RECENT ACTIVITY OF GLACIERS OF MOUNT RAINIER, WASHINGTON

GEOLOGICAL SURVEY PROFESSIONAL PAPER 387-B

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FRONTISPIECE.—Tahoma Glacier, shown here at left center of the photograph, cascades down the west slope of Mount Rainier where it forms the headwaters of South Puyallup River. South Tahoma Glacier rises on the side of Mount Rainier to the right, flows around a bedrock hill and terminates in a gray tongue of ice from which Tahoma Creek flows off to the right. The bare valley bottoms just below the termini were covered by the glaciers less than 60 years ago. (Photograph taken from Gobbler's Knob, September 20, 1967.)

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By ROBERT S. SIGAFOOS and E. L. HENDRICKS

BOTANICAL EVIDENCE OF GLACIER ACTIVITY

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An investigation of the chronology of terminal and lateral moraines of eight glaciers at Mount Rainier, Washington

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RECENT ACTIVITY OF GLACIERS OF MOUNT RAINIER, WASHINGTON

By Robert S. Sigafoos and E. L. Hendricks

ABSTRACT

Knowing the ages of trees growing on recent moraines at Mount Rainier, Wash., permits the moraines to be dated. Moraines, which are ridges of boulders, gravel, sand, and dust deposited at the margins of a glacier, mark former limits of a receding glacier. Knowing past glacial activity aids our understanding of past climatic variations.

The report documents the ages of moraines deposited by eight glaciers. Aerial photographs and planimetric maps show areas where detailed field studies were made below seven glaciers. Moraines, past ice positions, and sample areas are plotted on the photographs and maps, along with trails, roads, streams, and landforms, to permit critical areas to be identified in the future. Ground photographs are included so that sample sites and easily accessible moraines can be found along trails. Tables present data about trees sampled in areas near the glaciers of Mount Rainier, Wash.

The data in the tables show there are modern moraines of different age around the mountain; some valleys contain only one modern moraine; others contain as many as nine. The evidence indicates a sequence of modern glacial advances terminating at about the following A.D. dates: 1525, 1550, 1625–60, 1715, 1730–65, 1820–60, 1875, and 1910. Nisqually River valley near Nisqually Glacier contains one moraine formed before A.D. 1842; Tahoma Creek valley near South Tahoma Glacier contains three moraines formed before A.D. 1528; 1843, and 1864; South Puyallup River valley near Tahoma Glacier, six moraines, A.D. 1544, 1761, 1841, 1851, 1863, 1898; Puyallup Glacier, one moraine, A.D. 1846; Carbon Glacier, four moraines, 1519, 1763, 1847, 1876; Winthrop Glacier, four moraines, 1655, 1716, 1760, and 1822; Emmons Glacier, nine moraines, 1596, 1613, 1661, 1738, 1825, 1850, 1865, 1870, 1901; and Ohanapecosh Glacier, three moraines, 1741, 1846, and 1878.

Abandoned melt-water and flood channels were identified within moraine complexes below three glaciers, and their time of abandonment was dated. Outwash in three areas was deposited by melt-water of Tahoma Glacier before A.D. 1862, 1873, and 1910, respectively. Flood channels or melt-water channels on either side of Carbon River near Carbon Glacier dated from about 1901 to 1907. Melt-water channels of three different ages cut through Emmons Glacier moraines were dated as being abandoned before 1865, 1871, and 1917, respectively.

Although the evidence at Mount Rainier indicates a sequence of glacial advance and retreat and of melt-water flow through different channels at different times, their climatic and hydrologic significance is not yet known.

INTRODUCTION

Gleaming snow and glacial ice on the upper slopes and the deep forests on lower hills and narrow valleys are the dominant features of the imposing landscape that is Mount Rainier volcano, Wash. (frontispiece). The glaciers have scoured the valleys repeatedly and have left well-formed moraines and scattered gravel deposits to mark their past positions. The ages of trees growing on these landforms record the sequence of formation of the landforms. Ideal growing conditions at elevations far below timberline allow tree seeds to germinate within 1 to 16 years after the ice has melted from a moraine or after melt water has ceased to flow across gravel deposits. Hence, the age of the oldest trees on a landform is reliable evidence of the landform's minimum age.

Melt water from glaciers of Mount Rainier and other mountains is used for hydroelectric power, and glaciers in some places pose a threat to works of man. An understanding of past glacier activity and mechanism of ice movement, therefore, has considerable economic importance in providing an understanding of fluctuating water supplies. In addition, as advance and retreat of glaciers is related to climate, knowledge of the past behavior of glaciers allows inferences to be drawn about past climatic variations.

Inferences about fluctuations in climate cannot be made from the observed sequences of past glacier activity because adjacent glaciers may not necessarily respond similarly to climatic fluctuations. End and lateral moraines from which glaciers started to recede just before 1835–40 may have climatic significance when more is learned about glacial response to climate. Moraine segments of this age were found downvalley from seven of eight glaciers studied. Below Nisqually and Tahoma Glaciers moraines of this age represent advance farther downvalley than at any other time in the last 10,000 years.

PURPOSE AND SCOPE

Since our initial reconnaissance work (Sigafoos and Hendricks, 1961), we have studied the young moraines below five additional glaciers and more areas on moraines below the three glaciers reported earlier. This report, which primarily documents our work to date, shows sample areas, moraines, and a few other periglacial features on aerial photographs and planimetric maps, presents summaries of our data, and discusses the significance of ages of trees on certain landforms. Each glacier is discussed in turn clockwise around Mount Rainier, starting with Nisqually Glacier (pl. 1). Additionally, the work is so documented that future investigators may visit the sites and observe the changes that passing years have brought about. We hope that the report will help the interested person understand some of the periglacial features that he sees along the trails and from some vantage points along the roads that overlook the major glaciers. The folded maps in the case present a summary of data about each glacier.

METHODS, DOCUMENTATION, AND TERMINOLOGY

The methods used in this study have been previously reported (Sigafoos and Hendricks, 1961), but several underlying premises and details of the methods need to be emphasized. One of the most important, and at the same time most overlooked, facts is the significance of living plants in the environment. Plants will grow in every environment unless some force prevents them from growing. The force may be related to climate, such as hot, dry conditions prevalent in deserts, or the perennial snowfields on mountain tops. It may be the physical power of glaciers, of flowing water, or of movement of rock and soil in landslides or by frost heaving. It may be fire, or it may be man's activity. It may even

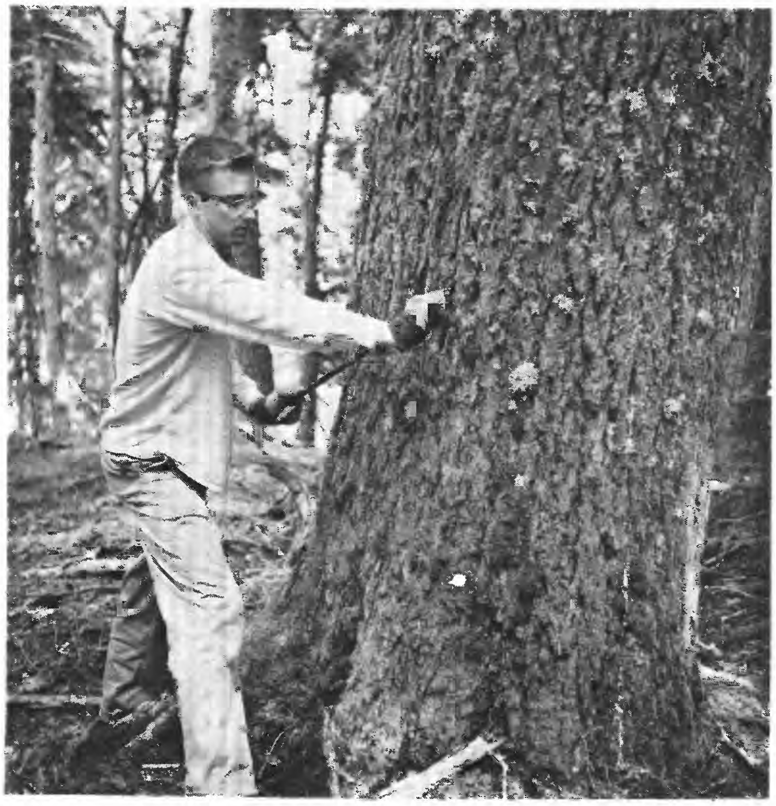


FIGURE 1.—*Left*: Samples can be taken from larger trees no closer than 2–3 ft above the ground; so the error in age determination is equal to the age of a small tree 2–3 ft tall and may be as much as 50 years. This 43.4 in. western hemlock was 4 ft tall in A.D. 1542 and is growing on an old Carbon Glacier moraine, area 8 (fig. 1 on pl. 5). *Right*: Each annual ring, seen here diagrammatically in vertical section, consists of an elongated cone; the trunk is composed of ever-larger cones superimposed one upon another. The upper tip of each cone was once the tip of a small tree and, with the cone, remains in the same position throughout the life of the tree. Each line represents the tree shown in the photograph as it probably appeared in A.D. 1542.

be passive by being related to space; for example, a large area may be denuded of forest by fire, and much of the area may be too remote for seed to travel from sources in living trees and other plants. Thus, if plants are not present at certain places in areas where plant cover is otherwise generally complete, then some force is keeping the plants from growing.

We worked in areas of moraines, outwash, and flood plains in the bottoms of densely forested canyons. These environments are ideal for the germination and growth of trees. Physical instability of moraines that results from the melting ice plus the scour of alluvium and moraines by flood and melt water are the primary forces that prevent survival of seedlings. Once these forces disappear, trees will become established in 1 to 16 years (Sigafoos and Hendricks, 1961, p. A13). This period was established by determining the ages of trees on surfaces whose date of formation is known from other evidence (Sigafoos and Hendricks, 1969).

The age of a tree is estimated from a count of annual rings in a section or a core extracted from a tree with an increment borer (fig. 1). The $\frac{3}{16}$ inch-diameter core is then placed in a special clamp, cut across the grain with a razor-sharp knife, and rings counted. The age, species, sample number, core height, and trunk diameter are recorded. Back in the office annual rings in each core are again counted.

By sampling several trees of each species at a locality, the authors were able to identify the probable oldest tree at that locality. By sampling at many localities, we are able to plot ages of the oldest trees on a map. Lines then are drawn to connect points with similar ages; thus, positions of the glaciers during several periods in the last 600 years are shown. In the study, a total of 1,373 trees were cored. A diligent attempt was made to include the center ring of each tree at a level as close to the ground as possible (fig. 2), and it is the year that this ring grew that is listed in the table. This date is obtained by subtracting the number of annual rings in a complete sample from the number of the year after the outer ring was formed. The next year must be used, for although the last year of growth of a tree is not complete by midsummer, for dating purposes the outer ring and growth year are complete.

The error in determining absolute tree ages increases with the size of the tree. The age of the smallest and youngest, up to 3 inches in diameter and 20 to 30 years old, is exact because most of the few trees of this size were already cut, and a section that provides a complete set of rings was taken from the lowest part of the trunk. Other larger trees were cored as close to the base as possible; so the error in age determination of trees up to 2 feet in diameter and 200 years old is probably less than 10 years. Age

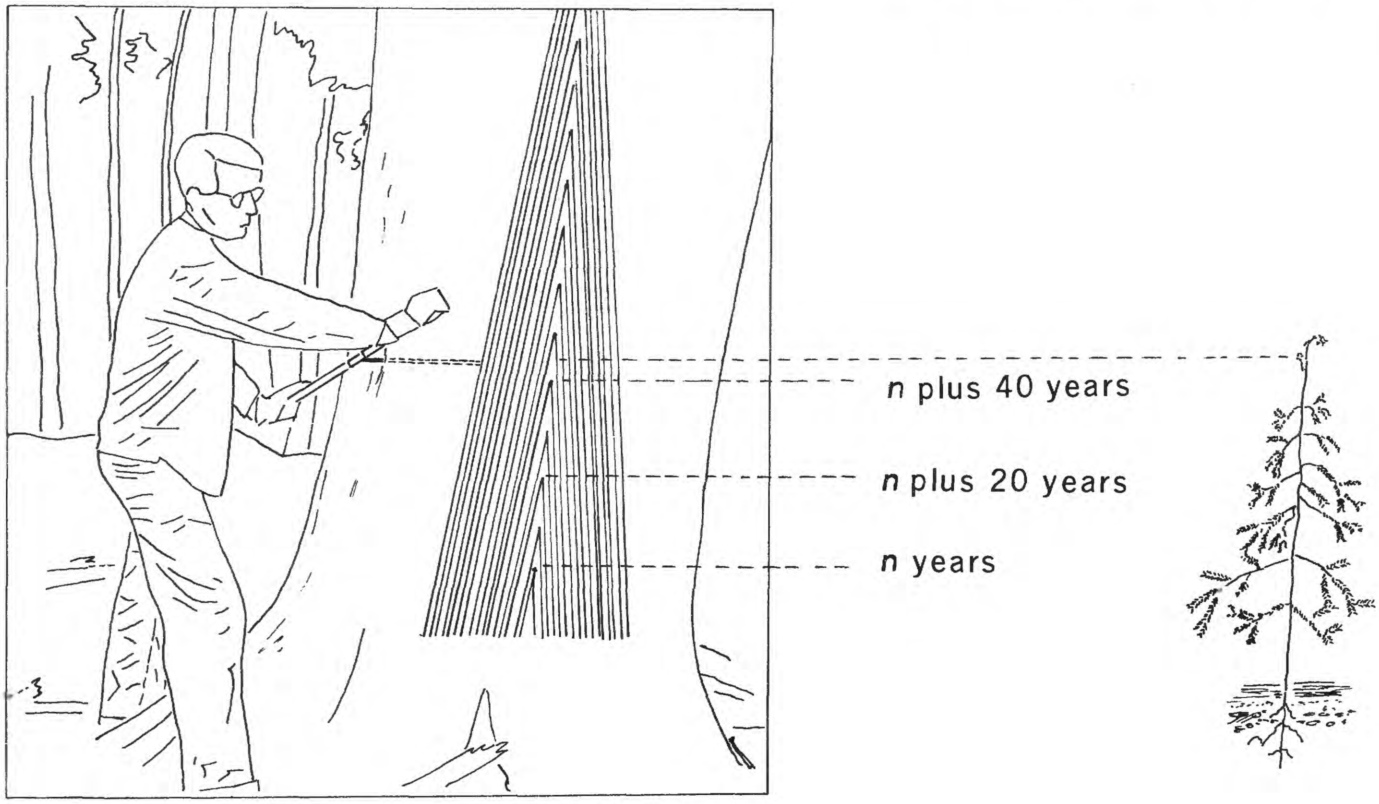


FIGURE 2.—Trees are sampled at the lowest possible level to determine their age. Carbon Glacier started to recede from here about 1845 (area 11, Carbon Glacier) (fig. 1 on pl. 5). July 17, 1963.

determinations of these trees are fairly accurate because the age of the oldest trees at different places on nearly continuous moraines is nearly the same. The error in age of trees up to 4 feet in diameter and 400 years old, however, may be as much as 50 years. Core samples cannot be taken easily lower than 2 to 3 feet above the ground because of the length of the borer handle and the physical effort required to core large trees.

Each vertical aerial photograph included in this report shows positions of former ice margins that are marked by prominent moraines or by other field evidence. Positions of significantly different age, generally a hundred years or more, are differentiated by colored lines. Positions marked by lines of the same color on different plates indicate our belief that different glaciers occupied these positions contemporaneously. Prominent ground features can be identified on the photographs unless the features were destroyed since the photograph was taken. With the aerial photographs, the maps, and the ground photographs of selected key places, the interested person can locate himself with reference to moraines and other surface features. The photographs are not orthographically true; that is, the scale of the photograph varies from place to place depending upon the distance between the ground and the aerial camera. This distortion on the photographs accounts for the anomalous curvature of some lines. Measurements made from the photographs, furthermore, are inaccurate.

The glacier maps, made by photogrammetric methods from 1960 aerial photographs, are believed to be sufficiently accurate for general cartographic measurements to be made from them. They are included, not only to permit measurements to be made, but to identify named features discussed in the report and to show the location of features that may be destroyed in the future by glacier advance or other cause.

The dated lines on the photographs and maps represent the position from which the ice started to recede at the date specified. The dates are derived by adding five years (for seedlings to become established) to the age of the oldest tree and rounding the figure to the next older five years. For example, if the innermost ring of the oldest tree sampled in 1967 grew 121 years ago, then the approximate date the ice began receding is 121+5, subtracted from 1968, yielding 1842, rounded to 1840. The interval between the computed date and the present date represents the minimum time that the area has been free of glacial ice.

The periglacial feature designated for each area is a general descriptive name for the site. Some are common terms, but certain features may not be familiar to all readers. Old surface (OS) refers to an area that has not been glaciated for periods as long as 10,000 years. Outwash (OW) is a deposit of the sand, gravel, and boulders left by the melt-water stream emanating from the glacier. Melt-water channel (MWC) is a small valley or gully cut through a moraine by melt water and floored with outwash. Flood plain (FP), as used in this report, is the surface inundated by the glacial melt-water stream once a year or more often.

NISQUALLY GLACIER

Just 130 years ago, in the 1840's, about the time Europeans settled the Puget Sound region (Brockman, 1940, p. 21), it would not have been possible to walk in the small stand of trees between the present parking area and the old road under the Nisqually Glacier bridge at the Nisqually River. Not only did the forest not exist, but ice many tens of feet thick filled the valley bottom at this point and extended about 750 feet downvalley from the present bridge site (figs. 1, 3, and map on pl. 2). The position occupied by Nisqually Glacier in the 1840's is marked by a prominent, bouldery ridge representing the maximum advance in at least 10,000 years (Crandell and Miller, 1964). The moraine, here called the 1840 moraine, is seen, in the photograph, just inside the dense forest (area 24) north of the parking area (fig. 2 on pl. 2) at the west end of Nisqually Glacier bridge, and then it slopes steeply across the road to the bare gravel of the Nisqually River flood plain. The difference in appearance of the forest on opposite sides of the moraine is striking. The forest is open on the east side where trees range from 1 to 2 feet in diameter and only small logs are present on the ground. On the west side the forest is dense; trees are large, ranging from 2 to 5 feet in diameter, and the ground is littered with logs equally large (see table 1).

TABLE 1.—*Nisqually Glacier: ages of trees sampled from periglacial features*

[Periglacial feature: OS, old surface; M, moraine; OW, outwash]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
9	2	1696	OS
16	4	1804	OS
35	1	1735[1]	OS
3	5	1834	OW
8	7	1688	OS
6	9	1670	OS
31	7	1760[1]	OS
1	4	1682	OS
19	21	1656	OS
25a	1	1757	OS
10	11	1844	M
17	3	1847	M
26	10	1845	M
7	4	1843	M
5	8	1843	M
4	4	1868	M
24	3	1895	M
20	33	1847	M
2	2	1858	M
25	9	1842	M
28	5	1855	M
11	8	1862	M
27	2	1858	M
21	7	1852	M
23	5	1874	M
30	1	1890	M
29	2	1906	M
34	7	1912	M
14	4	1904	M
13	3	1908	M
12	5	1900	M
11a	4	1923	M
18	2	1905	M
22	5	1912	M
32	10	1913	M
15	4	1921	M
33	3	1924	M

[1] 4.0-ft hemlock, inner 2.0-ft rotten.

During the last 10,000 years, when Nisqually River valley below the 1840 moraine was free of ice, at least eight geologic events affected the forested slopes. Four or more of these were debris flows that deposited varying amounts of rock and mud as far as 25 miles downvalley from Nisqually Glacier (Crandell and Mullineaux, 1967, p. 10). The other four events were deposition of layers of pumice from eruptions of Mount Rainier and of other volcanoes.

The most prominent pumice deposit here is yellowish to reddish brown and can be seen at the top of road embankments opposite the parking area west of the 1840 moraine. Excavation in the old forest floor reveals that a thick humus mat of decayed wood overlies the ash layer. This ash erupted from Mount St. Helens 3,000 to 3,500 years ago (Crandell and others, 1962).

Lt. A. V. Kautz, stationed at nearby Fort Steilacoom, first recorded observations of the front of Nisqually Glacier and reported in 1857 that it was at a "rock throat" (Brockman, 1938, p. 769–770; Giles and Colbert, 1955, p. 4; Meany, 1916, p. 82–83). Three trees mark the approximate position of the glacier reported by Kautz (fig. 2 on pl. 2). The older of two trees, area 27, was about a foot tall in 1858 and the oldest of five at area 28 was the same size three years earlier in 1855. The glacier terminus in 1857 was not beyond the location of these trees.

Two other moraines are especially prominent on the open and shrubby slopes above the river upvalley from the bridge; these possibly represent minor readvances of stillstands of the glacier margins in the last 100 years. The end of the older moraine is seen on the bank north of the old bridge site. The other, largely hidden by alders on the slope near Tato Falls, is apparent as a narrow ridge on the nearly bare slope above Tato Falls and upvalley. The assigned dates are arbitrary, as insufficient data are available to define them precisely. The glacier margin probably was at the indicated position within 10 to 15 years of the assigned dates.

Like other glaciers at Mount Rainier, Nisqually Glacier until just a few years ago has, in general, been receding for more than a century. Also like the other glaciers, it has been advancing the past few years. Between July 1960 and September 1966, the front of Nisqually Glacier advanced about 1,250 feet (derived from examination of aerial photographs).

SOUTH TAHOMA AND TAHOMA GLACIERS

South Tahoma and Tahoma Glaciers (fig. 4 and map on pl. 3), descending the west slope of the volcano, are separate throughout most of their lengths. The two glaciers were, however, connected at altitudes between 7,500 and 8,500 feet in 1967 (M. F. Meier, U.S. Geological Survey, written commun., 1967). One fork of Tahoma Glacier also joined South Tahoma Glacier at about 5,000 feet in altitude (fig. 3) until sometime after 1910. (See also Mount Rainier National Park topographic map, U.S. Geological Survey, 1910 (revised 1955)). Because of these interconnections now and in the past, one might expect the two glaciers to behave similarly; however, South Tahoma left two datable moraines, whereas Tahoma left three, only one of which has a South Tahoma counterpart. This moraine is referred to as the 1835–40 moraine; for these two glaciers, as well as Nisqually and Puyallup Glaciers, the moraine of this approximate date is the most extensive of any that was dated. Moraine segments of this age were also found at Carbon, Emmons, and Ohanapecosh Glaciers.

SOUTH TAHOMA GLACIER

South Tahoma Glacier (figs. 5 and 6 on pl. 3, frontispiece) was an extensive and almost as far downvalley in 1840 as it was in 1550. During these two periods, the glacier formed moraines about 2 miles east of the former site of Tahoma Creek Campground.

The Tahoma Creek trail meets the Wonderland Trail (fig. 4) at the front of the outermost end moraine. Southward the Wonderland Trail, toward Indian Henry Hunting Ground, climbs steeply from Tahoma Creek across the terminal moraine (fig. 5) before it passes into the old forest along the stream draining Mirror Lakes.

Northeastward from the trail junction, the Wonderland Trail follows a prominent lateral moraine toward the nose of Emerald Ridge (fig. 6) or is just below it for another half-mile. At a switchback, the trail crosses the moraine to enter the old forest; farther on it rejoins the lateral moraine.

A short segment of moraine marking an old position of the glacier front lies at the junction of Tahoma Creek Trail and Wonderland Trail on top of a cliff above Tahoma Creek. The oldest of eight trees cored here was 3 feet, 5 inches tall in A.D. 1528, and others were about that size within a few years; so the advance that formed this moraine ended not later than the early part of the 16th century.

The most prominent moraine of South Tahoma Glacier rests along both sides of the valley upon which trees started to grow between about 1835 and 1860. This moraine was pushed there by the glacier after it overrode in most places all older moraines.

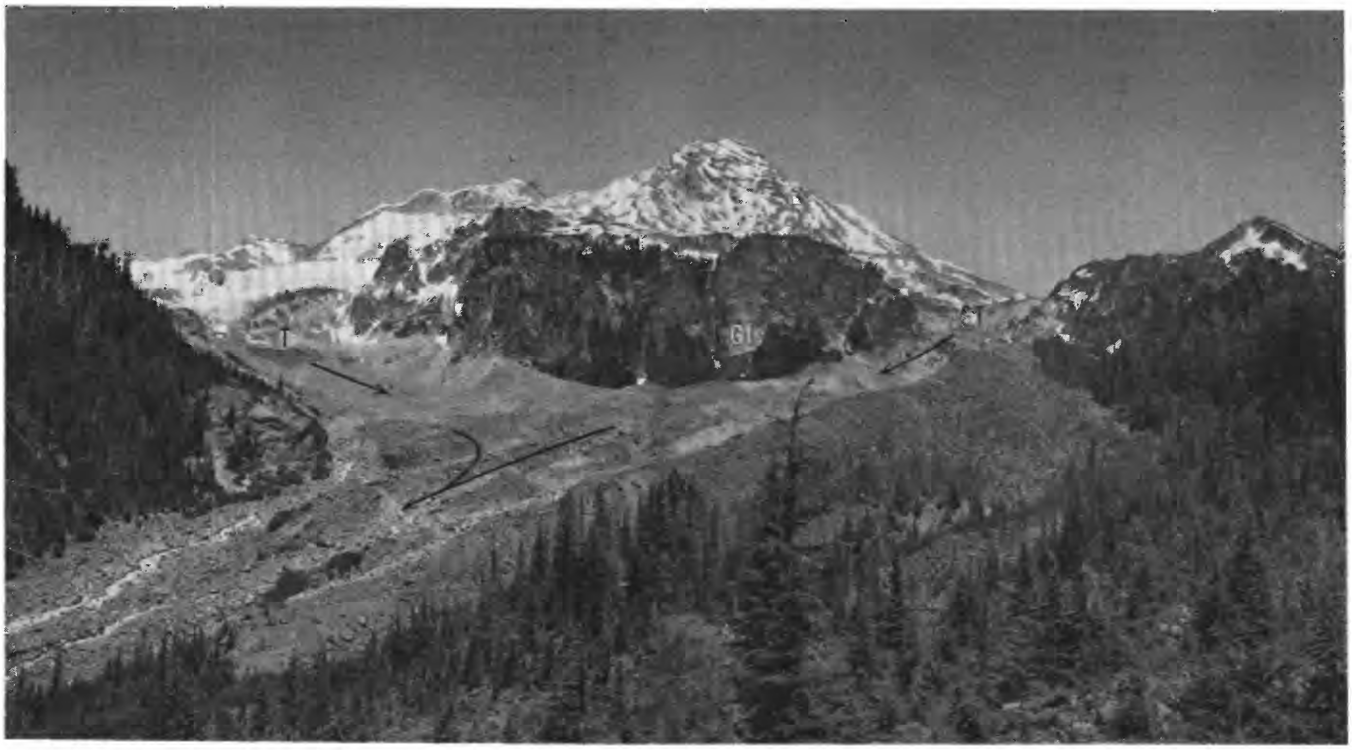


FIGURE 3.—South Tahoma Glacier (**ST**) and Tahoma Glacier (**T**) joined in 1910 below Glacier Island (**GI**) and extended out of view to the lower left. July 15, 1960.

FIGURE 4.—From its junction with Tahoma Creek Trail in the immediate foreground, Wonderland Trail leaves the 1550 moraine and crosses the 1840 moraine where the man is standing. View from area 16 looking toward area 13, taken on Sept. 9, 1967.

FIGURE 5.—The 1835–50 lateral moraine of South Tahoma Glacier is seen here where Wonderland Trail crosses it before entering the old forest. The men are standing on the moraine; the man on the left is on the crest, the other is standing near the edge of the old forest. Sept. 14, 1967.

FIGURE 6.—The small boy in the center is standing in the gully between the 1840 moraine (area 18) on the right and the older surface on the left. Wonderland Trail is to the right about 25 feet downslope from the moraine. July 8, 1961.

The moraine is plastered against the upvalley edge of the 1550 moraine. Ice started to recede from the extensive moraine about 1840 and has been receding nearly ever since, but at a variable rate. Maximum ages of trees in several places on post-1840 morainal ridges suggest that the glacier readvanced a short distance before 1860 and had receded from areas 13, 10, and 5 by about 1860 (table 2).

The smaller trees south of the moraine between areas 2 and 7 probably are younger than the older trees at area 1. Because they lie outside the moraine, their relative youth (started to grow about 1860), however, is not readily explained. Only one tree was sampled in this forest of smaller trees (area 6), thus the surface cannot be accurately dated. It is possible that the trees started to grow about 1860 and date the cessation of drainage of a small melt-water pond bordering the ice. Wonderland Trail passes through this stand of young trees beyond area 2 (map and fig. 6 on pl. 3).

TAHOMA GLACIER

In the 1830's, Tahoma Glacier (map on pl. 3, frontispiece) was more than a mile farther downvalley than it is today. The ice front towered 300 feet above the present level of Puyallup River, a mere 200 feet from the trail bridge. At least once

TABLE 2.—*South Tahoma Glacier: ages of trees sampled from periglacial features*

[Periglacial feature: OS, old surface; M, moraine; OM, old moraine; OW, outwash]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
18a	1	1778	OS
17a	1	1558	OS
14a	3	1616	OS
6	1	1860	OS
1	2	1609	OS
16	7	1528	OM
20	2	1877	M
18	6	1845	M
14	8	1843	M
19	6	1848	M
7	1	1855	M
4	9	1861	M
3	13	1849	M
2	10	1843	M
10	7	1862	M
11	5	1878	M
17	4	1868	M
15	2	1863	M
13	2	1863	M
5	6	1863	M
8	8	1864	M
9	8	1871	M
21	1	1904	M
12	1	1882	OW

before, nearly 400 years ago in the early 1600's, Tahoma Glacier was as extensive as it was early in the last century (map, figs. 3, 5 on pl. 3).

The 1835–40 moraine (dated by tree ages from 14 sample areas) is not prominent where Wonderland Trail crosses it about 100 yards east (upvalley) of the South Puyallup River Trail junction. South of the trail, the valley sides are steep; any moraine once here has since slumped to the valley bottom. From the trail to the South Puyallup River, the moraine consists of a low ridge of boulders that trends downvalley. Upslope from the trail the moraine is conspicuous in the forest and, except for a few gaps, can be followed nearly three quarters of a mile along the south side of the valley from area 10 to area 31 (map, figs. 3, 5 on pl. 3).

About 75 feet upslope from the point at which the 1835–40 moraine crosses the Wonderland Trail (map, figs. 3, 5 on pl. 3), two roughly parallel moraines may be seen (Sigafoos and Hendricks, 1961, fig. 15). The northern ridge is the 1835–40 moraine. The southern ridge is an older moraine; trees on it are conspicuously larger, and the oldest tree (area 14, table 3) started to grow before A.D. 1629. Most of the remainder of the older moraine represented by this segment was destroyed by a more recent glacial advance and by stream erosion and avalanches. Only two other segments have been found, at areas 19 and 34. The oldest tree on the moraine at area 34 started to grow before 1623; therefore, Tahoma Glacier receded from this position early in the 17th century.

Since about 1835, Tahoma Glacier has been shrinking, and although minor advances may have produced small morainal ridges, erosion and deposition

TABLE 3.—*Tahoma Glacier: ages of trees sampled from periglacial features*

[Periglacial feature: OS, old surface; M, moraine; OM, old moraine; YM, young moraine; OW, outwash]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
32	1	1681	OS
20a	1	1589	OS
8	3	1622	OS
15	3	1544	OS
19	4	1676	OM
7	6	1640	OM
14	2	1629	OM
34	4	1623	OM
39	4	1788	M
40	2	1777	M
41	6	1761	M
42a	3	1839	M
31	12	1844	M
22	3	1843	M
21	3	1845	M
20	8	1852	M
18	6	1847	M
17	10	1849	M
16	5	1844	M
13	5	1866	M
12	9	1844	M
11	7	1844	M
6	10	1841	M
9	8	1858	M
10	5	1851	M
35	4	1851	M
36	3	1859	M
52	7	1855	M
51	6	1862	M
4	11	1861	M
5	7	1857	M
57	10	1863	M
58	11	1852	M
44	4	1873	OW
43	4	1868	OW
60	4	1862	OW
24	3	1870	M
23	3	1862	M
56	10	1866	OW
59	10	1853	OW
42	7	1904	YM
45	8	1909	YM
37	5	1907	YM
46	6	1900	YM
47	6	1898	YM
48	2	1915	YM
49	11	1909	YM
50	10	1912	YM
55	4	1914	OW
54	6	1910	OW
30	3	1944	OW
29	6	1935	OW
28	4	1927	OW
27b	5	1925	OW
27a	2	1944	OW
26	7	1918	OW

destroyed or buried them, so that precise ice positions in the last century cannot be determined. The trail between the small stream (south of area 50) and areas 46–45 crosses gravel and boulder fields (fig. 7) deposited by water emerging from the ice when the glacier filled the valley eastward from a line between areas 27a and 45. The lines representing the ice margins in 1860 and 1910 are only approximately located; however, the glacier could not have been farther downvalley than the lines indicate because trees at sample areas 49 and 50, downvalley from the 1910 line, started growing before 1909 and 1912. Those at areas 4 and 5, downvalley from the 1860 line, started to grow before 1861 and 1857.

East of area 42 (fig. 2 on pl. 3), the trail follows a knife-edged ridge flanked by the Puyallup River on the north and a steeply sloping, gravel-floored valley on the south (fig. 8). To the southwest in the narrow open valley, morainal ridges (areas 39, 40, and 41) remain at the base of the hill. Tree ages at these areas suggest that the glacier tongue that extended down this valley started to recede about 1760.

Bouldery material was deposited in the same narrow valley by streams flowing from the side of Tahoma Glacier until about 100 years ago. The bouldery deposit is exposed in two deep gullies adjoining areas 43 and 44, which were eroded between about 1865 and 1910. During this interval a gravel and boulder fan (areas 54 and 60) was built just southwest of the camera point of figure 8. Flow of glacial melt water and deposition of gravel stopped about 1910 and permitted trees to grow in the channels. Melt water through this valley between about 100 and 60 years ago ceased or markedly declined in volume; otherwise the trees at areas 43, 44, and 60 would not have started to grow a little more than 100 years ago. Flow began again or continued at a low volume until about 60 years ago, when melt water from the glacier ceased completely.

The various moraines shown on plate 3, the trees, their ages, and deposits at areas 43, 44, 54, 55, and 60 suggest the following sequence: (1) A glacier advance that formed a moraine from which the glacier started to recede about 1625; (2) a readvance followed by a recession that started about 1760; (3) another glacier advance that formed the 1835–40 moraine; (4) recession from this moraine during which melt water deposited material to the southwest at areas 43, 44, and 60; (5) cessation of or marked decrease in melt-water flow southwestward which permitted the trees to become established at areas 43, 44, and 60 about 1860; (6) continued low flow of melt water southwestward that eroded the two gullies and deposited the gravel and boulders at areas 55 and 54; and (7) cessation of flow because the melt-water outlet receded below the narrow ridge (fig. 8) and permitted trees to start growing shortly before 1910 at areas 54 and 55.

EMERALD RIDGE, TAHOMA GLACIER

Tahoma Glacier splits into one arm that plunges down South Puyallup River valley and into a smaller

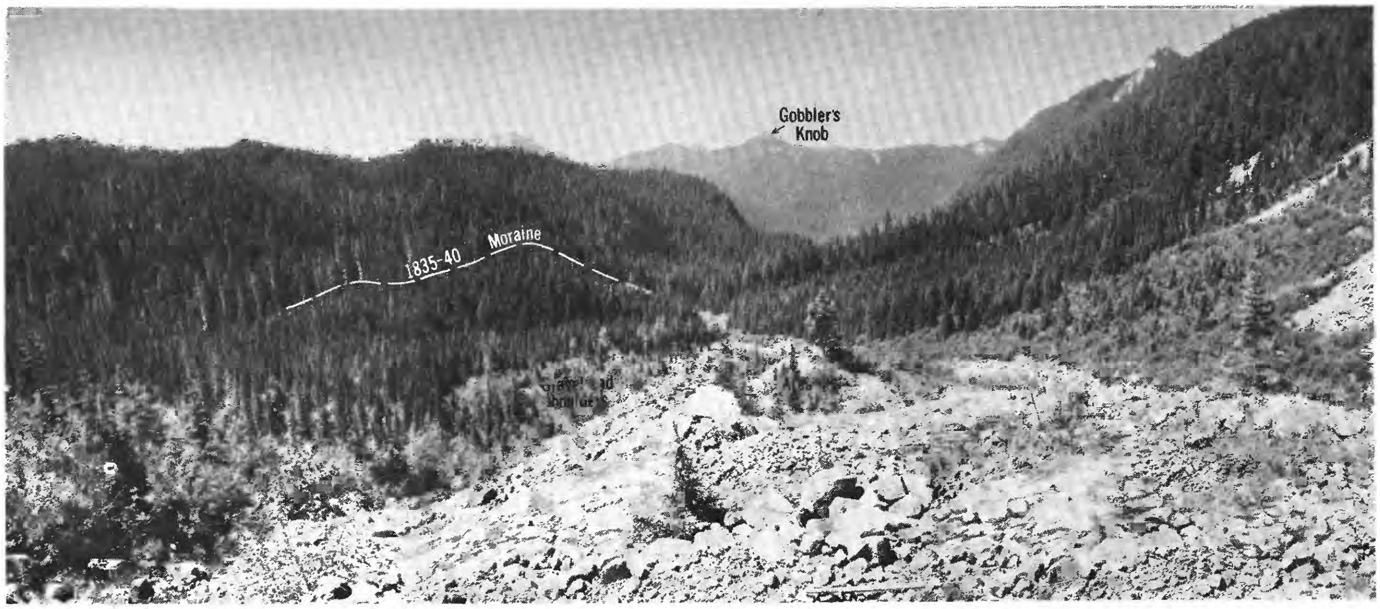


FIGURE 7.—Tahoma Glacier covered the rocks in the foreground and filled the lowland of South Puyallup River to the left of and just beyond gravel and boulders as recently as 1860. About 1835–40, Tahoma Glacier started to recede from area of the dashed line.

arm that extends southwestward toward Tahoma Creek valley (map and fig. 4 on pl. 3; fig. 3). The southwestward-trending arm left several prominent moraines on the east side of Emerald Ridge where Wonderland Trail descends into Tahoma Creek valley (map and fig. 1 on pl. 3). The glacier started to recede from these moraines before 1850.

The moraines here are between 5,000 and 5,400 feet above sea level and close to timberline. The time between the start of glacier recession and seedling establishment at timberline may well be longer than the 5 to 10 years estimated for moraines at lower elevations (Sigafoos and Hendricks, 1969). At Emerald Ridge, the date when South Fork Tahoma Glacier receded from the moraines is not known and how much time passed before seedlings started to grow cannot be determined. Thus, although the ages of the oldest trees on the Emerald Ridge moraine differ between areas, the age differences do not necessarily mean that the forest in area 22, for example, is younger than in areas downvalley, such as area 65b (table 4). Some trees are younger than others, but the moraine probably is one age.

The tree ages at Emerald Ridge show that South Fork of Tahoma Glacier in 1850 could not have extended beyond the moraine which the trail parallels. Apparently the glacier started to recede from this moraine, the highest on the slope, when Tahoma and South Tahoma Glaciers began to recede around 1835–40. If this is true, then the lag between glacier retreat and seedling establishment at timberline is from 15 to 35 years.

TABLE 4.—*Emerald Ridge: ages of trees sampled from periglacial features*

[Periglacial features: moraines]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree
22	5	1871
33	2	1866
65a	1	1886
65b	9	1857
65c	3	1863

A melt-water stream flowing from the west side of the south arm of Tahoma Glacier to Tahoma Creek eroded a deep gully diagonally across part of the 1850 moraine (between areas 33 and 65a). Because the stream eroded part of the moraine, the gully and the gravelly debris along the trail in the open valley north of area 22 are younger than the moraine.

FIGURE 8.—Wonderland Trail follows the narrow ridge extending from the trees in the right foreground to margin of photograph at the right. Tahoma Glacier extended down the steeply sloping valley on the left and formed a moraine which is out of sight. On the left the open valley supporting small scattered trees is floored with gravel deposited before 1865. This gravel was eroded by melt water between 1865 and 1910.

SUMMARY, SOUTH TAHOMA AND TAHOMA GLACIERS

Approximate dates that South Tahoma and Tahoma Glaciers started to recede, including the date for glacier arm below Emerald Ridge, are summarized in the following table:

Age of moraines, A.D.

South Tahoma	*Tahoma*	*Emerald Ridge*
1520	--	--
--	1620	--
--	1755	--
1835	1835–40	1850

The variety of moraines and their ages show that one cannot correlate glacier retreats closely without precise information on morainal ages.

PUYALLUP GLACIER

Puyallup Glacier (figs. 1 and 2 on pl. 4) came to within 250 yards of the present parking area at the end of West Side Road about 120 years ago. During the advance to this point, ice cascaded in tongues down two steep valleys (fig. 3 on pl. 4) and joined, to flow downvalley. The moraines that were left when the glacier receded are low and quite short. Two active rock slides eroded or buried lateral moraines on the steep valley wall north of the Puyallup River. These slides and snow avalanches or a wind storm, or both, destroyed a large area of forest that recently grew on the moraines. A few trees remain on two prominent ridges in the valley bottom on the north side of the river (map on pl. 4).

The 19 trees sampled in four areas (table 5) include most of the large trees on two moraines of Puyallup Glacier. This small number of trees did not permit us to select trees of many different species or of a wide range of trunk diameters. It is not possible, then, to conclude that the oldest sampled trees are among the first to grow after the ice receded. The oldest in areas 1 and 3 indicate that the moraine represents the position from which the northern tongue of Puyallup Glacier started to recede about 1840. Another more conspicuous moraine (area 4, map on pl. 4), visible from the parking area at the end of the closed part of West Side Road (fig. 3 on pl 4), is characterized by many fallen tree trunks, alder shrubs, and a few standing trees. This ridge is upvalley from the 1840 moraine.

These two ridges represent the maximum downvalley position of Puyallup Glacier in modern time. Tree ages show that the glacier was not farther downvalley after 1846 than the position of the moraines discussed above (map and fig. 3 on pl. 4).

TABLE 5.—*Puyallup Glacier: ages of trees sampled from periglacial features*

[Periglacial features: moraines]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree
1	9	1847
3	3	1846
2	3	1855
4	4	1873

CARBON GLACIER

The advancing front of Carbon Glacier (map and figs. 1 and 4 on pl. 5) is closer to moraines which mark its maximum advance since postglacial times than any other major glacier at Mount Rainier. In September 1966, the front was barely more than half a mile upvalley from a moraine formed about A.D. 1760. Unlike some other glaciers at Mount Rainier which are advancing over stagnant ice, Carbon Glacier advanced about 250 feet over bedrock and gravel between July 1960 and September 1966 (time derived by comparison of aerial photographs).

Wonderland Trail passes within a few feet of the remnant of the terminal moraine from which ice started to recede about A.D. 1760 (table 6) (area 4)

TABLE 6.—*Carbon Glacier: ages of trees sampled from periglacial features*

[Periglacial features: OW, outwash; M, moraine; FP, flood plain]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
7	3	1640	OW
3	5	1513	M
8	3	1519	M
4	12	1763	M
2	11	1840	M
10	9	1851	M
9	8	1856	M
11	10	1847	M
5	7	1851	M
1	2	1879	M
1a	3	1876	M
12	5	1903	FP
13	5	1901	FP
14	7	1907	FP
6	4	1937	FP

(fig. 5 on pl. 5). Two lateral moraines formed by minor readvances after the recession from the terminal moraine are prominent within the forest on the east side of Wonderland Trail (areas 1 and 2) opposite the point where the trail formerly crossed Carbon River. The older of these two, dating from 1835, is represented on the west side of Carbon River by a small ridge several hundred feet above the river (area 10), and at a lower altitude where it is crossed by the old trail (area 11).

The oldest moraines near the terminal moraine are short segments lying on each side of the valley. On the east side, the moraine (area 3) is 100 to 200 feet upslope from the younger moraines (areas 1 and 2). On the west side of the valley a small ridge (area 8) is seen where the Spray Park Trail turns up Cataract Creek a few feet south of the bridge (figs. 2 and 3 on pl. 5). A thick layer of yellowish-brown sandy volcanic ash which erupted from Mount St. Helens between 3,000 and 3,500 years ago (Crandell and others, 1962, p. D67) is present beneath till of the moraine and just beneath the forest humus less than 500 feet north of Cataract Creek. Thus Carbon Glacier has not advanced beyond this part of the valley in several thousand years.

Steep walls enclosing the narrow Carbon River valley combine with the steeply sloping valley floor to provide forces that have destroyed most moraines that once may have existed, especially on the east side of the valley. Gravity acting upon newly deposited moraines, aided by rock and snow avalanches from above, could have destroyed moraines that may have existed in many places on both sides of the valley.

The steeply sloping valley floor results in extreme velocities of water draining from the glacier. Floods of great size have destroyed parts of the terminal and lateral moraines and have left deposits of boulders like those in the Carbon River valley opposite the mouth of Cataract Creek. The Wonderland Trail crosses one of the flood channels supporting alder shrubs and small trees for some distance north (downvalley) of the 1760 moraine and south to the junction with the old trail near area 1a. Areas 12 and 13 are in this channel, as is area 14 west of Carbon River. The fact that the oldest trees in these areas started to grow between 1901 and 1907 suggests that a catastrophic flood occurred in Carbon River at the turn of the century which denuded most if not all of the flood-plain area. This flood probably was much larger than the November 23, 1959 flood that destroyed part of the Carbon River road upvalley from Ipsut Creek campground.

WINTHROP GLACIER

In a dense forest low on the west slope of Burroughs Mountain (fig. 1 on pl. 6), Wonderland Trail crosses a conspicuous pumice-covered lateral moraine of Winthrop Glacier marking an advance that occurred near the end of the Fraser Glaciation, probably between 11,000 and 12,000 years ago (D. R. Crandell, U.S. Geological Survey, written commun., 1972).

Farther downslope, the trail parallels, then crosses, younger moraines (area 4, fig. 5 and map on pl. 6, table 7) which show many features different from those on the higher slope. The trees are smaller and younger, the forest floor is rocky, humus is thin, and coarse pumice is not present. Where the trail enters the young moraines, the oldest tree found started to grow around 1670. A short distance upvalley, at area 7, trees started to grow about 1655. These trees are among the first to grow after Winthrop Glacier started to recede from a modern advance delimited by these moraines.

TABLE 7.—*Winthrop Glacier: ages of trees sampled from periglacial features*

[Periglacial features: M, moraine; OS, old surface]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
5	3	1670	OS[1]
4a	1	1666	OS[1]
10	2	1533	OS
7	10	1655	M
4	11	1672	M
1	10	1730	M
11	3	1723	M
9	6	1716	M
6	6	1794	M
7a	1	1773	M
8	5	1774	M
2	14	1760	M
1a	4	1725	M
3	10	1822	M

[1] Coarse pumice present.

West of Winthrop Creek, Wonderland Trail (shows faintly on photograph, fig. 5 on pl. 6) crosses nearly barren, rocky, morainal debris, most of which was deposited during the last century (fig. 3 on pl. 6). A short distance northward, downvalley from the trail, a low ridge (area 3) marks the position of a probable readvance of the ice front which started to recede early in the last century. Another 400 feet northward, about 500 feet from the trail, the bouldery surface ends abruptly at the forest margin (fig. 2 on pl. 6). This dense forest is growing on an older surface underlain by alluvium and mudflow deposits. The steeply sloping ridge here (area 1) is the terminal moraine of Winthrop Glacier from which the glacier started to recede early in the 18th century. The trail turns southwest from area 3 and is perched on the crest of the A.D. 1810 moraine until it enters the closed forest of small trees near the West Fork of White River about 750 feet north of area 9.

Two moraines, older than the A.D. 1810 moraine and younger than the 1670 lateral moraine crossed by Wonderland Trail east of Winthrop Creek, form prominent ridges in the valley but far from the trails. Both are present on the west side of the valley, whereas only one has been identified on the east side. A nearly continuous ridge skirts the east side of the low forested hill on the west side of the valley in the forest between areas 9 and 11 (fig. 5 and map on pl. 6). Ice started to recede from this moraine about A.D. 1710–20, probably contemporaneously with recession from the terminal moraine. A moraine of this age was not found on the east side of the valley, but another one from which ice started to recede about A.D. 1755–65 is present there (areas 6, 7a, and 8) (fig. 4 on pl. 6).

West of area 3, Wonderland Trail (fig. 5 and map on pl. 6) is perched on a bouldery ridge approximately 75 to 100 feet wide that protrudes about 350 feet westward across a flat, smooth plain (labeled "flat area" on the map on pl. 6). The west end of the bouldery ridge is cut by an abandoned melt-water channel. The plain is underlain by material deposited in a pond when melt water was temporarily dammed by the 1710–20 moraine. The pond was soon drained, however, when its level rose above the moraine and the water broke through, flowing into West Fork White River. The melt-water channel through the A.D. 1810 moraine was formed after the ice had receded southward farther upvalley.

The ice, seen from Wonderland Trail where it turns downvalley on the east side of Burroughs Mountain and starts to descend the inner face of the tree- and shrub-covered moraine (figs. 4 and 5 on pl. 6), is the stagnant part of Winthrop Glacier. From 1960 to 1966 the shape of the stagnant front has changed from convex to concave (based on photographic and visual evidence). Photographs (figs. 4 and 5 on pl. 6) show that Winthrop Creek flows under the stagnant ice.

The active part of Winthrop Glacier is upvalley (fig. 4 on pl. 6) opposite and south of area 6. One part of it advanced approximately 25 feet between 1960 and 1966.

EMMONS GLACIER

A massive terminal moraine that lies athwart the White River valley is the prominent hill about one-half mile west of White River Campground (map and fig. 8 on pl. 7). The earliest date when Emmons Glacier extended this far is not known, but it had receded sufficiently by 1660 for trees to begin growing at area 27 (map and fig. 9 on pl. 7). Later readvances left other ridges, the most prominent moraine being a steeply sloping one (dated 1745) that crosses the valley bottom (between areas 2 to 26, map and fig. 9 on pl. 7, table 8). In this complex of ridges and troughs, as well as in the remainder of Emmons Glacier's moraines, stand scores of mounds, gullies, and ridges as monuments to the ice front and to shifts in the landscape caused by changes in melt-water channels.

Ice started to recede about 1745 (fig. 9 on pl. 7) after leaving the prominent moraine trending across the valley, and until the last few years, the glacier has generally been shrinking; however, in the last 150 years at least two additional minor readvances left moraines. Trees started to grow on one of these between 1835 and 1850 and on another about 1900. The moraine from which the glacier started to recede between 1835 and 1850 is best seen where it is cut by Inter Fork and by the Glacier Basin Trail (fig. 1 on pl. 7) near area 31 (map and fig.9 on pl. 7). A climb 15 feet up the bank and into the woods provides one with a view of the prominent morainic ridge (area 31, fig. 2 on pl. 7). When this moraine was being formed, the margin of Emmons Glacier paralleled the present axis of Inter Fork for about one-quarter mile westward. Just upstream from the trail bridge crossing (fig. 3 on pl. 7), a moraine is present in the forest north of the trail (area 63). The glacier margin curved sharply southwestward to area 56 and thence westerly along the present channel of Inter Fork to area 34. One tree (area 56, map and figs. 6 and 9 on pl. 7) was 16 inches tall in 1866; so the glacier margin was not north of this point at that time.

Marking the last readvance of the glacier is the prominent, nearly bare inner ridge visible from the trail along Inter Fork through openings in the trees and from the promontory (area 54) about 100 feet south of the trail bridge (map and fig. 5 on pl. 7). This ridge supports only scattered small trees, but the oldest are more than 60 years old. This was probably the gravelly ridge that Willis, Russell, and Smith saw in 1896 and reported as bare (Russell, 1898, p. 407).

TABLE 8.—*Emmons Glacier: ages of trees sampled from periglacial features*

[Periglacial feature: OS, old surface; M, moraine; MWC, melt-water channel within moraine; FP flood plain]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree	Periglacial feature
41	4	1671	OS
4a	1	1552	OS
4	8	1695	OS
1	20	1773	OS
5	3	1266	OS
3	5	1541	OS
39	1	1748	OS
35	2	1778	OS
44	4	1824	OS
38	3	1563	OS
33	2	1760	M
40	6	1552	M
37	4	1596	M
36	3	1771	M
43	5	1613	M
27	5	1661	M
26	2	1738	M
25	5	1755	M
23	12	1750	M
7	11	1785	M
24	8	1749	M
6	4	1785	M
2	13	1749	M
32	4	1744	M[1]
45	8	1755	M
8	11	1803	M
28	6	1864	M
9	10	1855	M
30	8	1850	M
31	7	1825	M
63	6	1837	M
56	15	1866	M
34	2	1862	M
42	9	1854	M
59	13	1843	M
61	9	1858	M
46	9	1848	M
9a	7	1870	M
29	2	1870	M
10	6	1880	M
55	6	1882	M
47	9	1905	M
11	13	1902	M
49	7	1865	MWC[2]
50	11	1871	MWC
51	8	1917	MWC
52	14	1904	M
53	11	1920	MWC
54	11	1914	M
57	15	1909	M
58	11	1910	M
60	10	1901	M
62	8	1910	M
12–22	57	1903–57	FP[3]

[1] Location of area on slope not precisely known.
[2] Trees date minimum age of moraine channeled here by melt water.
[3] Trees sampled on flood plain existing in 1959 were destroyed by avalanches in December 1963.

Ice started to recede from lateral moraines (fig. 7 on pl. 7) about A.D. 1550, whereas only a fragment (area 27, fig. 9 on pl. 7) of an old terminal moraine was recognized. Later advances overran most of the terminal moraine dating from before 1550, or outwash from the receding glacier destroyed or buried it before 1661, as indicated by melt-water channels in the old moraine near area 27.

The older lateral moraine is prominent at area 43 about 0.8 miles from the trail bridge across Inter Fork, or about 1¾ miles from White River Campground. The trail upvalley from a point about 100 yards north of area 43 is walled in by two prominent lateral moraines before the trail turns westward across one and then another moraine and into the dense forest at areas 43 and 44. The innermost lateral moraine (area 62), toward the valley to the east and not visible from the trail, was formed before 1910; the moraine (area 46) above the trail on the east side was formed before 1845; the first moraine that the trail crosses to the west, which also has small trees on it, was formed before 1745; and the second lateral moraine(area 43) which supports large trees 1½ to more than 2 feet in trunk diameter was formed before 1600 and probably corresponds to the lateral moraine at areas 33, 36, 37, and 40 (fig. 7 on pl. 7).

The trees on the slope (area 44, map and fig. 7 on pl. 7) west of the old lateral moraine (area 43) are younger than those on the moraine, but evidence suggests that snow avalanches and fire destroyed an earlier forest. Here a moraine corresponding to the lowest one above the campground is seen 200 feet higher than the A.D. 1590–1600 moraine (area 43) (Crandell, 1965, p. 32).

Glacier Basin Trail leaves the Inter Fork flood plain just east of area 33, angles north, and steepens abruptly onto a sharp terrace at the end of an old lateral moraine. The moraine is banked against and deposited partly on top of a premoraine terrace. It continues almost uninterrupted from area 33 to area 36 and forms a high bank of Inter Fork for another quarter mile. At each end the moraine was destroyed by snow avalanches. The oldest tree (area 40) found on this section of the moraine was 2 feet high in A.D. 1552.

The moraine at area 43 probably corresponds to the moraine defined by locations of areas 33, 36, 37, and 40 (fig. 7 on pl. 7) because it is the oldest modern moraine here, and the oldest tree at area 43 is closer to the oldest at area 40 than at area 45, which defines the 1745 moraine. The range in age between the oldest tree sampled at area 43, 351 years, and at area 40, 411 years, may be expected of trees in stands of this age. The number of trees at area 43 is small, and the oldest to grow here evidently was not sampled or had died earlier.

Trees were sampled on the valley floor of White River in 1959 in areas 12 to 22 (map and fig. 9 on pl. 7), but all the sample areas were buried by rockfall-avalanches in December 1963. The deposits bury the area sampled to depths of 50 to 80 feet and are part of an estimated total volume of 14 million cubic yards of rock debris that roared down the valley (Crandell and Fahnestock, 1965). In the vicinity of area 47 living trees can be seen that had bark and branches torn from the upvalley side by flying rock debris (Crandell and Fahnestock, 1965, p. A10-A11). Many of these trees now alive will continue to survive, and the scars that remain will be datable throughout their lives (Sigafoos, 1964, p. A9-A12).

The forest downvalley from the terminal moraine (map and fig. 9 on pl. 7) appears to be composed of trees of two distinct ages, and no evidence was found of earlier generations of forest that have fallen and partly decayed. Most trees are relatively young; ages of the 30 trees sampled in areas 1, 4, and 26 range from 56 to 265 years, all younger than the oldest trees on the older lateral moraines. In the other areas (3, 4a, and 5) eight trees are more than 400 years old, and one is at least 700. The bases of the trunks of the older trees are straight sided and show no root flare (Sigafoos and Hendricks, 1961, fig. 13), suggesting that they were buried and hence are growing on a lower surface. The younger trees, however, are flared at the base, indicating that they began growing on the present surface, which may be outwash deposited when the glacier stood at the terminal moraine. This outwash may have killed most trees in its path but left a few old ones, some of which were sampled. The terminal moraine, however, represents the maximum known advance of Emmons Glacier in the last 10,000 years (Crandell and Miller, 1964, p. D113), because the next older moraines are on the slope 700 feet above White River Campground (Crandell, 1965, p. 32).

The continuity of the terminal and younger lateral moraines is broken by many small valleys cut by melt-water streams from the glacier when it filled the valley bottom. About 350 feet east of the point where the trail to the present glacier terminus climbs from the bridge to the top of the morainal ridge, at least two melt-water channels (areas 49, 50, 51, and 53) cut through the moraine complex and are floored with coarse gravel and boulders. Areas 49, 50, and 51 are successively lower surfaces in one channel (fig. 9), and ages of the trees on these deposits tell us that water flowed through area 49 not later than 1865, through nearby area 50 not later than 1870, and through area 51 not later than 1917. In 1917, water was flowing through another channel about 200 feet to the west (area 53, fig. 4 on pl. 7) and did so until 1920. At least part of the drainage from Emmons Glacier flowed from the north side and down Inter Fork from before 1865 until as recently as 1920. The older drainage ways, now high terraces of the eastern channel (areas 49 and 50), are

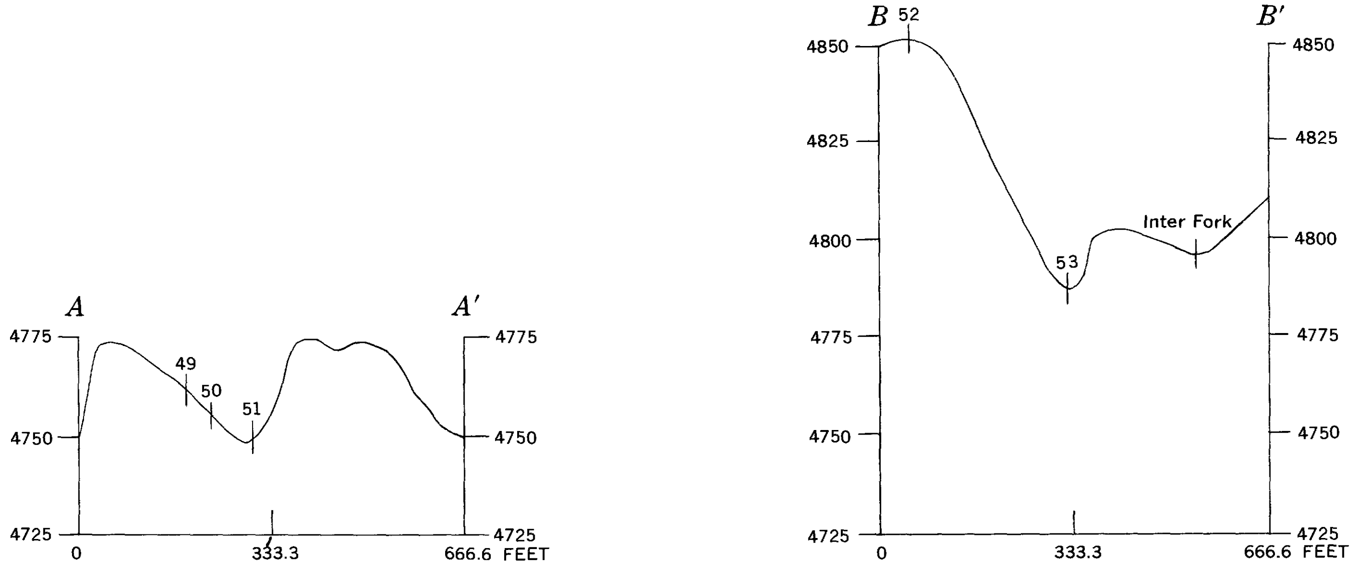


FIGURE 9.—These cross-sectional diagrams are drawn along lines through two melt-water channels shown on map of plate 7. Areas 51 and 53 are in the bottoms of the now-dry channels; areas 50 and 49 are on successively higher surfaces. Water stopped flowing over area 49 in 1865, over area 50 in 1871, over area 51 in 1917, and over area 53 in 1920. The vertical exaggeration is 6.6 times.

higher surfaces than that of area 51. It seems probable that continued flow eroded a deeper channel which dried up before 1917 when the terminus melted back from this overflow point. Either or both these two channels could be the one mapped as a stream in 1896 (fig. 10) (Russell, 1898).

Ages of trees growing in the channels between the rounded hills west of area 42 have not been determined; therefore, the periods of runoff through these cannot be related to those to the east. Because the channels cut through the 1835–50 moraine, water drained from the glacier through them into Inter Fork after the 1850's and probably when the water drained through the easternmost channels. These channels are apparent on the aerial photograph as breaks in the line of rounded hills that represent a lateral moraine.

SUMMARY, EMMONS GLACIER

Approximate ages of moraines and melt-water channels for Emmons Glacier are summarized in the following table:

Age af features, A.D.

Terminal moraine	*Lateral moraine*	*Melt-water channel*
—	—	1917
1902	1901	—
1870	—	1871
—	—	1865
1850	1848	—
1738	—	—
1661	—	—
—	1613	—
—	1552	—

The dates assigned to these features emphasize the variable behavior of Emmons Glacier and the periglacial features formed during the last 420 years. At certain times Emmons Glacier was broader and formed lateral moraines which were not overridden later, whereas at other times the glacier was narrower and extended farther downvalley, destroying or burying older terminal moraines. The melt-water channels, on the north side of the valley, show that at least some flow from the glacier was into Inter Fork, which was probably a larger stream then than it is now.

OHANAPECOSH GLACIER

Ohanapecosh Glacier lies at the head of a beautiful isolated valley high on the east side of Mount Rainier (pl. 1, fig. 12). The trail entering the valley from the southeast provides several vantage points below which the valley is laid out in full view (fig. 11). A bare amphitheater holding several perennial snowbanks, and an immobile icefield that was once Ohanapecosh Glacier, are seen near the head of the valley. The glacier remnant is a flat, sloping shelf of ice above the bedrock cliff. From these vantage points three to four curved moraines can be seen arcing down the north valley wall toward the river and partly encircling the lower end of the amphitheater (fig. 12).

The ages of trees growing on moraines formed in the recent past by Ohanapecosh Glacier tell us nothing more than the minimum ages of the moraines. At lower elevations the maximum ages of trees on a moraine, or any other young surface for that matter, closely match the ages of the surfaces, but the moraines at Ohanapecosh Glacier are close to timberline, 5,500 to 6,000 feet here. Environmental conditions affecting establishment of seedlings and growth of trees are adverse near timberline, and it is not known how long after a glacier recedes before seedlings will survive on the moraines at this altitude. The time interval may be 100 years or more on bouldery moraines in which there is no silt or fine sand in which tree seed can germinate (Sigafoos and Hendricks, 1969, p. B93). No trees or seedlings grow in the bouldery moraine shown on the right side of figure 13, and it is older than the moraine upon which the trees in the middle ground are growing. The oldest sampled tree was 3 inches tall in 1878 (table 9).

TABLE 9.—*Ohanapecosh Glacier: ages of trees sampled from periglacial features*

[Periglacial features: moraines]

Sample area	Number of trees sampled	Year (A.D.) represented by inner ring of oldest cored tree
1	4	1741
2	5	1846
3	10	1878

The three moraines upon which trees were sampled are many years older than the oldest tree. The oldest moraine (area 1) was formed before A.D. 1741; the middle moraine (area 2) before A.D. 1846; and the youngest (area 3) before A.D. 1878. At Emmons Glacier a pumice is present on moraines older than 148 years, and it is not present on moraines younger than 114 years, suggesting that the pumice was deposited between A.D. 1821 and 1854 (Mullineaux and others, 1969, p. B15–B18).

Because the pumice is present at area 3 below Ohanapecosh Glacier, this moraine must have been formed before A.D. 1820. The oldest tree, however, was only 3 inches tall in A.D. 1878; thus, a significant time interval, as much as 50 years, elapsed before the tree started to grow (Sigafoos and Hendricks, 1969, p. B92).

SIGNIFICANCE OF DATED MORAINES, CHANNELS, AND MELT-WATER DEPOSITS

The deposition of gravel and boulders by glaciers and by glacial melt water, the occurrence of slides and floods in the last few decades, and the record of similar events in the last 500 years testify to the marked changes that have occurred and are occurring in the landscape. When one views Mount Rainier from a distance, he really observes each detail for a mere instant. Because of the impressive mass of the mountain, he may depart believing that the mountain will remain in its present form forever. If, on the other hand, he could photograph the scene many times a year for 500 years and project the film on a movie screen, he would see rapid advance and melting of glaciers, frequent floods, avalanches, slides, and rapid shifting of stream channels.

Landscape features, such as hills and gullies, are silent evidence of these events, and the presence or absence of trees on some of them permit a close estimate of their age. Because trees start to grow and will survive after a landscape feature at low altitude becomes stable, the age of the oldest trees closely approaches the age of the feature. The absence of trees and other plants on a landscape feature containing fine, loose material probably means that the feature is presently active as, for example, a rock slide. If only shrubs are present on steep slopes well below timberline, trees are probably prevented from growing by frequent snow avalanches.

HYDROLOGIC INFERENCES

In initiating this study of the recent fluctuations in the positions of the glaciers on Mount Rainier, we had as a primary objective "* * * determining where modern water-supply data fit into the long-term pattern of fluctuating water supplies * * *" (Sigafoos and Hendricks, 1961, p. A1). We further stated, "The hypothesis is simple: Glaciers advance and retreat in a manner somehow related to climate; therefore, if something is known of a glacier's movement in the past, some kind of crude inferences about the climate existing at the time of movement may be drawn." It now appears that even this cautious statement was overoptimistic.

Through the collection of additional data since the initial report, it became apparent that no evidence exists to permit the dating of glacial advances. The data show only when glaciers started to retreat from terminal and lateral moraines. Nothing is known about how far they retreated following the formation of specific moraines. They could have retreated several thousands of feet or they could have retreated only a few tens of feet. Nothing can be inferred, therefore on the magnitude of climatic and hydrologic changes that preceded or followed moraine building.

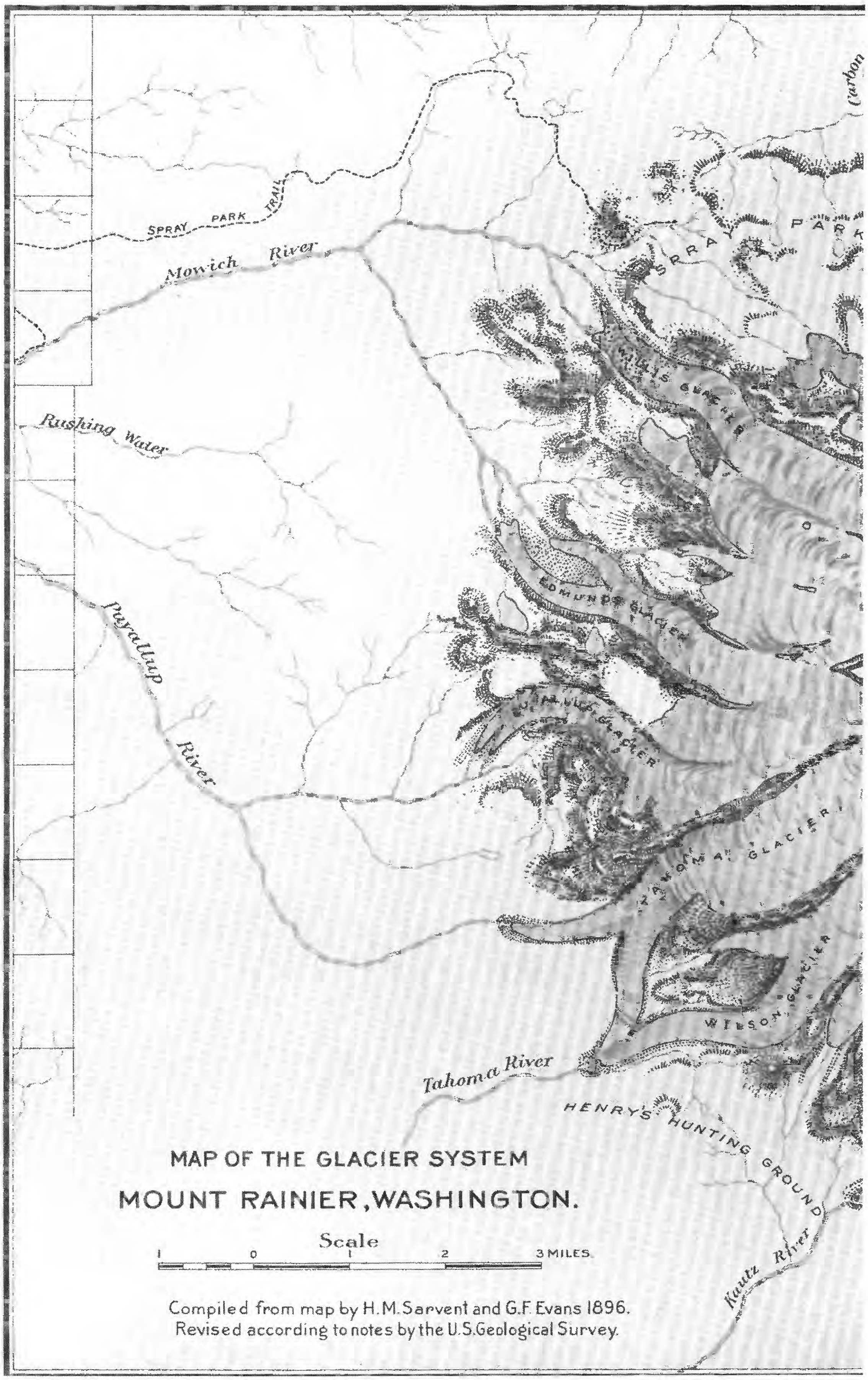
Meier (1965, p. 804–805), in summarizing existing knowledge of the relation between glacier behavior and climate, concludes:

> Glacier variations may reflect or indicate variations in climate, but the connection is indirect and complex. The general meteorologic environment controls the precipitation of snow, but local influences, caused largely by topography, may greatly modify the resulting accumulation on a glacier. Slight changes in seasonal temperature or precipitation distribution may affect accumulation totals in a glacier * * * Moraines and outwash features offer physical evidence of past glacier fluctuations, even though the exact meaning of some of these deposits is unclear. Botanical evidence of glacier variations can be especially useful. However, at the present stage of knowledge one cannot trace back from glacier variations to changes in climate, except in a gross, hypothetical way.

Meier (1965, p. 800) further stated:

> It should be possible in the future to determine response characteristics and delay times for different types of glaciers, up to and including ice sheets of continental dimensions * * * It is well known that contemporary glaciers do not, in general, behave synchronously. This can result from variations in net budget resulting from different local meteorological conditions or it can result from variations in dynamic response. Time delays in dynamic response for large glaciers extend into hundreds or thousands of years. It is possible that some apparently different ice-sheet advances, which have been assumed to have general chronological significance, could just be different dynamic responses to the same climatic event.

FIGURE 10 (next page).—In 1896, White River drained Emmons Glacier as it does today but had two tributaries flowing through the moraines. The northern one probably flowed through the melt-water channels at areas 53 and 51. Inter Fork in 1896 joined the northern fork of White River near its head and about 3,000 feet west of the present junction. The south fork of Tahoma Glacier joined with South Tahoma Glacier, here named Wilson Glacier. Redrafted from Russell (1898, pl. 66).



MAP OF THE GLACIER SYSTEM

MOUNT RAINIER, WASHINGTON.

Compiled from map by H. M. Sarvent and G. F. Evans 1896.
Revised according to notes by the U.S. Geological Survey.


West Fork White River
White River
CARBON GLACIER
MORAINE PARK
WINTHROP GLACIER
Inter Fork
INTER GL.
The Wedge
EMMONS GLACIER
Frying Pan River
FRYING PAN GL.
Liberty Cap
Gibraltar
Little Tahoma
Pt Success
INGRAHAM GLACIER
STEVENS GLACIER
VAN TRUMP GL.
NISQUALLY GLACIER
PARADISE GL.
WILLIWAKAS GL.
COWLITZ GLACIER
KAUTZ GLACIER
Van Trump River
SLUISKIN FALLS
River
Cowlitz River
PARADISE PARK
PARADISE FALLS
TAHOMA FALLS
Nisqually River
Paradise

From these considerations it is clear that some risk exists in developing an overall chronology for Mount Rainier glaciers by piecing together the record of movements of all the glaciers, because of the possible anomalies in responses of adjacent glaciers. Even if one could safely do this, the present knowledge of time delays in dynamic response of individual glaciers permits only the grossest inferences on the fluctuations in climate that produced the observed sequence of glacial responses. Thus we leave climatic inferences to others, with the hope that the data recorded here may help some investigator of the

FIGURE 11.—The bare amphitheater in the center holds immobile ice that was once part of Ohanapecosh Glacier. Today, Ohanapecosh (**OP**) Glacier is restricted to the sloping, partly snow-covered surface above the bedrock cliff. The glacier could not have been beyond area 3, the youngest dated moraine, after 1878, beyond area 2 after 1846, nor beyond area 1 after 1741. Mount Rainier summit is the snow-clad mound forming the apparent horizon at the left. View northwestward. Sept. 27, 1967.

future unravel the mysteries of past climatic change as indicated by these glacial histories.

If one draws hydrologic inferences from the glacial record, it is clear that, although precipitation may have varied in the past, changes in the regional water supply may also have resulted from changes in storage of water in ice. When glaciers were extended, more regional water was frozen in ice; when and if they were smaller, less water was frozen. Again, because little detail is known relating variations in glacier response to climate, we can only speculate upon the effects of greater or lesser storage of water as ice in glaciers upon discharge of water downstream.

Changes in climate and the concurrent storage of water in ice might have been in opposition in their effects upon downstream water supplies, or they might have been complementary. More water was taken from the environment and stored as ice when glaciers were larger than now, so that one might expect smaller flow in streams merely because of an increase of water in storage. However, the expansion of glaciers might well be the result of an interval of greater precipitation during which there was also increased flow in streams because of increased runoff from rain and snowmelt. The two phenomena, increased flow because of increased melt-water discharge and decreased flow because more regional

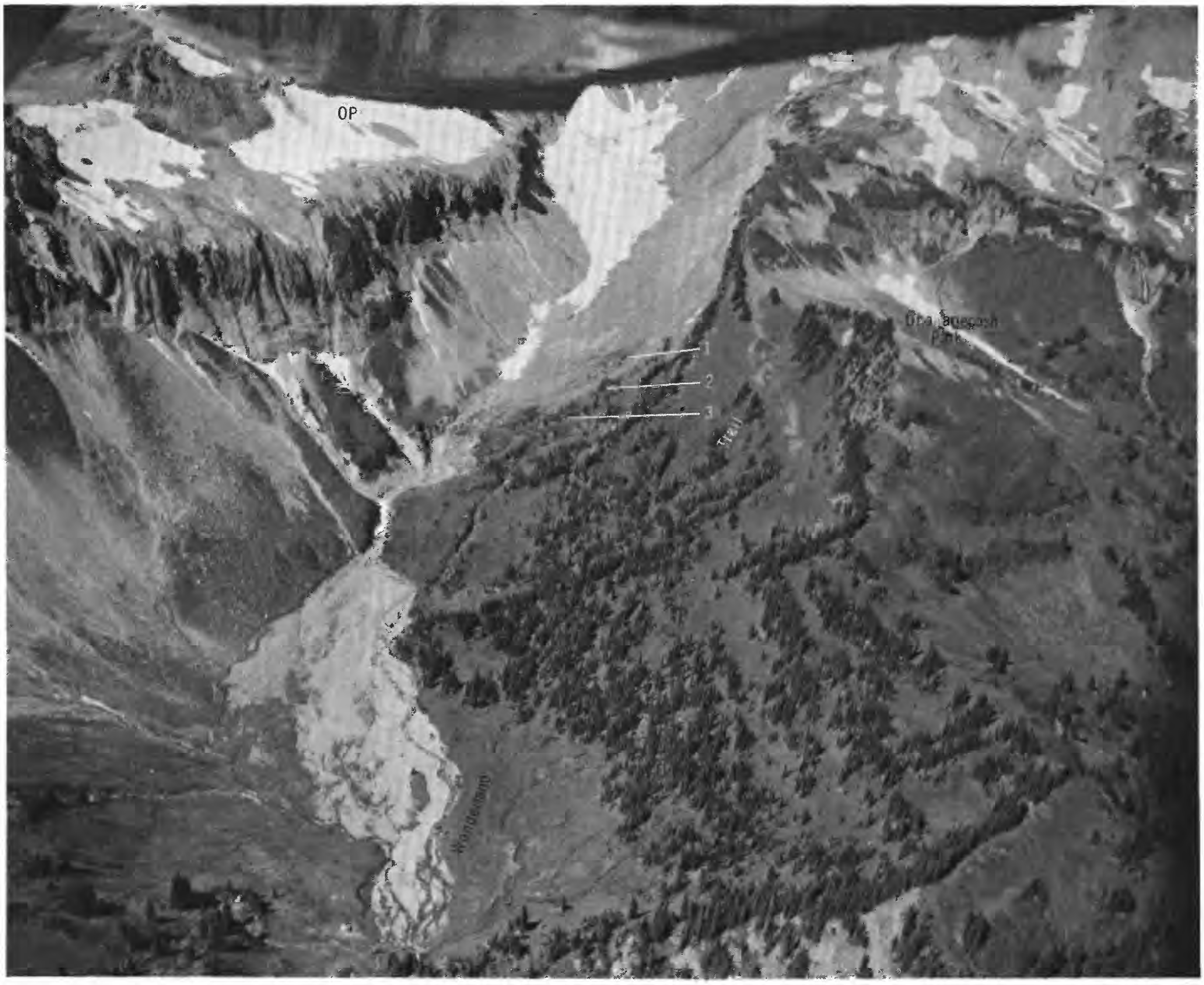


FIGURE 12.—Oblique aerial photograph of Ohanapecosh River valley near Ohanapecosh Glacier. An immobile remnant of the glacier is marked **OP**. Numbers refer to study areas. Aug. 29, 1969.

FIGURE 13.—These trees are the closest to Ohanapecosh Glacier, and the oldest was 3 inches tall in 1878. Pumice erupted by Mount Rainier between 115 and 150 years ago is present on the surface here; so the moraine is older. The bare bouldery surface on the right is older than the surface upon which the trees are growing and does not support trees, presumably because no fine soil is present in which seed can germinate. Ohanapecosh Glacier is out of view to the left. Sept. 26, 1967.

water was frozen in ice, tend to offset one another. Flow in streams below extended glaciers in the recent past, then, could have been virtually the same as it is now. If, on the other hand, glaciers expanded because of a general lowering of temperatures, more water would be held not only in glacier ice but in longerlasting snow cover. The effect then would be decreased flow below glaciers, with less water available for use.

Although the evidence around the mountain indicates a sequence of recession from moraines, its climatic significance and the effects upon water supply are not known. Recessions started on the following approximate A.D. dates: 1525, 1550, 1625–60, 1715, 1730, 1765, 1820–60, 1875, and 1910. More water may have drained from receding glaciers than from the advancing glaciers of the present; certainly water drained through different channels below some glaciers than it does today.

Discharge of melt water in some valleys below some glaciers is believed to have been greater (Tahoma, Winthrop, and Emmons Glaciers, p. B7, B12, and B13) when glaciers were larger than they are now. It is not known if the total quantities of melt water from each of these glaciers were greater than it is now, because discharge could have been less in some valleys than in them today, or it could have been nonexistent. These periods when discharge was greater in some valleys occurred when glaciers were receding and melting faster than they do now. If glacier recession resulted from lowered precipitation, total discharge could have been the same as or less than it is now, and valleys that earlier carried more water may merely represent a physical shift in the site of melt-water discharge.

SUMMARY OF MORAINE AGES

During the early part of the last century, Mount Rainier presented a different face when viewed from afar by an Indian than it does today when viewed by visitors. Eight major glaciers were considerably farther downvalley 125 to 130 years ago than they are now. The upper slopes, heavily weighted with ice, exposed little bedrock to view, and valleys were filled with long tongues of ice protruding between the dark, forested slopes.

All glaciers studied receded from this maximum stand in the last century. For Nisqually, Van Trump (Crandell and Miller, 1964), Tahoma, and Puyallup Glaciers, this stand represented the farthest downvalley advance of the last 10,000 years. The others—South Tahoma, Carbon, Winthrop, Emmons, Ohanapecosh, and Cowlitz Glaciers—also were far advanced 125 to 130 years ago but earlier, within the last 750 years, were even larger and more extended (table 10). A lateral moraine of Carbon Glacier was formed before A.D. 1217 (Crandell and Miller, 1964). These 125- to 750-year-old moraines were formed during the Garda Stade of the Winthrop Creek Glaciation, recognized by drift laid down since deposition of pumice layer C (Crandell and Miller, 1964). Some of these moraines are separated into old Garda drift overlain by pumice layer W (deposited about 450 years ago) and young Garda drift not overlain by layer W (Crandell, 1969, p. 30).

End and lateral moraines, from which eight glaciers started to recede between 1830 and 1850, indicate a consistent pattern of recession around the mountain for this period of time. The older moraines, however, do not show this correlation. This may be the result of insufficient data or may indicate different recession patterns of the glaciers. The older moraines generally are small segments that remain after the more extensive parts were destroyed by later glacier advances, by landslides, or by stream erosion. Some glaciers, such as Emmons, Carbon, and both Tahoma Glaciers behaved differently at

TABLE 10.—*Ages of glacial or pyroclastic deposits at Mount Rainier, Washington*

[E, end; L, lateral]

Years before 1968	This paper Sigafoos and Hendricks (1961)	Crandell and Miller (1964)	This paper							Crandell and Miller (1964)	Pyroclastic deposits	Years before 1968
	Nisqually	Van Trump	South Tahoma	Tahoma	Puyallup	Carbon	Winthrop	Emmons	Ohanapecosh	Cowlitz		
						Moraine (L) 1876		Moraine (E) 1901	Moraine (E) 1878			
100	Moraine (E, L) 1842	Moraine 1853	Moraine (L) 1864 Moraine (E) 1843	Moraine (L) 1857 Moraine (E, L) 1841	Moraine (E) 1846	Moraine (L) 1840	Moraine (E) 1822	Moraine (E) 1854	Moraine (E) 1846	Moraine (E) 1779	Layer X	100
200				Moraine (L) 1761		Moraine (E) 1763	Moraine (E) 1760 Moraine (E) 1730	Moraine (E) 1749	Moraine (E) 1771			200
300				Moraine (L) 1640 Moraine (E) 1623			Moraine (L) 1655	Moraine (E) 1661 Moraine (L) 1613				300
400			Moraine (E) 1528			Moraine (L) 1519		Moraine (L) 1552			Layer W	400
500												500
600										Moraine (E) 1363		600
700						Moraine (L) 1217 (Crandell and Miller 1964)						700

different times. Earlier they must have been thicker and not as long as during later times (Sigafoos and Hendricks, 1961, p. A7–A8). In spite of the vagaries of Mount Rainier glaciers, their dynamic nature is clear. That we are able with considerable accuracy to date the modern moraines of Mount Rainier by using botanical evidence is a step toward solving the problems of dynamic glacial processes.

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