Botanical Evidence of the Modern History of Nisqually Glacier Washington

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By ROBERT S. SIGAFOOS *and* E. L. HENDRICKS

BOTANICAL EVIDENCE OF GLACIER ACTIVITY

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A description of botanical methods used to determine dates of recession of three glaciers at Mount Rainier, Washington

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By Robert S. Sigafoos and E. L. Hendricks

ABSTRACT

A knowledge of the areas once occupied by mountain glaciers reveals at least part of the past behavior of these glaciers. From this behavior, inferences of past climate can be drawn. The maximum advance of Nisqually Glacier in the last thousand years was located, and retreat from this point is believed to have started about 1840. The maximum dawn-valley position of the glacier is marked by either a prominent moraine or by a line of difference between stands of trees of strikingly different size and significantly different age. The thousand-year age of the forest beyond the moraine or line between abutting stands represents the minimum time since the surface was glaciated. This age is based on the age of the oldest trees, plus an estimated interval required for the formation of humus, plus evidence of an ancient fire, plus an interval of deposition of pyroclastics. The estimate of the date when Nisqually Glacier began to retreat from its maximum advance is based upon the ages of the oldest trees plus an interval of 5 years estimated as the time required for the establishment of trees on stable moraines. This interval was derived from a study of the ages of trees growing at locations of known past positions of the glacier.

Reconnaissance studies were made on moraines formed by Emmons and Tahoma Glaciers. Preliminary analyses of these data suggest that Emmons Glacier started to recede from its maximum advance in about 1745. Two other upvalley moraines mark positions from which recession started about 1849 and 1896. Ages of trees near Tahoma Glacier indicate that it started to recede from its position of maximum advance in about 1635. About 1835 Tahoma Glacier started to recede again from another moraine formed by a readvance that terminated near the 1635 position.

INTRODUCTION

A common problem in hydrology is that of determining where modern water-supply data fit into the long-term pattern of fluctuating water supplies. Streamflow and other water records are too short a base from which to extrapolate most long-range water-development plans. Therefore, water-resources investigators have sought, from time to time, to reconstruct past climatic trends by interpreting the physical evidence left by modern hydrologic events.

This study of the recent moraines of Nisqually Glacier, Mount Rainier, Wash., is one of the efforts to reconstruct past climatic trends. 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. A larger study, of which the study of Nisqually Glacier is a part, is concerned with dating the terminal positions of several glaciers on Mount Rainier at several times in recent history when points of maximum advance were reached. Furthermore, because the present study is based on the ages of trees adjacent to the glaciers, only glacial advances during the last 1,000 years or less are being investigated. This report is concerned primarily with Nisqually Glacier but includes a brief discussion of a reconnaissance study of moraines formed by Emmons and Tahoma Glaciers. It is the first report of a series on the broader study.

Acknowledgment is made for the great assistance offered by the staff of Mount Rainier National Park, especially by V. R. Bender, chief naturalist. The writers benefited from discussions in the field and office with Arthur Johnson, D. R. Crandell, R. D. Miller, and D. R. Mullineaux of the U.S. Geological Survey. Arthur Johnson first interested the authors in the study, and he kindly compiled a planetable map of part of Nisqually Glacier terminal moraine especially for this report. Ethel W. Coffay of the U.S. Geological Survey provided considerable help in the study of core samples.

AREA OF STUDY

Nisqually Glacier, on the south slope of Mount Rainier, was chosen as the initial subject for study because of the large volume of data on its terminal positions during the last 60 years (Bender and Haines, 1955, p. 275–280). Also, it is the most accessible glacier and is part of the largest single-peak system in the conterminous United States. The recorded positions of the terminus together with the ages of trees at these positions provide data for use in interpreting tree ages as a means of dating the ice positions marked by moraines deposited before detailed observations began. In addition, a reconnaissance was made of both Emmons and Tahoma Glaciers to determine whether botanical evidence shows their history to be similar to that of Nisqually Glacier.

Nisqually, Emmons, and Tahoma Glaciers are valley glaciers that radiate from the central ice cap of Mount Rainier. Nisqually Glacier extends down the south side of the mountain, Emmons down the northeast side, and Tahoma down the southwest side (fig. 1). The present terminus of Nisqually Glacier is at an altitude of about 4,500 feet, the terminus of Emmons Glacier is at about 5,300 feet, and that of Tahoma Glacier is somewhat higher, possibly at about 5,600 feet. The valleys are U-shaped with steep sides that are nearly vertical at several places. At other places slopes are so steep that perennial rock slides and snow avalanches are common. Trees grow in profusion where the valley slopes are gentler.

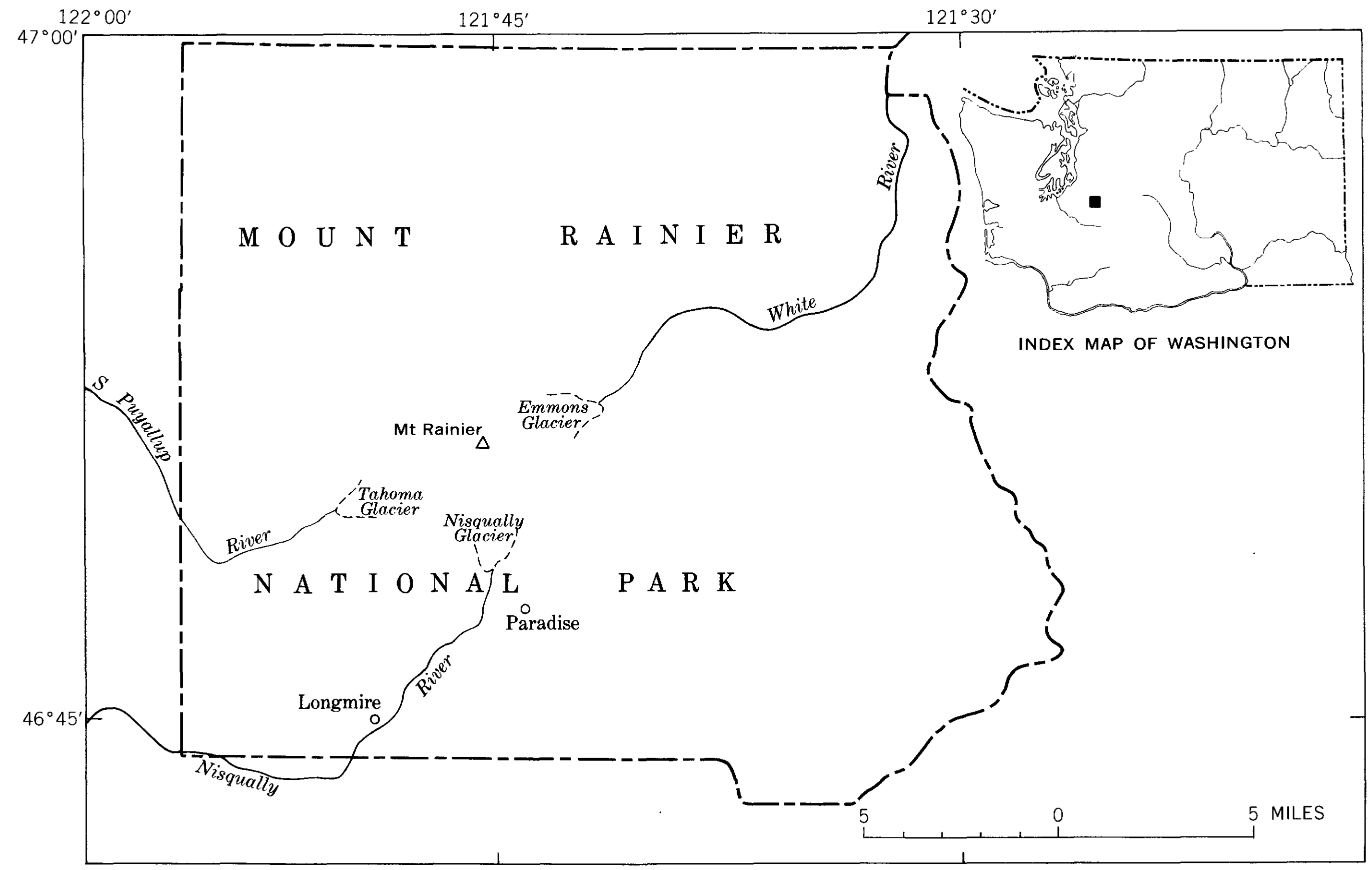

FIGURE 1.—Index map of Mount Rainier National Park, Wash.

The flood plains immediately downvalley from existing glaciers are largely the products of streams that now occupy the valleys. Nisqually River emerges from an ice cave in the terminus of Nisqually Glacier. White River originates at a few points along the broader terminus of Emmons Glacier. South Puyallup River, which flows from Tahoma Glacier, was not examined in much detail during the short reconnaissance. Nisqually and White Rivers meander over boulder-strewn flood plains built up largely from debris deposited by glaciers, floods, and mudflows. Floods, like the one of October 25, 1955 on Nisqually River within the park boundary, consist of surges of water released at the snout of Nisqually Glacier following exceptionally heavy rain. This flood roared down the steep valley at a high velocity carrying a large amount of bedload material that included boulders more than 6 feet in diameter. The highway bridge, a short distance below the glacier was swept away, as were previous bridges at the same location. The volume of water over the flood plain was so great for about 4 miles downstream from the glacier that virtually all vegetation was either buried or swept away in this reach.

For the greater part of the summer season, however, the main streams and small tributaries entering below the glaciers' termini derive their water from melting snow and ice. As would be expected the rate of flow fluctuates diurnally in direct response to the heat available for melting and to the area of exposed ice and snow. Owing to the steep longitudinal gradients of the valleys, much energy is available in melt water for the movement of flood-plain gravel and boulders. These streams at all times, and especially during periods of high flow, are working and reworking the flood-plain sediments by the constant migration of meanders from one side of the valley to the other.

As a result of lateral migration and flooding, vegetation on the flood plains stands little or no chance of growing old. Thus, in order to find both topographic and botanical evidence of past glacier positions, this study is limited to the vegetation growing on the valley sides.

Below an altitude of about 5,000 feet the vegetation on these side slopes, where not destroyed by recent floods, consists of a dense forest of coniferous trees (Brockman, 1949, p. 3–6). Above 6,500 feet, the country is treeless, and the ground is covered with alpine meadow vegetation or is bare. Between 5,000 and 6,500 feet, the forest is open and parklike. Thus the modern terminal moraines and present termini of glaciers (p. A–11) are below the upper timberline. This fact permits the use of botanical methods in dating surfaces once occupied by glaciers.

The old forest on slopes above and beyond the trimline in the vicinity of Nisqually, Emmons, and Tahoma Glaciers consists primarily of western white pine, western hemlock, Douglas-fir, Pacific silver fir, noble fir, and Alaska-cedar. Trimline is a term suggested by R. P. Sharp, according to Lawrence (1948, p. 26), to designate a boundary between types of vegetation differing in age of plants, in species, or in the density of the stand marking a position from which a valley glacier has recently receded. Lodgepole pine and Engelman spruce are common on the modern moraines of Emmons Glacier. Whitebark pine grows on the moraines of Tahoma Glacier. Sitka alder forms dense thickets in places on the younger morainic surfaces where coniferous trees are small and widely scattered. Vine maple and Douglas maple grow in the forest and form dense thickets in most open areas within the forest. Black cottonwood trees are scattered along some of the streams. A complete list of common and Latin names is given in table 1; these names are the ones used by Little (1953).

List of species

Common name	*Latin name*
Alaska-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Bigleaf maple	*Acer macrophyllum* Pursh
Black cottonwood	*Populus trichocarpa* Torrey and Gray
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Engelmann spruce	*Picea engelmannii Parry*
Lodgepole pine	*Pinus contorta* Douglas
Noble fir	*Abies procera* Rehder
Pacific silver fir	*amabilis* (Douglas) Forbes
Red alder	*Alnus rubra* Bongard
Sitka alder	*Alnus sinuata* (Regel) Rydberg
Vine maple	*Acer circinatum* Pursh
Western hemlock	*Tsuga heterophylla* (Rafinesque) Sargent
Western redcedar	*Thuja plicata* Donn
Western white pine	*Pinus monticola* Douglas
Whitebark pine	*albicaulis* Engelmann

METHODS OF STUDY

TOPOGRAPHIC AND BOTANICAL EVIDENCE OF SURFACE AGE

In this study two kinds of evidence of recent positions of the ice front were used: Topographic and botanical. The maximum downvalley position reached by a glacier in a period of advance may be marked by a prominent ridge of rock debris, a terminal moraine. Positions at which the glacier terminus halted for an appreciable time during a period of recession also may be marked by a ridge, a recessional moraine (fig. 2). All such positions, however, are not marked by debris, because the glacier may not have carried a sufficient load or may not have remained in a given position long enough for a moraine to form. At some locations in the valley, the slopes may be so steep and unstable that previously existing moraines have been removed by erosion.

Where topographic evidence for the recent ice position is absent or masked, the position is marked by a line of sharp difference in age between forests. As a glacier advances it destroys all trees in its path. As a glacier recedes it leaves a trimline between the preexisting forest beyond its margin and the fresh glacial debris on its bed. After the glacier's recession, trees again begin to grow on the scoured areas and, in time, a forest becomes well established. However, the location of the old ice margin remains clearly delimited by the difference in size and age of the adjacent forests.

The primary method of dating a historical ice position used here consisted of studying adjacent forests of different ages. Where moraines exist they were used as evidence of an ice position. The age of a tree is interpreted to be the minimum period that has elapsed since the ice left the position occupied by the tree. In order to establish a minimum age of a given surface, an attempt is made to determine the age of the oldest tree on that surface.

In order to explain the significance of the ages of trees found on moraines in terms of the regimen of glaciers, a brief description of glacier shrinkage may be helpful. Glaciers shrink in two different ways, each resulting in a particular topographic expression (Sharp, 1951b, p. 108–109). The terminus of a receding glacier is distinct and may be relatively free of surface debris, because the ice in the terminus is moving forward while the leading edge is receding. The terminus of a stagnant glacier is quite different, because a larger loss in volume results from vertical shrinkage than from terminal recession. Consequently, the leading edge and surface are covered with superglacial debris derived from englacial material and from avalanched material from the valley walls. The chaotic surface of the glacier in the zone of stagnation consists of knobs and ridges separating ponds and streams. The decayed condition of the ice is further indicated by numerous arches, caverns, and tunnels. Such a stagnant reach results from the ice becoming too thin to show appreciable motion.

The superglacial debris on a stagnant glacier, ranging from clay-sized particles to large angular blocks (Sharp, 1949, p. 294), is subject to extensive reworking as the underlying ice melts, causing the overlying debris to slump. The finer fractions in the debris are partly removed by superglacial streams. However, modification of the superglacial features decreases as the amount of debris increases relative to the amount of ice (Sharp, 1949, p. 295–312).

Trees become established on superglacial debris that is not completely stabilized or that overlies a slowly moving glacier (Matthes and Phillips, 1943, p. 18–19, 23). Trees as old as 100 years grow on thick superglacial deposits on Malaspina Glacier (Sharp, 1951a, p. 726). Trees ranging from 1 to 3 feet tall and from 47 to 56 years old were found growing on an ice-cored moraine at the approximate position of Emmons Glacier terminus in 1910–13 (fig. 2) as represented on the quadrangle map of Mount Rainier National Park. Although seedlings start to grow on superglacial debris on moving glaciers, most of them are believed to survive only after debris ceases to collapse repeatedly.

The age of the oldest tree at a given place, therefore, is equivalent to the time that has elapsed since the glacial debris upon which the tree is growing became stable enough for seedlings to survive. The time required for superglacial debris to accumulate and become stable along the margins of a glacier or on stagnant ice must be determined and added to the age of the oldest tree in order to estimate the length of time since cessation of active scouring. Determination of this interval is done by sampling trees and seedlings growing at known past positions of the glaciers.

FIGURE 2.—Moraine at the approximate position of Emmons Glacier terminus in 1910–13, as shown on map of Mount Rainier National Park. A stream that rises near Baker Point is in left background. Melting ice is present under the slumping moraine at right. Tree seedlings from 1 to 3 feet tall are numerous in this area.

The availability of tree seed is also of primary importance because it dictates which species become established and, along with the physical suitability of the seed bed, the rate at which the forest increases in density. The presence of seedlings on the youngest moraines of Emmons and Nisqually Glaciers formed in the last 10 years lends validity to the assumption that at least some seed is available in all years.

When the older modern moraines, such as those downvalley from Nisqually Glacier upon which the trees are less than 120 years old and those downvalley from Emmons Glacier upon which the trees are less than 210 years old, first became stabilized, they were much closer to a seed source than are the younger surfaces upon which trees are now starting to grow. Mature forest trees grew on surfaces adjoining and partly surrounding these older moraines (figs. 7, 9). Therefore, abundant quantities of tree seed were available and seedlings undoubtedly became established as soon as the morainic debris became stabilized.

Data are presented later (p. A–11) to show that the period between the stabilization of the seed bed and the establishment of tree seedlings is only a few years. The short time interval illustrates the fact that the tree species that make up the mature forest are among the first plants to become established on new surfaces. Willow species, alder, and heaths form dense thickets in places; tree species are scattered. Thus the evidence discloses that growth of the shrubs, including alder, is coincident with the establishment of tree species. Insufficient time between the formation of new surfaces and the start of tree seedlings rules out any sort of plant succession before the germination and growth of tree species that make up the mature forest. Any change in vegetation through time, which might be inferred from differences in vegetation on surfaces of different age, seems to be related to the death of shorter lived species and the continued growth of trees.

GROWTH INCREMENTS OF TREES

The oldest trees whose age is determined by counting the annual-growth rings, provide the basis for estimating the minimum age of the surface upon which they grow. These rings can be seen in a stump section or in a core sample removed from the trunk. The number of annual rings that can be counted in stumps is believed to be close to the true age of the trees, because nearly all stumps examined measured less than 6 inches high. Trees are probably older than the age indicated by core counts, because most cores were taken more than 12 inches above the ground, which is above the height of trees in the seedling stage. However, error from this source is negligible, because the ages determined from cores are comparable to those determined from stumps. In fact, the highest count of rings in a stump in a young forest was 112, whereas the highest count of a core in the same forest was 117.

The diameter growth of trees and the characteristics of wood, including the identification of annual rings are discussed by Brown, Panshin, and Forsaith (1949, p. 12–27, 35, 52, 96–111, 126–163, 196–238), Eames and McDaniels (1947, p. 175–231), and Esau (1953, p. 125–136, 338–411).

AGE SAMPLING AND MAPPING PLAN

APPEARANCE OF THE FOREST

Several botanical characteristics are considered in the problem of seeking the oldest trees in several localities in order to date past ice positions. The gross appearance of a forest provides the primary means of making a broad estimate of the relative age of the surfaces upon which the forest grows (Lawrence, 1950). Just as a population of older people can be distinguished by sight from a population of younger people, so can an old forest be distinguished from a young forest. Within each area the ages of the oldest trees were estimated by their appearance before the trees were cored.

OLD FOREST

The largest trees in an area grow in the old forest, and at Mount Rainier most of them have trunks that range from 3 to 5 feet in diameter (fig. 3). A few trees are

FIGURE 3.—Forest of living trees, 300 years old, fallen logs, and rotted stumps. Old surface is downvalley from 1840 terminal moraine of Nisqually Glacier. (See fig. 4.)

as large as 6 feet in diameter. Ancient trees bearing broken tops, open foliage, or branches only part way around the crown are characteristic. The forest floor is covered with fallen logs in all stages of decay, of which the soundest are of about the same diameter as the largest living trees. Seedlings and small trees grow on the still identifiable rotted logs.

Scattered through the forest are barely perceptible mounds and pits that may be the erosional remnants of soil mounds formed by the fall of ancestral trees. Such mounds are common in the deciduous forest of the eastern United States and persist for a long time (Shaler, 1892, p. 273–274; Lutz, 1940; Goodlett, 1954, p. 66–81; Denny and Goodlett, 1956, p. 59–66). Thick humus layers almost completely cover the forest floor except on the youngest mounds formed by uprooted trees and along banks of small streams.

Humus, as used in this report and by foresters (Munns, 1950; Trimble and Lull, 1956, p. 2–8), is defined as the organic matter and intermixed mineral matter in soil profiles. It includes the partly decomposed surface litter in which plant parts can be recognized by sight. The humus consists of layers of rotten wood derived from old logs lying at all angles one on top of the other and differing in the degree of decay. The humus alone appears to represent a long interval of time. The largest living trees, whose ages can be estimated only from a count of annual rings found in a core of part of the radius, appear to represent only the most recent of several generations of trees.

Study of soil profiles reveals additional evidence of the antiquity of the forests on the old surfaces. Large fragments of charcoal and partly charred wood are found commonly beneath humus layers and close to the roots of the largest living trees. The charcoal is evidence that fire swept through an ancient forest that existed before the growth and death of the trees which rotted to form the humus and before the present forest began to grow. Volcanic ash layers, where present, are used to estimate the relative age of different surfaces.

YOUNG FOREST

The largest living trees in the young forests are smaller than the average size trees in the old forest and have well-formed crowns and dense foliage (fig. 4). Fallen trees are present, but logs are smaller in diameter than the trunks of standing trees indicating that they were members of a more dense stand in its early stage of development. Humus layers generally are thin, consisting primarily of decayed leaf litter. Bare or nearly bare boulders protrude through the humus, and mineral soil can be exposed by merely scratching the humus.

FIGURE 4.—Forest of young trees, smaller logs, and nearly bare boulders near the downvalley limit of the 1840 terminal moraine of Nisqually Glacier; trees are 1 to 2 feet in diameter. (See fig. 3.)

The only evidence of earlier forest growth in soil profiles on the younger surfaces consists of humus which is being formed from litter from the living trees. All evidence indicates that the present forest is the first to grow; thus the age of the oldest trees nearly equals the time the surfaces have been exposed to plant colonization.

SELECTION OF TREES

Within each forest population, that is, within the old forest and within different age groups in the young forest, trees at many localities were selected for detailed study. In localities where moraines exist, trees on both sides of the moraine or close to the presumed historic position of the ice were chosen. They included the oldest tree in the population, whose age was determined in order to provide an estimate of the minimum age of the surface at the trees' location. Individual trees that appeared to be the oldest were selected for sampling.

Trees in the Mount Rainier area apparently reach a maximum diameter of 4 to 6 feet. Because of the relatively rapid growth rate, only about 300 years is required for trees in the Nisqually River valley to grow to this diameter. Near Emmons Glacier, on the other hand, more than 400 years are required for trees to reach the maximum size before they die. However, some trees near Nisqually Glacier are growing more slowly than any trees sampled near Emmons Glacier. Thus the maximum age of trees cannot by itself be used to determine the age of an old surface, and it is necessary to search for additional evidences of age. Furthermore, if the growth rate of trees in a given area is determined to be relatively rapid, then the chances are low of finding an individual significantly older than the average of those sampled. If, on the other hand, the growth rate is relatively slow, diligent search might disclose an ancient specimen that is significantly older than its neighbors.

The general appearance of the bark of trees is the best single criterion for estimating the relative age of several trees of the same species within a stand. Because the bark consists primarily of cork produced continuously during the growing season by a layer of living cells within the inner bark, the outer cells remain unaffected by growth, and thus the bark of older trees looks more weathered and eroded than the bark of younger trees.

Twisted and gnarled trees that have stems bent in several directions generally are older than larger trees which are more symmetrical. Close study of the branches of these bent trees shows small closely packed needles and exceedingly short annual increments of twig growth. These anual increments can be identified as the length of the twig between successive minute scars remaining from the abscission of the terminal-bud scales. These scars are closely spaced lines in the bark running normal to the axis of a twig. Exceedingly short annual increments of twig growth during recent years combined with a twisted form suggests that such trees have always grown slowly and thus may be of considerable age.

Because the diameter of the trunk is a function of the growth rate as well as of age, it is the poorest single criterion to use in selecting trees for a core sample. For example, three Pacific silver fir trees growing in the same area on a slope above the Nisqually River all are about the same age, but differ markedly in diameter as shown in the table below.

Tree	Diameter (inches)	Age (years)	Annual radial growth rate (inches)
A	24	104	1/10
B	16	96	1/12
C	30	113	1/8

The largest tree within a given species was cored, but other trees which appeared to be older on the basis of the other criteria previously outlined, were also cored. If all trees within a group appeared to have nearly the same vigor, the largest of each species was cored.

Many trees must be sampled at many different sites in order to determine the age of the oldest tree in the forest, primarily because the mortality of individual trees is extremely high. A so-called good stand of established seedlings ranges from 500 to 1,000 seedlings per acre. Thus, where the oldest trees in any area of several acres number only one or two it is apparent that the mortality rate from seedling to maturity is extremely high. On many newly formed morainic surfaces there are far fewer than 500 to 1,000 seedlings per acre, yet the ages of the oldest trees on different parts of what appears to be a single moraine are remarkably similar. This demonstrates the effectiveness of the sampling procedure used in this study.

Because of the many environmental influences that lead to the destruction of trees at Mount Rainier, many trees were sampled at each place selected for study. Initially, in the life of a stand on the newly formed moraines, seedlings are subject to uprooting and burial on the unstable surfaces. Some slow-growing trees die in dense young stands in which most other trees are growing rapidly, probably because of excessive amount of shade. Rock and snow slides, insects, disease, and fire destroy individuals and large areas of forest. One or more of these influences have been of such magnitude and frequency in certain areas that trees in them were not used as samples in the present study.

In summary, many characteristics must be taken into consideration in selecting forest stands and individual trees for sampling to determine the maximum age of the forest. The appearance of individual trees, as well as the species and trunk diameters, is used to determine which individuals should be sampled once the stand is selected for study.

GEOGRAPHIC DISTRIBUTION OF KEY TREES AND AGE GROUPS

Experience in tracing the position of moraines quickly demonstrates that a given advance of a glacier does not necessarily follow the same pattern as its predecessor. Therefore, a younger and an older moraine may not necessarily parallel each other in all parts of the valley. In fact, such symmetry seems to be the exception. Thus it is necessary to obtain the ages of trees that grow within geographic bounds sufficiently extensive to cover virtually all parts of the valley.

The dissimilarity in the pattern of movement of two successive glacial advances may, for convenience, be classed as: those that are dissimilar because of a lateral shift in the axis of flow (fig. 5*A*); those that result from a difference in slope of the surface of the ice streams (fig. 5*B*); and those that differ because the last advance did not extend as far downvalley as an earlier one but that both follow the same axis of flow (fig. 5*C*). In the class of two advances similar in downvalley extent and surface slope, but with lateral displacement of the axis of flow, the lateral moraine of the younger will show on one side of the valley, the lateral moraines of both the younger and the older will show on the other side of the valley, and the moraines will intersect somewhere near the terminal positions. In the class of two advances nearly similar in downvalley extent, but with differing longitudinal slopes, the lateral moraines of the younger or of both the younger and the older will be found on both valley sides, and the moraines will intersect at two places near the terminal positions.

In the third class of the last advance extending a shorter distance downvalley than an earlier one, the resulting moraines are roughly parallel and the younger ones occur within the older ones. Furthermore, a preexisting moraine tends to modify the course of a later advance, especially where the glacier moves through a breach in the older moraine.

In Nisqually River valley the most recent major advance overrode and obliterated all evidence of the moraines left by possible earlier, less extensive advances. This advance fits the class in which the terminal moraine and lateral moraines in the area studied are of the same age.

Limited observation of Emmons and Tahoma Glacier moraines indicate, however, that the existence of one class alone may be uncommon. Combinations of various degrees of each class produce a complex pattern of relationships between the positions of two glacial advances. A previous position of the glacier may be represented by only small widely separated segments.

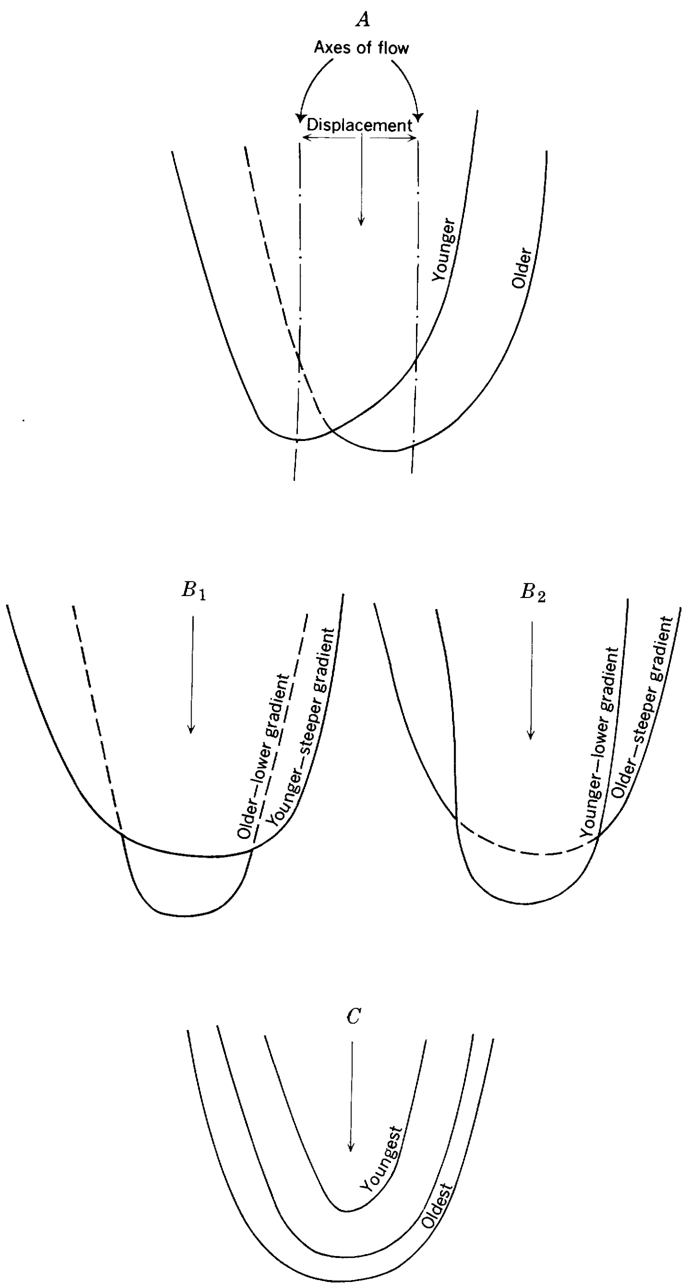

FIGURE 5.—Diagrams showing possible relations between successive advances of a glacier. Solid lines show position of moraines that remain after readvance. *A*. Similar in downvalley extent but with axes of flow displaced laterally; *B*. Closely similar in downvalley extent but differing in longitudinal gradient; *C*. Different downvalley extent but with same axis of flow.

Thus careful tree-age sampling on an extensive geographic pattern is required to correlate the identifiable ice-front positions. Although the complex pattern of ice-front positions adds to the sampling problem, it is also a fortunate circumstance in that the evidence of a larger number of glacier positions is more likely to exist than if the advances followed a simple pattern. The sequence of advances and recessions of Emmons Glacier formed a complicated pattern of moraines, and studies to date are insufficient to unravel the complete history. At Tahoma Glacier, an older advance in the area studied is represented by a small segment of a lateral moraine that is bounded by a younger moraine.

MODERN HISTORY OF NISQUALLY GLACIER

Conspicuous remnants of a terminal moraine are located approximately 1 mile downvalley from the terminus of Nisqually Glacier (fig. 6) or about 800 feet downvalley from the bridge under construction in 1958–60 on the highway between Longmire and Paradise. Lateral moraines extend upstream from the terminal moraine on both valley walls. These moraines mark the maximum advance of Nisqually Glacier during perhaps the last thousand years.

Field study was concentrated in the valley reach shown in figure 6. Thirty-two groups of trees in the entire study area were sampled. A total of 179 trees were cored, and annual rings were counted on 74 stumps, cut in the winter of 1957–58 as a part of the new road construction. Annual rings on cores were counted in the field and recounted later in the laboratory. The location of the area and the location of some of the key trees are shown on figure 6.

MAXIMUM ADVANCE IN LAST THOUSAND YEARS

An old forest grows downstream from the terminal moraine and upslope from the lateral moraines. The age of this forest is a minimum estimate of the age of the drift-covered surface on which it grows. The appearance of the forest, the humus, and the soil profile, suggest that the surface is at least a thousand years old; probably it is much older.

BOTANICAL EVIDENCE

The living trees in this part of the Nisqually River valley range in size from 2 to 4 feet in diameter; some of the recently cut stumps in the old forest are as large as 6 feet in diameter. Annual ring counts of 21 of these older stumps were made, and the age of the trees at the end of their last growing season (1957) ranged from 285 to 303 years. In addition, 23 trees in the old forest were cored, but the borer was long enough to obtain a sample of the entire radius from only 3 of them.

Throughout the old forest are many fallen logs and broken stumps (fig. 3). The wood in some of the logs is solid and appears to be sound; in others, the bark is intact and little decayed, but it conceals a punky, partly decayed trunk. Some logs are almost completely decayed and consist solely of rotten wood. Evidence of still older rotten logs can be found in places on the forest floor by digging in barely perceptible elongate ridges that are completely covered with mosses and

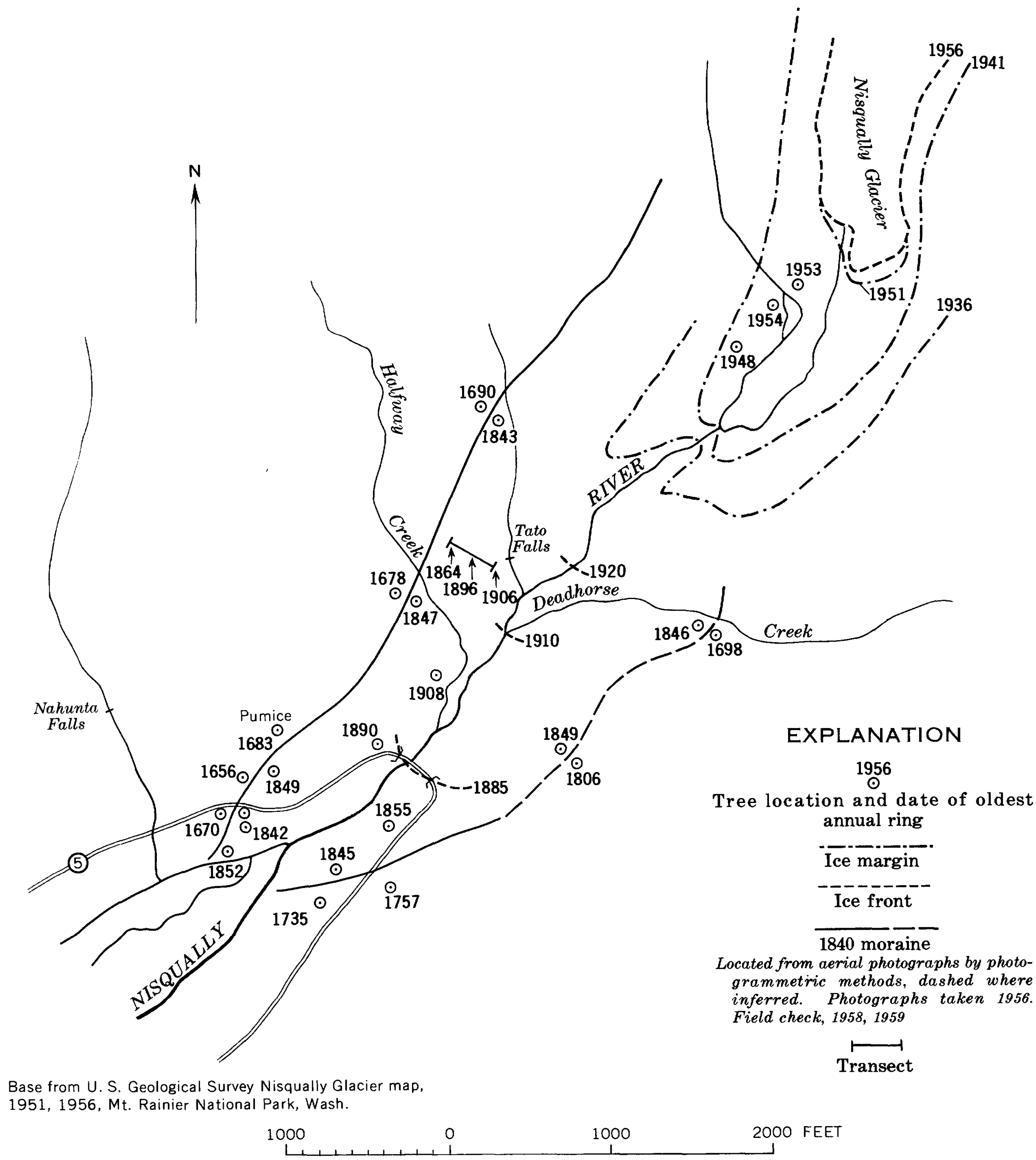

FIGURE 6.—Map of Nisqually Glacier terminal moraine and vicinity showing the location of maximum modern advance and location and age of the key trees. Arthur Johnson and R. S. Sigafoos located trees, road, and 1840 moraine by plane table survey, August 30, 1958.

forest litter. The humus consists of layers of rotten wood in which the grain of the parent trunks is still apparent. A plane section through these layers cuts along and across the grain at all angles. This decayed wood almost completely carpets the forest and comprises the upper 0.5 to 1.0 foot of the soil profile. Because the sound and partly decayed logs are the same size as the standing trees it is assumed that they were as old as the oldest standing trees, or about 300 years old when they fell. Although the mounds of rotten logs are considerably smaller than the sound fallen logs and standing trees, it is assumed that they, too, were about this old when they fell. The evidence, then, consists of living trees that are approximately 300 years old and logs that are assumed also to have been 300 years old when they fell.

The different degrees of wood decay suggest that the falling of trees is a continuing thing and show, furthermore, that trees have fallen throughout a long period of time. Clear-cut evidence of the minimum amount of time that has elapsed since the death of the earliest generation of trees was not found. Evidence was found, however, that permits a rough estimate of the rate of wood decay in this area. The ages of two trees growing on the pit wall formed when a 4-foot noble fir was uprooted indicate that at least 50 years have elapsed since the tree fell. The wood in the fallen tree is sound. As will be discussed in more detail on page A–14, trees ranging in age from 111 to 117 years are growing on the Nisqually Glacier end moraine. Beneath the boulders comprising the moraine is an only partly decayed stump, 4 feet in diameter, which has been dead for at least 117 years. The partial decay in this length of time demonstrates that much time is required for logs to rot completely. In the Kautz Creek drainage basin, a western hemlock, 142 years old, was found growing on a fallen log of western redcedar in which the heart wood had the appearance of freshly cut lumber. These data, scanty though they are, indicate that at least 200 years was required to form the humus layers composed of decayed wood.

The fact that all fallen logs, whose original diameters still can be measured with accuracy, are similar in size to the 300-year old living trees, indicates that perhaps most of the rotten wood in the humus was formed from trees that were of this size and age when the fell. No evidence was found to suggest that any appreciable amount of the humus was formed by smaller trees. Therefore, if these two assumptions are valid, that at least 200 years was required for the wood to rot and the trees which fell were 300 years old, then these trees must have begun to grow at least 500 years ago.

A fire occurred before the death of the first trees, which are represented by the oldest humus. Evidence of this fire consists of large fragments of charcoal and charred wood, 2 to 5 inches in diameter and 8 to 12 inches long, between the humus layers on the surface and mineral soil below. Measurement of the annual-ring curvature in two larger fragments shows that one has a radius of about 1 foot and the other about 1.5 feet. These fragments came from logs with minimum diameters ranging from 2 to 3 feet, thus the minimum ages of the trees represented by these fragments ranges from 100 to 200 years. The fire required to char wood of this size probably destroyed all humus and killed the contemporary trees. Therefore, the fallen logs and humus layers postdate the fire which formed the charcoal. The charcoal represents an additional interval during which trees grew on the drift-covered surface. Thus, the botanical evidence, consisting of the age of living trees, fallen logs in all stages of decay, humus layers, and charcoal beneath the humus suggests that the subsurface has been forested for at least 600 to 700 years. This evidence is summarized as follows:

	Age (years)	Thickness (feet)	Depth (feet)	Age determined by—
Living trees	300			Ring count.
Soil humus	200	0.5–1.0	0.5–1.0	Inference from estimated rate of decay.
Charcoal	[1] 100–200	0.05–0.15	0.55–1.15	Inference from estimated diameter.
Total	600–700			

[1] The result of a carbon-14 analysis of a wood sample (unit 2, p. A–11, collected by R. D. Miller nearby at a level between the humus and the underlying pyroclastics was received subsequent to this study. The age is 1640±250 years Before Present (B.P.) (sample W–922, Rubin and Berthold, 1961).

These characteristics of old age are present in all parts of the old forest that were studied except on the southeast side of the valley. Here, a recent fire destroyed much of the evidence of the older forest. However, the presence of a few charred snags suggests that the forest downvalley from the moraine in this part of the valley is comparable in age to that on the northwest side. Charred logs found beneath the moraine boulders indicate that the fire, which largely destroyed the old forest, occurred before the last glacial advance which formed the end moraine.

PYROCLASTICS AND HUMUS SEQUENCE

From available botanical evidence alone, extrapolation of the age of the surface upslope from the 1840 moraine beyond 600 to 700 years is impossible. However, the material below the modern humus layer and charcoal suggests that more time, perhaps much more than 600 to 700 years, has elapsed since the surface beneath the old forest was last overridden by ice. The location of a section illustrating this is labeled pumice on figure 6, and the description (R. D. Miller, written communication, July, 1959) is given on page A–11.

The following section does not provide a basis for an age estimate, because the ages of the ash falls are not yet known. The till, designated as unit 10, represents the last glaciation of the valley outside the 1840 moraine. The essential question being discussed here is what length of time is represented by the pyroclastics, charcoal, humus, and living forest that now lie above the till. Arguments have been presented to support the conclusion that the present forest plus the preceding generations of trees represented by the rotten logs in the humus layer (unit 1) and charcoal (unit 2) represent a period of at least 600 to 700 years. The duff, or organic matter, units 4, 6, and 9, between

Unit	Material	Thickness (feet)
1	Rotten logs; humus	0.5 –1.0
2	Duff,[1] black	.05– .15
3	Pumice, white, fine- to medium-sand-sized	.0 – .3
4	Duff, black	.05–----
5	Pumice(?), reddish-brown, silty; fine-sand-sized ash	.5 – .7
6	Duff, black, fine- to medium-sand-sized; contains charcoal	.0 – .1
7	Pumice, white to light-gray, fine- to medium-sand-sized; silty in places; may be A_2 of podsol soil; pumice grades from fine sand sized at top to coarse sand sized at base; grades into underlying pumice	.3 – .4
8	Pumice, yellow, coarse-sand-sized	.9 –1.0
9	Duff, dark-brown; overlies oxidized till; fills spaces between boulders and cobbles at surface of till	.2 – .9
10	Till, oxidized; wood fragments in upper part	----–----
	Total thickness, units 1–9	2.50–4.55

[1] Carbon 14 age is 1640±250 years B. P. See footnote p. A–10.

layers of pumice is evidence of still earlier forests and may easily represent several hundred years. If the organic matter and pumice layers represent only 300 years, which seems to be a minimum, at least 900 to 1,000 years have elapsed since the surface downvalley from the 1840 moraine was last glaciated.

Although detailed studies of the pyroclastic sequences in this area have not been made, the sketchy data indicate that the age of this surface is much older than one thousand years. For example, R. D. Miller and D. R. Crandell reported that the sequence found under the surface immediately downvalley from the 1840 moraine corresponds closely to one that they examined, located approximately 900 feet higher in altitude than the moraine (oral communication, July, 1959). The similarity of the pyroclastic sequences indicates that the age of the two surfaces is probably comparable and much older than one thousand years.

RECESSION BETWEEN 1840 AND 1900

LOCATION AND DESCRIPTION OF MORAINE

The 1840 moraine of Nisqually Glacier is 10 to 20 feet high, 25 to 50 feet wide, and is composed of angular blocks. The moraine is treeless at many places and thus forms an open lane between the old forest and the young forest.

Within the bounds of the 1840 moraine 22 areas were studied. The authors took cores from 104 trees and counted rings on 32 stumps. The location of the oldest trees in some of these areas is shown on the map in figure 6; the trees and the moraine in the vicinity of the highway were located by plane table. Other trees and moraines were located photogrammetrically from aerial photographs made in 1956.

The young forest within the bounds of the end moraine on each side of the valley occupies a crude wedge-shaped area, which narrows upstream (fig. 7). The forest extends approximately 1,000 feet upstream from the terminal moraine. The forest is only about 100 feet wide at an altitude of about 400 feet above Nisqually River in the vicinity of the stream that forms Tato Falls on the northwest side of Nisqually River valley. The forest is somewhat wider on the southeast side of the valley in the vicinity of the stream opposite Tato Falls; its upper limit is about 600 feet in altitude above Nisqually River.

The trees in this forest consist of western white pine, western hemlock, Douglas-fir, Pacific silver fir, noble fir, and Alaska-cedar. They range in diameter from 0.5 to 2.5 feet, hemlock and cedar trees are smaller than the others.

In contrast to the old forest, large fallen logs are not present in the young forest (figs. 3 and 4). Many trees have fallen, but trunks are smaller in diameter than those of the standing trees; thus the fallen logs are assumed to be of the same age or younger than the standing trees. The forest floor consists predominantly of large boulders only partly overgrown by mosses and lichens. Little humus has accumulated, and it consists primarily of decayed litter. Almost no rotten wood is found in the humus indicating that too little time has elapsed since the moraine was formed for trees to grow, die, and decay. No charcoal is found in the soil profile from which a preexisting forest could be inferred.

TIME INTERVAL BETWEEN CESSATION OF ADVANCE AND ESTABLISHMENT OF SEEDLINGS

In order to determine the time interval between the accumulation and stabilization of superglacial debris during the final stages of advance of Nisqually Glacier, trees and seedlings were sampled at locations of known positions of the glacier in the past. Only a few seedlings were found immediately below the present position of Nisqually Glacier. Trees are growing, however, at places that are near older dated locations of the terminus of the glacier, and some seedlings are present on surfaces that are known to have been covered with ice during certain recent years. These trees started to grow from 2 to 13 years after ice was known to have covered the site. The dated positions of the ice front and year that the trees started to grow are shown in figure 6. Trees were sampled along a transect extending from Tato Falls about 350 feet northwest to a point at the edge of the dense forest. The location of this transect and of other sampled trees are shown on figure 8.

FIGURE 7.—Nisqually Glacier is partly covered with snow at the head of Nisqually River valley near top of photograph; the 1840 moraine is indicated by a dashed line. Larger trees upslope from the line comprise the old forest; smaller trees downslope comprise the young forest. A new bridge (under construction) is visible in center; the older bridge is hidden by a fir tree in right foreground. July 9, 1959.

On the basis of data collected only in Nisqually River valley, the time interval between stabilization of the moraine and establishment of seedlings averages about 5 years. However, an analysis of tree ages on surfaces downvalley from Emmons Glacier reveals that the time interval may be shorter. North of the stream flowing from Baker Point (figs. 9 and 10), two nearly bare moraines are located in the approximate position of Emmons Glacier in 1913, as represented on the quadrangle map of Mount Rainier National Park, 1955. On the moraine farther downvalley, trees started to grow between 1901 and 1904. On the other moraine, approximately 100 to 200 feet upvalley, the oldest tree sampled started to grow in 1903, four trees started to grow in 1910, and one in 1912 (fig. 2). If the map of Mount Rainier National Park is accurate, then the glacier front could not have been far from this position in 1913, so some of these trees must have been growing on a superglacial moraine when the map was compiled. Russell (1898, p. 396–397) reported that in 1896 the terminus was completely covered with morainic debris; and although he did not locate the front accurately, some of the trees sampled in this study probably started to grow on the moraine underlain by active ice. Stagnant ice was still present in 1959 under the moraines in this vicinity.

Tree seedlings become progressively younger on the younger surfaces in the White River valley upstream from the 1913 terminal position of Emmons Glacier. They are found only on surfaces 2 to 5 feet or more above the flood plain of White River, which is a braided stream that almost constantly reworks the flood-plain

FIGURE 8.—Right wall of the Nisqually River valley between Tato Falls at right and the old highway bridge at left. Trees were cored along a transect from the right bank at the crest of the falls at the right diagonally to the left to the lower edge of dense forest. The 1885 position is at the bridge on the left; the 1905 position located by LeConte (Arthur Johnson, oral communication) is halfway between Tato Falls and the stream to its left.

deposits during the summer. Sampling areas were located on these higher surfaces on the basis of known past locations of the ice front. At these areas the minimum time interval between the disappearance of the ice from a valley section and the establishment of tree seedlings is estimated to range from 1 to 10 years. Thus data from the vicinity of Emmons Glacier, summarized in figure 11, indicate a shorter time interval than that estimated from data in the vicinity of Nisqually Glacier. However, there is no apparent basis for assuming that there is any inherent difference in the time required for establishment of seedlings at the two locations on Mount Rainier. Data from both Emmons and Nisqually Glacier moraines indicate that tree seedlings become established early on exposed morainic surfaces.

Evidence from flooded areas also indicates that tree seedlings become established quickly on newly formed surfaces at Mount Rainier. A flood of considerable magnitude on October 25, 1955, destroyed parts of the forest on the bank of Nisqually River within Mount Rainier National Park. Seedlings of the same coniferous species that grow in the adjoining forest started to grow 1 to 2 years after the flood in fine material deposited or exposed by the flood. Kautz Creek, which drains Kautz Glacier and a small basin tributary to Nisqually River, was the locale of a mudflow on October 2, 1947, which destroyed a large area of forest along its lower reach. Sand, gravel, and boulders were deposited to a depth of as much as 30 feet in an area approximately 2,000 feet wide, resulting in the death of almost all trees in the area of deposition. Seedlings, of the same species as the trees that were killed and that make up the surrounding forest, started to grow on the new surface, 1 to 5 years after the mudflow.

The time interval between the formation of a new surface by a flood or mudflow and the establishment of tree seedlings is probably shorter than the interval between the melting of a glacier and germination of seedlings on the moraines. Surfaces affected by floods and mudflows probably become stabilized almost immediately. Data on the age of the trees growing on these surfaces indicate that seedlings may become established within a year.

Available evidence indicates that the time interval between the disappearance of the ice front from a valley section and the establishment of tree seedlings generally ranges from 1 to 16 years. This interval was probably less than 5 years but the authors conclude that the use of an average interval of 5 years is reasonable and is substantiated by their observations. As pointed out by Russell (1898, p. 407) in an area such as Mount Rainier where the environment is so

FIGURE 9.—Moraines of Emmons Glacier in the valley of White River and Inter Fork. Emmons Glacier is visible upstream to left of area 22. Baker Point is the prominent snow-covered ridge at top left. Numbered points indicate the approximate locations of areas studied. July 18, 1959.

favorable to tree growth, trees soon become established on surfaces where fine soil has accumulated.

Five years is considerably shorter than the 30-, 35-, and 50-year intervals which Harrison (1956, p. 681–682) used to estimate the age of moraines at Nisqually Glacier. The 35-year interval is based on the age of trees growing upvalley from the position of the ice front in 1885, as located by Longmire (Meany, 1916). These trees are shown in left and center of figure 8 between the trail and the base of the cliff. Harrison's estimate is based on incomplete data, because the authors found one tree that started to grow in 1890 in an area that probably had been covered with ice in 1885 and two other trees that started to grow side by side in 1908 and 1912, approximately 600 feet upvalley. These trees indicate maximum intervals ranging from 5 to 23 years. Ice undoubtedly did not disappear from the site of the trees that started to grow in 1908 and 1912 until long after 1885, thus the interval was much shorter than 23 years.

MAXIMUM AGE OF YOUNG FOREST

Trees were sampled in the young forest in seven areas near or on the terminal and lateral moraines in order to determine the date when the surfaces became stable. The oldest trees sampled ranged from 111 to 117 years in age. Their location and ages are shown on the map (fig. 6) and indicate that they started to grow on one contiguous moraine at about the same time. If 5 years is added to these ages, the moraine has been stable for an estimated period ranging from 116 to 122 years, indicating that Nisqually Glacier stopped its maximum modern advance between 1832 and 1843. Inasmuch as 1840 is 2 years before the germination of the 117-year old tree this moraine, for convenience, is called the 1840 moraine.

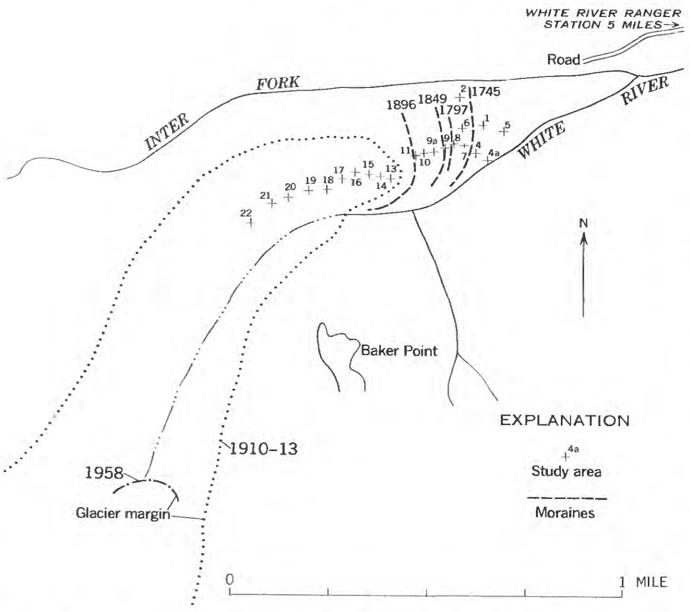

FIGURE 10.—Sketch map of terminal moraines and of areas studied in vicinity of Emmons Glacier.

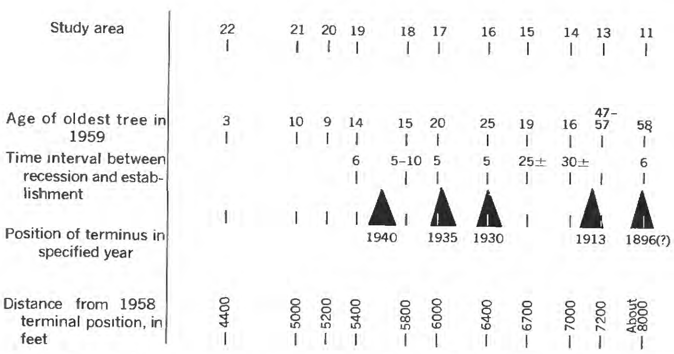

FIGURE 11.—Diagram showing ages of trees in 1959 and positions of the terminus of Emmons Glacier.

Although the maximum advance of the glacier downvalley marked by the 1840 moraine cannot be located because the moraine is not continuous across the valley, a small stand of trees on the flood plain approximately 2,000 feet downvalley from the older highway bridge marks a point beyond which the glacier could not have extended. The maximum advance of the ice front as estimated by projection of the lines representing the moraines is 500 feet upvalley from the oldest tree on the island. Most trees in this group died as a result of deposition during the 1955 flood (Arthur Johnson, oral communication) but a few are still living. An incomplete core from a Douglas-fir, 22 inches in diameter, showed 124 annual rings. The appearance of the innermost rings of the sound core and the fact that the core was taken well above the height of the first year's growth indicate that as many as 15 rings are missing, which would mean that the tree is at least about 140 years old. The mere fact that the tree is older than 124 years, which is 7 years older than the oldest tree found on the moraine, indicates that Nisqually Glacier could not have advanced this far downvalley during its maximum modern advance. These trees are young and not as old as those in the forest on the valley-side slopes because trees growing on the flood plain along streams are killed by occassional catastrophic floods.

DATES AND EARLY RATES OF RECESSION

Lt. A. V. Kautz observed the front of the Nisqually Glacier in 1857 and located it at a "rock throat" (Brockman, 1938, p. 769–770; Giles and Colbert, 1955, p. 4; Meany, 1916, p. 82–83). This rock throat is a valley constriction at an outcrop generally considered to be 760 feet downstream from the old highway bridge. One tree on the north side of the valley, which started to grow in 1858, and another on the south side of the valley, which started to grow in 1855, mark the maximum downvalley extent of Nisqually Glacier when Kautz saw it. The tree on the north side is approximately 200 feet from the old bridge, the other tree is approximately 400 feet. The location of these trees is shown (fig. 12) along with two possible locations of the ice front. One line extends across the channel about 760 feet from the old

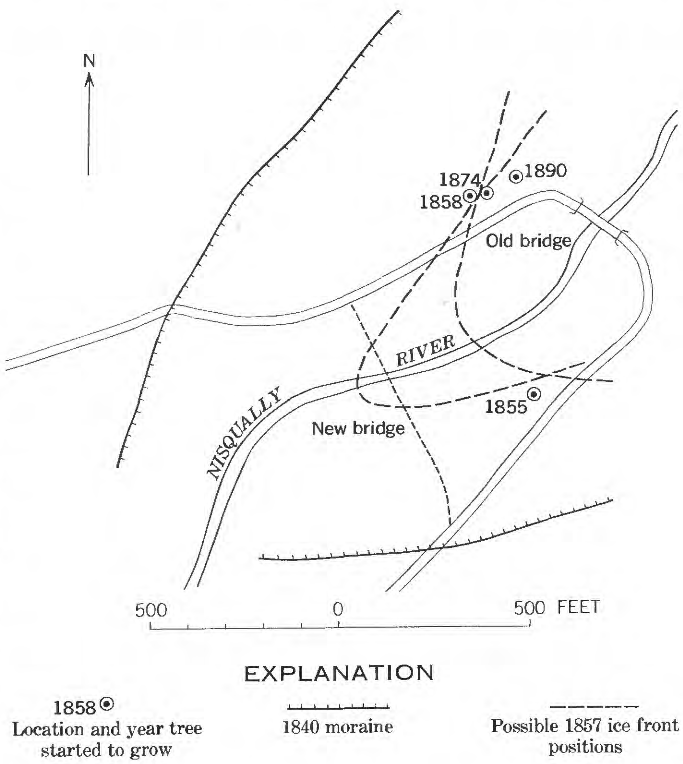

FIGURE 12.—Map of Nisqually Glacier showing the 1840 moraine and vicinity, and possible positions of the ice front in 1857 and location of key trees. Arthur Johnson located trees by planetable survey, August 30. 1958.

bridge and the other about 450 feet. The glacier front probably was located somewhere between these lines.

When seen by Longmire in 1885 (Meany, 1916), the ice front could not have been farther downvalley than a tree that started to grow in 1874. Five years later the front must have been farther upvalley than the location of a tree that started to grow in 1890 (fig. 12).

The data indicate that Nisqually Glacier has been receding since about 1840. The data also reflect a variable rate of recession but do not indicate fluctuations because during the period of general recession minor advances may have occurred as is suggested by small morainic ridges upvalley from the 1840 moraine. Neither the readvances nor their dates of occurrence can be determined from the available botanical evidence.

RECONNAISSANCE STUDY OF MORAINES OF EMMONS AND TAHOMA GLACIERS

Reconnaissance studies were made in the vicinity of Emmons and Tahoma Glaciers in the summer of 1959. These glaciers had histories somewhat different from each other and different from Nisqually Glacier, so a brief summary of them is presented in this report. A more complete study of the age of the modern morainic surfaces here as well as those in the vicinity of some other glaciers at Mount Rainier is in progress.

MORAINES OF EMMONS GLACIER

Emmons Glacier is located on the northeast side of Mount Rainier at the head of White River (fig. 1). The terminus in 1958 (R. K. Fahnestock, written communication) was approximately 6,000 feet upstream from its location in 1910–13 as shown on the quadrangle map of Mount Rainier National Park. Downvalley from the 1910–13 location for about a quarter of a mile, three prominent moraines extend across a neck of land between White River and Inter Fork (fig. 9). The area and approximate location of the line along which the trees were cored are shown on figure 10.

A prominent terminal moraine that extends across the neck of land approximately half a mile upstream from the confluence of Inter Fork and White River marks the maximum advance of Emmons Glacier in at least a thousand years. Ages of the trees in the forest on the slope downvalley from the moraine cover a considerable range. Because a complete core could not be obtained from the oldest trees, the maximum age of these trees was not determined. Two old trees were determined to be 411 and 419 years old (fig. 13). The largest count, 694 annual rings, was obtained from a 15-inch core from a tree having a 16-inch radius. This tree is more than 700 years old. A count of 408 rings was obtained from a 7.9-inch core of a trunk having a 38-inch diameter exclusive of the bark. These trees are located about 300 feet downvalley from the toe of the moraine and signify that Emmons Glacier could not have occupied their present sites within at least the last 700 years. They are located in areas 3, 4a, and 5 (figs. 9, 10, and 14). The presence of fallen logs of the

FIGURE 13.—Two Douglas-fir trees, 411 and 419 years old, in the old forest downvalley from the 1745 moraine of Emmons Glacier. (See area 3, figs. 9, 10, and 14.)

same diameter as the 400- to 700-year-old living trees and humus layers composed of rotten wood of ancestral trees indicates that the surface is at least 300 years older than the oldest tree.

The time interval between the start of recession and the establishment of seedlings on the moraines of Emmons Glacier is believed to average about 5 years. This estimate is based on a study of the ages of trees that grow in the transect across surfaces that were known to have been recently covered by Emmons Glacier and that have been previously discussed on pages A–12 and –13.

The oldest tree found growing on the terminal moraine is a 210-year-old Douglas-fir at the north end near Inter Fork (area 2, figs. 9 and 10). In the center of the moraine and at the south end, the oldest trees cored are 175 years old (areas 6 and 7, figs. 9, 10, and 14). These trees started to grow in 1749 and 1784. The terminus probably started to recede about 1745, but the surfaces at the south end of the moraine may have remained untable for almost 30 years. Melt water from the receding glacier may have flowed over this part of the moraine and destroyed any seedlings that were temporarily established. After a period of 35 to 40 years, however, the front probably had receded to a point sufficiently removed from the moraine so that melt water no longer flowed over it and the trees now 175 years old started to grow.

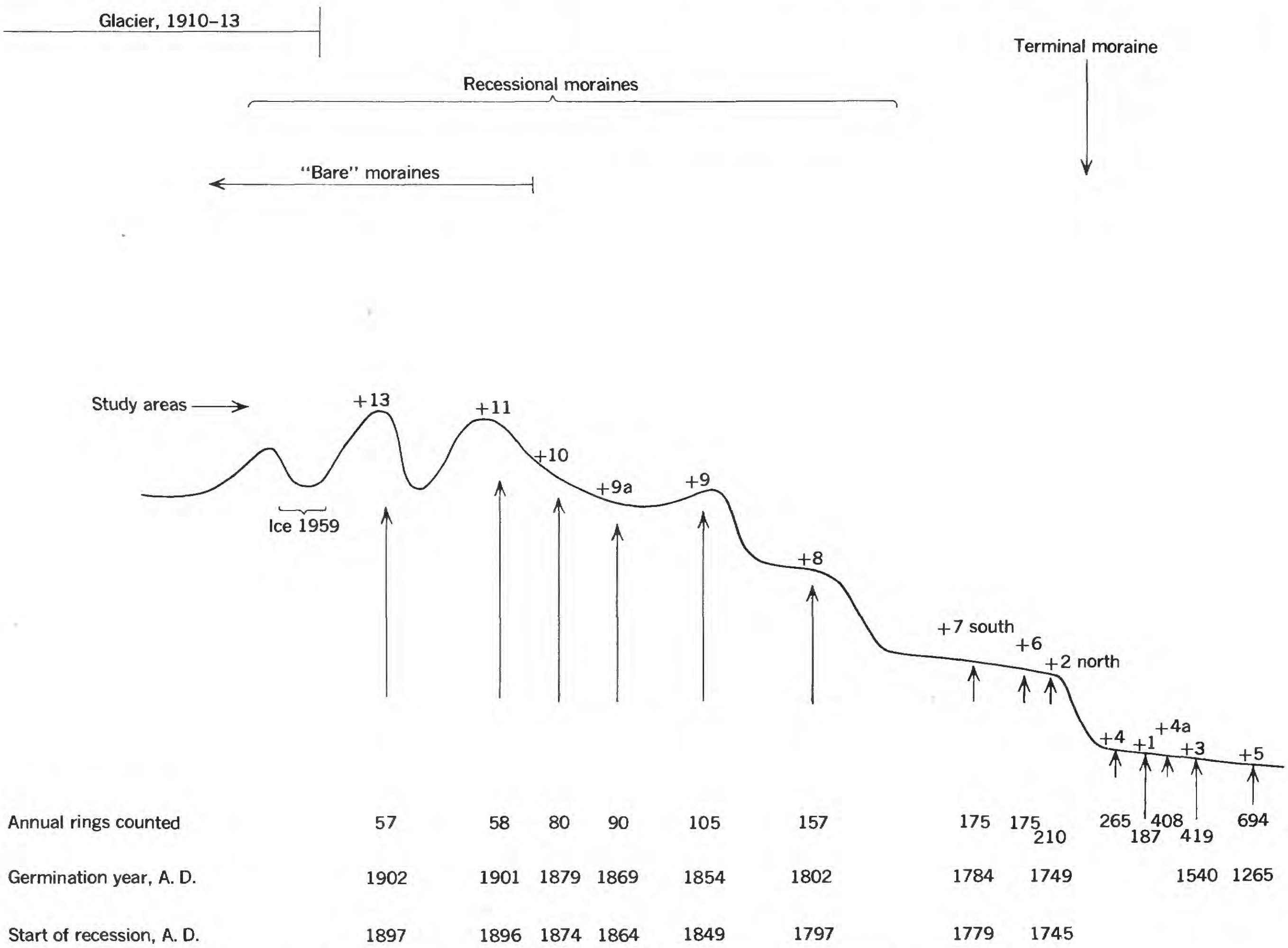

FIGURE 14.—Generalized profile across the moraines of Emmons Glacier.

A small ridge (area 8, figs. 9, 10, and 14) was formed inside the terminal moraine during the recession of Emmons Glacier. The oldest trees on it started to grow in 1802 suggesting that ice receded from here in 1797. Another prominent morainic ridge is located about halfway between the 1745 moraine and the approximate location of the ice front in 1910–13 (area 9, figs. 9, 10, and 14). The oldest trees on it started to grow in 1854, suggesting that recession started from here about 1849. This moraine may have been formed by an advance which was virtually contemporaneous with the maximum advance of Nisqually Glacier.

A fourth moraine (area 11, figs. 9, 10, and 14) is located a short distance downvalley from the 1910–13 location of the ice front but was formed earlier. The oldest trees on it started to grow in 1901. The ice could have been at this moraine in 1896 at the time Willis, Russell, and Smith made field studies at Mount Rainier (Russell, 1898). Russell (p. 407) observed that Emmons Glacier, as well all others that were visited, showed evidence of recent recession by the presence of nearly bare moraines around the margins of the glaciers upon which young trees were beginning to grow. The oldest trees between this moraine of Emmons Glacier and the next one downvalley, the 1849 moraine, are now 80 to 90 years old. Of 11 trees cored here, 9 range from 70 to 80 years. When Russell saw Emmons Glacier in 1896, the oldest trees between the end of the glacier and the 1849 moraine were 17 to 27 years old. Most of them were between 7 and 17 years. On the 1849 moraine, the oldest trees were 42 years old and half of them were less than 25 years old. Thus the trees upvalley from the 1849 moraine were the young trees that Russell (1896) mentioned. Because a conspicuous moraine is located near the position of the ice front where Russell saw it, a minor readvance of Emmons Glacier probably occurred at about this time; the recent recession which Russell found probably started about 1849 at Emmons.

The moraine marking the maximum modern advance of Emmons Glacier, from which the front started to recede about 1745 is not present in the Nisqually River valley.

MORAINES OF TAHOMA GLACIER

Tahoma Glacier is located at the head of South Puyallup River on the west side of Mount Rainier (fig. 1). A brief study was made in a small area on the left side of South Puyallup River valley near the location of the glacier terminus in 1913 and extending downvalley across two moraines into an old forest. A short arc of an outer moraine is present in only one part of the area studied. The remainder of the moraine represented by the outer arc was obliterated by a younger advance of the glacier that extended farther downvalley.

The inner moraine is younger and the trees sampled range in age from 107 to 119 years. The oldest tree started to grow in 1840 and thus the glacier probably started to recede about 1835. The stand has the appearance of a young forest, and these living trees are believed to be the first to grow on the moraine since the ice receded from this position.

The arc of the outer moraine curves more sharply at both ends toward the axis of the valley than does the arc of the younger moraine. The glacial advance that formed the 1835 moraine extended across the older moraine but probably extended only a short distance farther downvalley, as shown in class B_2 (fig. 5).

Only six trees on the older moraine were cored; the oldest tree is 320 years old, thus it started to grow in 1639. The trees on this moraine range in diameter from 18 to 40 inches, and they, too, appear to be of the first generation to grow since the ice receded. Many trees have fallen across this moraine but all are smaller than the standing trees. The young forest on the inner moraine is sufficiently close that the smaller trees could have grown on it and have fallen across the older moraine. There is no evidence that large trees have fallen on the moraine that are as old or older than the oldest living ones.

These two moraines, the young one and the one from which ice started to recede about 1635, are the only moraines found in the area studied on the left side of South Puyallup River valley (fig. 15). Evidence of the 1635 moraine was not found near either Nisqually or Emmons Glaciers.

The forest downvalley and upslope from both moraines below Tahoma Glacier is old. The largest count obtained was 338 years from a core from part of the radius of a 40-inch noble fir. Many fallen logs in all stages of decay as well as thick humus, composed largely of rotten wood, characterizes the old forest. Two trees, which are growing on fallen logs, are 182 and 198 years old; thus the fallen trees died before 1777 and 1761. The log upon which the 182-year old tree is growing

FIGURE 15.—The old forest and the 1635 and 1835 moraines downvalley from Tahoma Glacier. Man in extreme left center is standing on old surface; man in extreme right is standing on downvalley limit of the 1835 moraine. The ridge from the lower left to center is the 1635 moraine. Tree *A* is 320 years old; tree *B* is 317 years old. July 22, 1959.

is 13 inches in diameter 10 feet from the roots, and the wood in the center is still sound. Therefore, the presence of humus layers composed of completely decayed wood signifies that the surface has been forested for a long time.

The two moraines represent the maximum advance of Tahoma Glacier in a period that may also prove to be at least one thousand years. Their configuration shows that the ice front during the earlier advance had a shape different from that of the later advance even though both must have reached about the same distance downvalley. Furthermore, in the areas studied in the vicinity of three glaciers flowing from Mount Rainier, evidence of a recession in the 17th century was found only at Tahoma Glacier. The possibility that such evidence exists elsewhere, however, is not precluded although it apears doubtful that further work at Nisqually Glacier will uncover it. The examination of the area at Emmons Glacier was too incomplete to justify an early conclusion about a 17th century advance.

SUMMARY AND CONCLUSIONS

A prominent end moraine below Nisqually Glacier marks the greatest downvalley advance of the glacier in its modern history. The glacier started to recede from its point of maximum advance about 1840. This estimate is based on the ages of trees growing on the moraine and includes an interval of about 5 years for trees to become established after glaciation. Evidence in the Nisqually and White River valleys shows that trees become established 1 to 14 years after a glacier recedes from a given position. Although much information is available on the positions of the terminus of Nisqually Glacier during its recession from this maximum point, and a few sections of lateral moraines exist on the right valley slope in the vicinity of Tato Falls, no prominent moraines other than the 1840 moraine exist that can be dated from botanical evidence alone.

The relation of the maximum recent advance of Nisqually Glacier, marked by the 1840 moraine, to the next earlier advance is inferred from the age of the forest downvalley from the moraine and from examination of the layers of organic matter and pumice overlying the till representing the last glaciation of the area. The present forest with a maximum age of about 300 years, plus a humus layer at the surface consisting of rotten wood and representing at least 200 years, plus charcoal beneath the humus representing an earlier generation of trees of at least 100 to 200 years of age, represent a total of 600 to 700 years. The several organic matter and pumice layers underneath the humus and charcoal layers certainly represent 300 years or more. Thus the time that elapsed between the last major glaciation of Nisqually Valley and the advance marked by the 1840 moraine was probably at least a thousand years. Further study of the sequences of pumice layers may increase the estimate of the length of this period by several thousand years. However, the maximum advance of Nisqually Glacier in at least a thousand years undoubtedly occurred in about 1840.

Incomplete studies of the moraines below Emmons and Tahoma Glaciers revealed a prominent moraine in each valley corresponding in time to the 1840 terminal moraine of Nisqually Glacier. These studies indicate that Tahoma Glacier started to recede about 1835 and that Emmons Glacier started to recede about 1850. In contrast to Nisqually Glacier, however, prominent moraines below Emmons Glacier and botanical evidence indicate that maximum positions attained by two other advances occurred in 1745 and 1895. The maximum modern advance of Emmons Glacier is marked by the 1745 moraine. At Tahoma Glacier a small segment of a 1635 moraine was discovered which indicates that the advances marked by the 1635 and the 1835 moraines reached about the same extent downvalley. The 1635 moraine found below Tahoma Glacier was not found at Nisqually or Emmons Glaciers but present studies do not permit the conclusion that it does not exist at these places. The following table summarizes the history of these recessions.

Nisqually Glacier	Emmons Glacier	Tahoma Glacier
Estimated date of start of recession from maximum advance		
	1895	
	1850	
1845		
		1835
	1745	
		1635
Estimated age, in years, of surface beyond oldest dated moraine		
>1000	>700	>1000?

Evidence that ice started to recede from prominent moraines below three glaciers during the period 1835–50 suggests that the advance of each glacier during this period was approximately concurrent. No significance is attached to the 15-year spread in the three date determinations. However, the advance that occurred during this period was exceeded at Emmons Glacier by an advance that began to recede from the maximum point about 1745 and was equaled or exceeded by one at

Tahoma Glacier that began to recede from its maximum point about 1635. Thus the evidence indicates that because of the probable similarity of climatic trends around Mount Rainier the glaciers on its slopes may advance and retreat in approximate synchronization. However, the data indicate that the relative degree of downvalley advance varies considerably at the different locations in accord with glacier behavior as noted by other investigators (Sharp, 1951b, p. 106).

Thus, only a start has been made in the accumulation of data on glacial history at Mount Rainier from which climatic variations can be inferred within the past several hundred years. The authors expect to continue these studies in order to accumulate additional information on several other glaciers of Mount Rainier and their environs. In addition to the collection of data on specific glacier movements at other locations several related problems require further study: (a) Botanical evidence that can be used to determine the time of past glacier advances as well as the further refinement of evidence that is used to determine the time of the start of a recession; (b) evidence of flooding and ponding along possible marginal drainage channels; (c) data on the rate of wood decay in different environments and the development of methods of measuring the degree of decay so that more positive age determinations can be made on the basis of fallen logs; and (d) botanical evidence that can be used to distinguish mudflow deposits from glacial moraines.

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