The Glaciers of Mount Rainier

I.U.G.G. Glacier Study Tour ~ Sept. 2-5, 1963

edited by Mark F. Meier

1. GENERAL SETTING OF MOUNT RAINIER

by
Mark F. Meier, U. S. Geological Survey

Mount Rainier, an outstanding landmark, is visible from high points over much of western Washington. It was sighted from near Port Townsend in 1796 by Captain George Vancouver of the British Navy, and he named it after a friend, Admiral Peter Rainier. The mountain has also been referred to until very recently by its original Indian name of Mount Tacoma (also spelled Takoma or Tahoma). The mountain was first reached by a white man in 1857, and was not climbed successfully until 1870. Mount Rainier and its immediate environs was set aside as a National Park in 1899.

Western Washington is characterized by three different physiographic zones. On the west is a north-south strip of mountains culminating in the Olympic Mountains. The Olympic Mountains are a rugged jumble of folded rocks, mostly sedimentary in origin. None of the peaks rise higher than 2,500 m above sea level. Numerous small glaciers occur in these mountains, the best known being the Blue Glacier on Mount Olympus.

East of the Olympic Mountains and the Coast Range is the broad, low Puget Trough. Aside from a few hilly areas, altitudes in this trough rarely exceed 150 m. North of Olympia the floor of the trough was deeply dissected by streams and by glaciers which came down from the north.

East of the Puget Trough is the Cascade Range. In Washington the Cascade Range can be divided into two parts. The North Cascade Range is composed of ancient sediments which have been strongly folded, generally metamorphosed and granitized, and intruded by numerous plutonic igneous rocks. These mountains are rugged and comparatively inaccessible and unknown. Most of the glaciers in Washington (over 600) occur in the North Cascade Range.

South of the vicinity of Snoqualmie Pass the Cascade Range is of completely different character. The mountains here consist mainly of rather gently folded lava flows, which are Tertiary in age. Rising above these low mountains are several late Tertiary and Quaternary volcanic cones. Some of these volcanoes have erupted in historic time; lava emerged from Mount St. Helens as late as 1843. Glaciers occur in this section of the Cascade Range only on the high volcanoes (Mt. Rainier, 4,392 m; Mount Adams, 3,752 m, and Mount St. Helens, 2,950 m) and on Goat Rocks (2,500 m). The foothills around Mount Rainier rise to about 1,500 to 1,800 m above sea level, so this mountain stands with nearly two-thirds of its height above the general level of the terrain.

The climate in western Washington is characterized by cool wet winters and warm dry summers. Precipitation in the Puget Sound lowlands generally ranges between 800 and 1,300 mm per year, but the precipitation in the mountains is much greater. Mount Rainier lies west of the crestline of the Cascade Mountains and thus is exposed to the prevailing westerly winds which blow from the Pacific Ocean, less than 160 km distant. These winds meet no barrier of any consequence until they rise over the foothills of the Cascades, resulting in heavy orographic precipitation. About 86 percent of this precipitation occurs from October through May and so is mostly in the form of snow. Climatological data from Paradise Park (altitude 1,668 m) based on records from 25 to 46 years in length ending in 1954 are summarized in the following table:

	Temperature °C	Precipitation mm	Snowfall m		Temperature °C	Precipitation mm	Snowfall m
January	-3.1	385	3.05	July	11.6	42	0.01
February	-2.7	279	2.13	August	11.8	73	.005
March	-1.7	255	2.30	September	9.7	146	.17
April	1.6	152	1.30	October	4.8	252	.56
May	4.8	120	.54	November	.5	340	1.77
June	7.7	109	.13	December	-2.6	400	2.50
				Annual	3.9	2,553	14.47

In the winter of 1955-56, over 26 m of snowfall was recorded, and the snow depth on the ground reached 10 m.

Long-term precipitation and temperature measurements have not been made at higher elevations. It has been stated in the literature that there is a zone of maximum precipitation on Mount Rainier at between 2,500 and 3,000 m above sea level. However, no field data exist to substantiate this hypothesis. Strong winds are prevalent high on the mountain and snow avalanches continuously move the accumulated precipitation, so that the task of measuring precipitation directly at higher altitudes seems insurmountable.

2. BRIEF DESCRIPTION OF SURFICIAL GEOLOGY BETWEEN SEATTLE AND MOUNT RAINIER NATIONAL PARK

by
Dwight R. Crandell, U. S. Geological Survey

South of Seattle, the highway rises onto ground moraine of Vashon age (see table 1). A well drilled for water near the Seattle-Tacoma Airport encountered peat and wood at a depth of about 61 m, beneath the Vashon Drift. The wood was dated by Professor A. W. Fairhall at the University of Washington as 19,500 ± 500 years, which is a limiting date for the advance of the Vashon glacier in the Seattle area. This glacier originated in the mountains of western British Columbia, Canada, and advanced down the Puget Sound lowland as a piedmont glacier 97 km wide--the Puget lobe. The glacier reached southward to a point about 80 km south of Seattle, but by 14,000 years ago it had melted back and uncovered the Seattle area, for peat of this age is found on top of Vashon Drift on the floor of the Lake Washington basin.

About 24 km south of the Seattle-Tacoma Aipport, the highway descends into the valley of the Puyallup River, which has its headwaters in the glacier on Mount Rainier. During recession of the Vashon glacier this valley was occupied by a glacial lake that discharged westward to the Pacific Ocean while the Puget Sound lowland was still blocked by the Puget lobe. The town of Puyallup lies about 9 m above sea level and about 16 km from Puget Sound at Tacoma. This part of the Puyallup River valley probably was occupied by an arm of Puget Sound until about 5,000 years ago. About 500 years ago, a mudflow that originated on the west side of Mount Rainier moved down the Puyallup River to within 3 km of Puyallup.

South of Puyallup the highway again rises onto glacial drift of Vashon age, and crosses a major spillway of Glacial Lake Puyallup about 10 km south of town. At Eatonville the highway crosses several meltwater drainage channels formed along the margin of the Puget lobe. Southeast of this town the highway ascends the low western foothills of the Cascade Range and crosses the southeastern margin of the Vashon Drift. From here southward to Alder Lake the highway crosses drift of early and middle Wisconsin age that was deposited by ice-cap glaciers that headed in the higher parts of the Cascade Range to the east.

Alder Lake lies in the valley of the Nisqually River, which has been dammed to produce hydroelectric power for the city of Tacoma.

About 11 km east of Elbe, between the villages of National and Ashford, a single mound of glacial drift on the north side of the highway marks the maximum extent of the late Wisconsin (Evans Creek) glacier in the Nisqually River valley. This point is about 26 km downvalley from the present terminus of Nisqually Glacier.

Leaving the northeast corner of Mount Rainier National Park, the highway follows the valley of White River northwestward to the Cascade mountain front, which is also the path taken by the Osceola Mudflow 4,800 years ago. When the mudflow reached the mountain front, it spread into the Puget Sound lowland and covered an area of about 169 km^2 to depths of 1.5 to 24 m.

The maximum extent of the White River glacier in Evans Creek time is about 5 km downvalley from the north boundary of the Park. This represents a valley glacier that extended about 19 km beyond the present terminus of Emmons Glacier. Earlier Wisconsin glaciers reached downvalley nearly to the mountain front.

Table 1.--Tentative and generalized sequence of events in Mount Rainier National Park

	Pyroclastic chronology		
	Name of unit	Source	Age in years
Little Ice Age - 14th century to present. Minor advances of valley glaciers. Most cirques above 2,000 m occupied by ice.	"G" Ash -	?	>65 - < 215
	"W" Ash -	St. Helens	400±
Formation of debris flows in some valleys.	"C" Ash -	Rainier	>1000
	"Y" Ash -	St. Helens	3200±
Paradise debris flow - Osceola Mudflow. Inferred destruction of old summit of volcano. Osceola dated as 4,800 years old.			
Formation of debris flows in some valleys.	"O" Ash -	Crater Lake, Ore.	6700±
	"R" Ash -	Rainier	>8800
Late Wisconsin Glaciation: Unnamed Stade - estimated 11,000-10,000 years ago. Minor advance of valley glaciers; formation of rock glaciers and protalus ramparts. Most cirques above 1,200 m occupied by ice.			
(Vashon Stade - Cordilleran Glacier in Puget Sound Lowland 24,000-12,000 years ago; in Seattle area from <19,000 to >14,000 years ago.)			
Evans Creek Stade - major advance of alpine glaciers. Average cirque floor altitude 1,200 - 1,400 m.			
Two earlier glaciations in Wisconsin time (=post-Sangamon)			
Pre-Wisconsin glaciations			

3. RECENT VARIATIONS IN THE REGIME OF GLACIERS IN WESTERN WASHINGTON.

by

E. R. LaChapelle, University of Washington

Glacier ice in western Washington covers approximately 397 km^2 (Meier, 1961), the only area of significant existing glaciation in the United States outside of Alaska. About half of this ice area lies in the relatively inaccessible Northern Cascade Range, while the other half is distributed among the Olympic Mountains and the major volcanic peaks (Fig. 1). The largest volcano, Mount Rainier, supports an extensive glacier system totalling 88 km^2. A cycle of glacier advances, most prominent in the Northern Cascade Range, has lent special interest to the western Washington glaciers. The reversal of a general and long-standing recession phase was first brought to public attention by the prominent advance of the Coleman Glacier on Mount Baker (Bengtson, 1956), although thickening of Nisqually Glacier had been reported earlier by Johnson (1949). On the

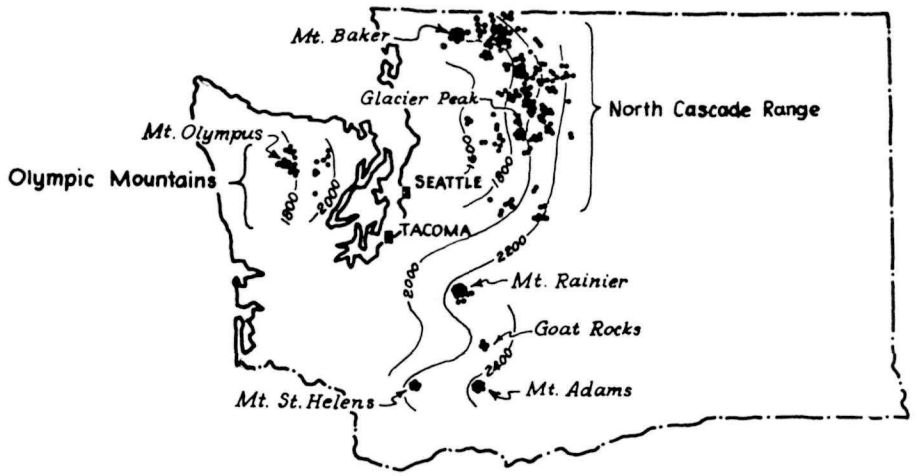

Figure 1.--Map of the State of Washington, showing locations of glaciers. Contour lines indicate mean altitude of small glaciers.

basis of comparisons between photographs obtained during a 1955 aerial reconnaissance and those taken at earlier dates for mapping purposes, Hubley (1956) was able to show that reactivation and glacier advance were a general phenomenon throughout the Northern Cascade Range, and were apparently related to a cooler, wetter climate trend.

Hubley repeated his reconnaissance in 1956 over a more extended area than in 1955. Since then, the annual aerial photography of western Washington glaciers has been repeated each September by M. F. Meier, A. S. Post, and E. R. LaChapelle. In 1959 the National Park Service began a similar photo reconaissance of glaciers on the Olympic Peninsula. LaChapelle (1960) has summarized the results of these observations through 1959. Meier and Post (1962) brought together results from a wider area and reported on variations in the glaciers through 1961.

The resurgence of glacier activity resultsng from increased snow accumulation after about 1948 was first discovered to extend throughout the Northern Cascade Range by the 1955 photo reconnaissance. Many of the larger glaciers were then actively advancing, and everywhere greatly increased activity over that of the 1940's could be seen. In several places, small cirque or apron glaciers which had nearly disappeared or had become stagnant were restored to growth and activity. This general glacier rejuvenation continued until 1956 and 1957. The advances reached a maximum earliest on Glacier Peak in the southern limits of the Range, and have been prolonged until most recently on Mount Baker near the northern limit. Little glacier advance has been noted on Glacier Peak since 1955, whereas active advancing on Mount Baker continued through 1957 and 1958, and on certain glaciers through 1959. Glaciers on the nonvolcanic peaks reached their maximum extent in 1956 and 1957, except Boston Glacier, part of which still advanced in 1959.

The summer of 1958 brought exceptionally heavy ablation to the western Washington glaciers, and general recession or thinning occurred. A few of the most vigorous glaciers, such as Coleman Glacier on Mount Baker, continued to make small advances. On some glaciers the heavy ablation removed several years of accumulated firn, and mass deficits were large. The following year brought a rather heavy accumulation which resulted in

positive mass budgets, especially in the Northern Cascade Range, but these surpluses were small compared to the large 1958 deficits. Successive years through 1962 have probably averaged near equilibrium budgets for many glaciers. Most glaciers have now reached steady-state configurations, and very little evidence of persistent advance remains.

With one exception, glaciers of the Olympic Mountains showed less response to this climate trend than those of the Northern Cascades and the volcanoes. Most of the Olympic glaciation is concentrated on the flanks of Mount Olympus, and the largest glaciers there have slowed down or ceased their extensive retreats of the past half-century. The Blue Glacier, for instance, ceased retreating in 1955 and has maintained nearly a stationary terminus since then. Mass budget measurements show this glacier averaged nearly mass equilibrium in the period 1956-63. The Black Glacier, also on Mount Olympus, made a marked advance during 1955-57 as a result of an ice wave which appeared to reach its maximum amplitude in 1956. The invigorated terminus advanced slightly in 1958, and has since been retreating. The rest of the glaciers scattered among the Olympic Mountains are all quite small and apparently continue to retreat.

4. GENERAL DESCRIPTION OF THE GLACIERS

by
Mark F. Meier, U. S. Geological Survey

Some of the largest glaciers in the United States exclusive of Alaska are on Mount Rainier. The Emmons Glacier, on the northeast side of the mountain, is about 6.9 km long at the present time and has an area of 10.7 km^2 (Fig. 2). The Carbon-Russell Glacier (essentially one glacier system with two named branches) on the north side is 9.7 km long and has an area of 13.0 km^2. A summary by Meier (1960) lists 41 glaciers totalling 88 km^2 in area. Eight of these glaciers are larger than 4 km^2 in area, and 18 are smaller than 0.5 km^2.

Most of the larger glaciers originate on the summit ice cap and flow down the mountain flank in roughly parallel-sided shallow troughs (e.g., Nisqually, Tahoma, Winthrop and Ingraham Glaciers). The Emmons Glacier flows in a complex of troughs, with the ridges between the troughs almost, but not completely, inundated by ice. Other large glaciers originate on the summit but spill over cliffs, breaking the continuity of the ice stream, then reform at the base of cliffs and flow on down as normal valley glaciers (e.g., Kautz, North Mowich, and Carbon Glaciers). The South Tahoma, South Mowich, Puyallup, and Cowlitz Glaciers originate in cirques at the base of steep cliffs. On the triangular facets or "wedges" between these major valley glaciers are many thin, roughly diamond-shaped glaciers; typical of these is Inter Glacier between the Emmons and Winthrop Glaciers. Numerous small cirque glaciers occur on the mountain and on several ridges and peaks nearby.

The firn limits of the major glaciers have normally been found between altitudes of 2,100 and 2,600 m during the last decade. According to Bender and Haines the elevation of the snowline has risen from about 1,800 m in 1910 to nearly 2,300 m in 1952. Ice mantles all but the steepest slopes and ridges above 2,500 m, and the larger valley glaciers extend down to as low as 1,060 m. Timberline occurs at about 2,000 m. Thus the major valley glaciers end in the forested zone, and trimlines are abundant.

Few mass-budget data are available for these glaciers because of the difficulty of working on the upper slopes. Ablation measurements on the lower tongue of Nisqually Glacier in 1961 suggest an average net mass budget of -8.7 m of water equivalent at the 1,600 m level. This deficit decreases to zero (the equilibrium line or firn limit) at an elevation of about 2,100 m (Meier and Post, 1962). Measurements were not made at higher elevations, but the net budget must average about +0.7 m of water equivalent above

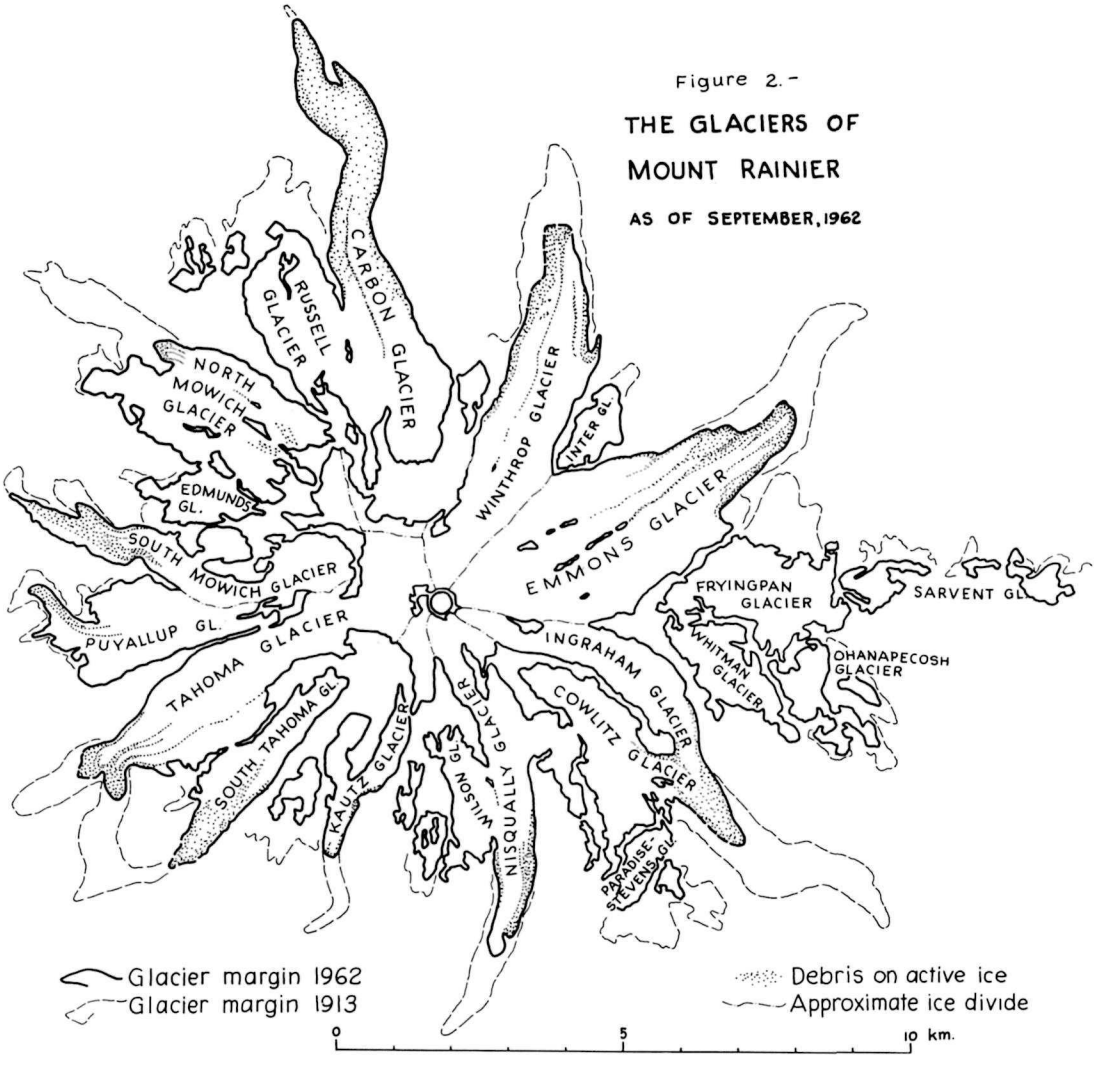

Figure 2.- THE GLACIERS OF MOUNT RAINIER AS OF SEPTEMBER, 1962

Note: Relatively stagnant ice is not included in the 1962 glacier margin. The names of several small glaciers are not indicated on this map.

Compiled by Mark F. Meier, 1958-63

the equilibrium line in order to maintain this glacier in the present steady-state condition. Measurements at the summit (4,392 m) revealed only 38 cm of snow ablation from July 1 to August 12, 1960.

The major glaciers of Mount Rainier are active and relatively fast-moving. Speeds in excess of 300 m per year have been measured on Nisqually Glacier at the 2,100 m level, and much greater ice flow rates are undoubtedly reached on the steeper portions above. The activity index (vertical gradient of net mass budget at the equilibrium line) is about 15 mm/m on Nisqually Glacier.

Several forms of life occur on the glaciers of Mount Rainier, including the red algae Protococcus nivalis, and the "glacier flea" Thysanura. Perhaps most interesting because of its limited geographic distribution is the ice worm Mesenchytraeus solifugus rainierensis.

5. MODERN HISTORY OF NISQUALLY AND EMMONS GLACIERS, WASHINGTON

by

R. S. Sigafoos and E. L. Hendricks, U. S. Geological Survey

Study and observation of locations and ages of modern moraines of Nisqually and Emmons Glaciers are presented as examples of the methods and results of a larger study in progress (Sigafoos and Hendricks, 1961). The study is designed to gain a knowledge of areas once occupied by mountain glaciers in order to reveal at least part of the past behavior of these glaciers and is one of the efforts made to reconstruct past climatic trends.

The maximum downvalley position reached by these glaciers in the last few hundred years is marked by a prominent moraine or, where no moraine exists, by a line separating forests of marked difference in age. A study of adjacent forests of different age was made to determine the age of the oldest tree in the younger forest, which in turn is interpreted as the minimum period that has elapsed since the ice left the position occupied by the tree.

To determine the date when the glacial debris became stable or when the surface became exposed upon melting of the ice, the age of the oldest tree is added to the interval required for trees to become established. Determination of this interval was done by sampling trees and seedlings growing at recorded past positions of the glaciers (Bender and Haines, 1955) and was found to be about 5 years.

Nisqually Glacier Moraine

The conspicuous remnant of the moraine seen in the road cut on the north side of Nisqually River at the approach to the highway bridge is part of a moraine that extends upstream on both valley walls. It represents the maximum advance of Nisqually Glacier in Recent time (D. R. Crandell, personal communication, 1961). In the old forest, downvalley from the moraine, trees range in diameter from 0.6 to 2 m, and in age from 285 to 300 years. Throughout the forest are many fallen logs and broken stumps in all stages of decay ranging from nearly sound wood to punky, completely decayed humus. Older rotten logs are evident as barely perceptible elongate ridges completely covered with mosses and forest litter. A long time is required for trees to grow, die, and decay; and an age of 1,640 ± 250 years (B.P.) was determined by carbon-14 analysis for charcoal collected beneath the surface humus layers. Underlying the humus, in the old forest, are layers of volcanic ash ranging from 0.6 to 1.5 m in thickness. The thick, most conspicuous layer is pale brown to yellow brown and is about 3,200 years old (Crandell and others, 1962). Underlying this ash is glacial till. The humus, charcoal, ash, and till are exposed in a hole about 8 m from the conspicuous moraine.

The study to determine the ages of trees on the moraine was concentrated in the valley reach extending about a mile upstream from the point where the moraine is cut by the road. Samples from 32 groups of trees were collected, comprising cores from 179 trees and counts of 74 stumps. The oldest trees started to grow between 1842 and 1848, so if 5 years intervened before establishment, Nisqually Glacier stopped its maximum modern advance about 1840. Locations of the moraine and key trees, together with the year that trees started to grow, are shown in figure 3.

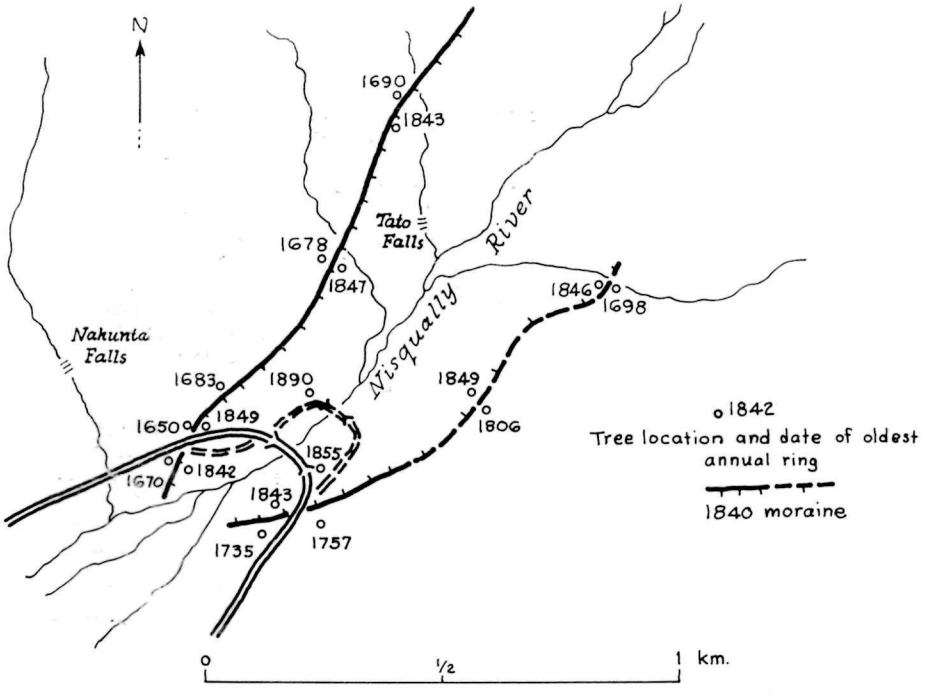

Figure 3.–Nisqually Glacier moraines

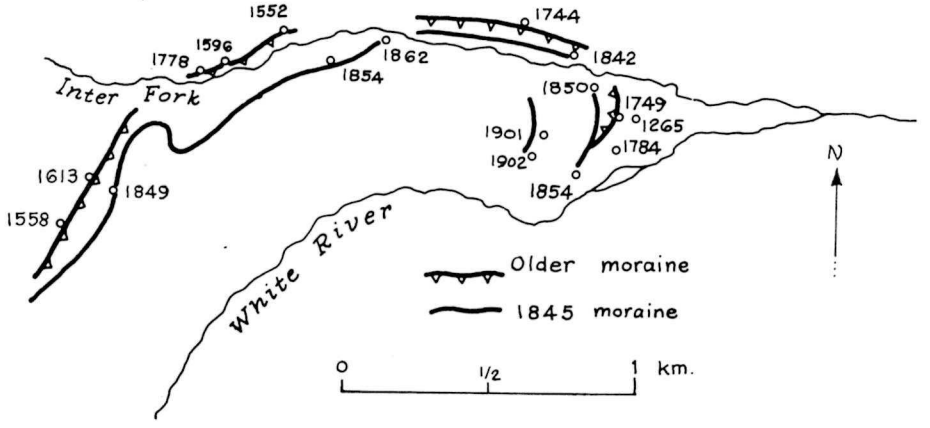

Figure 4.–Emmons Glacier moraines

Emmons Glacier Moraines

Emmons Glacier stopped an apparent advance about 1845, leaving a well-defined ridge upon which the oldest trees started to grow in 1850. This recession, unlike Nisqually Glacier, however, was from a readvance in the general recession of Emmons Glacier that started at the terminus about 1745. This older moraine, which marks the maximum advance, crosses the valley about 1.2 km upstream from the White River campground and is cut by Inter Fork and White River. It extends on the north side of the valley upstream to a point where it again is cut by Inter Fork then southwesterly on the forested slope on the west side of upper White River valley. About 2.4 km upstream from the terminal moraine, and about 1.6 km upstream from the trail bridge across Inter Fork, the oldest trees on the moraine started to grow in 1613. The glacier, here, stopped advancing and became stagnant about 1610, whereas 135 years elapsed before the terminus stagnated in 1745.

The recessional moraine lies wholly within the older moraine, and except where it is cut by Inter Fork or has been destroyed by land sliding on the slopes, it too can be traced upvalley. It crosses Inter Fork close to the 1745 moraine and recrosses it just upstream from the trail bridge thence extends in an arc curving southwesterly to the same forested slope west of upper White River valley. The oldest trees on the terminal and recessional moraines started to grow between 1848 and 1854; therefore it became stagnant after a minor readvance that ended about 1845.

The downvalley parts of the seemingly bare moraines south of the trail bridge became stable following stagnation of the glacier between about 1895 and 1910. Ice could have been at the highest, most easterly of these moraines when seen by Russell, Willis, and Smith in 1896 (Russell, 1898, p. 407). Russell observed that Emmons Glacier was shrinking and that young trees were beginning to grow on the bare moraines around the ice margin. When the Mount Rainier National Park Map was made in 1910-1913 the ice, as represented, probably rested close to the more westerly of the bare downvalley moraines. These younger recessionals were not traced upvalley. Locations of moraines and key trees are shown in figure 4.

6. SUMMARY OF RECENT CHANGES IN GLACIERS OF MOUNT RAINIER

by
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Changes in glaciers of Mount Rainier National Park have been determined by recent oblique aerial photography and are briefly described. Since 1958 such photography has been obtained in all years but 1961 by the U. S. Geological Survey (1958) and University of Washington (1959-1962). From these, the changes in terminal position, activity, and annual snow accumulation have been determined for the larger glaciers of the mountain.

During the middle of the 19th century, the glaciers of Mount Rainier covered an area of about 140 km^2. By 1913 this area had shrunk to about 104 km^2. In 1950 the area was down to about 88 km^2, but the glaciers had for the most part stabilized and only very minor further retreats have taken place; some advances have been recorded.

South Side

Nisqually Glacier evidently was moderately active to the terminal areas as late as 1910. Following this date accumulation of ice apparently was much reduced and the extended valley tongue stagnated. The slow melting of this dead ice has been measured but for obvious reasons has failed to disclose changes of activity in the upper portion of the glacier, which has remained active. By 1961 the dead ice had disappeared or had become incorporated into the active terminus, so terminal changes may again

become meaningful in relation to the state of the glacier's activity. In 1953 the active terminus began to advance, and by 1961 this advance had amounted to about 570 m. The terminus continues to advance but at a diminishing rate. The recent rejuvenation of Nisqually Glacier has been spectacular at elevations between 1900 m and 2600 m (Fig. 5).

The Cowlitz Glacier still retains a thin, almost disconnected, valley tongue of dead ice. Around 1951 the activity of the upper glacier and particularly its major branch, the Ingraham Glacier, experienced a strong rejuvenation, fortunately marked by a strong dirt band on the ice which has since moved down the glacier nearly 1 km. The increased activity below the confluence of the Cowlitz and Ingraham Glaciers has become especially noticeable since 1960. Evidently a "shock wave" is forming in the debris-covered ice. This activity is almost entirely due to ice from the high-altitude Ingraham branch. The only clearly discernible ogives on the mountain are found on this glacier. Above the dirt band mentioned above, 13 widely-spaced ogives were present in 1962; below the dirt band approximately 14 closely-spaced ogives could still be detected.

Paradise-Stevens Glacier has suffered great loss in area and much of the remaining ice is essentially inactive. Two tongues formerly extended into the Stevens Canyon area and a broad ice apron headed Paradise Creek; when mapped in 1913 much of this ice was still active. Stagnation of this ice permitted large and spectacular ice caves to form.

Kautz Glacier - This sinuous ice stream was 6 km long when mapped in 1913 but had retreated nearly 2 km by 1959 when evidence of readvance was noted. A forward movement of approximately 100 m had taken place by 1962.

West Side

Tahoma Glacier, which formerly joined South Tahoma Glacier below Glacier Island, stagnated in its lower reaches and small fragments of this ice still remain below the present double terminus. It has had a steep front on its Tahoma Creek terminus for at least 5 years which appears to have remained almost unchanged. Its Puyallup River terminus is obscured by inactive ablation moraine-covered ice.

South Tahoma Glacier in 1962 displayed a steep front which may be advancing slightly. Recent thickening has been observable from Paradise Park; seracs of this glacier now appear above the skyline of Success Cleaver.

Puyallup Glacier ends in a thin tongue with a cascading distributary which hangs over a steep cliff and acts as a sensitive indicator of the activity of the lower glacier. It is interesting to note that neither terminus has retreated as much as 0.6 km since mapped in 1913 by the U. S. Geological Survey despite very exposed positions--good evidence that this glacier has remained active in this area. There is definite evidence that the glacier has become increasingly active in recent years. A rock outcrop near the center of the glacier was overwhelmed by ice in 1962 after having been exposed on all former years since aerial photography was begun in 1957. If this wave continues it may reach the terminus in 1963 or 1964.

South Mowich Glacier is at present vigorous throughout most of its length and appears to be subject to strong waves of increasing activity which originate in the high cirque called Sunset Amphitheatre. In 1960 the ice descending from this steep catchment basin was very severely crevassed and shattered from rapid movement; in 1962 this area of the glacier was relatively smooth but the lower portion of the glacier showed increased activity. One of the two terminal lobes may have begun to advance in 1960.

North Mowich Glacier retreated more than 3 km since the 1913 map was compiled, although stagnant ice is present in portions of the old glacier bed. Since 1957 ice has actively spilled into the head of this basin but little change has been noted other than

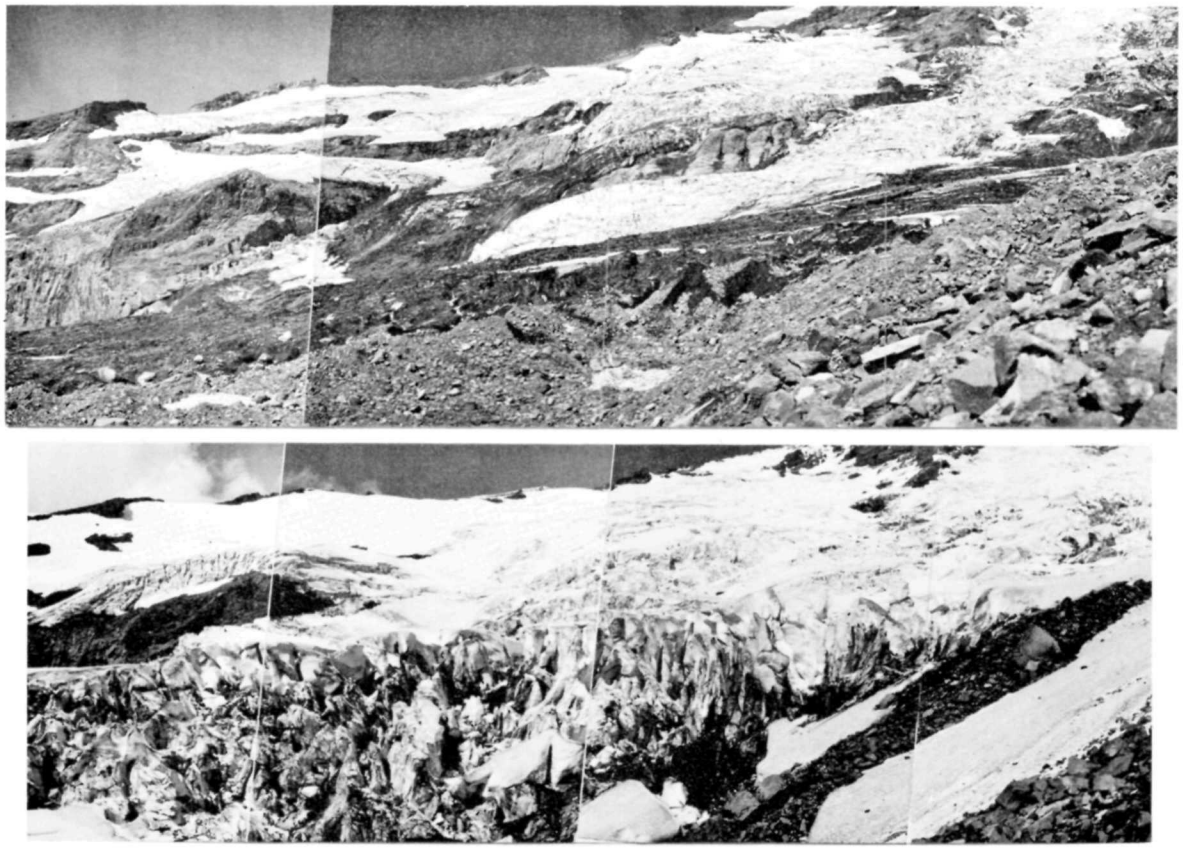

Figure 5.--Two views across Nisqually Glacier at Profile 3 (2,080 m). The main stem of the Nisqually Glacier flows from right to left across the field of view, and the Wilson (tributary) Glacier appears in the background. The upper picture was taken on September 3, 1944, the lower on September 6, 1960; the fields of view are exactly the same. Note that extensive thickening and rejuvenation occurred at all elevations in the field of view. The highest point visible is about 3,200 m above sea level. Photographs by F. M. Veatch.

the gradual wasting of the relic ice. It will probably be several years before this disappears and a well-defined terminus to the active glacier will become established.

Edmunds Glacier is a small but active ice mass between the two Mowich Glaciers. In recent years its west terminus has been stationary but its southwest terminus has advanced slightly.

North Side

Carbon Glacier is heavily covered with ablation moraine for much of its length and this may account for its very minor retreat, which amounts to only about 400 m since 1913. Recent Park Service measurements of the changes in the glacier snout show a slow retreat until 1958-59; since that date small advances have been recorded.

Winthrop Glacier has undergone very little change in area since its most recent maximum, which is marked by a well-defined trimline and two pronounced terminal moraines. The lower portion of the glacier has stagnated and the active ice abuts this moraine-covered ice approximately 0.7 km above the actual terminus, which is channeled deeply on the east side by Winthrop Creek. A wave of increased activity closed the upper portion of this creek channel in 1960 and the ice has continued to encroach on the channel slightly ever since.

East Side

Emmons Glacier retreated about 2 km since 1913 due to stagnation and collapse of its terminal area; much stagnant ice remains along the northerly side where some large ice caves are present. An active terminus of the glacier was first noticed in 1953. In the subsequent 4 years this terminus advanced 200 m. Advance continues, but at a reduced rate.

Fryingpan Glacier retreated about 1.5 km from its 1913 position to the top of a high cliff. In 1955 activity of the glacier had increased and ice was being discharged over this cliff in quantity so that a large fan of ice had formed below. Since that date this accumulation has been much reduced, although some ice continues to be discharged from the glacier above. Parts of the ice cliff have advanced slightly in recent years.

Sarvent Glacier, largest of several tiny ice patches near Cowlitz Chimneys, is noteworthy as a small advance was recorded between 1957 and 1960, although the glacier superficially appeared so inactive that some retreat seemed likely.

7. HISTORY OF MEASUREMENT OF MOUNT RAINIER GLACIERS

by
Mark F. Meier, U. S. Geological Survey

Kautz in 1857, and Emmons and Wilson in 1870 visited and described several of the glaciers. Russell, Smith and Willis in 1896 examined more glaciers, recommended a program of measurement, noted that recent recession was obvious on every glacier they observed, and in two instances--the Carbon and North Mowich Glaciers--were able to make rough estimates of the amount of recession in the last 15 years. The first step in Russell's suggested program was accomplished by Le Conte in 1905, who measured the position of the terminus of Nisqually Glacier and the rate of movement of the glacier at a point about 1,000 m above the terminus. Matthes of the Geological Survey began work on the Mount Rainier quadrangle map in 1910. This work was the first accurate determination of the extent of most of the glaciers. Annual measurement of the position of the terminus of Nisqually Glacier was begun in 1918 by Schmoe of the National Park Service and Landes of the University of Washington. Linear measurements of the position of the terminus were instituted by National Park Service personnel on Emmons Glacier in 1930, South Tahoma in 1931, and Carbon and Paradise Glaciers in 1932 (table 2).

Table 2.--Summary of glacier recession measurements, Mount Rainier National Park
by V. R. Bender, National Park Service

Year	Nisqually (feet)	Paradise (feet)	Emmons (feet)	Carbon (feet)	South Tahoma (feet)
1857-85	760				
1885-92	140				
1892-1918	1,310				
1918-19	59				
1919-20	46				
1920-21	106				
1921-22	67				
1922-23	44				
1923-24	83				
1924-25	73				
1925-26	86				
1926-27	43				
1927-28	89				
1928-29	52				
1929-30	118				
1930-31	49		142		
1931-32	50		19		37
1932-33	44		32	12	13
1933-34	155	7 (2 yrs.)	132	29	73
1934-35	54		30	25	42
1935-36	65	72 (2 yrs.)	100	62	37
1936-37	55		16	20	13
1937-38	90	83 (2 yrs.)	107	18	76
1938-39	85	65	57	25	67
1939-40	70	30	97	46	91
1940-41	125	80	89	54	244
1941-42	56	15	72	45	+ 45
1942-43	79		150	45	+ 17
1943-44	79	83 (2 yrs.)	296	35	
1944-45	68	48	184	27	114 (2 yrs.)
1945-46	45	0	255	35	140
1946-47	112	40	89	34	75
1947-48	88	36	107	35	21
1948-49	126		90	66	
1949-50	65	36 (2 yrs.)			168 (2 yrs.)
1950-51	72		88 (2 yrs.)	75 (2 yrs.)	
1951-52	76	48 (2 yrs.)			78 (2 yrs.)
1952-53	(50)	82	160 (2 yrs.)	84 (2 yrs.)	
1953-54	(47)		+ 145*	52	
1954-55	(80)		+ 182		
1955-56	(67)		+ 181	49	
1956-57	(75)		+ 147	13	
1957-58	(78)		**	18	
1958-59	(117)		**	+ 26	
1959-60	(124)		**	+ 20	
1960-61	Residual ice gone		**	+ 8	

\+ indicates advance

() indicates measurement of residual, stagnant ice, not indicative of the advance or retreat of active portion of the glacier

* definition of terminus changed from stream portal in stagnant ice to active front

** linear recession measurements replaced by phototheodolite surveys; data not yet analyzed but advance known to continue

A program of topographic mapping of the lower part of Nisqually Glacier at 5-year intervals was initiated by Evans of the Tacoma City Light Department and Parker of the Geological Survey, in 1931. These studies were initiated because the city of Tacoma was interested in the effect of the recession of this glacier on its extensive hydroelectric power developments on the Nisqually River. This 5-year mapping program has been continued to the present time. The earlier maps covered only the lowest part of the tongue and were obtained by plane table techniques. Since 1951 the mapping has been done by aerial photogrammetry and the mapping extends to higher elevations. Recently the Geological Survey published seven maps of Nisqually Glacier representing 5-year intervals from 1931 to 1961. In 1952, Hofmann from Munich, Germany, made a survey of Nisqually Glacier by means of terrestrial photogrammetry. This mapping was repeated in 1956. He also determined the surface velocity of Nisqually Glacier using terrestrial photogrammetry.

The Geological Survey has made yearly surveys of changes in surface elevation along three profiles of Nisqually Glacier. These measurements were made in 1931, 1932, 1933, 1936, then discontinued, resumed in 1941, and continued to the present under the direction of Johnson. Measurements of velocity from year to year have also been made as part of this program.

A careful program of yearly photographs of Nisqually Glacier from a number of fixed locations was instituted by Veatch of the Geological Survey in 1942 and has been continued to the present. The two views of Nisqually Glacier (Fig. 5) are taken from this extensive collection of photographs. Systematic photography of Nisqually Glacier has also been undertaken by Harrison of the University of Washington.

Other glaciological projects have been accomplished on Mount Rainier, but few of these have been continued for very long periods of time. These include studies of ice crystal orientation at Emmons Glacier (Rigsby), glaciologic and climatic observations at the summit (M. M. Miller), time-lapse photography of Emmons and Nisqually Glaciers (R. D. Miller), and ablation measurements on Nisqually Glacier (Meier).

8. THE KINEMATIC WAVE ON NISQUALLY GLACIER

by
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The annual Nisqually Glacier ice elevation surveys of Arthur Johnson detected in 1946 a thickening of the glacier at the 2,200 m level. Because of the general prevalence of glacier recession at the time, this surprising discovery was thought to represent an anomalous or temporary condition. However, Nisqually Glacier continued to thicken at this level, developing a bulge which progressed rapidly downglacier, causing great changes in ice velocity, crevassing of the surface, and eventually the formation and advance of a new, active terminus. Similar effects have been observed on other glaciers in western Washington since 1946, but nowhere has the change been documented so completely as at Nisqually Glacier. The data collected by Arthur Johnson (1960) have been partially analyzed by Meier and J. N. Johnson (1962).

The annual variation of ice surface elevation at Profiles 3, 2 and 1 (located 2,042, 960, and 213 m upglacier from the 1960 terminus, respectively) is shown in figure 6. These graphs clearly show that the bulge progressed downglacier with a distinct change in wave-form, the crest travelling faster than the trough. The amplitude of the bulge reached 30 m. The ice velocity, as observed at a point fixed in space (Profile 2) varied from about 6.5 to over 131 m per year as the wave passed, a factor of 20 times. These changes actually preceded changes in surface elevation, because of the effect of slope (Fig. 7).

The field data can be conveniently summarized on a time-distance plot (Fig. 8). On

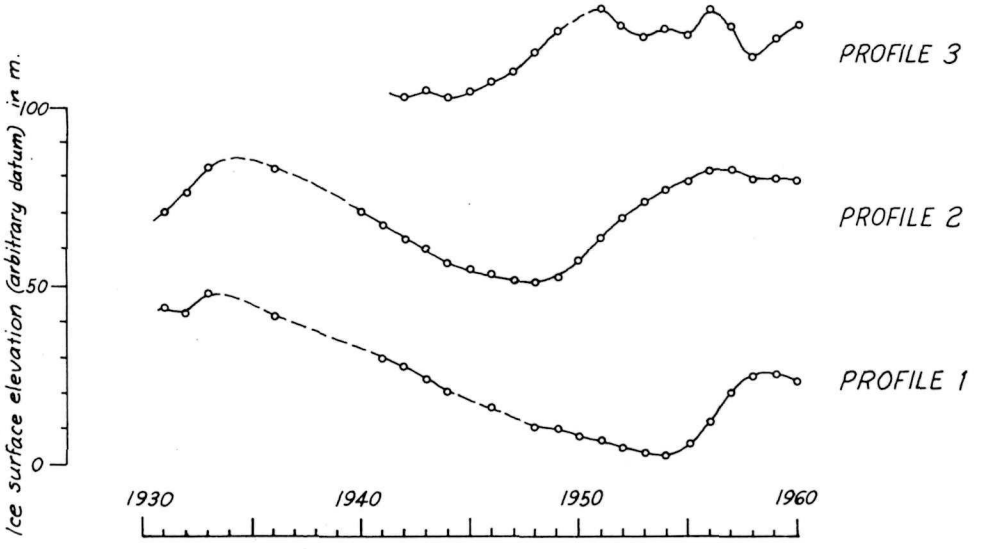

Figure 6.--Variations in ice surface elevation, Nisqually Glacier.

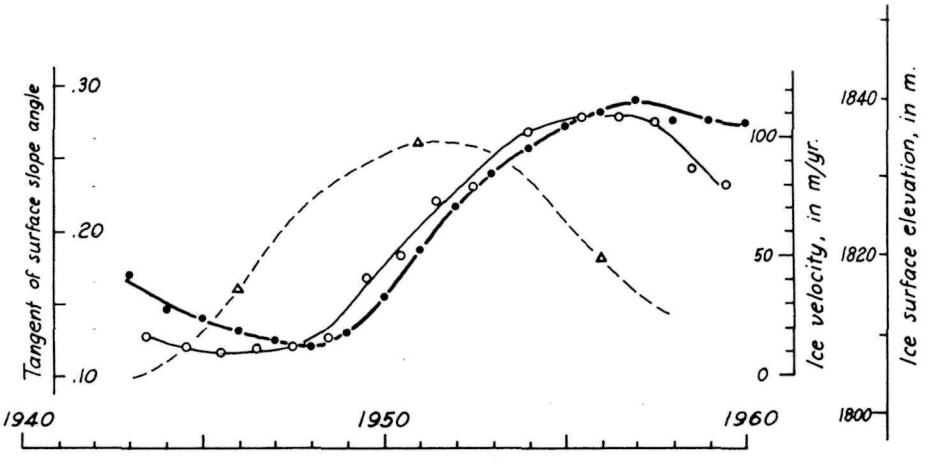

Figure 7.--Variation of ice velocity (circles), ice surface elevation (solid dots), and ice surface slope (triangles) as a function of time at Profile 2, Nisqually Glacier.

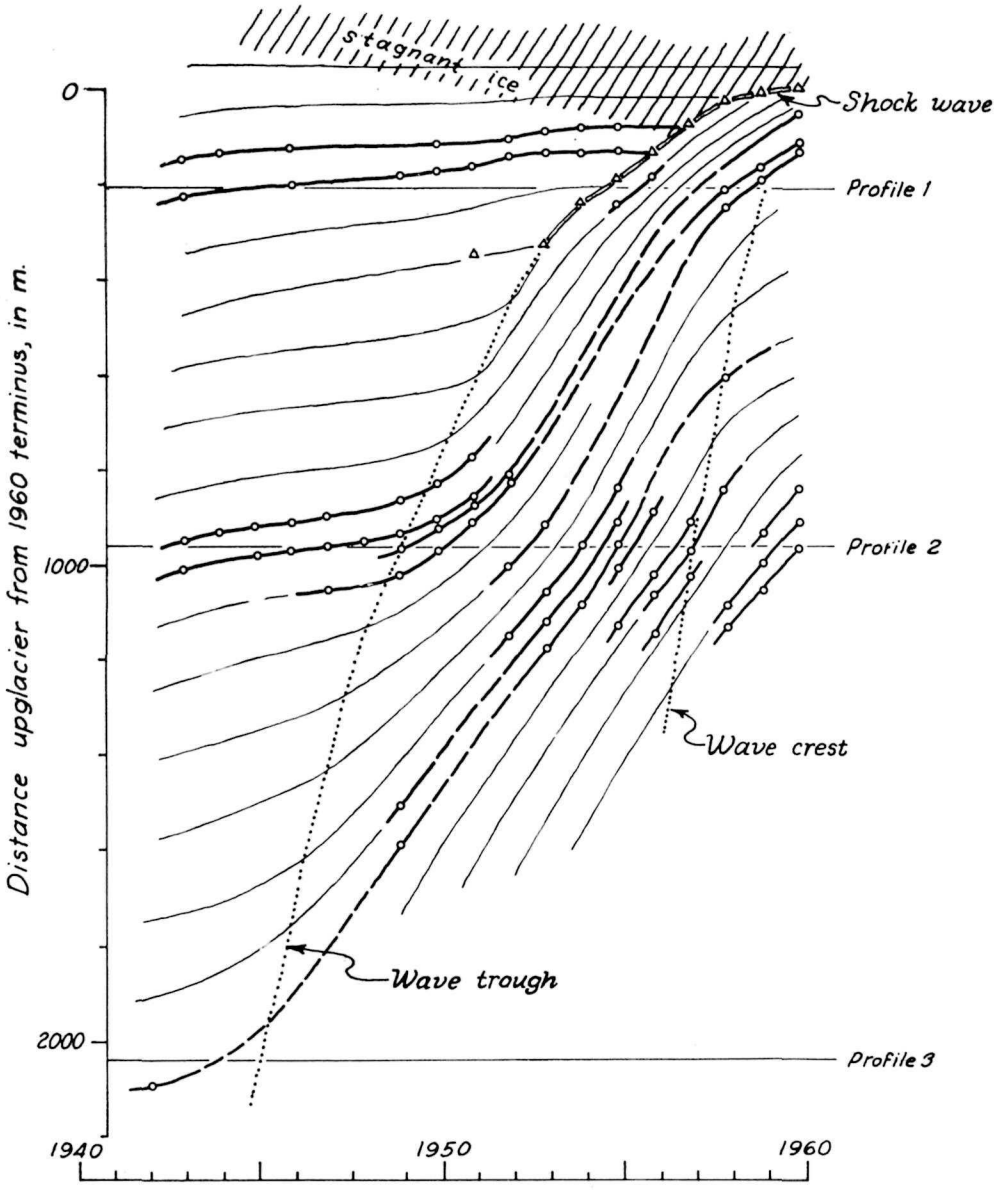

Figure 8.--Time-distance diagram, Nisqually Glacier. Circles and heavy lines represent motion of marked objects on ice surface. Thin line represents assumed motion of surface ice. Triangles show surveyed locations of advancing ice front.

this plot, velocity is indicated by the slope of a line, and a line which slopes steeply represents a rapid velocity. The progress of the wave down the glacier is indicated by dotted lines. The slopes of these lines are obviously steeper than the lines representing the surface ice, indicating a wave velocity 2 to 6 times greater than the ice velocity.

In the vicinity of Profile 1 the rapid change in velocity due to the approaching wave became so abrupt as to become discontinuous. Discontinuities such as these are known to form in certain kinematic wave situations, and have been termed shock waves. The shock wave on Nisqually Glacier can be seen on the surface in the form of active ice abruptly and discontinuously encroaching over slower, nearly-stagnant ice. Similar shock waves can be observed on the Emmons and the Cowlitz-Ingraham Glaciers.

Analysis of the Nisqually Glacier wave lends insight into several important problems in glacier flow dynamics. First, observation of figure 7 suggests that the ice velocity as measured at one point in space is a function of ice thickness and surface slope. This observation confirms the most crucial single assumption behind Nye's treatment of the response of glaciers to climatic change. Another conclusion which follows from the change in the shape of the kinematic wave as it travels downglacier (Fig. 6) is that the linearized perturbation analysis of kinematic waves, as developed by Weertman and Nye, cannot be used in this case. Some information can also be obtained about the slippage of Nisqually Glacier on its bed. Thickness of the glacier has not been measured but it can be calculated in several different ways. A method of calculation using changes in the kinematic wave velocity yielded results very similar to a calculation utilizing glacier ice discharge found by integrating the net budget on the surface of the glacier. When these values, or other reasonable values of initial glacier thickness, are used in an analysis of changes in the slip of the glacier on its bed it appears that all existing theories of bed slip are disproved. Analysis of the Nisqually Glacier wave is not yet complete.

9. JÖKULHLAUPS FROM KAUTZ AND NISQUALLY GLACIERS

by
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At infrequent intervals floods have occurred on Kautz Creek and Nisqually River. Both streams head in glaciers, and it appears that these floods were typical jökulhlaups (glacier outburst floods).

One of the most spectacular of these floods occurred on Kautz Creek in October 1947. This flood destroyed part of the lower tongue of Kautz Glacier, and carried an estimated 50,000,000 m^3 of debris downstream to Nisqually River. A sea of moving boulders (up to 4 m in diameter) and thick, cement-like volcanic sand poured down on a front 1 km wide, buried the paved highway under 5 to 6.5 m of debris, and snapped off fir trees up to 1.6 m in diameter. Evidence in cut banks suggests that other floods had occurred on Kautz Creek in earlier years. In August of 1960, a small flood occurred on the Kautz Creek. On August 23, 1961, a flood occurred on Kautz Creek which destroyed trail crossings and threatened the Kautz Creek bridge. The stream channel was deepened about 3 m at the road bridge at this time. This last event occurred during a period when no precipitation had been reported at Longmire for eight days.

The best documented jökulhlaup on Nisqually River occurred on October 25, 1955. This flood, which occurred during a rainstorm, destroyed several bridges over Nisqually River and damaged roads, grounds, and power lines in the National Park. The flood was characterized by great surges of water and debris. The discharge at the peak of the flood was estimated at 4,200 m^3/sec (this estimate may be somewhat high). Because of these floods on Nisqually River the Park Service was forced to install, at considerable expense, a new high bridge to replace several low bridges which had been destroyed.

It is interesting to note that both Nisqually and Kautz Glaciers were advancing at the time of the more recent jökulhlaups (the condition of the Kautz Glacier in 1947 is unknown). There is a possibility that the glacier advance may have created the necessary subglacier ponding conditions to store sufficient water to permit these outbreak floods. Numerous hot springs occur on and near Mount Rainier. The possibility that volcanic heat might have something to do with these jökulhlaups has neither been confirmed nor denied.

10. THE WHITE RIVER VALLEY TRAIN

by
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The processes by which a valley train is formed by a glacier have been studied in the White River valley, between the present terminus of Emmons Glacier and the moraine marking the terminus in 1913. Figure 9 shows the 1913 profile of the glacier and the 1958 profile of the valley train. Figure 10 shows successive positions of the melting ice face as shown by National Park Service surveys. Thirteen km^2 of the 19 km^2 drainage basin above the 1913 moraine are ice covered.

Mudflows have played an important role in the formation and modification of the valley train. They are a major agent in the supply of debris to the valley train from both the lateral moraine and the stagnant ice. A large flow shown in figure 10 occurred in June of 1961. It is being reworked by the stream, leaving boulders exceeding the competence of the stream in the midst of a stream deposit.

Measurements of channel characteristics were made in 112 channels developed in non-cohesive materials. Widths ranged from 0.2 to 18 m, depths from 1 cm to about 63 cm, and mean velocities from 10 to 270 cm/sec for discharges of 0.3 to 12,000 l/sec. Width, depth, and velocity were found to be power-law functions of the discharge. The power-law exponents for White River channels were found to be similar to the average of those for streams in the southwestern United States. In contrast, channels reported for Brandywine Creek, Pennsylvania, have higher velocity exponents and extremely low width exponents, reflecting its cohesive bank materials. Width and depth of channels in noncohesive materials may change by scour and deposition as well as by flow at different depths in predetermined channels. White River channels, in coarse and noncohesive materials, are narrower, slightly shallower, and have much higher flow velocities than the channels of Brandywine Creek in cohesive materials.

Pebble counting demonstrated a systematic decrease in median diameter of the valley train materials with distance from the source. A decrease of 60 mm (160 to 100 mm) in median diameter in a distance of 1,280 m suggests that selective transportation must be capable of producing radical changes in size without abrasion. The slope of the valley train is a function of particle size and discharge. The slope-forming discharge is approximately 14,000 l/sec. On a logarithmic plot of grain size versus velocity, a line with a slope of 2.6 fits the White River data better than a slope of 2.0 suggesting that for coarser materials the "sixth power law" of competency should be the 7.8 power law. Samples of suspended load showed that there is diurnal fluctuation in load as well as in discharge.

The most graphic evidence of the amount of material transported by White River is the erosion and deposition on the valley train itself. The average elevation change for the period 1957-1963 for each cross section surveyed is shown in figure 10. These changes are the net result of erosion and deposition of up to a meter of material in periods of as little as a few hours. These data are provisional and subject to change.

Description and analysis of the pattern change of White River channels was difficult because of the rapidity of the change. In time-lapse motion pictures at high flows the

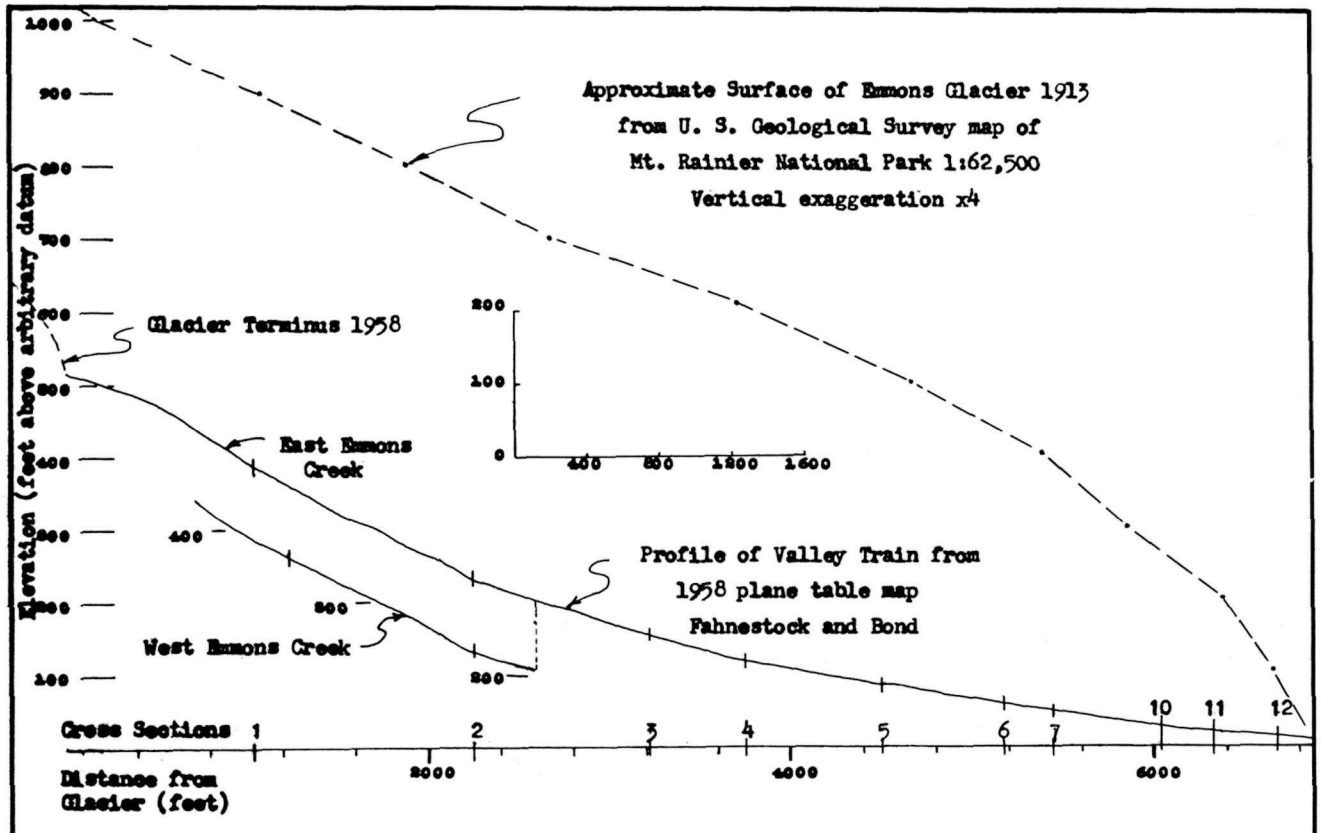

Figure 8. Profiles of Valley Train and Former Glacier Surface

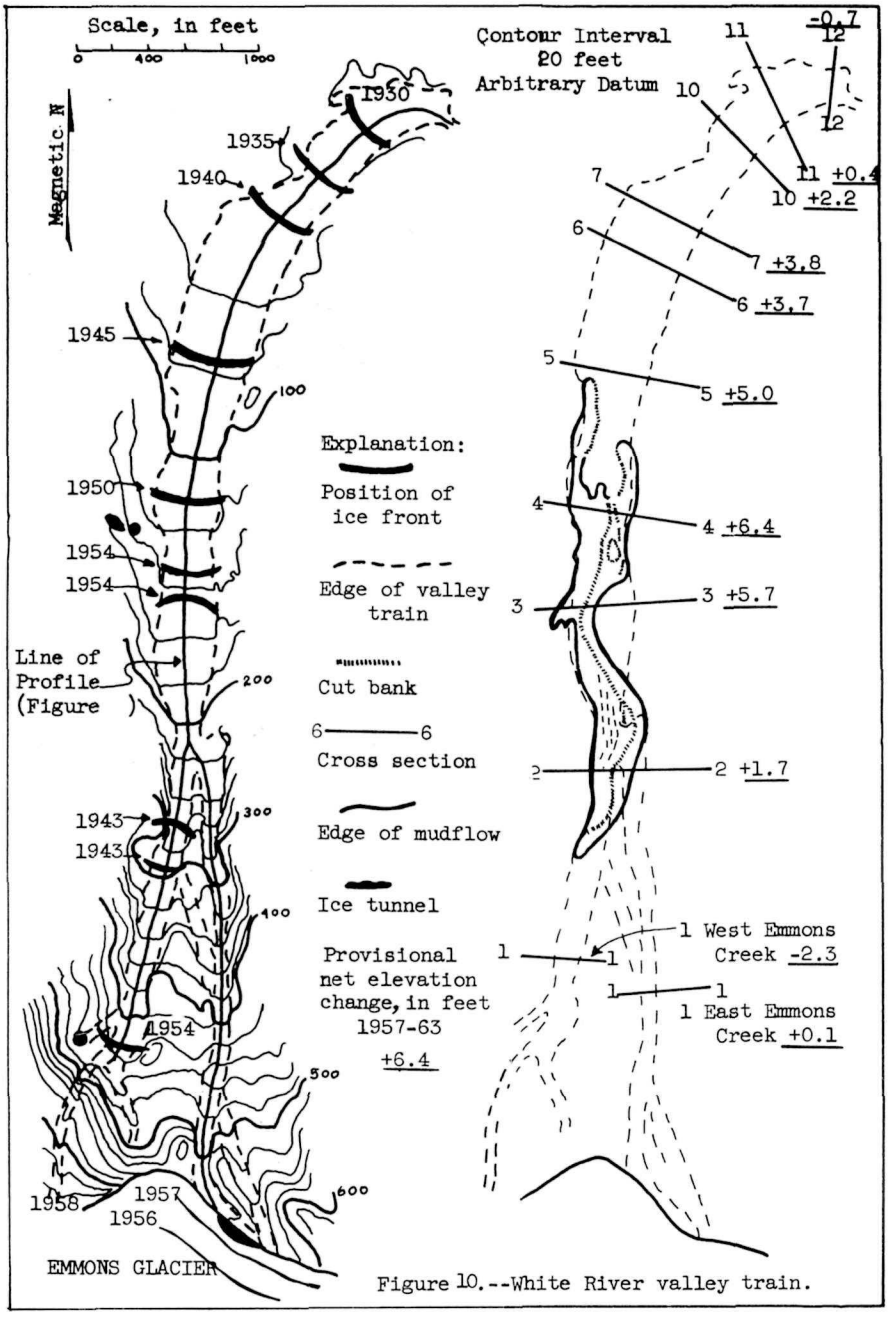

Figure 10.--White River valley train.

stream changed so rapidly during the period of a day that it resembled the discharge of a hose being played across a bed of sand. Individual features of the channel patterns mapped by plane table methods and described are topographic noses, "levees," and pools. Although braiding in an aggrading stream is common, examples were found to illustrate braiding in a degrading stream. The common element in all explanations of braiding appears to be a movement of bed load sufficient to permit deposition within the channel, causing the diversion of flow from one channel into other channels. In this reach White River is an aggrading stream showing "quasi-equilibrium" between the variables of slope and channel cross section and discharge.

Although the regimen of the glacier has long term effects in providing debris to the stream, short term effects of weather and runoff influence hydraulic characteristics, rate of deposition and erosion, and channel pattern.

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