazards from Future Eruptions

by James E. Beget

ABSTRACT

Eruptions and other geologic events at Glacier Peak volcano in northern Washington have repeatedly affected areas near the volcano as well as areas far downwind and downstream. This report describes the evidence of this activity preserved in deposits on the west and east flanks of the volcano.

On the west side of Glacier Peak the oldest postglacial deposit is a large, clayey mudflow which traveled at least 35 km down the White Chuck River valley sometime after 14,000 years ago. Subsequent large explosive eruptions produced lahars and at least 10 pyroclastic-flow deposits, including a semiwelded vitric tuff in the White Chuck River valley. These deposits, known collectively as the White Chuck assemblage, form a valley fill which is locally preserved as far as 100 km downstream from the volcano in the Stillaguamish River valley. At least some of the assemblage is about 11,670-11,500 radiocarbon years old.

A small clayey lahar, containing reworked blocks of the vitric tuff, subsequently traveled at least 15 km down the White Chuck River. This lahar is overlain by lake sediments containing charred wood which is about 5,500 years old. A 150-m-thick assemblage of pyroclastic-flow deposits and lahars, called the Kennedy Creek assemblage, is in part about 5,500-5,100 radiocarbon years old. Lithic lahars from this assemblage extend at least 100 km downstream in the Skagit River drainage. The younger lahar assemblages, each containing at least three lahars and reaching at least 18 km downstream from Glacier Peak in the White Chuck River valley, are about 2,800 and 1,800 years old, respectively. These are postdated by a lahar containing abundant oxyhornblende dacite, which extends at least 30 km to the Sauk River. A still younger lahar assemblage that contains at least five lahars, and that also extends at least 30 km to the Sauk River, is older than a mature forest growing on its surface.

At least one lahar and a flood deposit form a low terrace at the confluence of the White Chuck and Sauk Rivers, and were deposited before 300 years ago, but more recently than about 1,800 years ago. Several small outburst floods, including one in 1975, have affected Kennedy and Baekos Creek and the upper White Chuck River in the last hundred years.

East of Glacier Peak the oldest postglacial deposits consist of ash-cloud deposits that underlie tephra erupted by Glacier Peak between 12,750 and 11,250 radiocarbon years ago. Although pyroclastic-flow deposits correlative with the ash-cloud deposits have not been recognized, late Pleistocene pumiceous lahars extend at least 50 km downstream in the Suiattle River valley. A younger clayey mudflow extends at least 6 km down Dusty Creek. This lahar is overlain by deposits of lithic pyroclastic flows and lahars that form the Dusty assemblage. This assemblage is at least 300 m thick in the upper valleys of Dusty and Chocolate Creeks, and contains more than 10 km^3 of lithic debris. Lahars derived from the Dusty assemblage extend at least 100 km down the Skagit River valley from Glacier Peak. This assemblage is younger

than tephra layer O from Mount Mazama, and older than tephra layer Yn from Mount St. Helens, and thus was formed between about 7,000 and 3,400 years ago. The Dusty assemblage may have been formed at the same time as the Kennedy Creek assemblage.

A 100-m-thick assemblage of pyroclastic flows and lahars preserved in the Chocolate Creek valley is about 1,800 radiocarbon years old. A clayey lahar in the upper Chocolate Creek valley extended at least 2 km downvalley after 1,800 years ago, but before pyroclastic flows and lahars were deposited in upper Chocolate Creek 1,100 radiocarbon years ago. Several clayey lahars in the Dusty Creek valley east of Glacier Peak are also about 1,100 years old. A lahar in the valley of Dusty Creek, which contains rare prismatically jointed blocks of vesiculated dacite, and a white ash that is locally as much as 50 cm thick may be the products of small pyroclastic eruptions at Glacier Peak about 200-300 years ago.

Tephra deposits from past eruptions of Glacier Peak are mostly confined to the east side of the volcano. At least nine separate tephra layers were produced between 12,500 and 11,250 years ago. Two of these eruptions each produced about 2 km^3 of ejecta. Tephra eruptions of much smaller volume occurred between 6,900 and 5,500 years ago, between 3,450 and 200 years ago, and between 316 and 90 years ago.

Future eruptions at Glacier Peak similar to those of postglacial time could affect people and property downstream and downwind from the volcano. Pyroclastic flows and lahars would affect valleys near the volcano. Lahars and floods could affect areas at low elevation along valley floors and in the Puget Lowland west of the volcano. Tephra from future eruptions will probably fall primarily east of Glacier Peak because of prevailing westerly winds.

INTRODUCTION

Glacier Peak (3214 m) is a dacitic stratovolcano in the North Cascade Range of Washington State. It is located about 100 km northeast of Seattle and 110 km south of the International Boundary with Canada (fig. 1). Glacier Peak lies in a rugged and scenic part of the Glacier Peak Wilderness Area, in Mount Baker National Forest. Adjacent peaks reach altitudes of 2700 m and local relief near the volcano exceeds 2000 m.

The crystalline bedrock in the vicinity of Glacier Peak consists of pre-Tertiary metamorphic rocks which have been intruded by Tertiary stocks and plutons of diorite and granodiorite (Crowder and others, 1966). The age of the volcanic cone of Glacier Peak itself is poorly known. Lava flows in the cone are normally magnetized, and so were erupted during the Brunhes magnetic epoch of the last 700,000 years (Tabor and Crowder, 1969, p. 27-28). Rocks of Glacier Peak provenance have been found in alpine glacial drift of the last major glaciation (Vance, 1957). This drift was deposited during the Evans Creek Stade of the Fraser Glaciation and implies that the volcanic cone existed at least 18,000 years ago. However, no radiometric dates on lava flows at Glacier Peak are now available. Some lava flows that today cap ridges 300-400 m above adjacent stream valleys on the flanks of the volcano may be as much as several hundreds of thousands of years old.

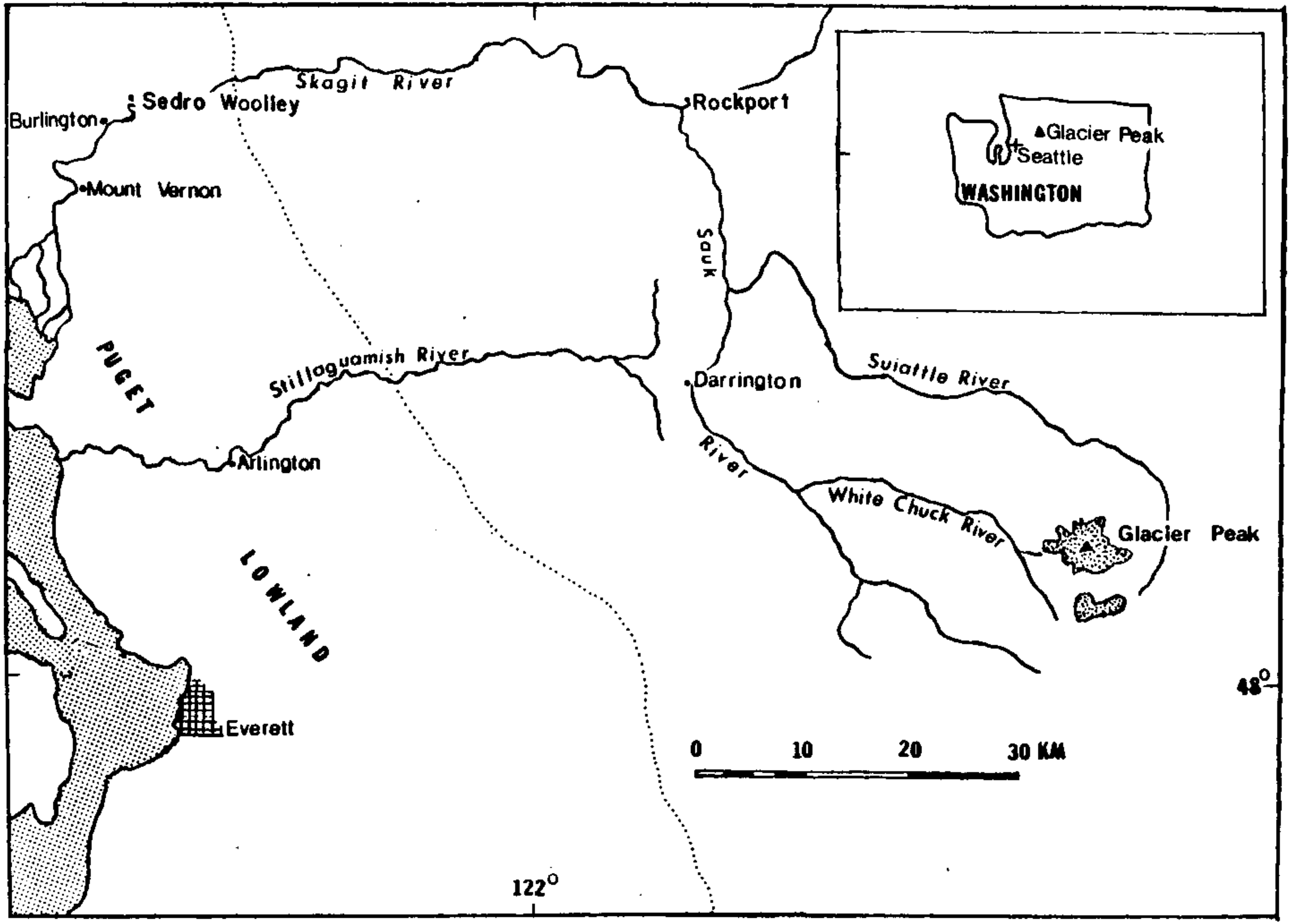


Figure 1.--Regional geography of the Glacier Peak area showing streams which drain the volcano. Flowage deposits produced during eruptions of Glacier Peak are present in the valleys of the White Chuck, Suiattle, Sauk, Stillaguamish, and Skagit Rivers. Cascade Mountain front shown by dotted line.

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 the Suiattle drain into the Sauk River, which is a major tributary of the Skagit River. The distribution of volcanic deposits from Glacier Peak indicates that during part of postglacial time the Sauk River flowed through the valley of the North Fork of the Stillaguamish River (fig. 2).

No fumaroles are known at Glacier Peak, although two small hot springs occur on its flanks, and a third is present at Sulphur Creek, 15 km north of the volcano (Tabor and Crowder, 1969). A considerably 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. The groundmass of some lava flows near the summit has been partly replaced by carbonates and clay minerals. 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).

The purpose of this report is to describe the stratigraphy and distribution of volcanic deposits that originated at Glacier Peak during late glacial and postglacial time, and to assess the hazards that could result from future eruptions of Glacier Peak. This report is based on approximately 20 weeks of fieldwork done during the summers of 1978 and 1979.

Previous studies

Glacier Peak was first explored and studied by I. C. Russell of the U.S. Geological Survey in 1899 (Russell, 1900, p. 134-135). Russell considered the volcano to be a large cinder cone. The next geologic study was not undertaken until the 1950's, when Ford (1959, p. 250-331) 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 1960's. This study resulted in the publication of a geologic map of the Glacier Peak quadrangle (Crowder and Tabor, 1966) and a U.S. Geological Survey Professional Paper (Tabor and Crowder, 1969) which included many detailed petrologic descriptions and geochemical analyses of the volcanic rocks. Tabor and Crowder (1969, p. 28) stated in their report that "there is no evidence of eruptions of Glacier Peak more recent than 12,000 yrs. B.P." They recognized only one late Pleistocene tephra layer and one late Pleistocene pyroclastic-flow deposit.

Most recent studies of the eruptions at Glacier Peak have concentrated on the stratigraphy and chronology of the late Pleistocene tephra deposits and have revealed that they are more complex than had previously been believed. Wilcox (1969) suggested that the eruption which produced the Glacier Peak tephra actually consisted of two separate eruptions, which were closely spaced in time. Subsequently, Lemke and his colleagues (Lemke and others, 1975) showed that deposits of Glacier Peak tephra in Montana were associated with mollusk shells about 12,750 radiocarbon years old. More recently, Porter (1978) subdivided the tephra deposits into nine separate layers. Finally, Mehringer, Blinman, and Peterson (1977) have shown that tephra layer B, the youngest of Porter's nine layers, is about 11,250 radiocarbon years old.

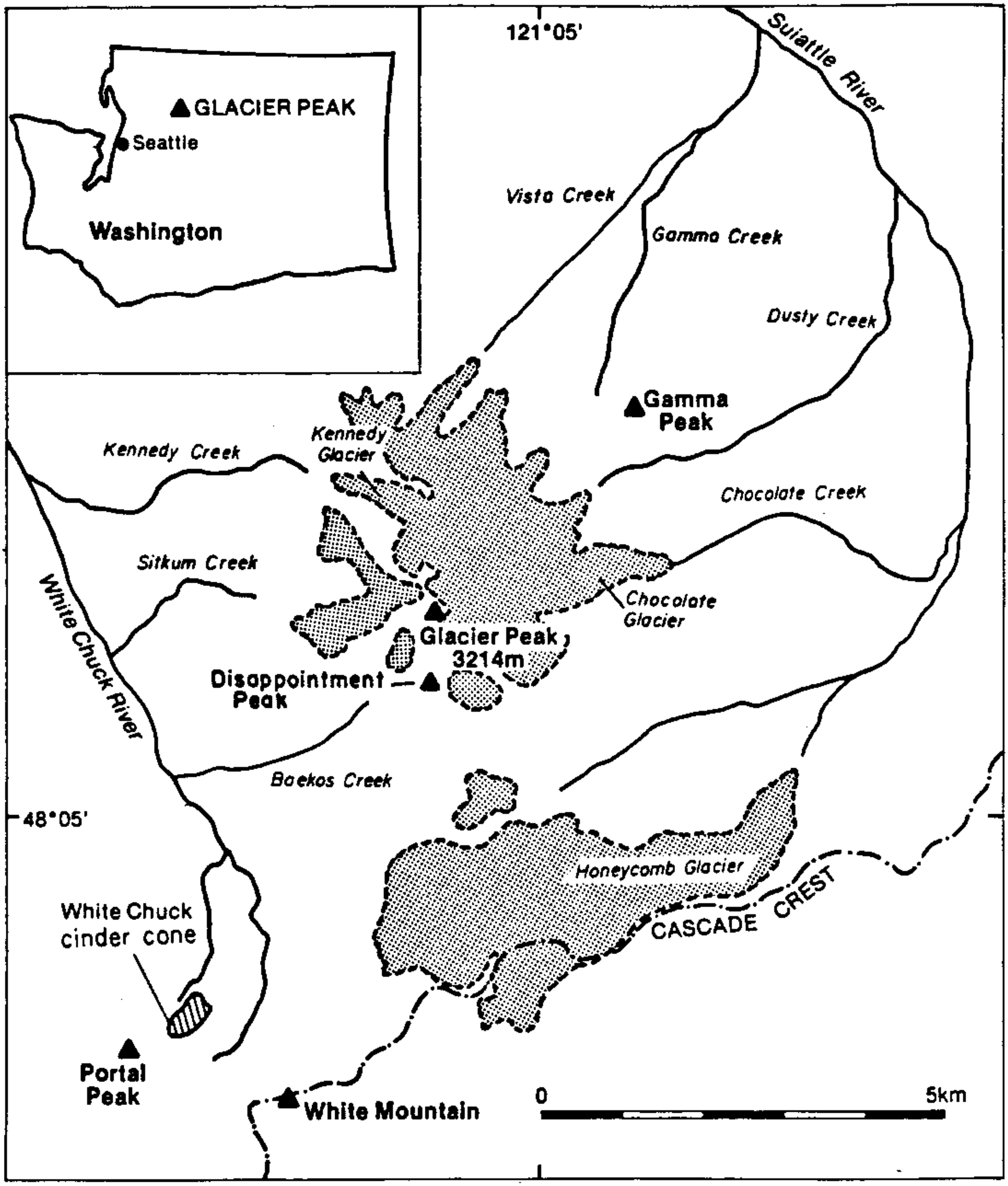


Figure 2.--Index map of Glacier Peak and its immediate vicinity.

Terminology

The term tephra is used here to refer to pyroclastic volcanic debris thrown from a vent and transported through the air as a result of a volcanic explosion. Tephra deposits may consist of pumice, scoria, mineral crystal fragments, glass shards, dense lithic fragments, or a mixture of any of these components.

Pyroclastic-flow deposits are produced by transport of hot, dry volcanic rock debris created during an eruption. Pyroclastic-flow deposits may consist of pumice, dense rock fragments, or both. A fine matrix of glass shards, crystal and lithic fragments is generally present. Pyroclastic flows most commonly are a product of eruptions from volcanic domes, spines, or vents, or result from the collapse of a vertical eruption column. Air trapped within the pyroclastic flow is heated and combines with hot gases emitted by rock fragments in the flow to give pyroclastic flows a high degree of mobility. The downslope movement of the flows is primarily due to gravity, although the explosive eruption of the volcanic debris may provide a high initial velocity. Such flows may travel tens of kilometers beyond the base of the volcano. Pumiceous pyroclastic-flow deposits commonly result from the explosive eruption of gas-charged magma; pyroclastic flows composed largely of nonvesicular rocks often result from the eruption and collapse of lithic domes, from which hot rock debris may avalanche down the flanks of the volcano.

The deposits of pyroclastic flows can be differentiated from some other diamictons by evidence that they were once hot. This can be demonstrated if the thermoremanent magnetism (TRM) possesses a preferred orientation, indicating that rock fragments came to rest while still above their Curie or blocking temperature (Hoblitt and Kellogg, 1979). A reddish oxidized zone in the upper few meters of the deposit, or an abundance of prismatically jointed blocks, may also indicate a pyroclastic-flow origin.

Ash-cloud deposits are produced concomitantly with at least some pyroclastic-flow deposits. These deposits consist of fine-grained beds of mineral fragments, glass shards, and lithic fragments, or a combination of these materials. Ash-cloud deposits are produced as a result of the elutriation of fine debris from a moving pyroclastic flow by the heated gaseous clouds which rise above and may travel independently of the pyroclastic flow. Deposits are restricted to areas near associated pyroclastic-flow deposits, and generally show rapid lateral changes in thickness and grain size away from the margins of the pyroclastic-flow deposits. Ash-cloud deposits consist of material which closely resembles the pyroclastic flows from which the ash cloud was generated.

Lahars are water-saturated debris flows composed primarily or exclusively of volcanic rock fragments, which move downslope under the influence of gravity. Rock fragments carried by lahars may be either hot or cold. Eruptions may produce lahars in several ways. Melting of snow and glacier ice by freshly erupted hot debris may produce lahars that contain hot rock fragments.

Volcanic explosions or earthquakes may initiate avalanches of water-saturated rock debris. Dome extrusion or explosive eruptions may cause spillover or draining of a crater lake, or slumping of part of the old volcanic cone. Pyroclastic-flow deposits may temporarily dam or choke streams and subsequently be reworked to form lahars. Lahars may also be produced without being triggered by an eruption. Precipitation may saturate loose rock debris, and unconsolidated volcanic deposits or rock decomposed by hydrothermal alteration may slump or avalanche and form lahars. In addition, glaciers on volcanoes may impound and then suddenly release large amounts of water. Such a glacier-outburst flood generally picks up loose rock debris and forms a lahar. Glacier-outburst floods commonly occur independently of a volcanic eruption.

TEPHRA DEPOSITS AT GLACIER PEAK

Tephra deposits that resulted from eruptions of Glacier Peak are subdivided into those of late Pleistocene age, and those of Holocene age.

Late Pleistocene tephra deposits

Tephra eruptions of large volume occurred repeatedly at Glacier Peak during late-glacial time. The resulting deposits include nine layers in an area approximately 20-40 km east of Glacier Peak (Porter, 1978), which are designated, from oldest to youngest, G, N, C, F, M, T1, T2, T3, and B. The characteristics of each layer, including thicknesses, textures, and distribution, are summarized in table 1. These deposits thin regularly downwind to the east of Glacier Peak. In a cirque on the northwest side of Carne Mountain, approximately 24 km east of Glacier Peak, the composite thickness of airfall tephra deposits exceeds 1 m (measured section 1).

Nearer the volcano, the individual tephra layers thicken as does the composite section. At Buck Creek Pass, 8 km east of Glacier Peak, layers F, C, N, M, and T can each be subdivided into two or more lithostratigraphic units. These thinner layers have not been consistently identified in sections east of the volcano, and so have not been assigned separate letter designations in this report.

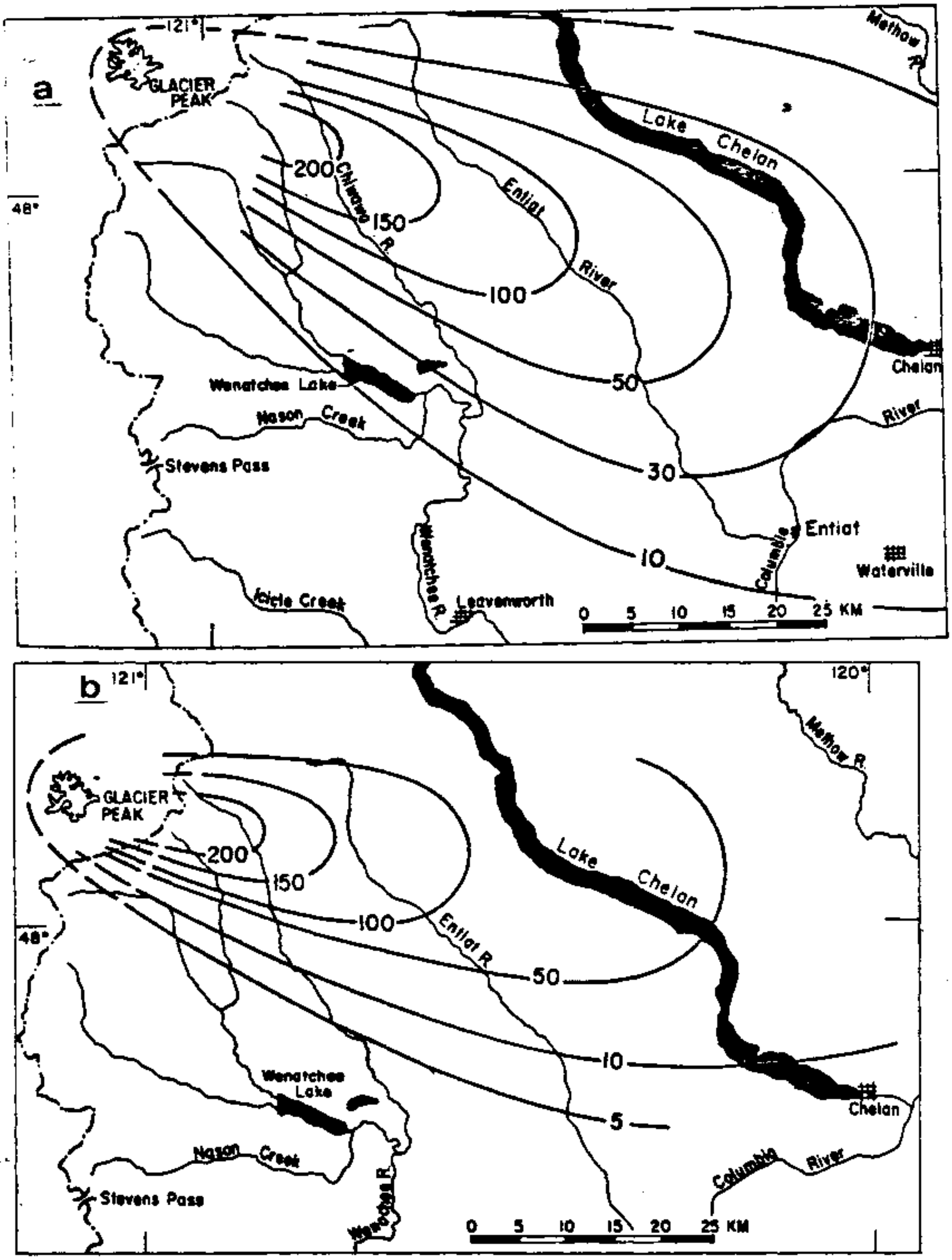
At some places, there are minor unconformities between lithostratigraphic units of set M, and some sections contain lenses of reworked tephra within set M. However, there is no evidence of soil development or weathering within the succession of tephra deposits of late-glacial age (measured section 2). This suggests that all the late Pleistocene tephra layers were deposited during a period too short to permit soil development or erosion.

The regional distribution of the late-glacial tephra layers was determined by measuring the thicknesses, modal grain sizes, and maximum grain sizes for each layer at several dozen locations on the flanks of the volcano and downwind to the east. These sites are located over an area of approximately 500 km^2 and extend from 4 km northwest to 50 km southeast of the volcano. The tephra layers are distributed in lobes whose axes range from southeast to northeast. The distribution and trend of these lobes have previously been delineated by Porter (1977, 1978), and some are shown in figure 3. The distribution of tephra layer M as mapped in this study is in

Table 1.--Characteristics of tephra layers at Glacier Peak

Tephra unit	Field description	Typical thickness within 10 km of volcano (cm)	Fe-Mg phenocrysts[1]	Refractive indices of glass	Direction of plume axis	Inferred age years B.P.[2]
X-------	Lapilli and bombs of gray pumice.	Doesn't form discrete layer.	hy, hb, ox, au.	1.504-1.510	N. 65° E.	<316 >90
Grass-roots ash.	Mostly fine ash, but contains some lapilli which resemble those of X.	0-50	ox, hb, hy, au.	1.504-1.510	East-----	Similar to layer X.
A-------	Fine to medium lapilli, generally angular.	6-10 (discontinuous).	hy, ox, hb--	1.494-1.500	Northeast	<3,400 >90
Yn[3]-----	Fine pumiceous ash with glass shards and crystal fragments.	1- 5	cu, hb------	1.493-1.508	---------	3,400
Set D---	Fine to medium lithic and crystal ash; locally includes as many as 3 beds.	5-15	hb, hy------	1.496-1.500	S. 80° E.	<6,700 >5,100
O[4]------	Very fine crystal ash and glass shards.	5	hb, au, hy--	1.497-1.508	---------	6,700
B-------	Bombs of yellow pumice in matrix of pumice and lithic lapilli and crystal ash.	200	hy, hb------	1.501-1.508	S. 65° E.	11,250
Set M---	Fine to medium lithic and crystal ash with some pumice lapilli interbedded between layers B and G. Subdivided into lithostratigraphic layers F, C, N, M, and T.	50-75	hy, hb------	1.496-1.508	Southeast	<12,500 >11,250
G-------	Bombs and lapilli of white to gray pumice, lithic lapilli, and crystal ash.	200-300	hy, hb------	1.496-1.504	S. 85° E.	12,500(?)

[1]hy = hypersthene, hb = hornblende, au = augite, ox = oxyhornblende, cu = cummingtonite.
[2]Based on dendrochronology and radiocarbon dating.
[3]Erupted from Mount St. Helens.
[4]Erupted from Mount Mazama.



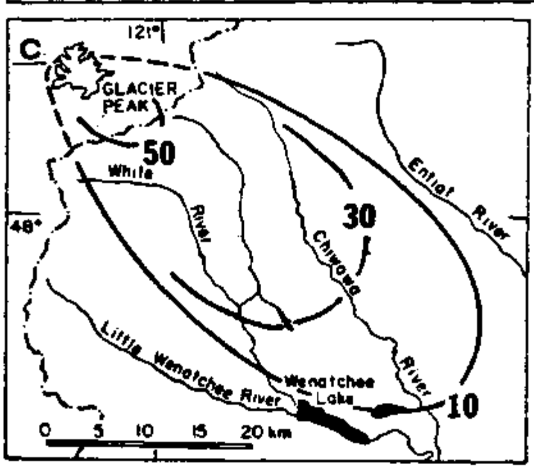


Figure 3.--Isopachs, in centimeters, of some Glacier Peak tephra units erupted in late Pleistocene time: (a) maximum thickness of tephra layer B; (b) maximum thickness of tephra layer G; (c) maximum thickness of tephra set M. (Figs. a, b from Porter, 1978; fig. c based on data in Porter, 1978.)

Measured section 1

[Stream cut 30 m south of Carne Mountain Trail in cirque basin floor, approximately 0.7 km southwest of Carne Mountain, about 20 km east of Glacier Peak. Color notations are those of the Munsell system (Munsell Color Co., 1954)]

	Thickness (cm)
12. Colluvium: reworked volcanic ash and forest duff	25-40
11. Tephra layer Yn (from Mount St. Helens)	2
10. Colluvium: reworked volcanic ash and forest duff	30
9. Tephra set D:	
c. Sandy ash, d-ave.[1] = 0.25 mm, in blue-gray ash matrix (5B 6/1)	2
b. Brown ash (7.5YR 6/2)	1
a. Purple ash (5P 6/1)	1
8. Colluvium: reworked pumice and forest duff, oxidized 1 cm at top	30
7. Tephra layer B: pumice lapilli, d-ave. = 1.5 cm	40
6. Tephra layer T:	
b. Ash, fine, gray (HN 6/0)	9
a. Ash, d-ave. = 1.0 cm	4
5. Tephra layer M: fine lapilli in a yellow-orange ash matrix (7.5YR 8/3)	7
4. Tephra layer F:	
b. Coarse ash, d-ave. = 1.0 mm	3
a. Ash, d-ave. = 0.5 mm	2
3. Tephra layer C: ash, d-ave. = 1.0 mm	3
2. Tephra layer N:	
b. Gray ash	1
a. Light-purple ash (5P 6/1)	3
1. Tephra layer G: pumice lapilli	>70

[1] The notation "d-ave." in this and other measured sections refers to a field measurement of the average diameter of particles.

Measured section 2

[About 100 m southeast of intersection of Forest Service trails 1513 and 787 at Buck Creek Pass, 12 km east of Glacier Peak]

	Thickness (cm)
16. Colluvium: reworked ash and forest duff	40
15. Tephra layer A:	
b. Ash, dacitic fragments, d-ave. = 1.5 mm	5
a. Ash, grayish-purple, with small dacitic fragments	4
14. Colluvium: reworked ash and forest duff	20
13. Tephra layer Yn	2
12. Colluvium: reworked ash and forest duff	30
11. Tephra layer D:	
d. Ash, purple (5P 6/1)	2
c. Ash, grayish-purple, fine lapilli	9
b. Ash, purple (5P 6/1)	2
a. Ash, brownish-gray (7.5YR 6/2)	5
10. Tephra layer O (from Mount Mazama)	10
9. Forest duff: contains abundant carbonized wood	5
8. Colluvium: reworked pumice and forest duff	19
7. Tephra layer B: pumice lapilli	120
6. Tephra layer T:	
j. Ash, light-brown (5YR 6/1)	2
i. Ash, coarse	15
h. Ash, fine, black	2
g. Ash, brown (5YR 6/3)	4
f. Ash, gray (5PB 7/1)	2
e. Lapilli and medium ash	3
d. Lapilli and coarse ash	2
c. Lapilli and medium ash	4
b. Lapilli, fine	2
a. Lapilli, fine	2
5. Tephra layer M: pumice lapilli in a yellowish-orange ash matrix	
c. Ash, yellowish-brown (2.5Y 5/4)	1
b. Ash, coarse, lenticular	0-3
a. Ash, yellowish-brown (2.5Y 5/4)	3
4. Tephra layer F: fine lapilli	2
3. Tephra layer C:	
c. Lapilli, fine	2
b. Lapilli, fine	3
a. Lapilli, medium	3
2. Tephra layer N: fine lapilli	5
1. Tephra layer G: coarse lapilli	>100

part different from that described by Porter (1978, p. 37). Deposits of layer M occur farther east than has been previously thought (measured section 1), but were not recognized at any localities south of Glacier Peak.

The ages of tephras erupted during late Pleistocene time are not well known. Only layer B has been positively identified at a site where it was possible to bracket it with radiocarbon-dated samples. It was found to have been deposited about 11,250 radiocarbon years ago (Mehringer and others, 1977). Other radiocarbon dates associated with Glacier Peak tephra deposits range from 14,360±400 (W-2780) to 12,000±310 (WSU-155) radiocarbon years ago. Lemke and his associates (1975) determined that an ash in late-glacial lake sediments in Montana originated at Glacier Peak. This ash was subsequently identified as layer G (Westgate and Evans, 1978). Mollusk shells associated with the ash were about 12,750 years old, suggesting that all the known late Pleistocene tephra layers from Glacier Peak were erupted between approximately 11,250 and 12,750 radiocarbon years ago.

Major ferromagnesian minerals in late Pleistocene tephra units from Glacier Peak are hornblende and hypersthene (table 1). Glass shards from these tephra units have refractive indices that range from 1.496 to 1.506, and measured modal values of refractive index for individual layers systematically increase from 1.498 (layer G) to 1.501 (layer B) (Westgate and Evans, 1978).

Holocene tephra deposits

The oldest Holocene tephra deposit at Glacier Peak is a layer of ash that was produced during large eruptions of Mount Mazama at the site of Crater Lake in Oregon about 6,700 years ago. The deposit, known as tephra layer O (Crandell and others, 1962), is a useful stratigraphic marker bed at Glacier Peak, and is readily identified in the field by its well-sorted, fine-sandy-silt texture, and its distinctive yellowish-orange color (2.5Y 8/6-10YR 8/6). In addition, the mineralogic characteristics and refractive indices of constituent glass shards distinguish it from tephras erupted at Glacier Peak and Mount St. Helens, which are also present in this area (table 1).

A tephra unit that stratigraphically overlies layer O is found on the north and east flanks of Glacier Peak, and extends at least 25 km to the southeast of the volcano (fig. 4). The tephra unit, designated tephra set D, typically contains several thin beds of ash and lapilli (measured section 3). These include a widespread olive-brown (2.5Y 4/4) ash layer, which near the volcano contains lithic lapilli, some of which are oxidized and partially altered. Tephra set D also contains beds of unaltered lithic ash and dacitic lithic lapilli. This unit is as much as 15 cm thick near Glacier Peak (measured section 3), and thins to 2-4 cm at Boulder Pass, about 10 km to the southeast, and to 1-2 cm in the Entiat Mountains, about 25 km east of Glacier Peak (measured section 1). The deposits of tephra set D are estimated to have a volume on the order of 10 million m^3. The initial, uncompacted volume was probably somewhat greater (Mullineaux, 1974).

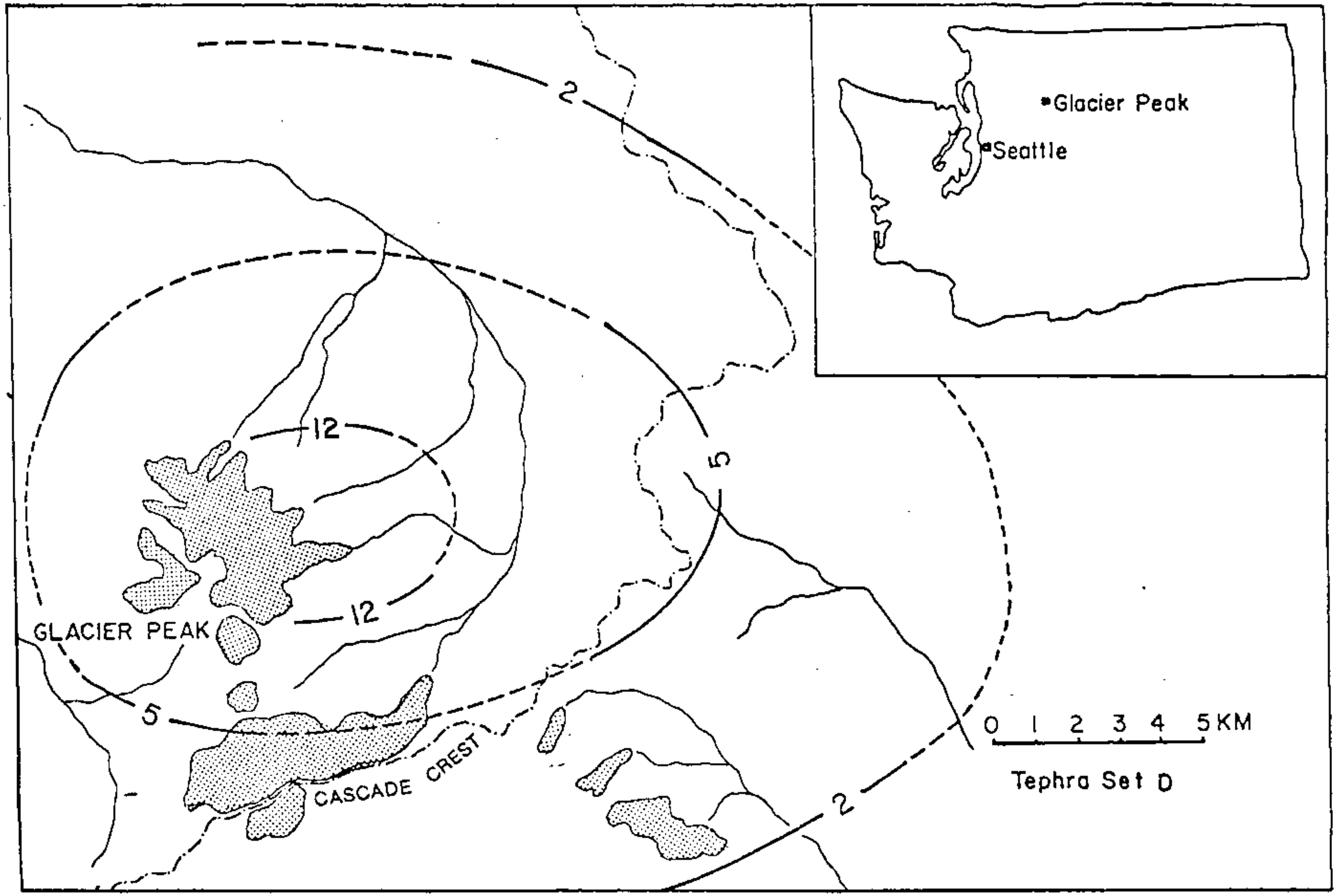


Figure 4.--Distribution of tephra set D at Glacier Peak. Tephra set D consists of several thin tephra layers. Isopach thicknesses are in centimeters.

Measured section 3

[Exposure on north side of the Pacific Crest Trail, approximately 0.1 km north of the junction with the Glacier Ridge Trail, and about 5 km northwest of Glacier Peak]

	Thickness (cm)
8. Colluvium: reworked volcanic ash and forest duff	9
7. Tephra layer Yn	3
6. Colluvium: reworked volcanic ash and forest duff	3
5. Ash, white	5
4. Tephra set D:	
d. Ash, poorly sorted, angular, dacitic	1
c. Ash, gray	0.5
b. Fine lapilli and coarse ash, poorly sorted (1-8 mm) with clasts up to 15 cm in diameter, openwork common	3-5
a. Ash, olive-brown (2.5Y 4/4), clay to silt size, with rare fine lapilli, some of which are stained and oxidized	13
3. Colluvium: reworked volcanic ash and duff	4
2. Tephra layer O	3
1. Colluvium: reworked volcanic ash and forest duff, with some pumice lapilli	>50

The next younger tephra deposit at Glacier Peak was produced by an eruption of Mount St. Helens in southern Washington about 3,400 years ago (Mullineaux, 1974). This tephra unit, designated tephra layer Yn, is locally present on the west side of Glacier Peak, and is generally 1-2 cm thick on the eastern flank of the volcano, although in places it may be absent or somewhat thicker. Layer Yn consists of fine pumiceous ash and glass, and is mineralogically distinct from other tephra layers at Glacier Peak in that it contains cummingtonite (table 1).

Stratigraphically overlying layer Yn at Glacier Peak is a poorly sorted unit consisting mostly of fine lithic dacitic lapilli, but also containing clasts as large as 10 cm in diameter. Ash is rare and voids between clasts are common. This unit, designated tephra layer A, reaches a maximum thickness of 10 cm on Gamma Ridge, about 4 km northeast of the volcano's summit (fig. 5). It has also been recognized north and east of Glacier Peak. Its poor sorting, variable thickness, and irregular distribution suggest that tephra layer A may have resulted from phreatic explosions high on Glacier Peak. These explosions may have been produced during the emplacement of a lithic dome on the volcano sometime during the last several thousand years. The estimated volume of tephra layer A is on the order of 1 million m^3. Its original, uncompacted volume was probably somewhat greater.

The age of layer A is poorly known. It overlies and so is younger than layer Yn, and it underlies pumiceous ash deposits which are younger than 316 years old.

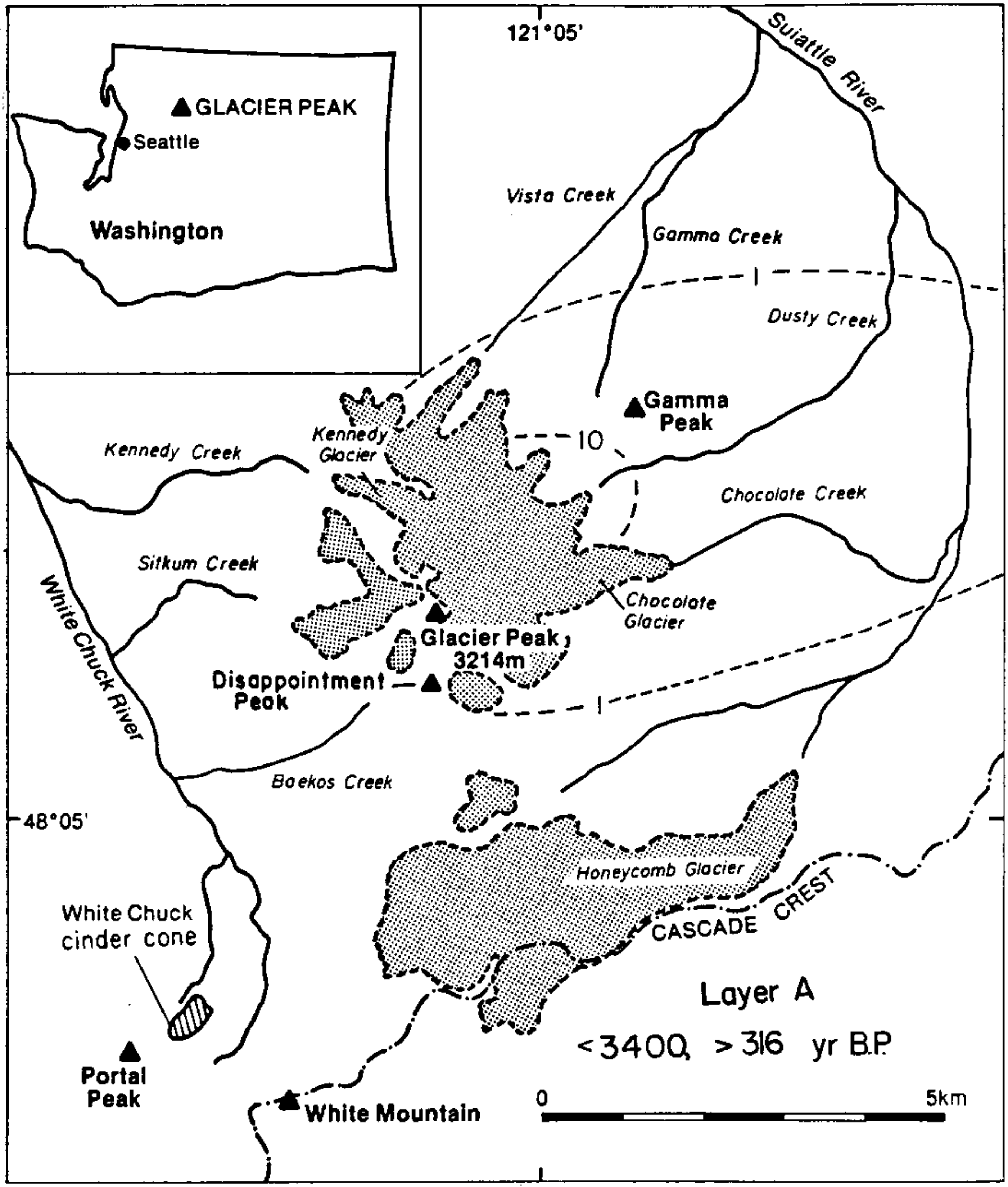


Figure 5.--Distribution of tephra layer A at Glacier Peak. Isopachs in centimeters.

The youngest tephra deposits recognized at Glacier Peak consist of scattered pumice lapilli as much as 10 cm in diameter. These deposits are named tephra layer X. These lapilli have been found in Chocolate Creek valley on lateral moraines which support trees at least 316 years old. Younger moraines on which trees at least 90 years old are growing do not have layer X on their surface. These pumice lapilli contain augite and oxyhornblende in addition to hornblende and hypersthene, and so are mineralogically distinct from the pumice produced during earlier tephra eruptions at Glacier Peak (table 1). They have been found only on the western part of Gamma Ridge, and on Dusty Ridge up to 4 km east of the volcano. The distribution of layer X is shown in figure 6. Layer X has an estimated volume on the order of 100,000 m^3.

Associated with layer X is a widespread ash layer occurring at the grassroots east and northeast of Glacier Peak. This ash is as much as 30 cm thick near the mouth of Dusty Creek, about 5 km east of the volcano. Layer X and this vitric ash occur on moraines which support trees as old as 316 years, but are absent from the surface of younger moraines which are more than 90 years old. This ash is probably the same as the grassroots "pumicite" noted by Carithers (1946). The ash is similar to deposits of tephra layer Wn from Mount St. Helens, which are present east of Glacier Peak and east of the Cascade Crest, but it can be distinguished from Wn on the basis of mineralogy, distribution, and texture (table 2).

This ash was found in a buried soil between two lahars exposed in the bank of Chocolate Creek. Both lahars were deposited less than 200 years ago (W-4274, W-4268). The vitric ash layer does not become coarser grained toward Glacier Peak, although on Gamma Ridge it does contain rare pumice lapilli similar to those of layer X.

At least three beds, separated by thin sandy layers, can be distinguished within the vitric ash. The ash may have been generated during a series of phreatic eruptions, or may be an ash-cloud deposit associated with a pyroclastic flow. The volume of the vitric ash is on the order of several hundred thousand cubic meters.

In addition to the tephra deposits described above, thick and widespread ash-cloud deposits mantle the ridges east of Glacier Peak (fig. 7). These deposits exceed 3 m in total thickness in some areas (measured section 4).

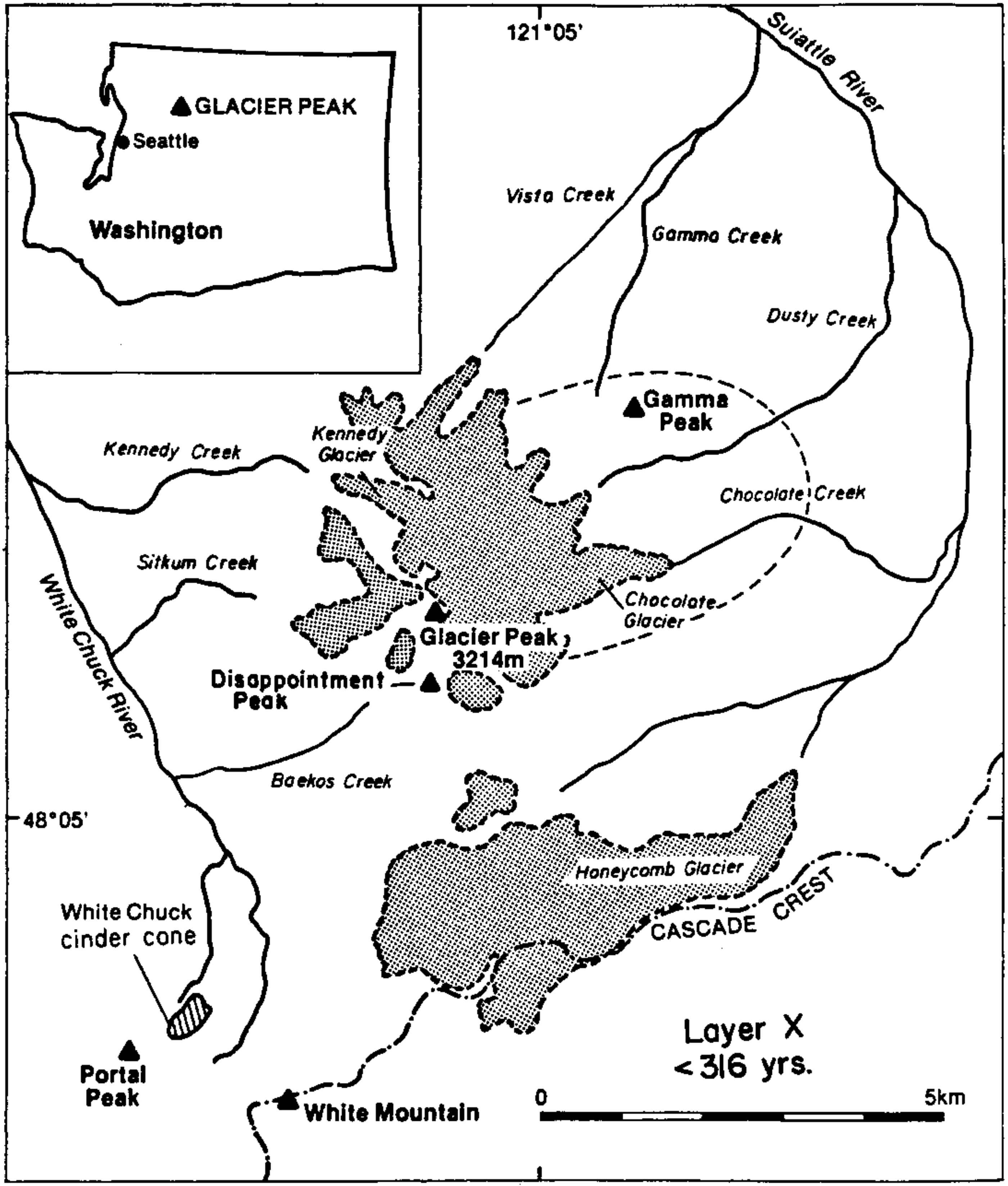


Figure 6.--Distribution of tephra layer X at Glacier Peak is shown by dotted line. Deposits consist of scattered pumice lapilli as much as 10 cm in diameter. Lapilli are more common and larger in the center of the fallout area than at the margins.

Table 2.--Comparison of characteristics of tephra layer Wn and a vitric ash found at the grassroots east of Glacier Peak

Unit	Fe-Mg phenocrysts	Refractive index of glass shards and pumice glass	Distribution	Location and thickness	Texture
Layer Wn--	Hypersthene, hornblende.	1.490-1.494[1]	North and east from Mount St. Helens.	Present east of the Cascade Crest, not recognized at Glacier Peak.	Fine ash.
Grassroots ash.	Oxyhornblende, hornblende, hypersthene, augite.	1.504-1.510	East of Glacier Peak.	As much as 50 cm thick at the mouth of Dusty Creek, and 30 cm thick near Gamma Peak: present as a layer as much as 5 cm thick over much of the eastern flank of the volcano.	Mostly fine ash but contains rare pumice lapilli at some sites near Gamma Peak.

[1]Layer Wn is too fine grained to contain pumice lapilli at locations as far north as Glacier Peak.

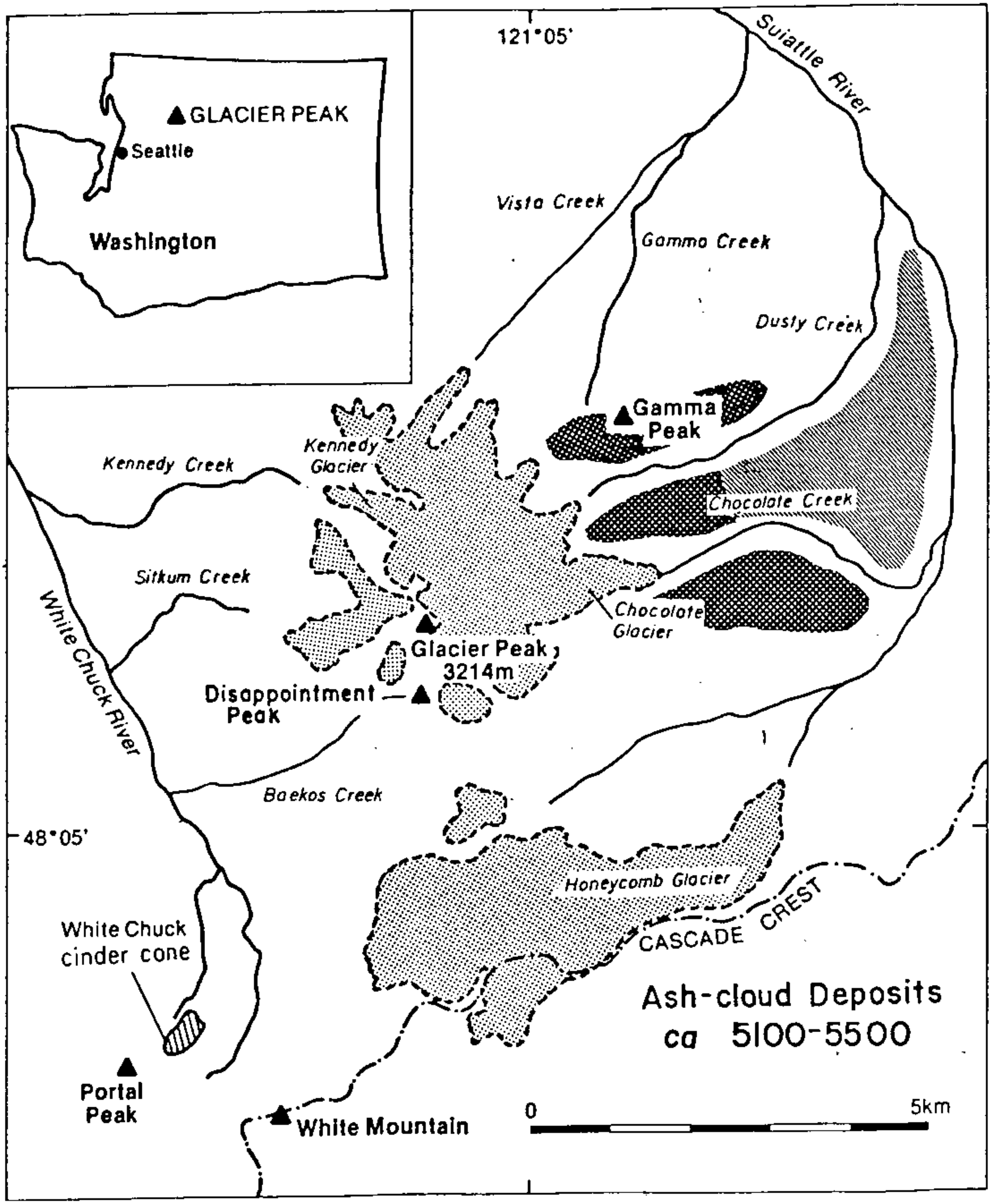


Figure 7.--Distribution of thick ash-cloud deposits east of Glacier Peak. The dark pattern indicates areas where these deposits are 1 m or more thick, and the line pattern shows areas where the deposits are less than 1 m thick.

Measured section 4

[Stream cut, about 1 km south of the terminus of the Chocolate Glacier and approximately 0.25 km southeast of point 6549 (see U.S. Geological Survey Glacier Peak 15-minute topographic quadrangle map)]

	Thickness (cm)
64. Colluvium: reworked ash and forest duff	4
63. Silt, dark-brown	10
62. Fine ash, light-bluish-gray	4
61. Medium ash	5
60. Fine ash, bluish-gray	14
59. Silt, brown	1
58. Fine ash, bluish-gray	7
57. Colluvium: reworked ash and forest duff	4
56. Fine ash, light-gray (2.5Y 8/1)	1
55. Colluvium: reworked ash and forest duff	3
54. Coarse lithic ash	6
53. Colluvium: reworked ash and forest duff	7
52. Coarse lithic ash	11
51. Medium to coarse ash	31
50. Coarse lithic ash and fine lapilli	13
49. Fine ash, blue and purple	7
48. Colluvium: reworked ash and forest duff	14
47. Tephra layer Yn	3
46. Fine ash, light-gray	4
45. Fine ash, white to gray (7.5Y 7/1)	1
44. Coarse ash, blue-gray	3
43. Medium ash, black	4
42. Coarse ash and fine lapilli	1
41. Fine ash, reddish-gray (2.5YR 8/1)	4
40. Coarse ash, grayish-black	3
39. Fine ash, bluish-purple	6
38. Medium ash	1
37. Colluvium: poorly sorted sand and silt	6
36. Fine ash, bluish-purple	1
35. Medium ash	1
34. Fine ash, bluish-gray	2
33. Medium ash	1
32. Fine ash, bluish-gray	12
31. Fine ash, cream color (7.5YR 8/4)	1
30. Medium ash, black	1
29. Medium and fine ash, bluish-gray	8
28. Medium ash,	1
27. Fine ash, bluish-gray	6
26. Medium ash	1
25. Fine ash, bluish-gray	35
24. Medium ash	2
23. Fine ash, bluish-gray	21
22. Fine ash, bluish-gray	15
21. Coarse ash, black	6

Measured section 4--Continued

		Thickness (cm)
20.	Medium ash, black	4
19.	Medium ash	1
18.	Fine ash, light gray (5YR 6/1)	1
17.	Fine ash, reddish brown (2.5YR 5/3)	2
16.	Medium ash	8
15.	Fine ash, bluish purple	7
14.	Medium ash	1
13.	Fine ash, grayish purple	10
12.	Colluvium: reworked ash and forest duff	1
11.	Tephra set D:	
	c. Ash, red (5YR 5/3)	3
	b. Ash, brown, with minor lithic lapilli (7.5YR 5/4)	8
	a. Ash, light-blue	3
10.	Tephra layer O	4-8
9.	Duff, contains carbonized wood and twigs	10
8.	Colluvium: contains abundant pumice lapilli and ash	30
7.	Medium to coarse sand	30
6.	Colluvium: contains abundant pumice lapilli and ash	5
5.	Fine ash, grayish blue	2
4.	Medium ash	15
3.	Fine ash, grayish blue	4
2.	Medium ash	4
1.	Tephra layer B: pumice lapilli and bombs	>200

The ash-cloud deposits consist of thin, laminated beds of silt- to sand-size lithic ash. Individual beds range from 0.5 to more than 30 cm in thickness. Although there is some involution of the layers, they vary little in thickness laterally, and individual beds can generally be traced several meters across outcrops.

The coarse ash and lapilli-rich beds consist exclusively of dacitic lithic debris, together with eucrystic mineral fragments. These deposits are mineralogically similar to the pyroclastic-flow deposits preserved in large fans between Dusty and Chocolate Creeks. Finer grained ash-cloud deposits consist of glass shards and mineral fragments, and range in color from gray (HN 6/0) to purplish gray (5P 5/1). The succession of ash-cloud deposits thins rapidly eastward from Glacier Peak, and cannot be recognized at Buck Creek Pass, only 10 km to the east (measured section 2). These deposits also thin rapidly north and south of the Dusty Creek-Chocolate Creek area. The rapid thinning reflects the origin and mode of deposition of the ash-cloud deposits (that is, elutriation from pyroclastic flows) and is typical of ash-cloud deposits described elsewhere (Crandell and Mullineaux, 1973).

These deposits were produced when pyroclastic flows formed valley-filling debris fans which are preserved in the upper parts of the Chocolate and Dusty Creek valleys. This coeval relationship is strongly indicated by the similar mineralogy and by stratigraphic relations of the deposits to older and younger tephras. Both groups of deposits postdate tephra layer O. The most voluminous volcanic debris fan and the thickest sequence of ash-cloud deposits both predate tephra layer Yn. Ash-cloud deposits east of Glacier Peak also overlie tephra set D. Minor amounts of charcoal occur in a layer beneath the ash-cloud deposits on Gamma Ridge and above tephra set D. This charcoal may have resulted from the burning of alpine vegetation by hot debris transported in the ash clouds.

FLOWAGE DEPOSITS IN THE VALLEYS OF KENNEDY CREEK AND THE WHITE CHUCK RIVER

Crystal Creek mudflow

The oldest postglacial deposit in the White Chuck River valley is an extensive clayey lahar containing hydrothermally altered rock debris. This lahar, informally referred to as the Crystal Creek mudflow, is well exposed in roadcuts along the White Chuck River Road (Forest Service Road 319) between Crystal Creek and Pugh Creek. It is also exposed along the White Chuck River trail in landslide scars beneath the vitric tuff, between 5 and 8 km from the trailhead. The Crystal Creek mudflow typically consists of a light-gray to brown (2.5Y 7/1-2.5Y 7/3) clayey sand that contains abundant clasts of volcanic rock and as much as 10 percent of local crystalline bedrock. Most of the volcanic clasts are stained yellow or red, and are partly or entirely altered. The mudflow may have originated when hydrothermally altered rocks at the summit or on the flanks of Glacier Peak avalanched down the west side of the volcano.

Deposits of the Crystal Creek mudflow can be found as far as 30 km downstream from Glacier Peak in the White Chuck and Sauk River valleys (fig. 8). The age of the mudflow is not well known, but inferences can be drawn from its stratigraphic relation to glacial drift of the last major glaciation (Fraser Glaciation), from the absence of certain distinctive late Pleistocene rock types, and from its relation to younger lahars which have been dated. At a locality 5 km up the Sauk River from its confluence with the White Chuck River, the Crystal Creek mudflow overlies till and outwash gravel deposited by the Puget glacier lobe; thus, the mudflow occurred after the Puget lobe had begun to retreat. It is believed that the Puget lobe reached its maximum stand about 14,000 radiocarbon years ago, and retreated quickly thereafter (Armstrong and others, 1965).

Similar relations occur in the central White Chuck valley near Crystal Creek. Deposits formed by a tongue of the Puget lobe that advanced 15 km up the White Chuck occur along the valley floor. These deposits contain clasts of phyllite, which crop out west of the Straight Creek fault; thus, these deposits were formed by glaciers that advanced up the White Chuck valley. Although not in direct contact, these glacial deposits must predate the Crystal Creek mudflow, otherwise the mudflow deposits would have been mantled with till.

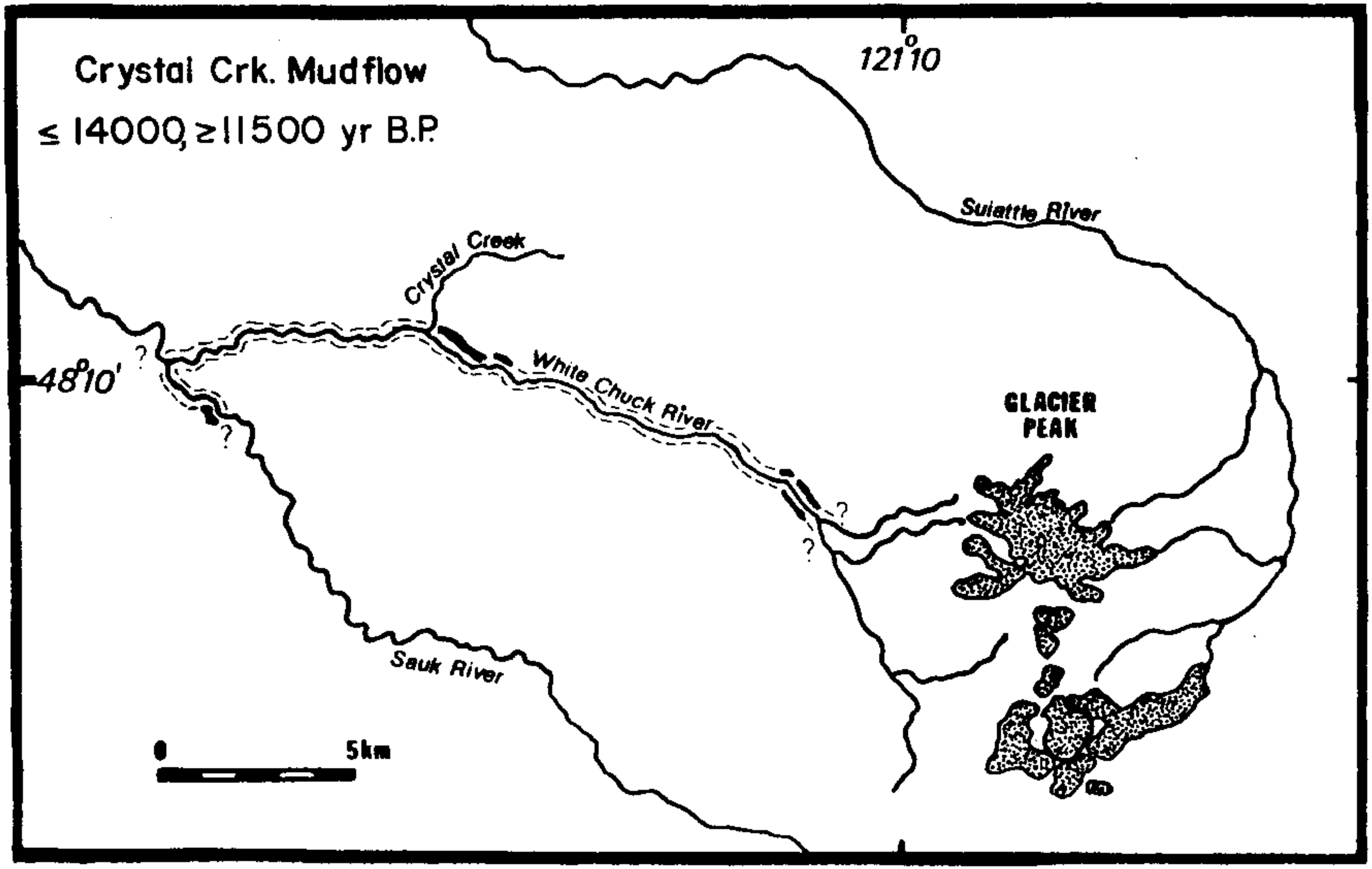


Figure 8.--Distribution of the Crystal Creek mudflow. Solid where preserved. The inferred original extent is shown by the dashed line. The mudflow probably originated in a massive landslide of hydrothermally altered rock debris from near the summit of Glacier Peak.

The Crystal Creek mudflow underlies, and thus predates, deposits of pyroclastic flows and lahars that were formed during late Pleistocene eruptions of Glacier Peak. These lahars are thought to have formed between 11,670 and 11,250 radiocarbon years ago (see below). Rock types produced during these late Pleistocene eruptions, including an indurated vitric tuff, are not present in Crystal Creek mudflow deposits. This indicates that the Crystal Creek mudflow occurred some time before the late Pleistocene pyroclastic eruptions began at Glacier Peak (table 3), but after the Puget lobe retreated from its maximum extent--that is, between about 14,000 and 11,800 years ago.

Ice of the Puget lobe may still have been present in the Sauk River drainage when the mudflow occurred. The mudflow crops out in the Sauk River valley 5 km upstream from, and 200 m higher than, the present mouth of the White Chuck River, but has not been found downstream from the mouth of the White Chuck River (fig. 8). The deposits in the Sauk River may be the remnants of a backfill. One possible explanation of the distribution of the mudflow in the Sauk River valley is that the retreating Puget lobe was still present and obstructing the lower Sauk valley when the mudflow occurred. If so, the glacier may have caused the lahar to pond in the upper Sauk River valley upstream from the mouth of the White Chuck River. It is also possible that the Crystal Creek mudflow had enough volume to become hydraulically ponded at the confluence of the Sauk and the White Chuck Rivers, and that the deposits upstream from the mouth of the White Chuck represent a temporary backfill of the mudflow. The main mass of such a large mudflow would presumably have continued down the Sauk, but no deposits correlative with it have yet been recognized downvalley.

White Chuck assemblage

The next younger deposits in the White Chuck and Sauk River valleys consist of a thick sequence of deposits formed by pyroclastic flows and lahars. These deposits are informally referred to here as the White Chuck assemblage. The base of these deposits is not exposed in sections near the volcano, where they are more than 100 m thick. Farther down the White Chuck River valley the White Chuck assemblage overlies the Crystal Creek mudflow (measured section 5).

Individual pyroclastic-flow deposits range from 1 to 10 m in thickness. The predominant rock type in the deposits is a light-gray (7.5Y 8/1) nonvesicular dacite that contains hornblende and hypersthene (table 4). Most deposits contain some pumice which typically is concentrated in their upper parts. Some pyroclastic-flow deposits are reversely graded, as noted by Tabor and Crowder (1969, p. 43). Alluvium and thin lahars are also present in the White Chuck assemblage. These deposits form lenticular beds, generally less than 1 m thick, which pinch out laterally within a few meters.

The White Chuck assemblage is discontinuously preserved downstream from Glacier Peak in the valleys of the White Chuck, Sauk, and North Fork of the Stillaguamish River. The distribution of terraces formed by remnants of this assemblage suggests that the deposits once comprised a massive valley fill extending many tens of kilometers downvalley from the volcano. Deposits of the assemblage form a terrace 150 m above the White Chuck valley floor near Kennedy Hot Springs, 6 km downstream from Glacier Peak. The correlative

Table 3.--Radiocarbon dates on samples from deposits at Glacier Peak, Washington

Laboratory No.	Description and location	Stratigraphic significance	Radiocarbon age years B.P.
W-4274----	Bark and wood, stream cut, Chocolate Creek (48°07'15" N., 121°04'08" W.).	Sample provides limiting date on young lahar.	<200
W-4268----	Small branch, stream cut, Chocolate Creek (48°07'15" N., 121°04'08" W.), underlying W-4274.	----do----------------------------	<200
W-4614----	Wood, stream cut, Dusty Creek (48°02'14" N., 121°02'14" W.).	Sample dates lahar composed of hydrothermally altered rock debris.	1,100±50
W-4276----	Branch, stream cut, Chocolate Creek (48°07'15" N., 121°04'10" W.).	Sample dates group of lahars and pyroclastic flows (South Guardian assemblage).	1,080±50
W-4568----	Wood from log, stream cut, Dusty Creek (48°02'14" N., 121°02'14" W.), underlying W-4614.	Sample dates lahar composed of hydrothermally altered rock debris.	1,130±70[1]
W-4567----	Wood from log, stream cut, Dusty Creek (48°02'14" N., 121°02'14" W.), underlying W-4614.	----do----------------------------	1,220±60[1]
W-4613----	Wood from log, stream cut, Dusty Creek (48°02'14" N., 121°02'14" W.).	----do----------------------------	1,150±50
W-4262----	Wood from log, cliffed section of lahars, White Chuck River (48°[illegible]'29" N., 121°19'46" W.).	Sample dates assemblage of at least three lahars.	1,750±70
W-4265----	Wood from large branch, in cliff exposure, Chocolate Creek (48°07'15" N., 121°04'09" W.).	Sample dates assemblage of lahars and pyroclastic-flow debris.	1,860±70
W-4266----	Wood from log, cliffed section of lahars, White Chuck River (48°10'29" N., 121°19'46" W.).	Sample dates assemblage of at least three lahars.	2,820±60
W-4279----	Charcoal in lahar in roadcut, near Hazel (48°17'01" N., 121°46'25" W.).	Sample dates extensive lahar in Kennedy Creek assemblage.	5,020±100
W-4275----	Charcoal from charred log, White Chuck River (48°06'48" N., 121°11'33" W.).	Sample dates pyroclastic-flow deposit in Kennedy Creek assemblage.	5,120±90
W-4214----	Wood from log, White Chuck River (48°06'48" N., 121°11'33" W.).	Sample dates lacustrine deposits interbedded in Kennedy Creek assemblage.	5,520±250
W-4277----	Charcoal in till, stream cut, White Chuck cinder cone (48°03'05" N., 121°09'50" W.).	Sample closely dates till and provides an upper limiting date on eruption of the White Chuck cinder cone.	8,380±90
W-4616----	Wood from log in roadcut, near mouth of White Chuck River (48°10'41" N., 121°27'36" W.).	Sample dates lahar in the White Chuck assemblage.	11,420±150
W-4283----	Charcoal in soil below lahar, French Creek (48°16'15" N., 121°45'18" W.).	Sample provides lower limiting date on lahar in White Chuck assemblage.	11,670±160

[1]Samples W-4567 and W-4568 were both run on the same field sample. Part of the field sample was burned prior to running W-4567, and part was reduced directly and run as W-4568.

Table 4.--Fe-Mg bearing minerals in lahars, pyroclastic-flow deposits, and ash-cloud deposits at Glacier Peak, Washington

[ox, oxyhornblende; hy, hypersthene; ol, olivine; hb, hornblende; au, augite; bt, biotite]

Unit	Fe-Mg minerals in order of decreasing abundance	Lithology	Location of deposits	Age years B.P.
Pumiceous ash and lapilli (phreatic airfall or ash-cloud deposit).	ox, hy, au, hb	Fine white to gray ash with some pumice lapilli.	Gamma Ridge, Dusty and Chocolate Creeks, and Dusty Ridge.	200[1]
Lahar and flood deposit.	ox, hb, hy, au	Dacite, some clasts altered.	Mouth of White Chuck River.	>300[2]
South Guardian assemblage.	hy, hb, au, ox	Dacite lahars, pumiceous pyroclastic-flow deposit.	Upper Chocolate Creek valley.	1,080±50
Lahar assemblage------	hy, hy, au	Lithic lahars-------------	White Chuck River valley	>300[2], <1,750±70
--Do----------------	hb, hy	----do--------------------	----do-----------------	1,750±70
Lahar and pyroclastic-flow assemblage.	hb, hy	Lithic dacite-------------	Lower Chocolate Creek valley.	1,860±60
Lahar assemblage------	hb, hy	----do--------------------	White Chuck River valley	2,820±60
Baekos assemblage-----	hb, hy, ol	----do--------------------	At mouth of Baekos Creek	>3,400, <6,700[3]
Dusty assemblage------	hb, hy, ol	----do--------------------	Suiattle River valley---	>3,400, <6,700[3]
Kennedy assemblage----	hb, hy, ol	----do--------------------	Kennedy Creek and White Chuck River valleys.	5,100-5,500
White Chuck assemblage	hy, hb, au, bt	Pumice and nonvesicular dacite.	White Chuck, Sauk, Stillaguamish River valleys.	11,250-11,700

[1]This deposit has also been determined to be between about 90 and 316 years old, based on the ages of trees growing on moraines associated with the deposit. It may have been produced during an eruption about 200 years ago which was witnessed by Indians.

[2]The assemblage is older than the stump of a cedar which was more than 300 years old when cut.

[3]The assemblage is older than tephra layer Yn, but younger than tephra layer O. It is likely that this assemblage is correlative with the White Chuck assemblage; if so, it was deposited 5,100-5,500 years B.P.

Measured section 5

[Landslide scar north of White Chuck River trail, in NW 1/4 sec. 36, T. 31 N., R. 12 E.]

	Thickness (m)
9. Colluvium: reworked ash and forest duff	0.32
8. Tephra layer O	0.10-0.20
7. Forest duff: contains fragments of burned branches	0.10-0.50
6. Reworked ash and duff, contains lapilli	0.40
5. Fluvial sand and gravel, and thin lahars: interbedded pumiceous alluvium, 1-20 cm thick, and lahars as much as 50 cm thick; contains blocks of vitric tuff as large as 1 m in diameter	3.00
4. Lahar: subangular to subrounded cobbles and boulders as large as 50 cm in diameter in sand and silt matrix; no apparent sorting or stratification; contains blocks of vitric tuff	4.00
3. Pyroclastic-flow deposit: semiwelded vitric tuff, contains abundant unflattened pumice lapilli; has well-developed columnar jointing, columns average 1-2 m in diameter; forms prominent cliff in outcrop	8.00
2. White Chuck assemblage: at least 10 pyroclastic-flow deposits; mostly light gray; light-gray nonvesicular dacite with subordinate white to medium-gray pumice in pumiceous ash matrix; some deposits are reversely graded; some contain boulders as large as 1 m in diameter; prismatically jointed boulders are common, as much as	25.00
1. Crystal Creek mudflow: subangular to subrounded cobbles and boulders in a reddish-gray matrix of sand, silt, and clay; cobbles are typically stained red or yellow and are commonly altered throughout	8.00

terrace is about 50 m above the Sauk River 30 km downstream from the volcano, and is 25 m above the Stillaguamish River at Fortson Mill, some 70 km downstream from Glacier Peak. The White Chuck assemblage represents a very large volume of fragmental material produced during a major eruptive period at Glacier Peak in late Pleistocene time. Pyroclastic flows comprise most of the White Chuck assemblage near the volcano, but beyond about 20 km downstream the assemblage consists entirely of volcanic alluvium and lahars. Some lahars probably consist of rock debris reworked from the pyroclastic flows deposited near Glacier Peak, and others may have originated as lahars at the volcano itself. Lahars which are correlated with the White Chuck assemblage are exposed 3 km west of Arlington in the Stillaguamish Valley, at least 100 km downstream from Glacier Peak (fig. 9). Even at such a great distance from the volcano this lahar contains more than 95 percent volcanic debris, indicating that the lahar did not erode and entrain nonvolcanic debris during movement. This lahar is at least 2 m thick, and caps a terrace some 13 m above the Stillaguamish River. It contains clasts of dacite as much as a meter in diameter.

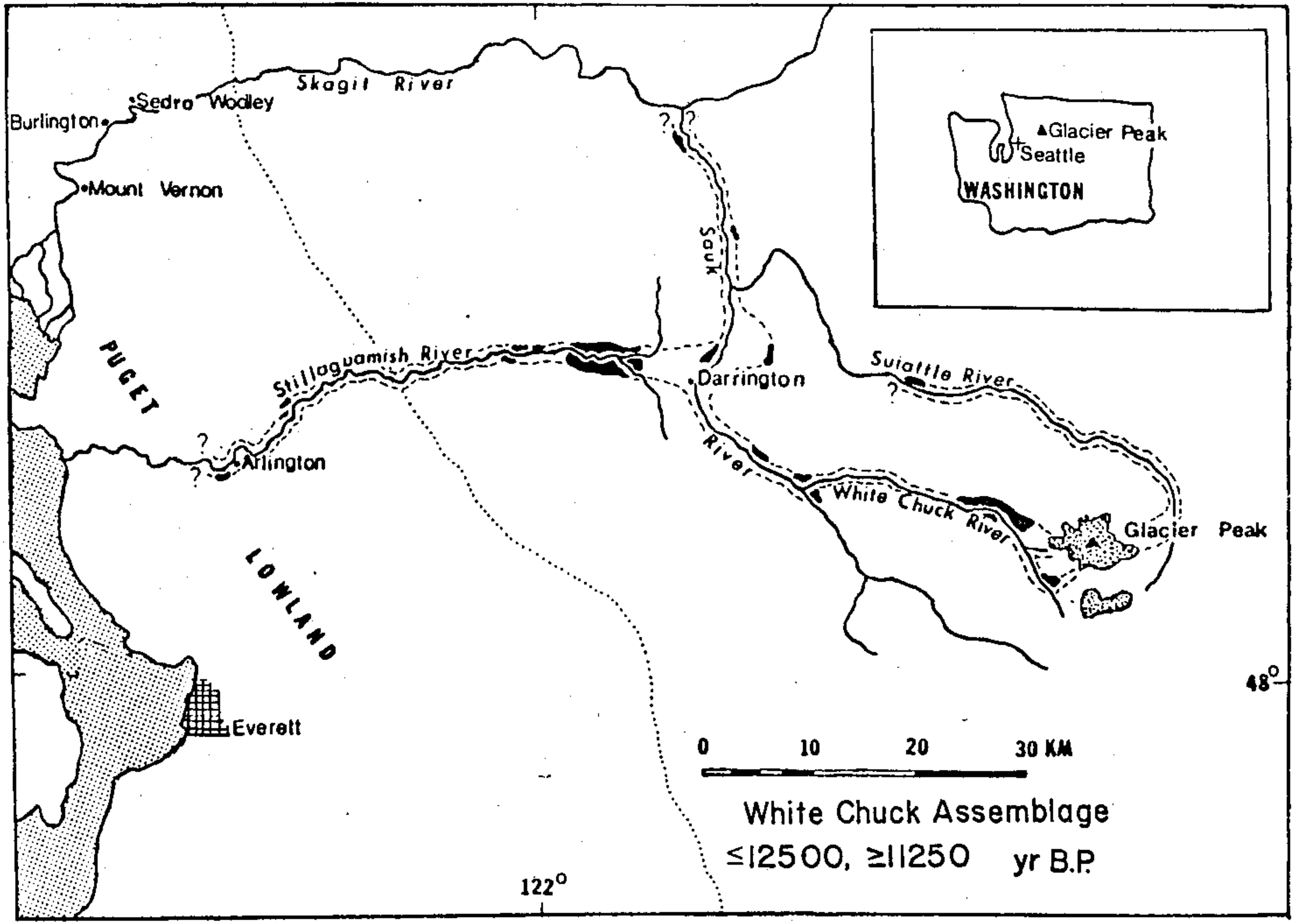


Figure 9.--Distribution of the White Chuck assemblage downstream from Glacier Peak. The solid pattern indicates remnants of the assemblage; its inferred original extent is indicated by the dashed line. Pyroclastic-flow deposits in this assemblage occur as much as 15 km downvalley from Glacier Peak in the White Chuck River valley. Lahars extend as far as 100 km downstream in the Stillaguamish River valley.

The age of part of the White Chuck assemblage is indicated by a lahar which forms a terrace above Little French Creek, 12 km west of Darrington (table 3). This lahar is as much as 3 m thick and contains gray to light-gray dacite which generally is only slightly vesiculated. This lahar overlies a soil which has a radiocarbon age of about 11,700 years (table 3). This is probably a close lower limiting age for the lahar and at least part of the White Chuck assemblage.

Measured section 6

[Stream cut along Little French Creek, 150 m north of State Highway 530, in the NE 1/4 sec. 10, T. 32 N., R. 8 E.]

	Thickness (m)
4. Lahar: subangular to subrounded cobbles and boulders as much as 0.6 m in diameter in a matrix of sand and silt; consists mainly of nonvesicular dacite	3.00
3. Forest duff: charcoal in a matrix of orange silt and clay; a sample of the charcoal had a radiocarbon age of 11,670±160 years	0.05
2. Silt: brown to purple, finely laminated	0.03
1. Pebble to boulder gravel: crossbedded and horizontally bedded; some sand lenses; beds typically pinch out laterally within several meters	10.00
Covered to river level	2.00

The vitric tuff in the White Chuck assemblage was first recognized by Ford (1959) and was described in detail by Tabor and Crowder (1969, p. 43-44). This unit is indurated and has well-developed columnar jointing as far as 15 km downstream from Glacier Peak in the White Chuck River valley. The joint columns are most commonly six-sided, and generally extend from the top almost to the bottom of the tuff. A thin zone at the base, ranging from 10 cm to a meter in thickness, is less well indurated and lacks jointing. This friable zone is preferentially eroded, and forms a reentrant at the base of the indurated tuff. Pumice lapilli are common in the tuff, but only occasionally show "fiamme" structure due to melting and collapse. The lapilli are not homogeneously distributed through the tuff, but are concentrated near the base. The largest pumice fragments, some of which are as much as 50 cm in diameter, occur in the upper parts of the flow. This reverse grading is more noticeable at some localities than at others. The tuff also contains 5-10 percent clasts of lithic dacite and a few percent of clasts of nonvolcanic rock that evidently were incorporated during transport. Pumice in the tuff contains primarily hornblende and hypersthene, with minor amounts of mica. The vitric tuff conformably overlies other flows in the White Chuck assemblage and so is thought to be no more than about 11,670 years old. The vitric tuff forms a caprock 3-8 m thick on terrace remnants of the White Chuck assemblage in the White Chuck River valley, and is responsible for the excellent preservation of the underlying volcanic deposits.

In outcrops near the end of the White Chuck River Road, about 15 km from Glacier Peak, the upper 1-2 m of the vitric tuff is brick red to pinkish red. This discoloration probably formed when the pyroclastic-flow deposit was cooling, and is thought to be diagnostic of a high temperature of emplacement (Crandell, 1980, p. 38-41).

In an outcrop (measured section 7) along the Mountain Loop Highway, about 30 km west of Glacier Peak, approximately 50 m above the confluence of the White Chuck and Sauk Rivers, pumiceous lahars as much as 3 m thick comprise the downvalley continuation of the White Chuck assemblage. These pumiceous lahars may represent a distal facies of the pyroclastic-flow deposits exposed nearer to the volcano. The lowermost lahars lack fragments of the vitric tuff, although tuff fragments are very common in lahars and alluvium that immediately overlie them. One lahar is reversely graded, and consists largely of gray to white pumice lapilli and bombs. The centers of the larger lapilli and bombs are strongly oxidized. Fragments of charcoal are present near the top of this deposit. Several large logs, which have not been charred, occur at the top of the lahar.

The vitric tuff in the White Chuck River valley is overlain by at least one thick lahar. This lahar can be recognized at many places, and as far downvalley as the confluence of the White Chuck and Sauk Rivers (measured section 7), 30 km from the volcano. This lahar contains large dacite clasts in a sandy matrix, as well as reworked blocks of the vitric tuff. Its age is not known, although it is younger than about 11,670 radiocarbon years old.

Lahars and alluvium rich in pumice, and containing reworked blocks of vitric tuff, comprise the uppermost part of the White Chuck assemblage near the volcano, and also underlie terraces as much as 70 km downstream. In particular, an area of several square kilometers at and west of the town of Darrington is underlain by up to 15 m of pumiceous alluvium interbedded with lahars. This material constitutes a broad valley fill that now forms a divide between the North Fork of the Stillaguamish River valley and the Sauk River valley. Isolated outcrops of pumiceous alluvium and lahars can be traced downvalley to a few kilometers west of Arlington, at least 100 km from the volcano.

The distribution of late-glacial volcanic deposits of the White Chuck assemblage in the Sauk, Skagit, and Stillaguamish River valleys indicates that a major drainage change was caused by the volcanic eruptions at Glacier Peak. As first noted by Vance (1957), the Sauk River aggraded in response to the rock debris contributed to it by the eruptions at Glacier Peak. Near the present site of Darrington, the Sauk River apparently shifted between flowing westward down the North Fork of the Stillaguamish River, and draining northward to the Skagit River. At the conclusion of these eruptions, valley fills composed of lahars and volcanic alluvium must have extended down both valleys for many kilometers. Some lahars may have reached the late Pleistocene shoreline of Puget Sound along one or both valleys. Outcrops of pumiceous lahars have not yet been recognized in the Skagit River valley. In all, these valley fills originally contained an estimated minimum volume of 10 km^3. At the end of this eruptive period, the Sauk River became entrenched in its present northward course to the Skagit River, leaving the underfit North Fork of the Stillaguamish River to drain the valley west of Darrington.

Measured section 7

[Borrow pit along Mountain Loop Highway, in SW 1/4 sec. 13, T. 31 N., R. 10 E.]

	Thickness (m)
13. Alluvium, thin sand and silt beds, horizontally stratified and interbedded with pumice-bearing lahars; contains blocks as much as 0.3 m in diameter of the vitric tuff........	4.0
12. Lahar: sandy-silty matrix; no apparent sorting or stratification; contains rare blocks of vitric tuff..........	2.0
11. Lahar: pumiceous clasts in silty sand ash matrix; reversely graded; contains white to gray pumice lapilli; contains charcoal fragments near top; abundant unburned logs in upper 0.5 m (11,500 years; W-4616); may be correlative with the vitric tuff in the White Chuck River valley........	2.0-3.0
10. Silty alluvium: crossbedded, crystal-rich fine ash............	0.1-1.0
9. Lahar: pumice lapilli in fine sand matrix; light gray.........	1.0
8. Lahar; pumice lapilli in sand and granule matrix; light gray...	2.5
7. Lahar: pumice lapilli in fine sand matrix; light gray to gray........	>3.0
Covered........	5.0
6. Lahar: angular to subrounded pumice pebbles and cobbles in a light-gray matrix of ashy sand and silt; has zones which show horizontal planar structures which suggest bedding, contains layers of openwork pumice lapilli a few centimeters thick........	>4.0
5. Alluvium: openwork pumice bed; gray to yellow pumice gravel....	
4. Alluvium: fine to medium sand and pumice fragments............	0.3
3. Alluvium: openwork pumice gravel........	0.3
2. Alluvium: fine sand to silt, gray........	0.1
1. Lahar: angular to subrounded pebbles and cobbles of nonvesicular dacite in matrix of silt and sand; purplish gray, oxidized to light yellow orange in upper 1 m; contains rare prismatically jointed blocks in lower part; normally graded........	>2.5

Clayey lahar younger than the White Chuck assemblage

The next younger deposit on the west side of Glacier Peak is a clayey lahar. This lahar is exposed along the White Chuck River in landslide scars upstream from Kennedy Hot Springs, where it locally reaches 8 m in thickness. It is also exposed in an outcrop 100 m above the White Chuck River near the mouth of Pumice Creek, and it is about 15 m thick in exposures along the White Chuck River trail, 10 km downstream from Glacier Peak (fig. 10). This lahar contains blocks of the vitric tuff, and is exposed along the White Chuck River at heights of more than 100 m below the terraces capped by the vitric tuff. This indicates that the river had deeply entrenched the valley fill formed by the White Chuck assemblage before the clayey lahar occurred.

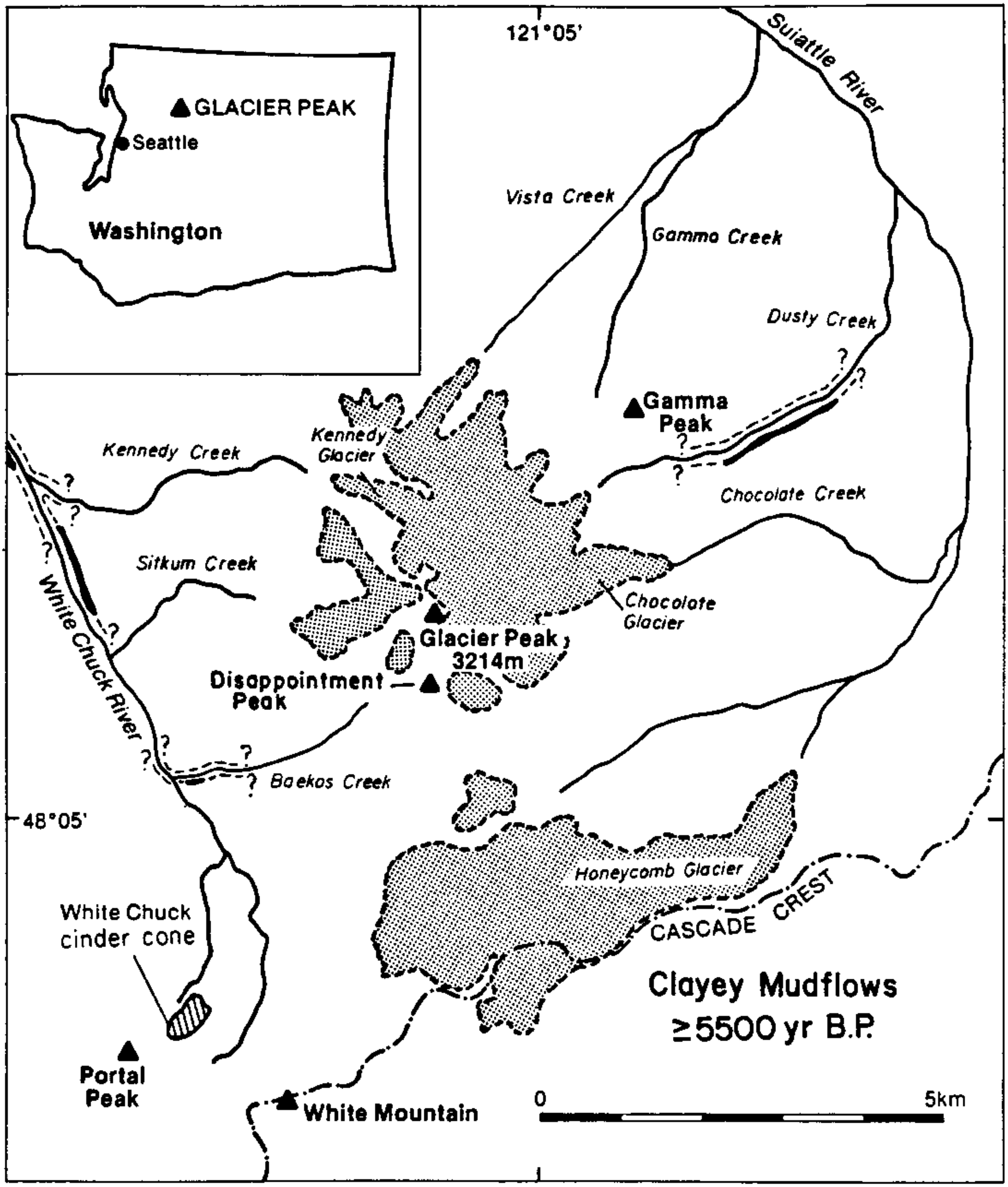


Figure 10.--Distribution and inferred former extent of a clayey mudflow in the White Chuck River valley. Preserved deposits of the mudflow are indicated by the solid pattern, its inferred original extent is shown by the dashed-line border. Similar clayey mudflows along Baekos and Dusty Creeks, which may be about the same age, are also shown.

This lahar consists of dacite clasts as much as 0.5 m in diameter in an unsorted matrix of sand, silt, and clay. The matrix is light brown to yellowish brown, and generally contains lenses of orange to reddish-orange plastic clay. This clay is commonly present between or around cobbles. In one area an indurated horizon, as much as 20 cm thick, can be traced for 100 m along a landslide scar near the top of this lahar. This indurated horizon seems to be the result of iron-oxide cementation of the lahar matrix, and may record a former water-table level within the lahar.

The clayey lahar is stratigraphically older than a deposit from which a radiocarbon date of about 5,500 years has been obtained (table 3, W-4214). This lahar may also be about the same age as a similar lahar in the Dusty Creek valley east of the volcano, which is in a similar stratigraphic position.

The clayey lahar in the White Chuck River valley is estimated to have had a volume of about 10 million m^3 and is known to have extended at least 10 km downstream from the volcano.

Kennedy Creek assemblage

The next younger group of deposits on the west side of Glacier Peak consists of a thick sequence of lacustrine deposits, alluvium, pyroclastic-flow deposits, and lahars. These deposits are referred to here collectively as the Kennedy Creek assemblage. The assemblage contains abundant clasts of nonvesicular, gray, hypersthene-hornblende dacite. Minor amounts of olivine are also present in some samples. Banded dacites, consisting of alternating layers of frothy light-gray to white rock and darker gray nonvesicular dacite, are present in some lahars and pyroclastic flows. Reworked fragments of the vitric tuff are a minor constitutent of some deposits in the asssemblage. Rounded pumice lapilli that occur in some of these deposits are probably also reworked. These deposits resulted when pyroclastic flows and lahars moved down Kennedy Creek, intermittently damming the White Chuck River. The deposits built a fan that extends 5 km upstream in the White Chuck valley, and underlie terraces that extend as much as 100 km downstream in the White Chuck, Sauk, and Skagit River valleys (figs. 11, 12). The fan deposits are at least 130 m thick where they are trenched by Kennedy Creek and the White Chuck River near Kennedy Hot Springs, and correlative deposits are at least 12 m thick at the mouth of the White Chuck River, 30 km from Glacier Peak (measured section 8).

The Kennedy Creek assemblage upstream from Kennedy Hot Springs is exposed in three landslide scars along the White Chuck River. It is not possible to trace individual deposits from one landslide scar to the next, as the scars are 0.5-1.0 km apart, and separated by dense forest.

The oldest deposits in the Kennedy Creek assemblage consist of at least two pyroclastic flows. These deposits contain white to gray (7.5P 8/1-HN 9/0) pumice lapilli and dark-gray nonvesicular dacite clasts in a sand and silt matrix. Lithologically similar lahars which occur near the base of the Kennedy Creek assemblage in exposures about 10 km downstream from Glacier Peak probably were derived from these pyroclastic flows, or produced at the same time.

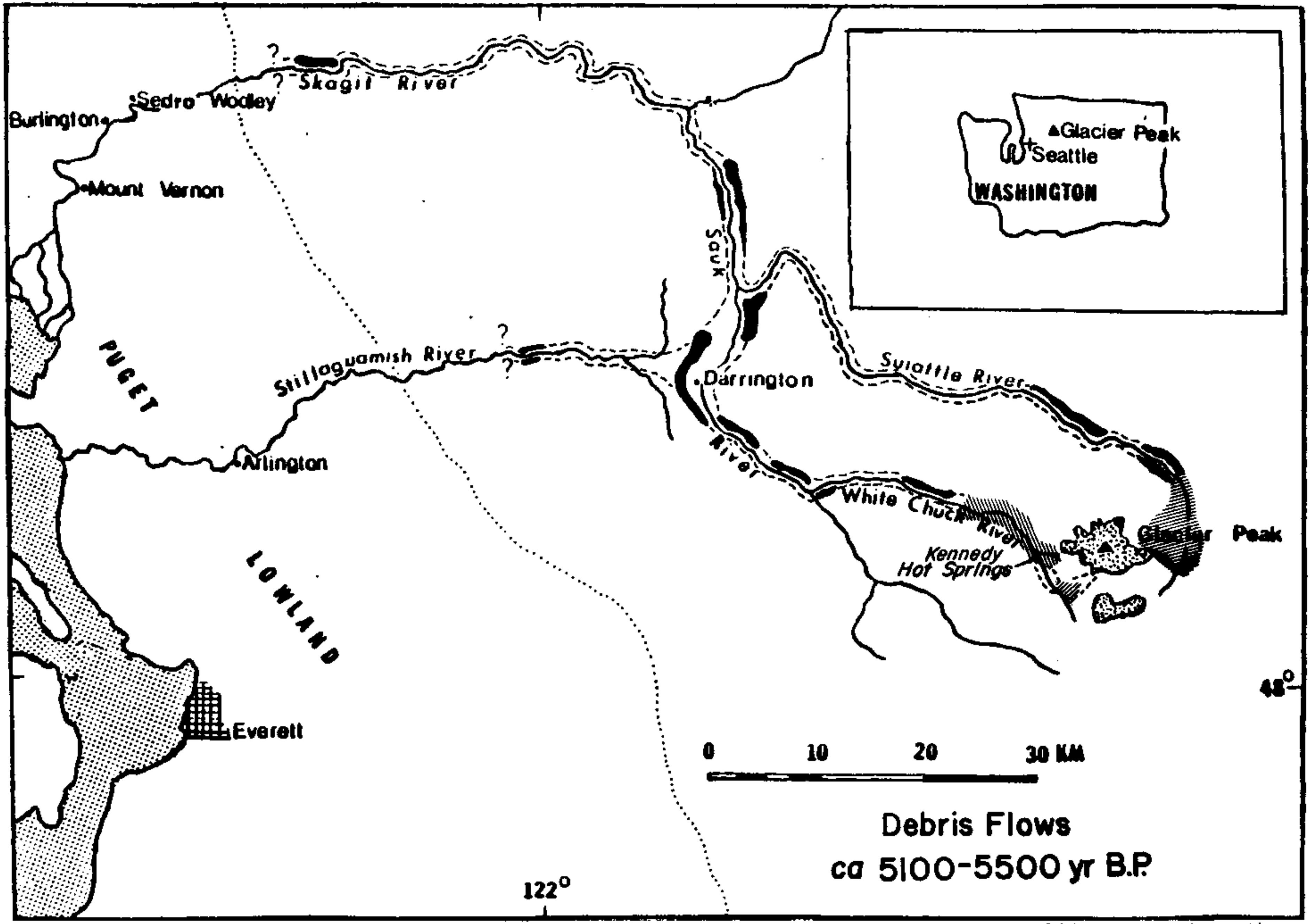


Figure 11.--Distribution and inferred former extent of the Kennedy Creek assemblage. The solid pattern shows the distribution of lahars preserved downvalley from the volcano. The line pattern shows the distribution of fans of pyroclastic debris on the flanks of Glacier Peak produced during eruptions of dacite domes at the volcano. The inferred original extent of the Kennedy Creek assemblage is indicated by the dashed line. Also shown is the extent of the Dusty Creek assemblage on the east side of the volcano, which may be the same age as the Kennedy Creek assemblage.

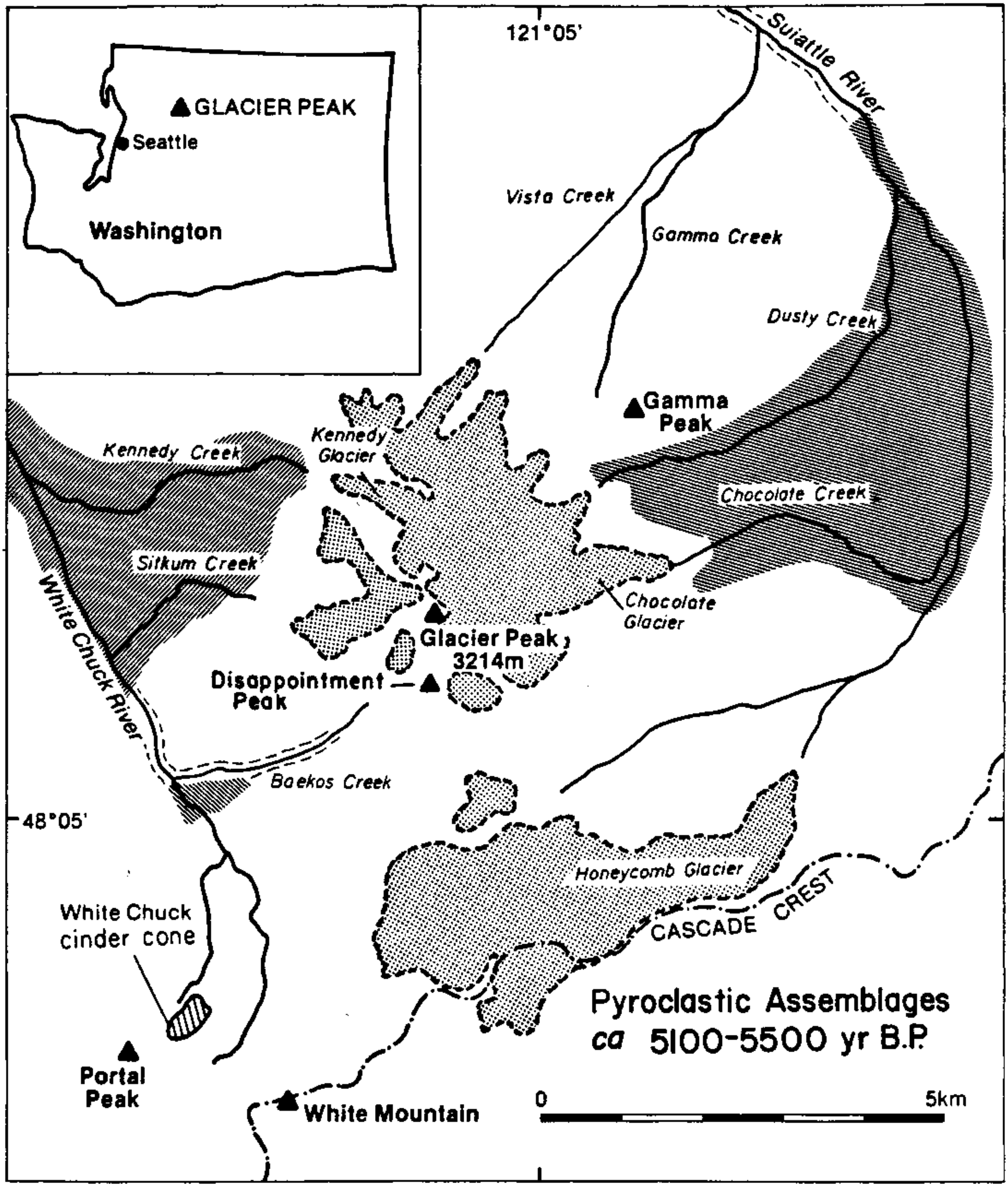


Figure 12.--Extent of pyroclastic-debris fans of the Kennedy Creek and Dusty Creek assemblages. Note the backfills in the upper White Chuck and Suiattle River valleys. Both debris fans postdate the deposition of tephra layer O and predate tephra layer Yn. The smaller Baekos Creek fan, which is in the same stratigraphic position with respect to tephra layers, is also shown.

Measured section 8

[Roadcut on logging road, east of the Mountain Loop Highway, in NE 1/4 sec. 14, T. 31 N., R. 10 E.]

	Thickness (m)
11. Lahar: subangular to subrounded pebbles and cobbles of dacite in a sand matrix; no apparent sorting or stratification; dark gray	1.0
10. Lahar: subangular to subrounded pebbles and cobbles in a sand and granule matrix; reversely graded	1.6
9. Sand, fine: dacitic; locally crossbedded; contains lenses of reworked pumice	1.7
8. Lahar: subangular to subrounded pebbles and cobbles in a fine granule matrix; normally graded; upper 10 cm consists of fine sand	1.5
7. Sand, medium: dacitic, locally crossbedded	0.2-0.4
6. Lahar: subrounded to subangular clasts as large as 5 cm in a matrix of medium sand	0.7
5. Sand: fine to medium, lenticular, as thick as	0.2
4. Lahar: lithologically similar to unit 6	0.5
3. Sand: fine sand and silt, dacitic, contains scattered charcoal fragments	0.4
2. Lahar: subangular to subrounded cobbles and boulders as large as 70 cm in diameter; sand matrix; normally graded	2.0
1. Lahar: lithologically similar to unit 6	4.0
Covered to river level	4.0

Lacustrine deposits as much as 3 m thick, interbedded with layers of forest duff, occur from 1 to 3 km upstream from Kennedy Hot Springs along the White Chuck River (see fig. 17). In several places these lacustrine deposits and duff layers contain charred logs. Dating of a log from the base of the lacustrine deposits yielded a radiocarbon age of about 5,500 years (table 3, W-4214). This suggests that eruptions at Glacier Peak started at about this time. A charred log from a pyroclastic flow well above the lacustrine deposits yielded a radiocarbon date of about 5,100 years (table 3, W-4275), suggesting that volcanism continued for some time and that the Kennedy Creek assemblage may be composite and include deposits produced during more than one eruptive period.

This interpretation is consistent with the complexity of the lacustrine record in the upper White Chuck valley. At one locality (measured section 9) five separate duff and soil layers are interbedded with the lacustrine deposits. This suggests that the White Chuck River was dammed at least five times. Some lahars in the Kennedy Creek assemblage downvalley from Kennedy Creek possibly were produced as a result of rapid draining of the intermittent lakes impounded by the volcanic fan in the White Chuck valley.

Measured section 9

[Large landslide scar along the White Chuck River, approximately 1 km upstream from Kennedy Hot Springs]

	Thickness (m)
9. Kennedy Creek assemblage: at least 26 pyroclastic-flow deposits and lahars consisting of angular to subrounded gray dacite in a loose sand matrix; flow units evenly bedded 1-4 m thick; some minor sand lenses; contains blocks as much as 5 m in diameter; some deposits contain completely carbonized logs; as thick as........................	100
8. Silt and clay: finely laminated, contains at least five layers of forest duff, 2-10 cm thick; some duff layers contain charred branches; also contains lenses of pumice; as thick as..	10
7. Pyroclastic-flow deposit: light-gray and white pumice and gray dacite in a brownish-yellow (7.5YR 6/8) ash matrix; contains prismatically jointed blocks, charcoal, and blocks as much as 0.5 m in diameter..........................	2
6. Silt and clay: finely laminated, contains a log with a charred exterior and lenses of pumice.........................	3
5. Pyroclastic-flow deposit: lithologically similar to unit 7.....	3
4. Silt and clay: finely laminated, contains a charred log 10 cm in diameter, 5,520±250 years old (W-4214)..............	2
3. Duff, mostly charred, contains charred logs.....................	1
2. Sand, medium: mostly horizontally stratified but also crossbedded; mostly yellow or brownish yellow; contains some altered lithic fragments................................	10
1. Lahar: altered dacite clasts as much as 0.7 m in diameter in a matrix of sand, silt, and plastic clay; more than........	6

Covered interval of 5 m to river

A thick sequence of lahars, pyroclastic-flow deposits, and ash-cloud deposits is exposed above the lacustrine silts in the landslide scars. At least 23 separate flowage deposits, ranging from 1 to 4 m in thickness, are present in one section. These deposits contain abundant prismatically jointed dacite blocks, and incorporated logs are completely charred. Determinations of remanent magnetism for 10 clasts in each of several flows indicated that most were above the Curie temperature when they came to rest. The total number of pyroclastic-flow deposits in the Kennedy Creek assemblage probably exceeds the 23 exposed in this section.

The volume of the fan of volcanic debris in the upper White Chuck valley is about 1 km^3, and the total original volume of the Kennedy Creek assemblage, including the valley fills that extend far downvalley, is estimated to be 2-3 km^3. Part of the Kennedy Creek assemblage is represented by lahars and alluvium at Minkler Lake in the Skagit River valley, 100 km from Glacier Peak. A 3-m-thick terrace east of the lake is composed almost entirely of dacitic debris, and contains clasts as much as 20 cm in diameter that are mineralogically similar to rock fragments in the Kennedy Creek assemblage. The terrace east of Minkler Lake can be traced for several kilometers up the Skagit River.

Deposits younger than the Kennedy Creek assemblage

Thick conformable sequences containing lahars and alluvium were deposited in valleys west of Glacier Peak at least five times since about 5,500-5,100 years ago (fig. 14). These sequences locally overlie or form fills within the valleys cut into high terraces formed by deposits of the Kennedy Creek assemblage.

Two assemblages of lahars are exposed in a cutbank along the White Chuck River near Crystal Creek. The older assemblage is about 2,800 years old, and the younger is about 1,750 radiocarbon years old (table 3, W-4266, W-4262). Each assemblage includes at least three lahars (measured section 10). Both assemblages extend at least 20 km downstream from Glacier Peak. It is not possible to distinguish these assemblages from one another in outcrops, as they are lithologically similar and rocks in them contain the same Fe-Mg minerals. The 1,750-year-old assemblage is tentatively correlated with a terrace deposit of dacite-rich alluvium which underlies the town of Burlington and which contains charcoal about 1,800 radiocarbon years old (Dave Dethier, oral commun., 1980). Both assemblages are estimated to have volumes on the order of 100 million m^3. However, if the 1,750-year-old assemblage is correlative with deposits beneath the terrace near Burlington, the volume of material erupted by Glacier Peak at this time may have been much greater than 100 million m^3.

Measured section 10

[Stream cut along the White Chuck River, approximately 2 km west of the Kennedy Hot Springs trailhead, and approximately 0.5 km west of the confluence of Owl Creek and the White Chuck River]

	Thickness (m)
10. Lahar: subangular to subrounded pebbles and cobbles in a reddish-gray sand matrix; almost all clasts are oxidized and red..........	1.0
Erosional unconformity	
9. Lahar: angular to subrounded pebbles and cobbles in a matrix of medium to fine sand; some clasts are stained by iron oxides..........	1.0
8. Lahar: angular to subrounded pebbles and cobbles in a matrix of medium to fine sand; normally graded..........	1.0
7. Lahar: subrounded to subangular pebbles and cobbles in a matrix of medium to fine sand; contains logs and wood fragments about 1,750 radiocarbon years old (W-4262)..........	1.0
6. Sand and pebble gravel, contains lenticular layer of open-work gravel; horizontally bedded..........	1.5
5. Forest duff, contains bits of charcoal; silty and sandy..........	0.1
4. Lahar: subangular to subrounded pebbles and cobbles in a medium to fine sand matrix..........	0.8
3. Lahar: lithologically similar to unit 4..........	1.5
2. Lahar: subangular to subrounded pebbles, cobbles, and boulders as much as 50 cm in diameter in a medium to fine sand matrix; contains logs and wood fragments, 2,800 years old (W-4266)....	2.0
1. Compact till, gray (2.5Y 4/0)..........	5.0

A single lahar that contains abundant highly oxidized clasts and has a distinctive red (7.5R 5/3) matrix overlies the 1,750-year-old lahars at measured section 10. This lahar reached at least 30 km downstream from Glacier Peak (fig. 13). It is exposed at many places along the White Chuck River, and is found upstream from Kennedy Hot Springs, suggesting that the lahar originated on the south side of Glacier Peak. Many of the clasts in this lahar are hypersthene-oxyhornblende dacites and resemble the predominant rock type of Disappointment Peak on Glacier Peak (Tabor and Crowder, 1969, p. 24). This suggests that this lahar may consist largely of rocks derived from Disappointment Peak. The lahar generally veneers terraces at heights of 10-20 m above the White Chuck River, but it crops out near river level near Kennedy Hot Springs. This suggests that a trench had been cut into older lahars and laharic valley fills before this lahar occurred, and that some of the higher remnants of this lahar where it caps older terraces may represent veneers left during its passage downstream. This lahar is less than 1,750 years old and is older than a mature forest, containing trees hundreds of years old, which is growing on top of it. This lahar is commonly 1-2 m thick and is estimated to have involved approximately 75,000 m^3 of debris.

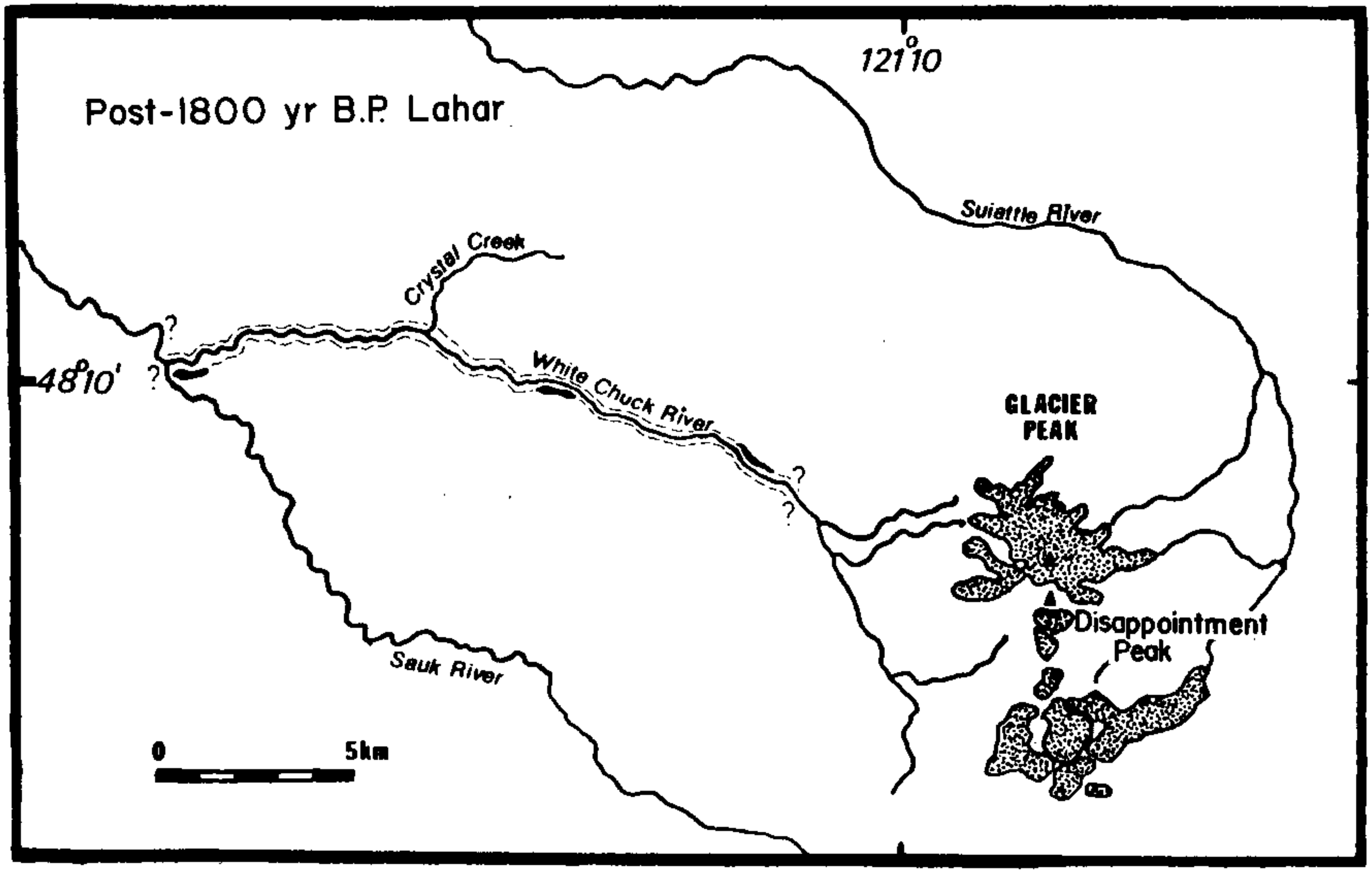


Figure 13.--Distribution (solid pattern) and inferred former extent (dashed lines) of the post-1,750-year-old "red" lahar, which consists mainly of oxidized oxyhornblende dacite clasts similar to the rocks of Disappointment Peak.

A younger lahar assemblage forms fill terraces within a valley cut into higher, older fill that is capped by the red lahar. This youngest lahar assemblage in the White Chuck River valley is therefore younger than the red lahar. The assemblage is older than a mature forest which is now growing on it. The lahars contain clasts of gray oxyhornblende-hornblende-hypersthene dacite and have a total thickness of about 8 m at the confluence of the White Chuck and Sauk Rivers (fig. 14), where there are at least five lahars (measured section 11). One of the lahars contains boulders as much as 3 m in diameter. The assemblage is preserved in numerous low terraces along the White Chuck River, and reaches a maximum thickness of 20 m near the mouth of Pumice Creek (fig. 15). These deposits are remnants of a valley fill whose estimated original volume was about 1 million m^3.

A lahar forms a low terrace just south of the confluence of the Sauk and White Chuck Rivers. Associated with this lahar is a remarkable flood deposit. Large foreset beds, as much as 2 m thick, dip upstream relative to the Sauk River. The foreset beds are generally 10-30 cm thick and contain cobbles as large as 30 cm in diameter. These beds are moderately well sorted, and openwork is common. This deposit resembles openwork foreset gravel in flood deposits in the channeled scablands of eastern Washington (Bretz, 1928; Baker, 1973).

The flood gravel is composed of approximately 60 percent of rock types derived from Glacier Peak, and the remainder consists of other crystalline rocks from the upper White Chuck valley. The composition of the gravel and the orientation of the large foreset beds clearly indicate that the flood came down the White Chuck River valley, and built a fan which prograded up the Sauk River valley. The low terrace underlain by these flood deposits extends more than 50 m upstream from the present mouth of the White Chuck River.

The flood deposits are overlain by a sandy lahar which is only 1-2 m thick. This lahar contains clasts as much as 0.5 m in diameter. A weak soil, represented by 10-20 cm of oxidation below a few centimeters of forest duff, is present on this lahar. The top of the lahar is only 3-4 m above the White Chuck River. The flood deposit and the lahar are clearly younger than the lahars that are about 1,750 years old. The forest growing on this terrace was logged many years ago, but trees as old as 300 years were growing on the terrace when they were cut, indicating that the flood deposits and the lahar are at least that old. The flood deposit could have been formed by a glacier-outburst flood or produced in some way by volcanic activity at Glacier Peak. No other evidence of volcanic eruptions has been found during the time interval within which this flood occurred.

A small rockfall deposit composed of boulders ranging from 0.5 to 5 m in diameter, and consisting largely of rock types present in cliffs below Kennedy Peak and above Kennedy Glacier, extends about 4 km down the Kennedy Creek valley from the present terminus of Kennedy Glacier. The deposit is unvegetated, and is no more than a few hundred years old. Much of the deposit has been overrun and reworked by the most recent advance of the Kennedy and Scimitar Glaciers. Trees growing on till deposited by these glaciers are as much as 90 years old, indicating that this rockfall is at least that old.

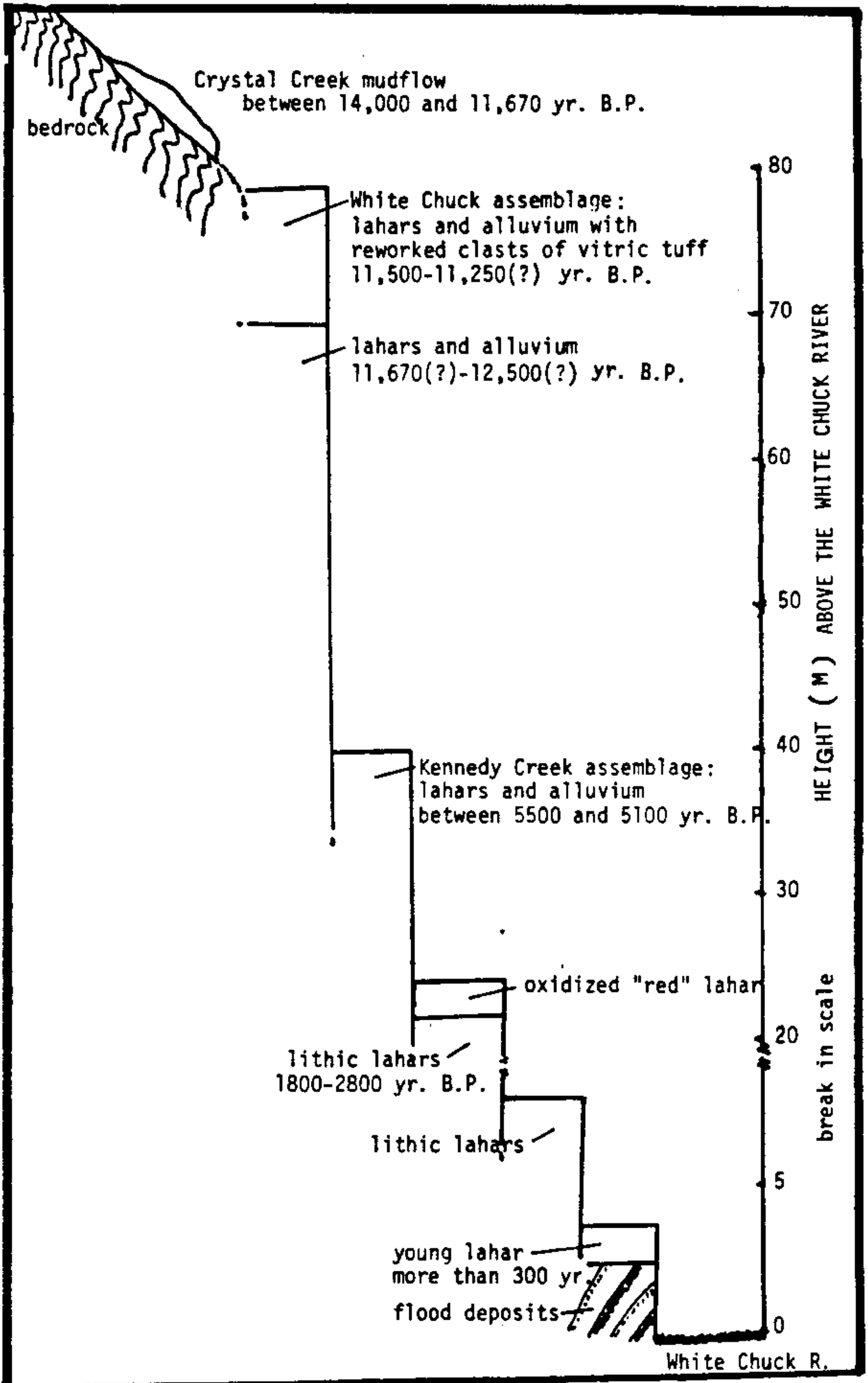


Figure 14.--Composite section of lahars and lahar assemblages near the confluence of the White Chuck and Sauk Rivers.

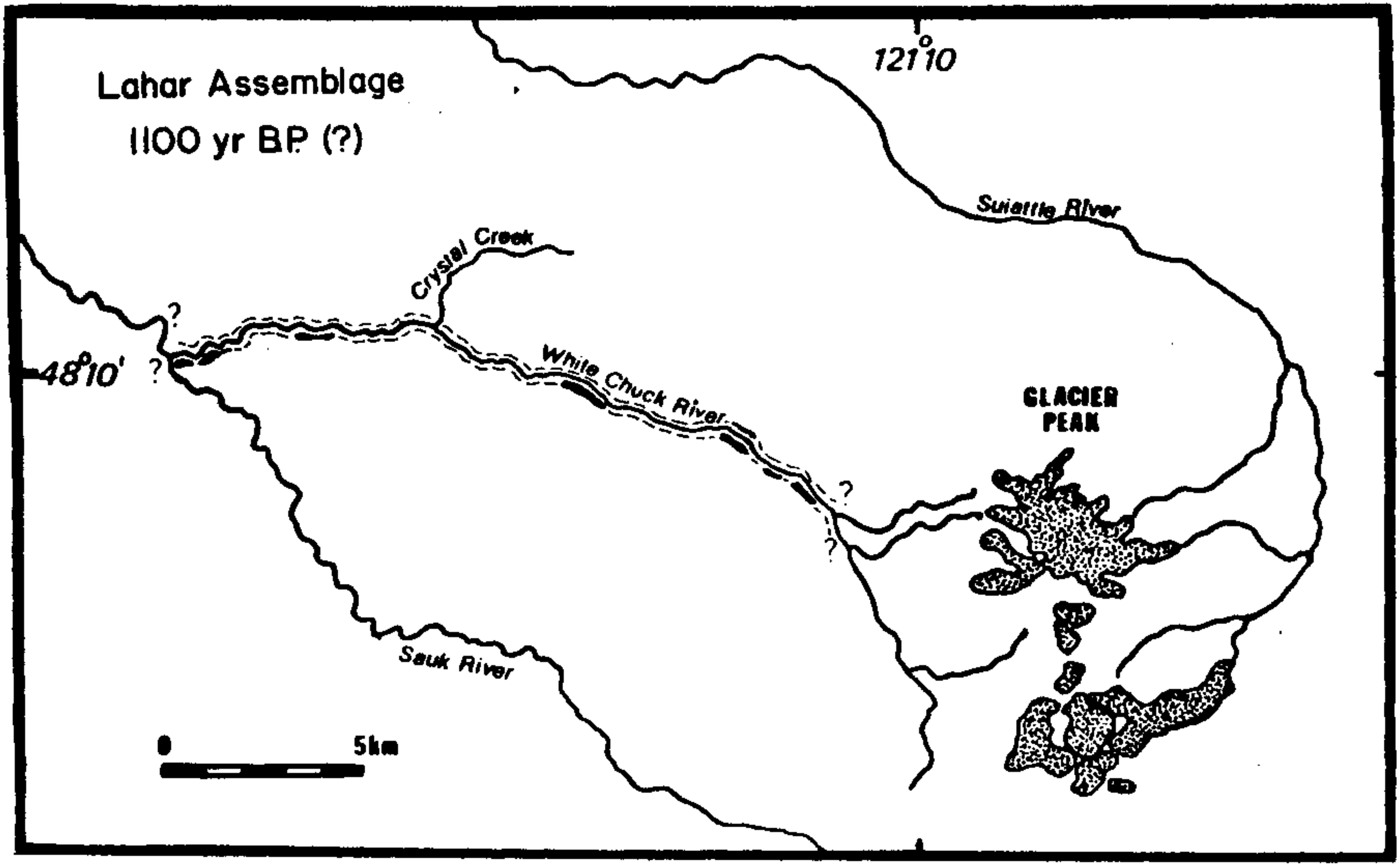


Figure 15.--Distribution and inferred former extent of a lahar assemblage in the White Chuck River valley that is less than 1,750 years old. Preserved remnants of the assemblage are indicated by the solid pattern; the inferred original extent is shown by the dashed line.

Measured section 11

[Borrow pit southeast of Sauk River bridge, in the SE 1/4 sec. 14, T. 31 N., R. 10 E.]

	Thickness (m)
6. Lahar: subangular to subrounded pebbles as much as 5 cm in diameter in a matrix of fine to medium sand; normally graded; 30-50 percent of the clasts are iron stained..........	1.0
5. Lahar: subangular to subrounded pebbles and cobbles as much as 8 cm in diameter, in a matrix of fine to medium sand; normally graded; lenticular; basal contact is wavy; as much as..	1.5
4. Sand, fine to medium, crossbedded, and openwork pebble gravel...	1.5
3. Lahar: subangular to subrounded pebbles as much as 5 cm in diameter in a matrix of sand and granules; normally graded; 1.5 percent of the clasts consist of the local bedrock........	1.7
2. Lahar: subangular to subrounded pebbles as much as 5 cm in diameter in a matrix of sand and granules; no apparent sorting or stratification....................................	>3.0
1. Lahar: boulders and cobbles in a matrix of gray medium to coarse sand; lenticular; clasts as much as 3 m in diameter; about 30 percent of the clasts are of local bedrock...........	>5.0
Covered interval of 5 m to river level	

Lahars and glacier-outburst floods have repeatedly occurred in Kennedy Creek and the White Chuck River during the last several centuries. In early 1975, an outburst flood in Kennedy Creek damaged trails as far as 8 km downstream from Kennedy Glacier. In addition, about 1 km^2 of forest was partially buried and killed in the vicinity of Kennedy Hot Springs. This outburst flood also deposited logs and sediment that is locally more than 2 m thick on the easternmost side of the campground at Kennedy Hot Springs.

FLOWAGE DEPOSITS IN THE VALLEY OF BAEKOS CREEK

Baekos Creek originates in a small, unnamed glacier on the southwest side of Glacier Peak below Disappointment Peak. The creek joins the White Chuck River approximately 5 km from Glacier Peak and about 4 km above the White Chuck River and Kennedy Creek confluence (fig. 2).

The oldest postglacial volcanic deposits in the valley of Baekos Creek are pumiceous pyroclastic-flow deposits and lahars. These deposits are best seen in a stream cut about 0.5 km west of the Pacific Crest Trail crossing of Baekos Creek. The pyroclastic-flow deposits and lahars underlie a wedge-shaped fan north of Baekos Creek and east of the White Chuck River which covers an area of about 2 km^2. This fan is probably a remnant of a formerly larger valley fill which may have merged downvalley with the White Chuck assemblage. The deposits that underlie the fan are at least 20 m thick near Baekos Creek. They consist largely of pumice, but light-gray dacite and occasional clasts of nonvolcanic rock are also present. These lahars are inferred to be of late Pleistocene age. They are overlain by tephra layer O but are not overlain by any of the Glacier Peak tephra layers of late Pleistocene age. In addition, the lithology of these deposits is identical to that of other late Pleistocene volcanic deposits at Glacier Peak. Lahars in this fan may consist partly of material reworked from late Pleistocene tephra deposits, as they consist largely of fresh, subrounded pumice lapilli (measured section 12).

Measured section 12

[Locality at approximately 3,900-ft altitude, exposed in stream cut on the north side of Baekos Creek, approximately 0.5 km west of the Pacific Crest Trail crossing of Baekos Creek]

	Thickness (m)
7. Sandy silt, gray, finely laminated; as much as	1.5
6. Tephra layer O, as thick as	0.1
5. Pyroclastic-flow deposit: light to medium gray; pumiceous-ash matrix; rock fragments mostly white to light-yellow pumice as much as 0.8 m in diameter; also contains light-gray nonvesicular dacite; reversely graded	3.0
4. Pyroclastic-flow deposit: lithologically similar to unit 5	2.0
3. Lahar: rock fragments mostly dacite with some pumice in a gray, pumiceous matrix; clasts are subangular to subrounded and as much as 25 cm in diameter; unstratified	2.0
2. Sand and silt: white to gray, horizontally bedded	1.0
1. Lahar: lithologically similar to unit 3, contains boulders as much as 1 m in diameter	>2.0
Covered to river level	5.0

A clayey lahar is discontinuously exposed for approximately 50 m along the south bank of Baekos Creek, approximately 0.8 km east of the Pacific Crest Trail. This lahar partly filled a valley cut into the late Pleistocene deposits adjacent to Baekos Creek and is therefore younger. The lahar is as much as 3 m thick and consists of altered and stained dacite clasts as much as 2 m in diameter in a yellowish-brown, sandy to clayey matrix. The clay in the lahar commonly veneers boulders and pebbles, and is quite plastic. This lahar may be correlative with a similar clayey mudflow which occurs several kilometers downstream along the White Chuck River (p. 31; also see fig. 10).

A valley fill of pyroclastic-flow deposits and lahars consisting of light- to dark-gray dacite is preserved in a fan west and south of Baekos Creek. These deposits are exposed only in shallow trail cuts. This fan is older than tephra layer Yn, but tephra layer O was not found anywhere on the fan surface. Rocks from these deposits resemble those in the Kennedy Creek assemblage (table 4). This resemblance, together with similar stratigraphic relationships to tephra deposits of known age, suggests that the fan is correlative with at least part of the voluminous Kennedy Creek assemblage. The top of the fan is a remnant of the surface of a former valley fill, and slopes upstream into the upper White Chuck valley. The fan surface extends approximately 1 km up the valley, indicating backfilling of the White Chuck valley from Baekos Creek for at least this distance. The top of this valley-fill remnant is as much as 25 m above the White Chuck River. Intermittent lakes may have formed in the White Chuck valley behind the fan of rock debris.

A series of pyroclastic-flow deposits interbedded with alluvium is exposed just below the confluence of the unnamed stream that drains Baekos Pass and Baekos Creek, where at least six pyroclastic-flow deposits can be seen in a section 20 m thick. These flowage deposits contain prismatically jointed blocks in an ash matrix. TRM determinations of clasts from two of these flows were made with a portable fluxgate magnetometer. In both flows the TRM directions of measured clasts coincided with the present geomagnetic field, indicating they were above the blocking temperature when they came to rest, and that the flows were hot. Tephra layers Yn and O were not found on the surface of the valley fill underlain by these flows. Oxyhornblende-bearing dacite is a major constituent of these pyroclastic-flow deposits, but is absent from deposits at the mouth of Baekos Creek (table 4). This suggests that these deposits are of different ages. The pyroclastic-flow deposits in upper Baekos Creek are younger than tephra layer Yn and thus are younger than about 3,400 years old, but they predate trees several hundred years old.

Several lahars have traveled down Baekos Creek during the last few hundred years. Some may have originated as outburst floods from the glacier at the head of the valley. At the mouth of Baekos Creek a lahar as much as 3 m thick that contains boulders as much as 2 m in diameter has trees growing on it that are more than 250 years old. Other smaller lahars are preserved in terraces along Baekos Creek. Trees growing on two of these terraces are more than 142 and 169 years old, respectively, suggesting that at least two lahars reached as far as 5 km from Glacier Peak between 100 and 200 years ago. Unvegetated lahars at the mouth of Baekos Creek and at several places upstream suggest that a small glacier-outburst flood occurred within the last decade or so. It was not possible to trace any of these lahars from the mouth of Baekos Creek down the White Chuck River.

FLOWAGE DEPOSITS IN THE VALLEYS OF DUSTY CREEK AND THE SUIATTLE RIVER

Dusty Creek originates in the Dusty and North Guardian Glaciers on the east side of Glacier Peak. The creek joins the Suiattle River about 8 km from the glaciers. It has cut a remarkable gorge known as "Multicolor Canyon" (Becky and Rands, 1977) into a thick section of volcanic deposits on the east side of Glacier Peak. The maximum depth of the canyon is more than 300 m.

Clayey lahar in Dusty Creek valley

The oldest postglacial deposit preserved in the upper valley of Dusty Creek consists of a lahar which crops out near the floor of the canyon between 5 and 7 km from the Dusty Glacier. This lahar is up to 30 m thick and consists of subangular to subrounded altered and oxidized clasts of dacite as much as 2 m in diameter in a red to yellowish-brown matrix of sand and clay. In places, this lahar exhibits normal grading. Rocks from Glacier Peak make up over 90 percent of the clasts in this lahar, with highly altered volcanic rocks from Gamma Ridge and assorted crystalline clasts constituting the rest. Plastic red clay coats many clasts and fills the interstices between pebbles and cobbles. This clay is probably a product of hydrothermal alteration of volcanic rocks by fumarolic activity on Glacier Peak. The estimated original volume of this lahar along Dusty Creek is on the order of a million cubic meters. The clayey lahar is lithologically similar to large mudflows exposed in Baekos Creek and along the White Chuck River (fig. 10) and is in the same stratigraphic position with relation to tephra deposits of known age. This suggests that this lahar may be about the same age as other clayey mudflows exposed on the west side of Glacier Peak (p. 31).

Dusty assemblage

Postdating the clayey lahar is a voluminous assemblage of deposits of pyroclastic flows, hot and cold lahars, ash clouds, and alluvium. Some lacustrine deposits are also interbedded in this assemblage. This unit includes most of what was previously referred to as the Suiattle fill (Tabor and Crowder, 1969), and is referred to in the present report as the Dusty assemblage.

South of Gamma Peak the Dusty assemblage is more than 300 m thick and its base is not exposed. The part of the assemblage between Glacier Peak and Canyon Creek, 18 km downstream from the volcano, is estimated to have had an original volume of at least 10 km^3. Lahars of the Dusty assemblage can be traced at least 100 km down the Suiattle, Sauk, and Skagit River valleys, indicating that the original total volume of the assemblage was much greater than 10 km^3.

The Dusty assemblage is preserved in a wedge-shaped remnant of a valley fill on the east side of Glacier Peak, which heads at an altitude of 2134 m. The top of the fill is a flat, little dissected surface which slopes eastward away from Glacier Peak and descends to 900 m in only 9 km. The preserved fill is more than 7 km across at its broadest point between Dusty and Chocolate Creeks. The Dusty assemblage extended 3 km upstream into the upper Suiattle River valley. At least 10 m of finely laminated silts and clays, composed largely of volcanic ash, are exposed in stream cuts along the Suiattle River near the mouth of Chocolate Creek. These are thought to be lacustrine deposits formed when the Suiattle River was briefly dammed during the accumulation of the valley fill.

The Dusty assemblage is entrenched by Dusty Creek on the north and Chocolate Creek on the south. Deposits of the assemblage are well exposed in huge landslide scars, some of which are more than 100 m high. Along upper Dusty Creek, where the fill is more than 300 m thick, more than 50 separate depositional units are exposed in a single vertical section. These units typically are normally graded, and have regular and conformable contacts with overlying and underlying deposits. The individual deposits range from 2 to 10 m in thickness, and most are 2-5 m thick. It is possible to trace some units across exposures for a distance of nearly a kilometer, but most units thin and pinch out within shorter distances. This suggests that the assemblage contains many more than the 50 depositional units noted at its thickest point. Individual units within the valley fill dip 8°-12° eastward, an angle that closely approximates the slope of the surface of the Dusty assemblage; thus, this surface evidently is the uneroded top of the assemblage.

Individual deposits within the Dusty assemblage are diamictons that typically have a medium to very coarse sand-size lithic matrix consisting largely of angular glass shards, dacitic lithic grains, and fragments of hornblende, plagioclase, hypersthene and, rarely, olivine crystals (table 4). The larger clasts within the depositional units are commonly breadcrust bombs or prismatically jointed blocks consisting of diktytaxitic dacite. These deposits are thought to be the products of pyroclastic flows. This conclusion is supported by TRM measurements of 5-10 clasts within each of nine flows measured at three different localities. TRM directions of all these clasts were coincident with the geomagnetic field, indicating that clasts were above the blocking temperature and that the flows were hot when they came to rest (Hoblitt and Kellogg, 1979). Further evidence that at least the upper part of the Dusty assemblage includes pyroclastic-flow deposits is provided by the presence of a 1- to 2-m-thick zone of brick-red alteration at the top of the Dusty assemblage; this zone is exposed in many places near the upper apex of the fill. Such discoloration in coarse volcaniclastic deposits are thought to be diagnostic of high temperatures during deposition (Crandell and Mullineaux, 1973; Crandell, 1980).

Circumstantial evidence of the presence of pyroclastic flows in the Dusty assemblage is provided by the presence and distribution of finely laminated dacitic ash which mantles ridges north and south of the Dusty assemblage. This ash mantle is up to 3 m thick on Chocolate Ridge, 1 km south of the margin of the Dusty assemblage. The ash thins rapidly away from the border of the Dusty assemblage, and cannot be recognized at Buck Creek Pass (measured section 2), only 12 km east of the volcano. The restriction of the ash to areas adjacent to the Dusty assemblage is similar to that of deposits of ash-cloud origin at Mount St. Helens (Crandell and Mullineaux, 1973). The dacitic ash layers at Glacier Peak also are thought to be ash-cloud deposits, produced concomitantly with pyroclastic flows in the Dusty assemblage.

The ash-cloud deposits on Gamma Ridge are underlain by tephra layer O and overlain by tephra layer Yn. Layer Yn also has been recognized at several localities on the surface of the Dusty assemblage, but layer O has not been found on that surface. These relations suggest that the Dusty assemblage is between 6,700 and 3,400 years old. It is possible that the assemblage is about the same age as the Kennedy Creek assemblage on the west side of Glacier Peak. Both assemblages include dacitic pyroclastic flows in which rock types are mineralogically similar. If both valley fills were formed during the same eruptive period, the Dusty assemblage is about 5,500-5,100 years old.

Deposits younger than the Dusty assemblage

At least one younger assemblage of lahars and pyroclastic flows is present in the valley of Dusty Creek. These deposits form a terrace on the north bank of Dusty Creek, about 4 km below the terminus of Dusty Glacier. The top of this terrace at this point is about 100 m above Dusty Creek. Deposits beneath the terrace include at least 12 flow units interbedded with sandy alluvium and deposits of possible ash-cloud origin. The flow units are mixtures of angular to subrounded fragments of nonvesicular dacite as much as 2 m in diameter in a matrix of loose, gray sand. Prismatically jointed blocks are common. TRM measurements of six clasts from the lowermost flow unit indicated that the clasts were above their blocking temperatures when they were emplaced. This assemblage is not overlain by tephra layer Yn, but is older than a mature forest growing on its top.

At least two clayey lahars underlie a low terrace along a section of upper Dusty Creek. The lowermost lahar contains abundant highly altered pumice lapilli; the uppermost lacks pumice but contains altered rock fragments in a clayey matrix. Samples of logs from the two lahars were both about 1,100 years old (table 3, W-4568, W-4567, W-4614).

A light-gray lahar, as much as 3 m thick, occurs opposite the mouth of Dusty Creek on the east side of the Suiattle River. This lahar contains vesicular and nonvesicular dacitic fragments. The oldest tree on the surface of this lahar is at least 186 years old. Measurements indicate random directions of TRM and suggest that clasts in this flow unit were below their blocking temperatures when deposited. It is believed that this deposit was either a cold or a hot lahar. The lahar is overlain by 20-40 cm of light-gray silt-size ash (measured section 14). These lahars may have been formed at about the time as tephra layer X (p. 16).

Several recent lahars and glacier-outburst floods have buried trees and soils along lower Dusty Creek. In 1978, a small lahar deposited as much as 2 m of unsorted, sandy debris at the mouth of Dusty Creek, about 6 km from the terminus of the Dusty Glacier. Bark was stripped from trees and mud was deposited on trees and the valley walls of Dusty Creek as much as 1 m above the lahar surface. The lahar moved blocks up to 4 m in diameter, buried about 20,000 m^2 of riverbank and adjacent forest, and had an estimated volume of about 10,000 m^3.

FLOWAGE DEPOSITS IN THE VALLEYS OF CHOCOLATE CREEK AND THE SUIATTLE RIVER

Chocolate Creek originates in the Chocolate Glacier on the southeast side of Glacier Peak and flows into the Suiattle River about 6 km from the terminus of the glacier. It has cut a deep gorge called "Outburst Canyon" (Becky and Rands, 1977) in loose, unconsolidated volcanic deposits on the east side of Glacier Peak. The maximum depth of this canyon is more than 250 m.

Measured section 14[1]

[Outcrop along riverbank on the east side of the Suiattle River, directly east of the southernmost distributary of Dusty Creek, approximately 110 m east of the Suiattle River trail]

	Thickness (m)
5. Bouldery alluvium in which crystalline rocks are abundant; as much as..	2.0
4. Lahar: angular clasts up to 10 cm in diameter in loose ash matrix; contains charcoal fragments; as thick as..........	0.3
3. Sand, fine to medium; gray; lenticular; as much as	0.1
2. Lahar: vesicular and nonvesicular dacite in a reddish-brown sandy silt matrix; locally some clay stringers; some semihorizontal yellow staining of matrix material; clasts as much as 1 m in diameter; some clasts are stained by iron oxides..	3.0
1. Lahar: subangular to subrounded pebbles, cobbles, and boulders as large as 0.5 m in diameter in a compact sandy silt matrix..	>1.0
Covered to river level...	0.3

[1]Measured section 13 deleted.

Deposits older than the Dusty assemblage

The oldest postglacial deposit in the Chocolate Creek valley contains abundant prismatically jointed blocks, and so was probably formed by a pyroclastic flow. This unit is lenticular in outcrops and reaches a maximum thickness of 1.5 m. It has been recognized at only one locality (measured section 15). It consists of angular to subangular nonvesicular light-gray dacite fragments in a sand and silt matrix, and crops out about 10 m above Chocolate Creek.

The pyroclastic-flow deposit overlies unweathered till of probable late Pleistocene age and underlies tephra of early postglacial age erupted by Glacier Peak, including tephra layers B and G. The till contains quartz diorite clasts. This rock type does not occur upstream in the Chocolate Creek drainage basin, but forms the Tenpeak pluton at the head of the Suiattle River (Crowder and others, 1966). This suggests that the glacier which deposited the till at measured section 15 moved 20 km down the Suiattle River from cirques below Tenpeak Mountain.

The oldest pyroclastic-flow deposit above the till (unit 3, measured section 15) postdates the retreat of late Pleistocene glaciers from lower Chocolate Creek, which must have occurred before the eruption of tephra layer G. Ash beds in the measured section (units 4 and 5) are interpreted as ash-cloud deposits that originated in pyroclastic flows, rather than air-fall tephra. This interpretation is based on three factors. The deposits consist almost entirely of sand- and silt-size ash at a site where they are almost 1 m thick. In contrast, tephra layers from Glacier Peak which are as thick as this typically consist of lapilli, blocks, and bombs. These ash-cloud deposits also consist primarily of lithic, nonvesicular debris, whereas most tephra deposits at Glacier Peak contain abundant pumice. In addition these deposits are found only adjacent to Chocolate Creek, and thin rapidly away from the valley floor. Only 2 km to the south, these deposits are only a few centimeters thick, and 12 km to the east they are no longer present. In contrast, tephra deposits typically thin less rapidly and in a systematic way that is not related to topographic features or altitude.

Overlying the ash-cloud deposits are tephra deposits, including layers B and G, which were erupted at Glacier Peak during early postglacial time. These deposits are in turn overlain by a thick section of pyroclastic flows and lahars which are part of the Dusty assemblage.

Dusty assemblage

The next younger deposits in Chocolate Creek are the deposits of the Dusty assemblage (fig. 12). In the Chocolate Creek valley this assemblage has been incised by Chocolate Creek and the Chocolate Glacier. It is at least 250 m thick near the terminus of the glacier. Deposits of the Dusty assemblage unconformably overlie 11,000- to 12,000-year-old tephra and flowage deposits of late Pleistocene age (measured section 15). The Dusty assemblage consists of laminated silts and clays at the mouth of Chocolate Creek (measured section 16). These deposits are believed to have accumulated in an intermittent lake. The inferred lacustrine sediments occur up to 15 m above the valley floor and up to 1200 m in altitude, suggesting that the surface of the lake

Measured section 15

[Outcrop in riverbank on the south side of Chocolate Creek about 1.2 km upstream from the Suiattle River trail crossing of Chocolate Creek]

	Thickness (m)
17. Dusty assemblage: horizontally bedded pyroclastic-flow deposits and lahars; nonvesicular dark-gray dacite in a loose sandy matrix; flowage units range from 1 to 3 m in thickness; contains boulders as much as 3 m in diameter	20.0
Erosional unconformity	
16. Fine sandy to silty ash; horizontally laminated, beds 1-3 cm thick; beds gray to bluish gray; bedding draped over underlying beds, dips 10°-20° to the east	0.10
15. Tephra layer B: pumice lapilli, unstratified and unsorted, as much as 15 cm in diameter; lower 8 cm has a matrix of yellow clay and silt, otherwise openwork common; dips 10°-20° to the east[1]	2.10
14. Tephra: fine sandy ash; dips 10°-20° to the east[1]	0.06
13. Tephra: coarse ash and fine lapilli up to 5 mm in diameter; dips 10°-20° to the east[1]	0.03
12. Tephra: coarse ash; beds, dips 10°-20° to the east[1]	0.02
11. Tephra: coarse lapilli and small bombs; pumiceous; dips 10°-20° to the east[1]	0.05
10. Tephra: coarse lapilli; dips 10°-20° to the east[1]	0.05
9. Tephra: coarse lapilli in grayish-red (7.5R 5/2) ash; dips 10°-20° to the east[1]	0.10
8. Tephra: fine lapilli set in grayish ash matrix; dips 10°-20° to the east[1]	0.06
7. Tephra: ash with rare pumice lapilli; dips 10°-20° to the east[1]	0.02
6. Tephra layer G: pumice lapilli and bombs up to 14 cm in diameter; unsorted; openwork common; dips 10°-20° to the east[1]	1.80
5. Fine sandy to silty ash: lithologically similar to unit 16; contains layer of charcoal 2 cm thick at base; dips 10°-20° to the east[1]	0.70
4. Fine sandy to silty ash: lithologically similar to unit 16; dips 10°-20° to the east[1]	0.50
3. Pyroclastic-flow deposit: angular to subrounded rock fragments of light-gray nonvesicular dacite as much as 0.3 m in diameter in silty ash matrix; prismatically jointed blocks present; lenticular; as thick as	1.50
2. Till: angular to subrounded clasts in a gray silty clay matrix; clasts of diorite common; lenticular; overlies a steeply sloping erosional unconformity that truncates older beds; as thick as	2.00
1. Flowage units: undifferentiated; horizontally bedded	>15.00
Covered to river level	10.00

[1] Unit is draped conformably over underlying unit.

Measured section 16

[Cutbank on west side of the Suiattle River, approximately 0.5 km north of the mouth of Chocolate Creek]

	Thickness (m)
4. Dusty assemblage: horizontally bedded pyroclastic-flow deposits and lahars; nonvesicular dark-gray dacite in a loose sandy matrix; flowage units range from 1 to 10 m in thickness; contains prismatically jointed blocks as much as 5 m in diameter..	100
3. Interbedded sand, silt, and clay beds; horizontally bedded; includes finely laminated silts and clays.....................	20
2. Pyroclastic-flow deposit: medium- to dark-gray; angular to subrounded dacite fragments in a loose sand matrix, contains clasts as much as 2 m in diameter; many clasts oxidized; contains prismatically jointed boulders; upper 1 m is grayish red (7.5R 6/2)...	5
1. Silt and clay: finely laminated; locally contains rounded pumice lapilli...	>5
Covered to river level...	8

impounded by the flowage deposits in the Dusty assemblage was at least this high. A pyroclastic-flow deposit interbedded within the laminated silts provides evidence that the eruptions which produced the Dusty assemblage were contemporaneous with the damming of the Suiattle River. Small lakes probably were also temporarily impounded at other localities farther up the Suiattle River as the fan of the Dusty assemblage grew and extended up the Suiattle River valley (fig. 16). This lake may have been formed about the same time as a lake in the White Chuck River valley which was dammed about 5,500 years ago. (table 3, W-4214).

The Dusty assemblage is thought to be about the same age as the Kennedy Creek assemblage preserved on the west side of Glacier Peak (5,100-5,500 years old). Both of these assemblages were formed during the extrusion or collapse of one or more domes near the summit of Glacier Peak. Ash deposits of approximately the same age as these voluminous valley fills are restricted in distribution and very small in volume, and appear to be mainly ash-cloud deposits. This suggests that the eruptions which produced these valley fills were probably relatively nonexplosive, and that the pyroclastic-flow deposits within the assemblages are not the result of the collapse of vertical eruption columns, but resulted instead from Merapi-type eruptions involving the extrusion and collapse of lithic domes (Williams and McBirney, 1979).

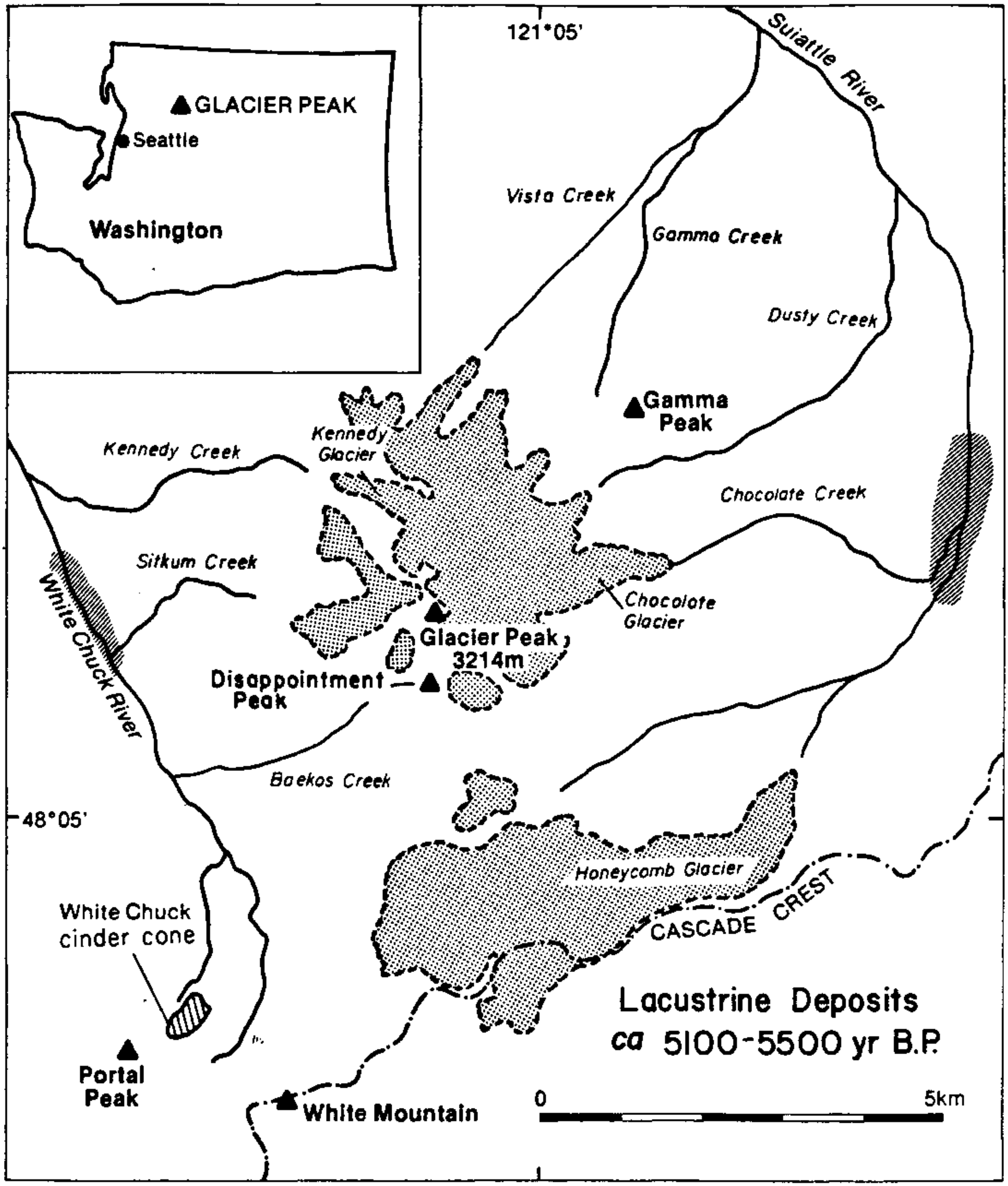


Figure 16.--Distribution of laminated ashy silts and clays (line pattern) interpreted as lacustrine deposits in the Dusty assemblage in the upper White Chuck and Suiattle River valleys.

Deposits younger than the Dusty assemblage

Younger deposits locally form a valley fill within a trench cut into the Dusty assemblage by Chocolate Creek. These deposits are as much as 100 m thick (measured section 17) and are mostly lahars, although pyroclastic-flow deposits are also present. Deposits of this assemblage backfilled the upper Suiattle River valley for at least 0.5 km, and a remnant of the valley fill extends at least 5 km downvalley from Glacier Peak. A wood sample from this assemblage is about 1,850 years old (W-4265). Dacitic alluvium in the town of Burlington, over 100 km downvalley from Glacier Peak in the Skagit River valley, contains charcoal which is also about 1,800 years old (Dave Dethier, oral commun., 1980). The part of this assemblage that is preserved in the valleys of Chocolate Creek and the upper Suiattle River has an estimated minimum volume of about 1 million m^3. This assemblage was probably produced during the eruption of domes near the summit of Glacier Peak. A lahar assemblage of similar age west of Glacier Peak may have been produced during the same eruptive episode (p. 38).

The next younger deposits in the Chocolate Creek valley consist of a thick, valley-filling assemblage of lahars, alluvium, and pyroclastic flows. This group of deposits is designated the South Guardian assemblage after South Guardian rock, which protrudes from the Chocolate Glacier above Chocolate Creek. The South Guardian assemblage forms a well-developed valley fill for 2-3 km below the terminus of the Chocolate Glacier (fig. 17). This assemblage was recognized by Tabor and Crowder (1969), who attributed it to deposition during a large outburst flood in Chocolate Creek in 1938. This is much too young an age, inasmuch as trees on moraines which overlie part of the terrace formed by the South Guardian assemblage are more than 238 years old.

The oldest flow unit in the South Guardian assemblage is a yellowish-orange (10YR 8/6) clayey lahar that contains blocks of lava as much as 1.5 m in diameter. This deposit was recognized as far downvalley as a point 2 km beyond the present (1980) terminus of the Chocolate Glacier. The observed thickness of this lahar is more than 7 m, and it is estimated to have had an original minimum volume of 10,000 m^3. Many lahars overlie and locally contain debris from this clayey lahar. The overlying lahars are well exposed in stream cuts for several kilometers along a 60- to 100-m-deep canyon that Chocolate Creek has cut into this assemblage. These lahars range from one to several meters in thickness, and are commonly interbedded with bouldery alluvium. Some of the beds of alluvium and some of the lahars are stained red and orange. These discolored flowage units are interbedded with fresh-appearing gray units of the assemblage.

Prismatically jointed blocks as much as 3 m in diameter are present in these lahars, indicating that the South Guardian assemblage was deposited as the result of the eruption of fresh volcanic material. The assemblage includes at least one pyroclastic-flow deposit. This deposit is a lenticular bed as much as 2 m thick that consists of prismatically jointed vesiculated dacite clasts in a matrix of fine ash. The deposit contains breadcrusted bombs as much as 0.5 m in diameter. All the clasts in this deposit are extremely fragile, and commonly disintegrate when removed from the outcrop and handled. The fragility of these bombs seems to preclude their transport in water-mobilized lahars and suggests that they were transported and deposited while still hot.

Measured section 17

[SW 1/4 sec. 6, T. 30 N., R. 15 E., cutbank on the north side of Chocolate Creek, about 0.5 km upstream from the Suiattle River trail crossing of Chocolate Creek]

	Thickness (m)
17. Lahar: subangular to subrounded fragments of dacite in a gray silty sand matrix; crudely stratified, normally graded, contains boulders as much as 1 m in diameter..........	3
16. Sand and silt; white to gray, horizontally bedded...............	1
15. Lahar: boulders and cobbles in a matrix of gray sand; clasts as much as 2 m in diameter; no apparent sorting or stratification...	4
14. Lahar: subangular to subrounded pebbles and cobbles in a matrix of sand and granules; unsorted; some horizontal stratification..	1
13. Lahar: boulders and cobbles in a matrix of gray sand; lenticular; as much as..	1
12. Sand and silt; white to gray; horizontally bedded; contains lenses of pebbles and cobbles................................	1-3
11. Lahar: boulders and cobbles in a matrix of gray sand; contains lenses of sand and boulders as much as 1 m in diameter..	2-4
10. Sand and silt alluvium; white to gray; horizontally bedded......	2
9. Pyroclastic-flow deposit: light- to medium-gray ash matrix; rock fragments consist of light- to dark-gray hornblende dacite; prismatically jointed blocks common; contains blocks as much as 0.5 m in diameter.................	4
8. Sand and silt alluvium; white to gray, horizontally bedded......	2-3
7. Lahar: subangular to subrounded boulders and cobbles in a light-gray sandy matrix, normally graded, contains boulders as much as 2 m in diameter..................................	5-8
6. Sand and silt alluvium; white to gray; horizontally bedded; contains lenses of pebbles and cobbles.......................	1
5. Pyroclastic-flow deposit: lithologically similar to unit 9, lenticular..	0-2
4. Sand and silt alluvium; white to gray, horizontally bedded......	1
3. Pyroclastic-flow deposit, lithologically similar to unit 9, reversely graded, contains logs, some of which are partially charred, sample of wood from incorporated log had an age of 1,860±70 years B.P. (table 3, W-4265) lenticular, as thick as	6
2. Fluvial gravel: cobbles and boulders as large as 1 m in diameter in a fine sand matrix, horizontally stratified, as thick as...	3
1. Lahar: subangular to subrounded cobbles and boulders in a gray sand matrix..	>2

Covered interval of 20 m to river level

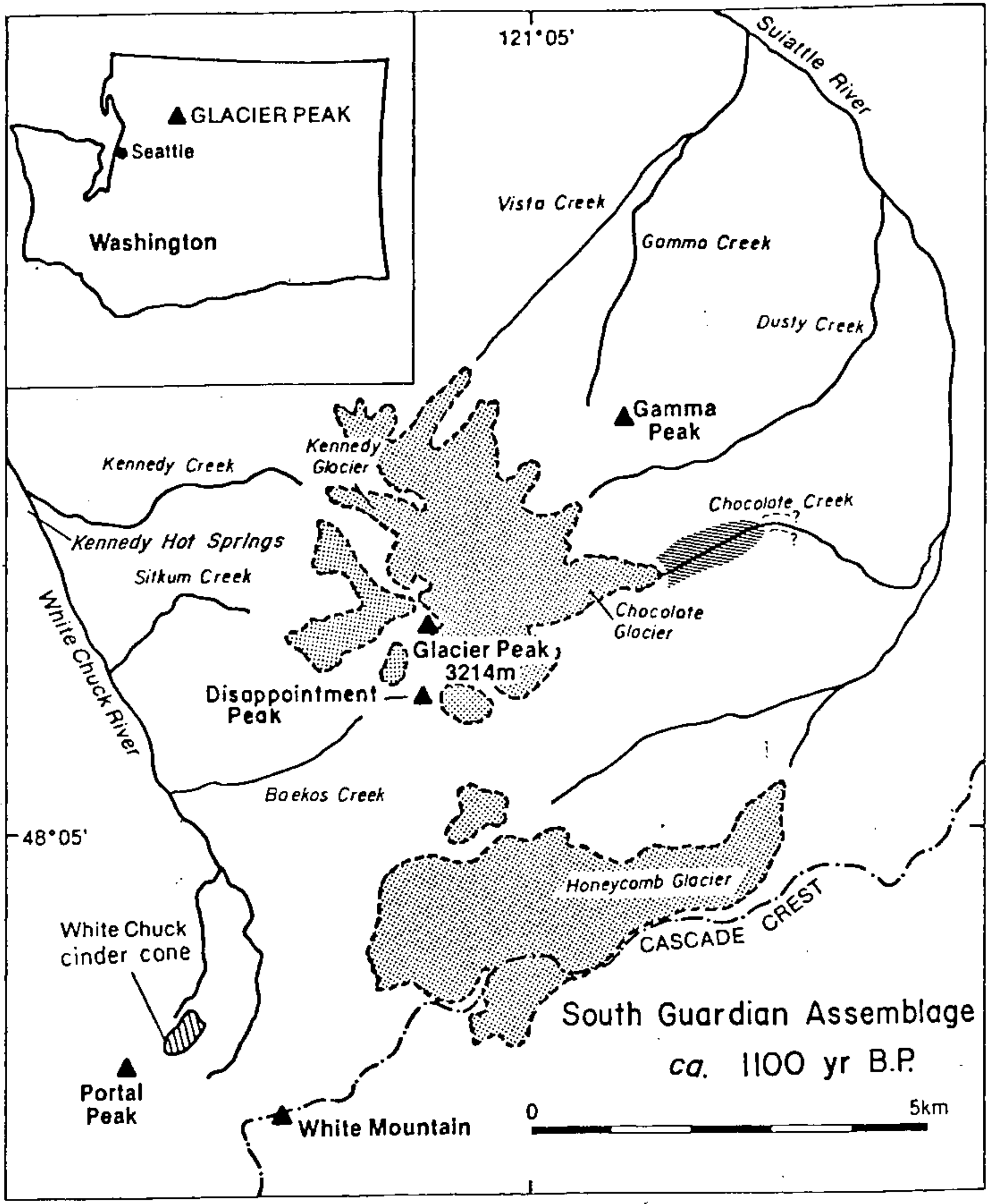


Figure 17.--Distribution of the South Guardian assemblage (line pattern) downstream from Chocolate Glacier. The South Guardian assemblage was erupted about 1,100 years ago.

Lahars in the South Guardian assemblage contain clasts of subangular to subrounded nonvesicular dacite in a loose, sandy matrix. Individual flowage units range between 0.5 and 4 m in thickness and commonly contain uncharred logs. A wood sample from a log in a lahar approximately 10 m below the top of the South Guardian assemblage yielded a radiocarbon date of about 1,100 years B.P. (table 3, W-4276). Unconformities were not recognized in this assemblage, so this date is believed to be the approximate age of the entire assemblage. The estimated minimum volume of the South Guardian assemblage downstream from the Chocolate Glacier to a distance of 3 km is about 10 million m^3.

Several bouldery lahars, deposited during the last two centuries, form high terraces in the Chocolate Creek valley. At a locality about 0.2 km west of the Suiattle River trail crossing of Chocolate Creek, two buried soils are interbedded with these lahars (measured section 18). Wood from a horizon near the base of these lahars had a radiocarbon age of less than 200 years; thus, all of these lahars occurred during the last two centuries. Trees on top of these terraces are as much as 70 years old.

In addition, at least two lahars have occurred in Chocolate Creek during historic time. The older of these occurred in 1938. This lahar buried and destroyed forests as much as 10 km downstream from the Chocolate Glacier. Although the lahar was not observed at the volcano, flooding caused by it occurred far down the Suiattle and Sauk Rivers (Ford, 1959). A more recent lahar, which occurred in 1957, was observed from the air (Richardson, 1968). This lahar was generated by a glacier-outburst flood and caused damage to forests and trails as far downvalley as 20 km from Glacier Peak.

THE WHITE CHUCK CINDER CONE

The White Chuck cinder cone, 7 km southwest of Glacier Peak, is a complex volcanic feature composed of hyaloclastic breccias, olivine basalt lava flows and a capping mantle of air-fall scoria and breadcrust bombs (fig. 18). The eastern flank of the cinder cone has been largely unaffected by erosion, and is locally mantled with a thin deposit of pumiceous tephra from Glacier Peak. This deposit consists of as much as 50 cm of well-sorted pumice lapilli, averaging 1-3 cm in diameter. The pumice is mineralogically indistinguishable from Glacier Peak tephra of late Pleistocene age which covers upland surfaces near the cinder cone. The tephra on the cinder cone is therefore correlated with one or more of the seven tephra layers erupted from Glacier Peak in late Pleistocene time, indicating that the cinder cone itself is at least as old as the youngest Glacier Peak tephra deposit. Thus, the cinder cone was erupted at least 11,250 years ago. The hyaloclastic breccias, which locally are at least 30 m thick, probably were produced during subglacial eruptions near the end of the last glaciation. The lava flows and scoria that comprise the upper parts of the cone were probably erupted either after glaciers had disappeared from the cirque, or were thin.

Measured section 18

[South bank of Chocolate Creek approximately 1 km upstream from Suiattle River trail crossing of Chocolate Creek]

		Thickness (m)
9.	Lahar: pebbles and cobbles in coarse to medium sand matrix	0.8
8.	Forest duff: silty; contains roots and stumps	0.5
7.	Lahar: boulders and cobbles in a loose medium to fine sand matrix	1.5
6.	Forest duff: silty and ashy; contains roots and stumps (radiocarbon sample W-4274, less than 200 years B.P.)	0.5
5.	Lahar: boulders as large as 1 m in diameter in a sand and granule matrix	3.0
4.	Sand, fine, dark-gray; contains some pebbles; horizontally bedded	1.0
3.	Lahar: lithologically similar to unit 5	3.0
2.	Sand, fine to medium, dark-gray, contains a log about 15 cm in diameter (radiocarbon sample W-4268, less than 200 years B.P.)	1.2
1.	Lahar: lithologically similar to unit 5	>1.0

Covered interval of 0.5 m to river level

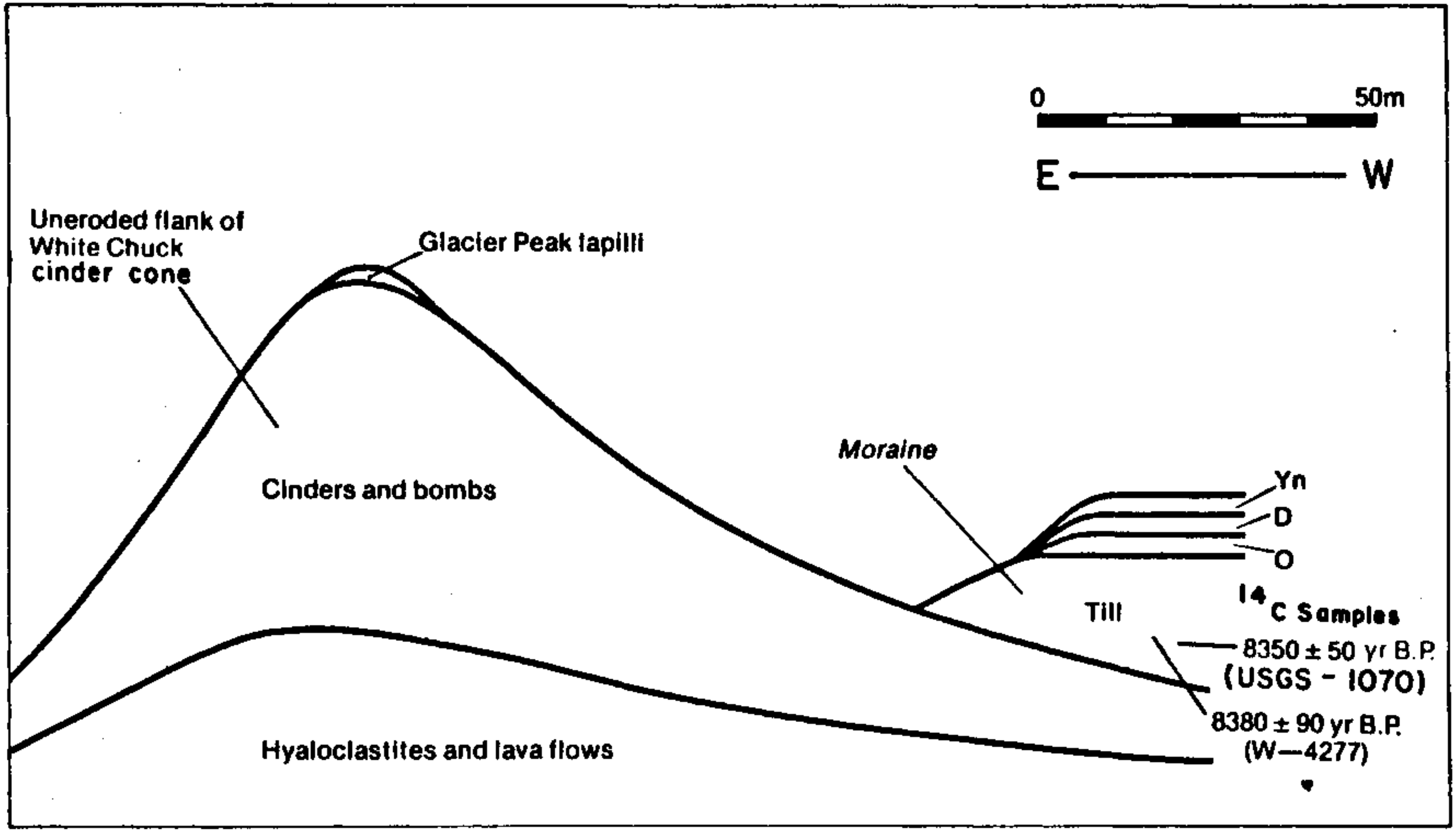


Figure 18.--Schematic cross section through part of the White Chuck cinder cone. The presence of late-Pleistocene Glacier Peak pumice lapilli on the crest of the cinder cone is interpreted to mean that the cinder cone is no younger than layer B, erupted 11,250 years ago. Hyaloclastites which underlie much of the cinder cone may have been formed during subglacial eruptions.

The westernmost parts of the cinder cone have been overridden by a glacier from the north face of Portal Peak. This drift is easily identifiable in the cinder cone because it contains abundant erratics of garnet-biotite gneiss, as well as abundant reworked and comminuted pumice lapilli and pumice fragments. Tephra layer O overlies the till within the cinder cone.

Disseminated charcoal fragments were recognized in the till in a stream cut near the eastern limit of drift within the cinder cone. These charcoal fragments occur within a semispherical zone approximately 1 m below the surface of the drift, and about 50 cm below the base of the Cox soil horizon. The charcoal fragments are rounded to semirounded and range from 1 to 3 cm in diameter. The age of this charcoal is 8,380±90 years (W-4277). This locality is at an altitude of about 1740 m, near modern tree line. Individual trees and small stands of subalpine fir grow today up to a few hundred meters above this site. The presence of the charcoal indicates that trees also grew at this altitude approximately 8,400 years ago.

This radiocarbon date is interpreted as indicating that the till which incorporates the charcoal is about 8,400 years old. In addition, the date indicates that the White Chuck cinder cone itself is more than 8,400 years old. This date is consistent with the tephrochronological date of more than 11,250 years for the eruption of the cinder cone. The cinder cone was probably formed during or soon after deglaciation of the high alpine cirque in which it occurs. The hyaloclastites underlying much of the cinder cone suggest that ice was still present in the cirque when eruptions began at the White Chuck cinder cone.

THE VOLCANIC CONE AND VOLCANIC DOMES

Glacier Peak volcano is a complex feature, made up of lava erupted at many different times. The oldest lava flows from Glacier Peak cap ridges north and east of the volcano. Erosion has caused topographic inversion of 300-400 m since these lava flows were erupted. The amount of inversion is similar to that adjacent to old lava flows at Mount Baker and Mount Rainier. Some of these flows have been radiometrically dated and determined to be 200,000-600,000 years old (Crandell and Miller, 1974; Easterbrook, 1975). The oldest lava flows at Glacier Peak may also be several hundred thousand years old.

An unconsolidated apron of tephra and pyroclastic-flow deposits produced at Glacier Peak in late Pleistocene time extends up onto the volcanic cone. Tephra layers B and G can be found up to an altitude of 2600 m on the north side of the volcano. Similarly, the tephra layers extend up to about 2400 m below Disappointment Peak on the south side, and to 2400 m on the east side. This indicates that Disappointment Peak and the main volcanic cone, up to at least 2400-2600 m, predate the late Pleistocene tephra eruptions.

No late Pleistocene tephra deposits are found on the upper parts of the volcano, although abundant deposits of lithic ash and breadcrust bombs as much as several meters thick, deposited during Holocene eruptions, are present on the north, south, and western slopes of the upper volcano. This suggests that the upper parts of the volcano postdate the late Pleistocene eruptions.

The uppermost 800 m of Glacier Peak can be subdivided into three parts. Disappointment Peak, on the southern slope of the volcano, is a large oxyhornblende dacite dome which flowed almost 800 m down the south and southwest sides of the volcano (Tabor and Crowder, 1969). Parts of the lower, gentle slopes of Disappointment Peak are overlain with a blanket of late Pleistocene tephra as much as 1 m thick, indicating that Disappointment Peak itself is more than 11,000-12,000 years old.

The actual summit of the volcano lies about 0.25 km north of Disappointment Peak. The summit is covered by the uppermost parts of the Chocolate Glacier on the east, but is partly exposed on the west and south. It consists of a massive dacite lava flow, which appears to be as much as 50 m thick. This lava is tentatively believed to be a remnant of a dome extruded during one of the major mid-Holocene eruptions.

Approximately 0.25 km north of the summit block is a small plateau or false summit. Projecting above this plateau are remnants of what may be a very recent dome. Two large dacite blocks, both protruding about 15 m above the false summit and about 20 m in diameter at their base, are preserved near the northern edge of the false summit. These glassy, fresh-appearing lithic blocks are conspicuously striated to a depth of 1-2 cm. The striations cut across the fragments at an angle of about 45°. The striations were probably produced when semisolid lava was extruded from the volcanic neck. The blocks are massive and generally lack structure, although the top 1-2 m of each block is highly fractured and broken into prismatically jointed blocks of varying sizes.

A small dacite lava flow, only about 25 m long and about 1.5 m thick, extends from near the center of the false summit to the edge of the headwall of the Dusty Glacier. This small lava flow is highly oxidized and has many large crystals of oxyhornblende.

It was not possible to determine the ages of these inferred Holocene domes and flows. The summit dome(?) may be correlative with the major eruptions that formed the Kennedy Creek and Dusty Creek assemblages about 5,500-5,100 years ago. The younger appearing dacite blocks on the northern false summit may have been extruded during one of the younger eruptive events recognized in this study.

It is interesting to note that all the domes and dome fragments are alined approximately north-south across the summit of the volcano. This suggests that a north-south structural trend has controlled the emplacement of domes at Glacier Peak for at least the last several thousand years. Circumstantial evidence that supports the existence of such a structural trend includes the presence of a radial dike, as much as 2 m thick, which extends north from the summit area. In addition, the volcanic cone itself comprises an elongate, north-south-trending volcanic pile.

ERUPTIVE HISTORY OF GLACIER PEAK

The variety and complexity of postglacial volcanic deposits at Glacier Peak indicates that the volcano has frequently been active during late-glacial and postglacial time. Postglacial activity may be divided into two main periods (tables 5, 6). Shortly after glaciers retreated at the end of the last glaciation, Glacier Peak produced widespread tephra layers and voluminous pyroclastic-flow deposits. This episode lasted at least from about 11,700 to 11,250 years ago. Lahars produced during this period probably extended to Puget Sound along the Stillaguamish River valley. The Sauk River was blocked from its previous course down the Stillaguamish valley by a volcanic valley fill, and has subsequently flowed north to the Skagit River.

Following the late Pleistocene eruptions, Glacier Peak was 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 many late Pleistocene volcanic deposits during this time, and streams incised deep canyons in the unconsolidated valley fills.

Pyroclastic eruptions resumed about 5,500 years ago. A large mudflow consisting of hydrothermally altered rock fragments may have been initiated early in this eruptive cycle. These eruptions continued until at least as recently as 5,100 years ago. During this period of time, thin tephra layers, possibly resulting from phreatic eruptions, were deposited as far as 25 km east of Glacier Peak. Pyroclastic flows and one or more domes were repeatedly erupted. Near the volcano, block-and-ash flows and ash-cloud deposits buried valleys both east and west of the volcano. Lahars associated with the eruptions extended far downstream in the Sauk, Suiattle, and Skagit River valleys.

Another apparent dormant interval occurred between 5,100 and 2,800 years ago. About 2,800 years ago lahars traveled as far as 30 km downvalley in the White Chuck drainage. These lahars consist of fresh lithic debris and may have resulted when pyroclastic eruptions melted ice and snow at Glacier Peak, or from the emplacement of a dome near the volcano's summit.

Another apparent dormant interval occurred between about 2,800 and 1,700-1,800 years ago. Pyroclastic-flow deposits and lahars erupted about 1,800 years 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 probably resulted from the melting of ice and snow by 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.

Table 5.--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]

YR. B.P.	
	Dormant interval of 200-300 years
200	Lahars, minor tephra eruptions, phreatic eruptions(?)
	Lahars, large flood
SCALE CHANGE	Apparent dormant interval of unknown duration
	Lahars
1000	Lahars, pyroclastic flows, dome eruptions(?)
	Apparent dormant interval of 600-700 years
	Pyroclastic flows, lahars, dome eruptions
2000	
	Apparent dormant interval of 900-1000 years
	Lahars, dome eruptions (?)
3000	
4000	Apparent dormant interval of 2000-2300 years
5000	
	Repeated eruptions of pyroclastic flows and domes, lahars
SCALE CHANGE	Tephra eruptions
6000	
8000	Apparent dormant interval of 5500-6000 years
10,000	
	Intermittent tephra eruptions of large volume, pyroclastic flows, lahars, dome eruptions
12,000	Apparent dormant interval of unknown duration
	Tephra eruption of large volume (?)
14,000	Lahar

Table 6.--Postglacial volcanic events and deposits on various sides of Glacier Peak

Time scale years B.P.	Tephra erupted at Glacier Peak: Layer or set name	Tephra erupted at Glacier Peak: Description[1]	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, single layer, contains hb, hy, au, ox. Scattered isolated lapilli on northeast flank of volcano.	Glacier 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.
SCALE CHANGE		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 extend at least 30 km down the White Chuck River valley.[2]	
1,000 --			At least five lahars moved >30 km.[2] Possible formation of dacite dome.[2]	At least two lahars moved >2 km down Dusty Creek valley. Lahars and pyroclastic flows moved down Chocolate Creek valley.
2,000 --			One lahar extended 30 km.[2]	
	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.[2]	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.[2]
3,000 --			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.
4,000 --				
5,000 --			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.[2]
	D	Several fine layers, ash and fine lapilli, olive brown to bluish gray, hy, hb, probably 15 cm thick, occurs on all flanks of the volcano. Extends to the east.		
6,000 --			One or more lahars extended >10 km.[2]	One lahar extended >3 km.[2]
CHANGE IN SCALE 11,000 --				
	B	Pumice, gray to grayish white, contains hy, hb; probably 200 cm thick, occurs on all flanks of the volcano, extends to southeast.	Possible formation of dacite dome.[2] 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.
	M	Several layers, light gray, contains hy, hb; probably 50 cm thick, lapilli and ash, occurs on all flanks of the volcano, extends to southeast and east.[2]		
12,000 --				
	G	Pumice, grayish yellow, contains hy, hb, probably 200 cm thick, occurs on all flanks of the volcano, extends to southeast.[2]	A single lahar moved >35 km down the White Chuck River valley.[2]	
13,000 --				

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

Some time after 1,800 years ago, a large lahar consisting almost entirely of oxyhornblende-dacite debris traveled at least 30 km down the White Chuck River. The origin of this deposit is not known, but it could have been triggered by a large landslide high on Glacier Peak.

Approximately 1,100 years ago, clayey lahars as well as pyroclastic flows and lahars of fresh rock debris were deposited in several valleys both east and west of Glacier Peak. All these deposits probably were formed during a single eruptive period.

Some time after 1,800 years ago, a lahar assemblage consisting of fresh lithic debris partly filled the White Chuck River valley at least 30 km downstream from the volcano. Five lahars were recognized in this assemblage. The assemblage is not radiocarbon dated, but its stratigraphic relations with older, dated deposits indicate that it may have been produced during the eruptive period about 1,100 years ago.

At least one lahar and a large flood occurred in the White Chuck River valley fairly recently. These both extended at least to the confluence of the White Chuck and Sauk Rivers, some 30 km from Glacier Peak. Trees growing on the resulting deposits indicate that they were emplaced more than 300 years ago. It is possible that the large flood and the lahar were both produced by eruptions at Glacier Peak, although no unequivocal evidence of eruptive activity at this time has been recognized.

About 200-300 years ago, small tephra eruptions caused isolated lapilli to fall east of Glacier Peak. A widespread fine ash that was formed at about this time may be an ash-cloud deposit, or may be the result of phreatic eruptions at Glacier Peak. Also at about this time, lahars were deposited in several valleys east of Glacier Peak. It is possible that Indians observed eruptions at this time, as they told pioneer naturalist George Cribbs that Glacier Peak had "smoked" in the recent past (Majors, 1980).

This eruption history suggests that Glacier Peak has erupted about every 900-1,100 years during the last 5,500 years. Furthermore, during the last 1,800 years, at least three and possibly four eruptive events have occurred, two of which (1,800 and 1,100 years B.P.) involved the formation of pyroclastic flows and the deposition of thick lahar assemblages. Similar events in the future could affect areas far downvalley from the volcano.

POTENTIAL GEOLOGIC HAZARDS

Glacier Peak has been intermittently active during the last 14,000 years and dormant intervals typically have lasted several hundred to a few thousand years. This history of intermittent volcanism, which apparently has continued to within a few hundred years ago, suggests that Glacier Peak is not extinct, but could erupt again. During future eruptions, the areas that will be most severely affected will be on and immediately adjacent to the volcano. Because the volcano lies in the center of the Glacier Peak Wilderness Area, these areas are now uninhabited and will remain that way. Recreational visitors to the area are most numerous in mid to late summer, when as many as several hundred people may be hiking or camping near Glacier Peak. At the first signs of an impending eruption, restriction of access to the volcano should be considered. Certain types of eruptions can also have far-reaching effects.

In particular, tephra, lahars, and volcanically induced floods can affect areas tens of kilometers downwind or downvalley from the volcano. The possible damage caused by future eruptions can be minimized through an awareness of potential hazards in planning use of land in areas most likely to be affected.

The following evaluation of potential volcanic hazards at Glacier Peak is based on the stratigraphic record of past activity of the volcano. This evaluation assumes that future eruptions will be similar in type and scale to those of postglacial time and that the extent of volcanic phenomena of various kinds will be similar to the distribution of deposits that resulted from previous eruptions.

Potentially hazardous events that have occurred at Glacier Peak in postglacial time include the eruption of tephra, the formation of hot pyroclastic flows, and the formation of rock avalanches, lahars, and floods. Possible dangers associated with each of these events are described in the following section.

Tephra

Potential hazards from tephra eruptions depend on the volume, rate, and duration of the eruptions. The distribution of tephra is controlled by the strength and direction of the wind at the time of the eruption (Wilcox, 1959). Within 10 km of the active vent the impact of large volcanic bombs thrown on ballistic trajectories may constitute a serious danger. 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. As demonstrated in the May 1980 eruptions of Mount St. Helens, lapilli and ash may damage or kill vegetation, contaminate surface water, and affect machinery and highway and aerial traffic.

Glacier Peak produced large volumes of tephra in early postglacial time, between about 12,500 and 11,250 radiocarbon years ago. Tephra layers B and G erupted at this time; each 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 only three 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 show the range of volumes that might result from future tephra eruptions at Glacier Peak. Thicknesses of tephra that might be expected in the future are based on three representative tephra deposits erupted from Glacier Peak in postglacial time (fig. 19). Because Glacier Peak has erupted only very small volumes of tephra during the last 7,000 years, it is likely that any future tephra eruptions will also be comparably small in volume. Tephra thicknesses from a small eruption could closely resemble those of tephra set D (fig. 4). Tephra eruptions of this volume are unlikely to create a significant health problem for people at distances greater than 25 km from Glacier Peak.

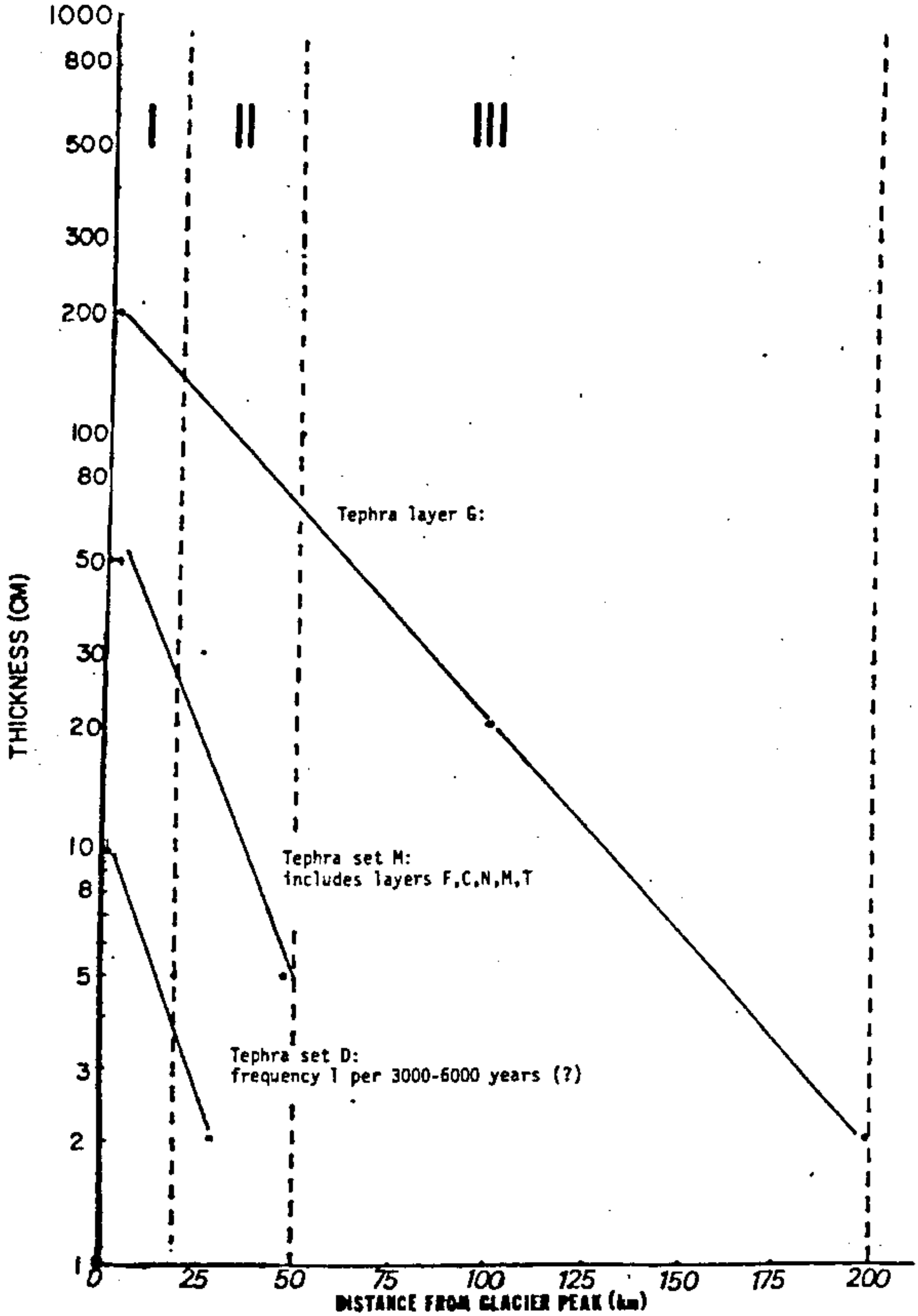


Figure 19.--Thicknesses of representative tephra deposits downwind from Glacier Peak along the axis of each tephra lobe. Tephra deposits G, M, and D are shown because their thicknesses are relatively well known. These deposits are estimated to have volumes on the order of 1 km^3, 0.1 km^3, and 0.001 km^3, respectively. Data in part from Porter (1978). Areas covered by tephra-hazard zones I, II, and III are shown in figure 20. 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.

The distribution of tephra deposits produced during previous eruptions suggests that the wind has generally blown from the west during the past. Only a few tephra deposits have been found to the west of Glacier Peak, and all of those seem to be restricted to areas within a few kilometers of the volcano. Modern wind-direction and wind-speed data compiled at Quillayute, Wash., a weather station 70 km west of Glacier Peak, indicate that at present winds blow predominantly toward the east, and suggest that most tephra from future eruptions of Glacier Peak will probably deposit material mostly east of the volcano (tables 7 and 8).

Tephra-hazard zones (fig. 20) are based on the extent and distribution of previous tephra deposits, as well as on the recent records of wind directions and speeds in northwest Washington (tables 7, 8). East of Glacier Peak the boundaries of tephra-hazard zones in figure 19 have been placed at 20, 50, and 200 km, because the distribution and thickness of the tephra deposits on which these subdivisions are based are relatively well known at these distances. These subdivisions do not have any special significance with respect to degree of risk. Most small future eruptions of tephra at Glacier Peak will probably have little or no effect outside of zone I. Very large and violent eruptions might have significant effects well beyond the limits of zone III. Tephra thicknesses should decrease away from the volcano in a uniform manner, although rainstorms during transport, variable local winds, and other factors may cause local variations.

Flowage deposits

The extents of flowage-hazard zones (fig. 21) are based on the frequency of occurrence, total number, and extents of pyroclastic flows, ash-cloud deposits, and lahars that have affected those areas during late-glacial and postglacial time.

Areas within flowage-hazard zone I, which includes Glacier Peak itself and the upper portions of valleys heading on the volcano, have been repeatedly affected by pyroclastic flows and associated ash clouds, lahars, rock avalanches, and floods in postglacial time. Areas within zone I have been affected by volcanic events at Glacier Peak at least as often as once every 1,000-3,000 years. Some individual volcanic events have included the eruption and deposition of pyroclastic flows and lahars. Within zone I, areas near Glacier Peak are 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 which are known to have been affected by lahars in postglacial time.

Potential hazards in zone II also generally decrease with distance downvalley from Glacier Peak. This is because areas within zone II which 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. The danger of such volcanically generated floods is similar to that of normal floods, except

Table 7.--Average windspeeds, in knots, at various altitudes (from Hyde and Crandell, 1978)

[One knot=1.15 mi/hr or 1.85 km/hr. Based on 20-year record (1950-70) at Quillayute, Wash. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Federal Building, Ashville, N.C. 28801)]

From----------	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Toward---------	S	SSW	SW	WSW	W	WNW	NW	NNW	N	NNE	NE	ENE	E	ESE	SE	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
5,500---------	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	13.8	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

Table 8.--Average percentage of wind directions, by month, at altitudes of about 3,000-16,000 m, averaged (from Hyde and Crandell, 1978)

[Based on 20-year record (1950-70) at Quillayute, Wash. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Federal Building, Ashville, N.C. 28801)]

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	1.0	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	3.7	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	2.6	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	7.5	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	.8	.8	.9	1.3	2.0	4.3	8.1	13.9	16.1	16.1	12.5	10.1	6.4

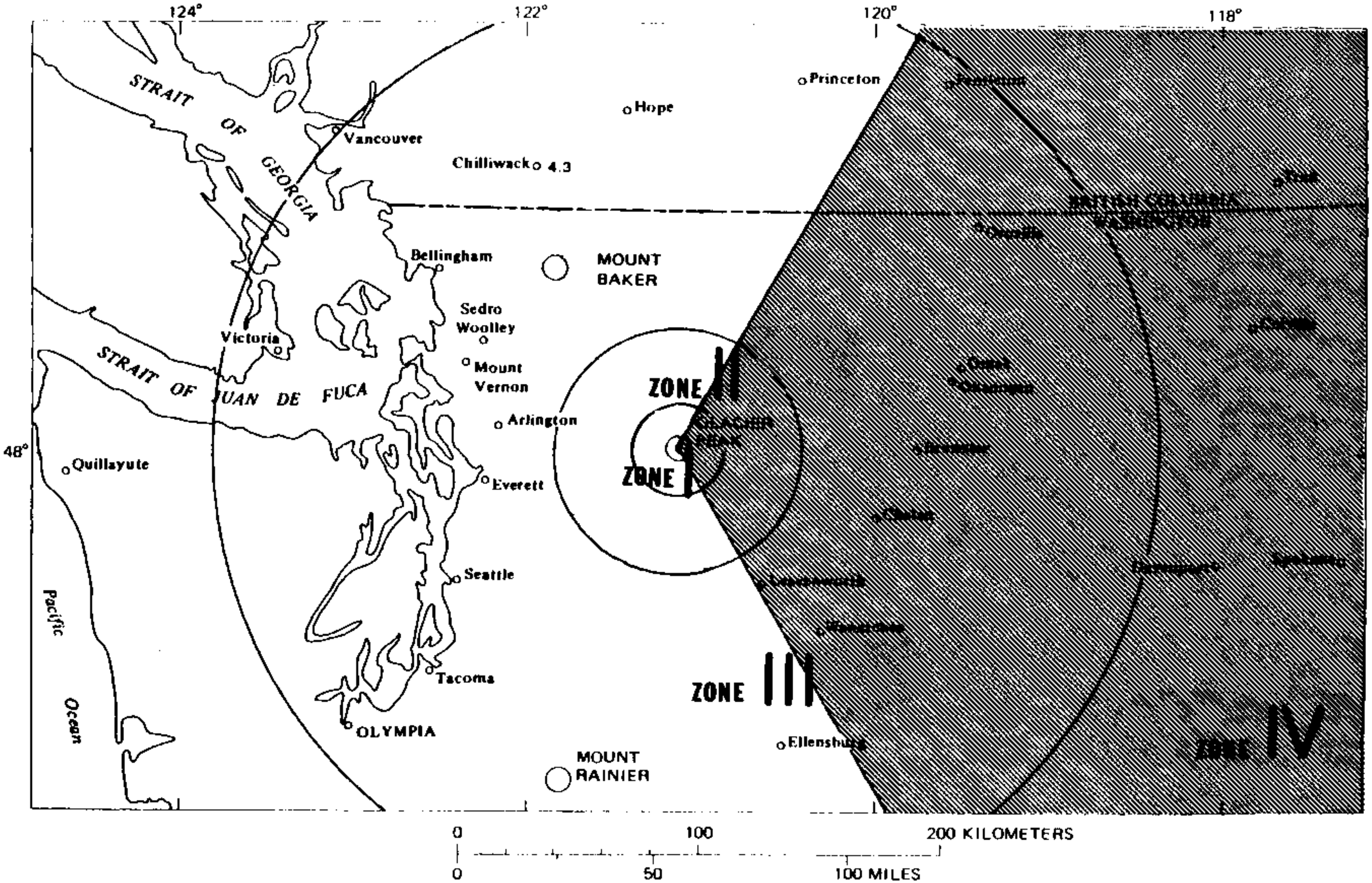


Figure 20.--Tephra-hazard zones for future tephra eruptions of Glacier Peak. Potential tephra thicknesses (see fig. 19), based on representative past eruptions, are greatest in zone I and decrease progressively away from the volcano across zones II and III. Tephra is significantly more likely to fall in the shaded portions of zones I, II, and III, because winds blow to the east approximately 80 percent of the time (tables 7 and 8). 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.

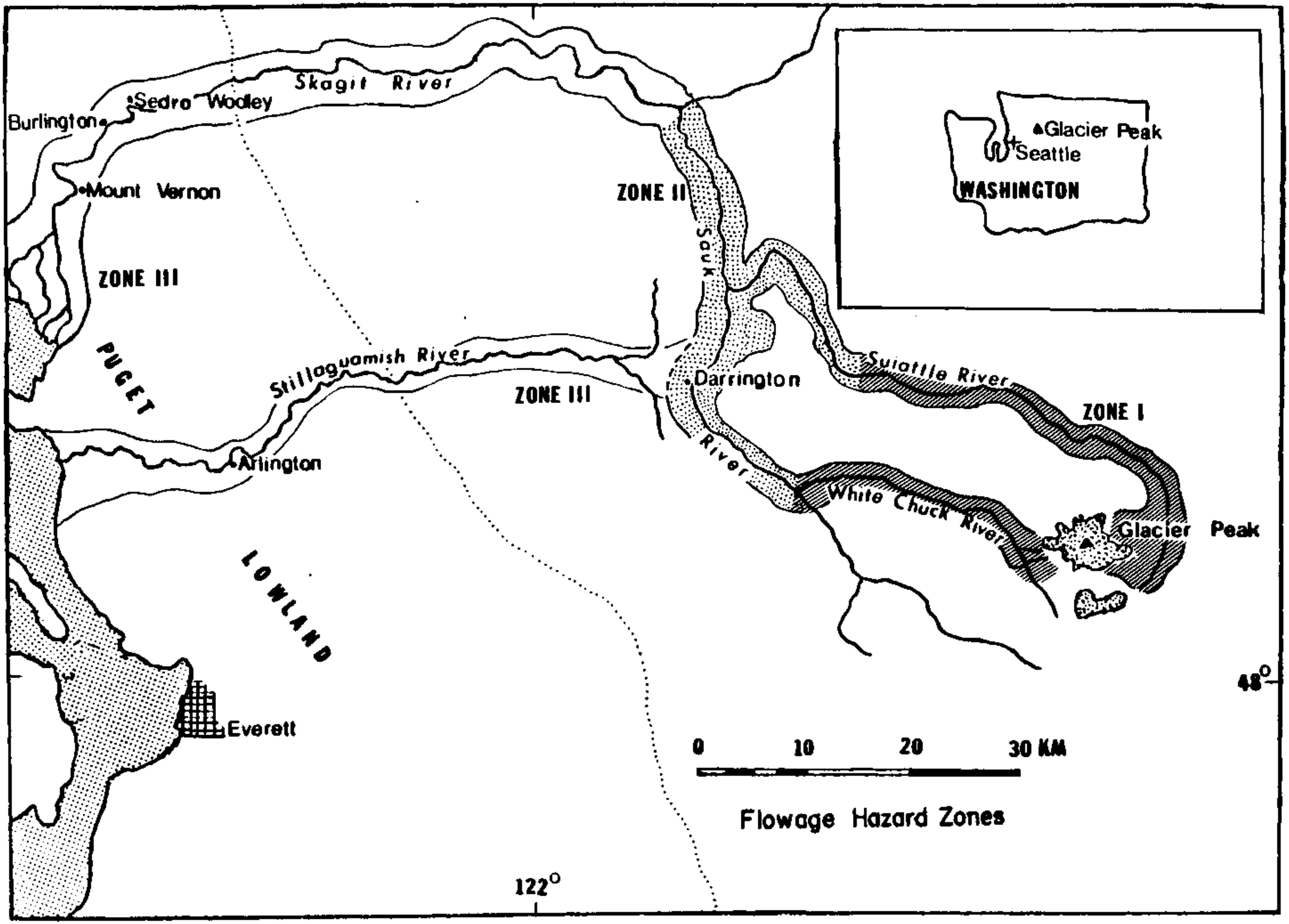


Figure 21.--Flowage-hazard zones for possible future eruptions of Glacier Peak. Potential hazards are greatest in zone I and decrease in zones II and III. Hazards decrease downstream within each zone and with altitude above the valley floor.

that unusually large amounts of rock debris might be transported down valleys, and deposits of sand and gravel many meters thick might be deposited on valley floors in areas above the river's normal flood plain.

Flowage-hazard zone III includes downvalley areas which have been affected 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. Floods produced during past eruptions at Glacier Peak probably have also affected parts of zone III. 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 and could affect valley floors as far downstream as Puget Sound.

Lava flows

No postglacial lava flows have been recognized on the lower slopes of Glacier Peak. Based on the extent of older lava flows at Glacier Peak, including those preserved in the modern volcanic cone, lava flows produced during future eruptions would probably not extend more than 4 km beyond the volcano's flanks, and most likely would not reach beyond the base of the cone. Such lava flows probably would move slowly, and would present little danger to human life. However, lava flows could initiate forest fires, and by melting snow or glaciers, cause flooding and produce lahars.

Discussion of potential hazards

Major eruptions that produced large volumes of tephra and pyroclastic flows could devastate areas near Glacier Peak, and could affect populated areas at greater distances from the volcano. Future tephra eruptions, if of the same volume as the largest late-glacial eruptions, could deposit several centimeters of tephra in areas as far as 200 km downwind from Glacier Peak and a meter or more in areas within 30-50 km of the volcano. Pyroclastic flows in the past have traveled as far as 20 km downvalley from Glacier Peak, and lahars and volcanic alluvium generated during past eruptions at Glacier Peak were deposited as far as 100 km downvalley in the Suiattle, White Chuck, Sauk, and Skagit drainages. The widespread distribution of volcanic debris from past eruptions indicates that lahars constitute the most serious threat to buildings and other property along valley floors during future eruptions. Pyroclastic eruptions of large volume would devastate the immediate vicinity of Glacier Peak and have decreasingly severe effects downwind from the volcano.

Some areas downstream from Glacier Peak could also be affected by drainage changes during a major future eruption. It will be noted that parts of flowage-hazard zones II and III extend into the Stillaguamish River valley (fig. 20), which does not presently receive any drainage from rivers heading at Glacier Peak. The extension of these zones is based on the presence of lahars and alluvium deposited during late Pleistocene eruptions at Glacier Peak, which now fill the upper portions of the Stillaguamish Valley and extend as far as 100 km downvalley. In addition, at least one lahar extended into the Stillaguamish River valley about 5,100 radiocarbon years ago, and reached at least as far as 20 km west of the town of Darrington.

During future periods of river aggradation by lahars and floods, the Sauk River could again change its course and flow into the valley of the Stillaguamish west of Darrington. If this happened, floods and lahars could again move down the Stillaguamish River valley as well as down the Sauk and Skagit River valleys.

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