GLACIER FLUCTUATION FOR SIX CENTURIES IN SOUTHEASTERN ALASKA AND ITS RELATIONS TO SOLAR ACTIVITY

by

Donald B. Lawrence

Juneau Icefield Research Project

and

Department of Botany, University of Minnesota

Reprinted from
THE GEOGRAPHICAL REVIEW
American Geographical Society
Volume XL, No. 2, 1950
Pages 191-223

GLACIER FLUCTUATION FOR SIX CENTURIES IN SOUTHEASTERN ALASKA AND ITS RELATION TO SOLAR ACTIVITY*

DONALD B. LAWRENCE

IN RECENT years advances and recessions of glacier termini have become the subject of careful study. These oscillations have been assumed to reflect changes in weather, but study of the mechanics by which the various elements of weather favor accumulation or ablation has just begun; the nature of the possible causal agent that ultimately produces net advance or recession has remained obscure. Change in the amount of energy coming to the earth from the sun has been suspected of being a primary cause, but up to the present time there has been little concrete evidence of this, mainly because the shortness of the record of annual change in the positions of glacier termini gives us little to work with. The shortness of the weather observations available for regions where glaciers occur and the almost complete absence of such observations for altitudes where accumulation goes on have aggravated the situation. In Switzerland a sporadically kept written record of advance and recession extending back to the late sixteenth century is available,[1] but there the surfaces of accumulation are so high and precipitous that the general relation to climatic trends has not been easy to discover. In western North America the written record extends back only to 1857 at best. Fortunately, however, woody plants have kept their own age records in their growth layers, and for the past 40 years North American

* I am deeply indebted to the several organizations that provided financial aid for last summer's work, on which this report is largely based. Among these are the American Geographical Society of New York, the Office of Naval Research, the Graduate School of the University of Minnesota, and the Mazama Hardesty Trust Fund. The Alaska regional office of the United States Forest Service was most helpful in providing transportation for the work in the vicinity of Juneau, warehouse space, and numerous other conveniences. I am grateful to the many people who have aided, particularly B. Frank Heintzleman and his staff in the Forest Service, and to Maynard M. Miller, William O. Field, Jr., Kenneth N. Phillips, and William S. Cooper. Waldo Glock provided some of the literature references, and Harlan T. Stetson, Andrew E. Douglass, and the late François E. Matthes stimulated and encouraged me greatly. My deepest thanks go to my assistant, Lloyd C. Hulbert, for his enthusiasm and boundless energy in carrying on the field work, and to my wife for help in the field and with the preparation of this report.

[1] F. E. Matthes: Glaciers, *in* Hydrology (Physics of the Earth, Vol. 9), edited by O. E. Meinzer, New York and London, 1942, pp. 149–219 (Chap. 5), reference on pp. 204–207.

➤ DR. LAWRENCE is associate professor of botany at the University of Minnesota, Minneapolis, and chairman of the Subcommittee on Ecology as Related to Glacier Studies, Committee on Glaciers, Section of Hydrology, American Geophysical Union. He was leader of the plant ecology unit of the Juneau Ice Field Research Project, 1949.

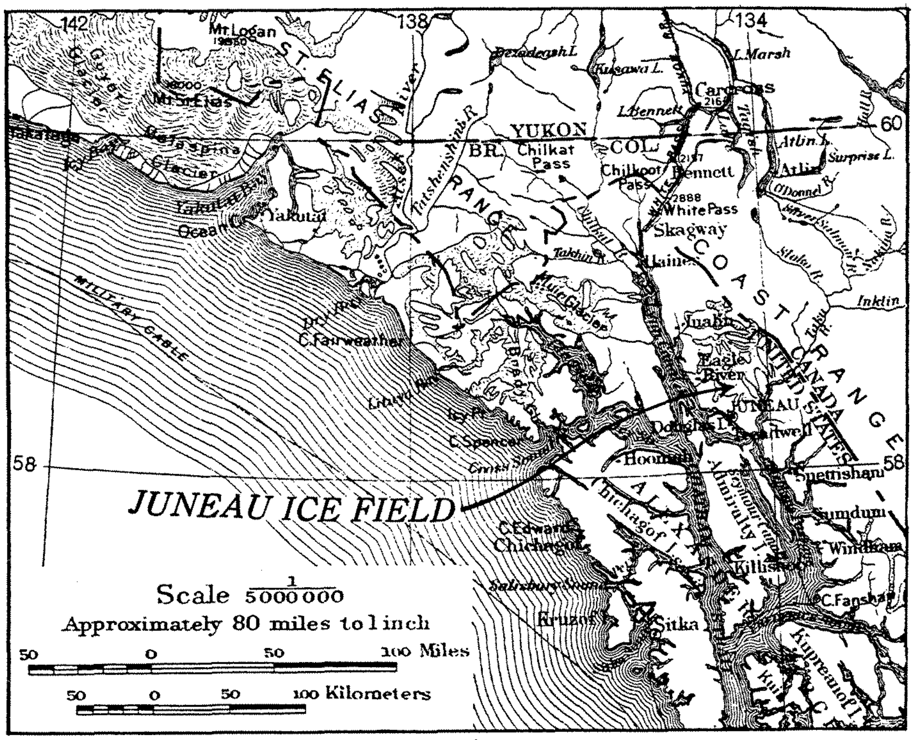


FIG. 1—The Juneau Ice Field. Modified from the U. S. Geological Survey's "Alaska," Map A, 1 : 5,000,000.

students of recent glacier history, particularly Tarr and Martin[2] and Cooper,[3] have been basing time estimates on evidence from the trunks of trees. In the past decade detailed work has been done[4] and the technique of study described,[5] so that at the present moment new vistas open before us into the chronology of recent glacier fluctuation on our own continent.

The fundamental assumptions on which these new studies are based are (1) that the number of wood-growth layers in the very base of a tree trunk accurately represents the number of years since the seed germinated, and (2) that a seedling does not become successfully established in a particular spot until the glacier ice has receded. Since rare exceptions to both these assump-

[2] R. S. Tarr and Lawrence Martin: Alaskan Glacier Studies of the National Geographic Society in the Yakutat Bay, Prince William Sound and Lower Copper River Regions, Washington, 1914.

[3] W. S. Cooper: The Problem of Glacier Bay, Alaska: A Study of Glacier Variations, *Geogr. Rev.*, Vol. 27, 1937, pp. 37–62.

[4] D. B. Lawrence: Mt. Hood's Latest Eruption and Glacier Advances, *Mazama*, Vol. 30, No. 13, 1948, pp. 22–29.

[5] *Idem:* Estimating Dates of Recent Glacier Advances and Recession Rates by Studying Tree Growth Layers, *Trans. Amer. Geophys. Union*, Vol. 31, 1950. (In press.)

tions have been reported,[6] it is important to find out whether the basic assumptions are correct for the area under study. The technique of study depends on obtaining a sample of wood extending from bark to center as near as possible to the stem base of the oldest tree growing on the terrain being investigated. Saws and the Swedish increment borer, a form of hollow auger, are the collecting tools, and a sanding machine and microscope are used in the analysis of samples. Vertical aerial photographs, though not absolutely necessary, greatly aid the field work and the organization of the resulting data.

Periglacial terrain features in Alaska, and in other areas where glaciers occur along the Pacific coast of North America (Fig. 1) with the exception of the Prince William Sound region, present incontestable evidence that a maximum recent advance occurred a very few centuries ago and that recession has subsequently been the general rule. The most notable evidences of this are the trimlines carved in old forests by the advancing ice and the youthful character of the first-generation forests that have occupied the land freed of ice since the maximum advance. Although these features are evident to the trained observer even on foot, they would not generally be recognized by the casual traveler, because he might not guess that trees three or four feet in diameter can be less than two centuries old. However, with the aid of vertical aerial photographs for reconnaissance, even a casual observer would probably recognize the notable difference in appearance of the vegetation beyond and behind the terminal moraines and above and below the forest trimlines and the symmetrical arrangement of multiple concentric moraines within a few thousand feet or a few miles in front of the present-day ice fronts. The trained investigator is particularly fortunate in Southeastern Alaska, now that the broad coverage in 1948 by the aerial photographers of the United States Navy has become available.

There are also in Southeastern Alaska other evidences that there has been notable reduction in snow accumulation within the past century or two. At moderately high levels, 4000 to 5000 feet, in the main regions of snow accumulation there is visible on the cliffs that project above the summer snow surface a band of very light color, which represents rock until recently covered throughout the year with a continuous mantle of snow and névé, the presence of which had prevented the rock from weathering to a darker color and kept it unavailable to colonization by alga and lichen pioneers.

[6] W. S. Glock and E. L. Reed, Sr.: Multiple Growth Layers in the Annual Increments of Certain Trees at Lubbock, Texas, *Science,* Vol. 91 (N.S.), 1940, pp. 98–99; Tarr and Martin, *op. cit.,* Plates 10B and 32A.

There is little evidence in this zone above timber line from which to ascertain the amount of time since shrinkage began. At intermediate altitudes, near 2000 feet—just below the general timber line—there is additional evidence that annual snow depth is much less than formerly. Here the floors of old cirques until recently bare of plants, or vegetated only with alpine meadow herbs that could maintain life in the brief growing season between the melting away of one year's snow cover and the beginning of the new, have been invaded successfully by shrubs and young trees that seem to require a much longer snowless season. An elfin forest of old gnarled hemlock trees extends downward from ridges part way into the cirques, but in the one carefully examined it ended abruptly, marking the high margin of the area of former short growing seasons induced by long-lasting snows that must have persisted up to perhaps a century ago. But even at these intermediate altitudes the evidence is too fragmentary to be of much use in dating the end of the years of deep, persistent snow cover in the cirques and the beginning of those of longer growing season. It is in the lowest altitudinal zone, within a hundred feet or so of sea level, that the most useful information can be gained. Here advancing glacier termini plowed into old forest, destroying everything in their paths but leaving occasional tilted trees along the forest trimline to continue growth after the last phase of the advance; and here trees become established quickly as the ice recedes. All the conclusions reported in this paper are derived from ecological studies at these low levels. Since the objective was a rather broad survey of several glaciers emanating from the Juneau Ice Field, the work was generally restricted to the study of tree age on the terrain deglaciated since the maximum of the middle eighteenth century and of the terrain just beyond the terminal moraines formed by that advance. The data for any one glacier must therefore be regarded as incomplete, and the conclusions derived from them as tentative.

With the exception of the Taku Glacier system, which has been advancing for about half a century, and a few others, most of the glaciers of Southeastern Alaska offer certain advantages not found elsewhere because they have receded a great deal farther since their recent maximum, which seems to have come to a close in the middle eighteenth century, and because a great many more recessional morainic ridges have been preserved to this day between the positions of maximum recent advance and the present ice fronts. For example, there are about twelve or thirteen clearly recognizable recessional morainic ridges between Herbert Glacier's 200-year-old terminal moraine and the present ice front, as compared with two that are recognizable between the present ice front of Eliot Glacier on Mt. Hood, Oreg., and the

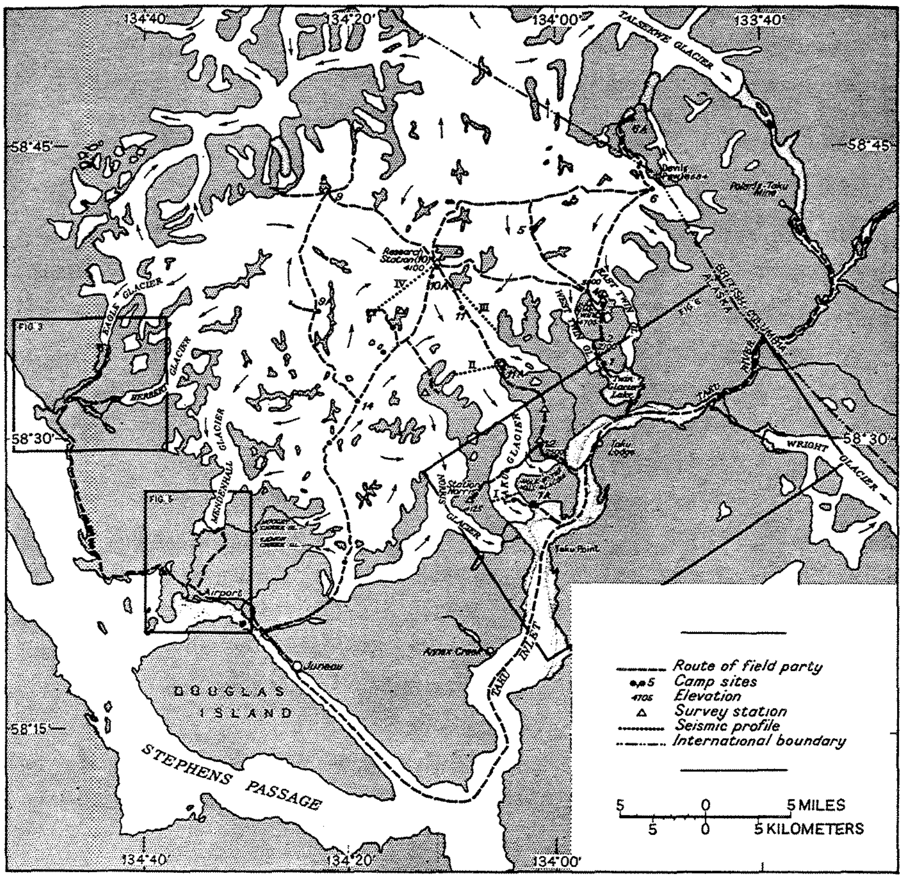


FIG. 2—Sketch map of southern part of the Juneau Ice Field, showing principal outflowing glaciers. Routes of all field units of the Juneau Ice Field Research Project are shown. Arrows indicate direction of ice flow. The ecological work was confined to the terminal areas of the valley glaciers.

terminal moraine of 1740.[7] In 200 years Herbert Glacier has receded two miles, Eliot two thousand feet. Each of the concentric moraines represents a time when the ice front hesitated in its recession or may even have re-advanced somewhat. The more morainic ridges there are in front of a glacier, the better is our opportunity to find out what peculiarities and possible cycles of weather cause glaciers to change their rates of accumulation and melting. The fact that the forests on the modern Alaskan glacier moraines have remained largely undisturbed by fire is also of great advantage to the student of glacier variation.

The main disadvantages in studying the Alaskan glaciers are the large areas that must be explored—for example, in Glacier Bay, where recent

[7] Lawrence, Mt. Hood's Latest Eruption (see footnote 4, above).

recession has amounted to the world record of 62 miles since the middle eighteenth century[8]—the density of the brush, the wetness of the normal summer weather, the inaccessibility, and the high cost of transportation.

The Juneau Ice Field

The Juneau Ice Field Research Project, of which the present work forms a part, is sponsored by the American Geographical Society. The work of the first field season (1948) has been reported in a progress report by Miller.[9] The Juneau Ice Field is a name applied for convenience to the series of névés which occupy the crest of the Coast Range immediately north of the city of Juneau. It lies in the angle between the valley of Lynn Canal on the west and the Taku Valley and its tributaries on the south and east. The work discussed in the present report was carried out in July and August of the second field season (1949); it was restricted to the main glaciers emanating from the southwest, south, and southeast sides of the ice field (Fig. 2). The main surface of this part of the ice field forms a broad plateau about 4000 feet above the sea, punctured by scattered peaks rising to 5000 and 7000 feet. The late-summer firn line, which marks the level where annual accumulation equals annual ablation, was reported by Miller[10] to lie at 3400 to 3800 feet at the end of the summer of 1948.

Let us now examine the histories of advance and recession of the individual glaciers studied last summer and consider a tentative hypothesis to explain them.

Glaciers Northwest of Juneau

Herbert Glacier

Of all the glaciers surveyed, Herbert Glacier (Figs. 2 and 3), about 20 miles northwest of Juneau, is the most promising for providing further detailed information. The position of the semicircular terminal lobe that existed at the time of maximum advance in the mid-eighteenth century and the numerous regularly arranged concentric recessional moraines are plainly visible in the aerial photograph (Fig. 4). The terminal moraine is accessible within three miles by road and from there by a well-worn trail, and the trees on the moraines have grown slowly enough that complete samples of

---

[8] D. B. Lawrence and E. G. Lawrence: Some Glaciers of Southeastern Alaska, *Mazama,* Vol. 31, No. 13, 1949. (In press.)

[9] M. M. Miller: Progress Report of the Juneau Ice Field Research Project, 1948, American Geographical Society, New York, 1949. (Mimeographed.) See also W. O. Field, Jr., and M. M. Miller: The Juneau Ice Field Research Project, in this number of the *Geographical Review.*

[10] Progress Report, p. 12.

their wood can be obtained without special techniques with the longest Swedish increment borers (15¾ inches) available commercially. A base camp was established in the abandoned Satko cabin by the Herbert River near the end of the Glacier Highway, and this served as a reasonably satisfactory but very moist operating headquarters for daily trips to the study areas. Detailed studies were made at stations 1–6 shown on Figure 3. All of these except

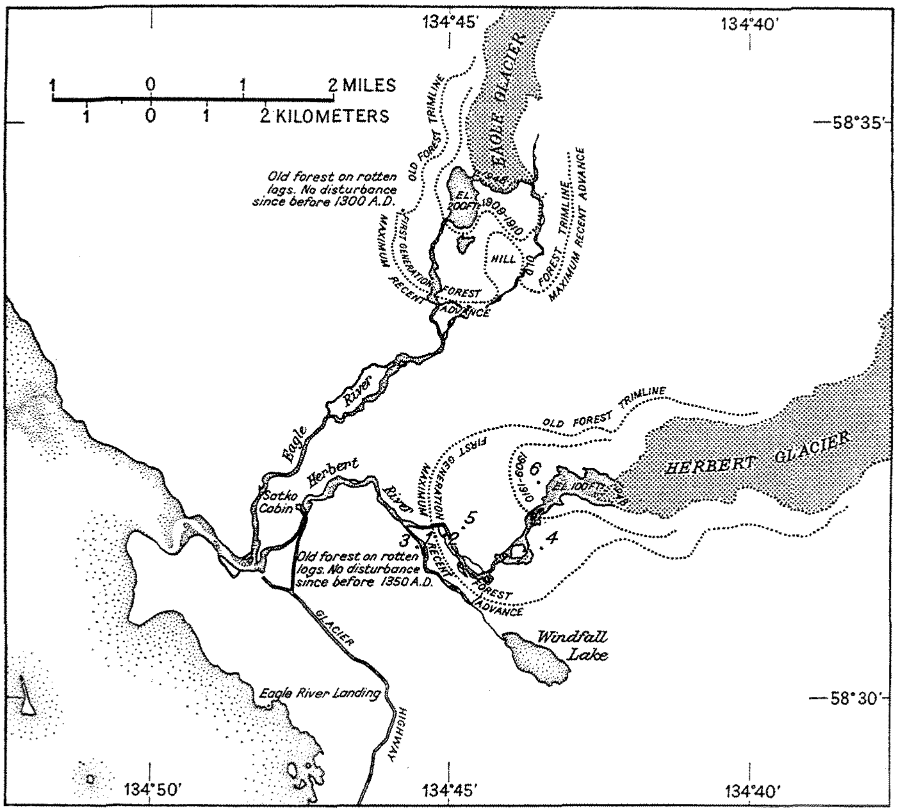


Fig. 3—Sketch map of the terminal area of Eagle and Herbert Glaciers, showing positions of maximum recent advance and 1948 termini. The numbers refer to study areas mentioned in the text. From U. S. Navy aerial photographs, 1948; control and 1909–1910 position from "Geologic Map of Eagle River Region, Alaska," *U. S. Geol. Survey Bull. 502,* 1912, Pl. 2, 1 : 62,500.

station 3 were on terrain occupied by the ice since the maximum recent advance. Studies of eleven of the oldest trees that could be found in the first-generation forest on the 20-foot-high terminal moraine at station 1 revealed that the ice must have receded from there by about 1765, but when the ice advanced to that position or how long it remained there, two miles beyond the 1948 ice front, is not yet known. The forest here was composed of an overstory of Sitka spruces 10 to 20 inches in diameter at breast height, a few old decrepit cottonwoods 20 to 30 inches thick, and an understory of younger hemlocks 3 to 6 inches thick that constituted 40 per cent of the stand; almost no decaying logs and stumps were present, further evidence that this was a first-generation forest. Examination of the forest floor revealed 7 to 12 inches of soft, spongy organic matter overlying fresh glacier till apparently un-

FIG. 4—Eagle (left) and Herbert (center) Glaciers flowing from the Juneau Ice Field, 1942. Concentric moraines may be seen in front of Herbert Glacier; part of Lynn Canal in foreground. View east. (Trimetrogon aerial photograph by U. S. Air Force.)

weathered and undiscolored; occasional boulders 6 to 8 feet long were perched on top and were decked with a dense layer of moss.

The forest of station 3, about 1000 feet beyond the terminal moraine, presented a great contrast. It consisted mainly (95 per cent) of hemlocks of all sizes and ages, from seedlings to trees 30 inches in diameter and 300 years old. These were perched on large old rotten logs and stumps that must have been at least 300 years old themselves before they died. Perhaps half a century elapsed between the time they died and the attainment of a state of decay sufficient to provide a satisfactory seedbed for germination of the present generation of old trees. We are therefore justified in assuming that this forest had a minimum age of 600 years; the high proportion of hemlocks to spruces would indicate that it was much older. The bedrock here is metamorphic, but it is overlain by rounded glacially transported granitoid boulders whose surfaces are stained and deeply pitted by weathering. This would seem to suggest that Herbert Glacier cannot have advanced more than 1000 feet beyond the terminal moraine of the middle eighteenth century for a long time. Six centuries is a conservative estimate; it may have been several thousand years; possibly station 3 has not been covered by ice since the waning stages of the Wisconsin glaciation.

Only two other strong moraines were sampled. If we call the terminal moraine the first one, then the third (station 2) and the eighth (station 5) were sampled. To judge from the oldest of the seven or eight largest trees that could be found at each of these stations, the ice receded from station 2 by 1786–1788 and from station 5 by 1844–1846. Stations 4 and 6 apparently do not represent moraines, but ridges of bedrock overlain by till. They became free of ice by 1887–1889 and 1920–1922 respectively. The twelve or thirteen strongest recessional moraines occur within the first half mile from the terminal moraine. Fortunately, the position of the ice front was mapped by Knopf[11] in 1909–1910; it is shown in Figure 3. Comparison with the position of the front in 1948 shows that half of the total two-mile recession since 1765 occurred after 1910. Just when the acceleration in rate of recession began is not known, but further field study should readily clarify that point.

Eagle Glacier

Only one day was devoted to Eagle Glacier (Fig. 3), and much of that time was expended in merely getting to it and back to the Satko cabin. We could do little sampling of tree age, but we saw nothing to lead us to believe that the history of advance and recession of this glacier is different from that of Herbert. One of the oldest of the recent recessional moraines seems to have been ice-free since about 1785–1787. Immediately above the western forest trimline we found the same evidences of a long time lapse since the last glaciation as have been described for station 3 at Herbert Glacier. An

[11] Adolph Knopf: The Eagle River Region, Southeastern Alaska, *U. S. Geol. Survey Bull. 502*, 1912, Pl. 1.

alder and a spruce cut at the west margin of the lake at 0.4 mile from the ice front show that this area was freed of ice about 1930–1932. The position of the ice front of this glacier also was mapped by Knopf in 1909–1910, and this is plotted in Figure 3. It is plain that half of the total recession of about 1.3 miles since the time of the maximum stage has occurred since 1910. The large hill in the center of the valley about half a mile from the present ice front is of special interest, because it formed an obstruction that divided the glacier as it moved ahead to its maximum of the middle eighteenth century. Study of the aerial photographs indicates that a fine forest trimline has been left on the slopes of this hill; if further field study should reveal the presence of old trees tilted by the ice that have continued to grow to this day, sections from these trees should enable us to learn the exact year of maximum advance.[12]

Mendenhall Glacier

For several reasons Mendenhall Glacier (Fig. 5) was the most important of our study areas for working out exact techniques for dating the terrain features found here and at the other glaciers studied in this vicinity. It had the further advantage of being within half an hour's drive from the dry convenience of our Hotel Juneau headquarters, from which daily trips were made to the area for about a week. The network of roads, a recently cut power-line right of way, and a logging operation served to reduce the manual labor involved in getting the information we needed. But most helpful of all was a series of maps of the ice front made by Mr. Charles H. Forward of the United States Forest Service regional office in Juneau, in 1931, 1933, 1936, 1940, 1945, and 1949. Copies of these maps served as a sort of "Rosetta stone" by which we could learn the exact number of years required for trees and shrubs of different kinds to germinate successfully after the terrain was freed of ice. From the charts of the positions in 1931 and 1933, we located marked survey points, and on till surfaces (stations 1, 2, and 14 of Fig. 5) that had emerged from the ice between these two years, we cut off at the very soil surface the largest woody plants we could find. We collected, in all, 31 spruces, 20 hemlocks, 18 alders, 7 willows, and 5 cottonwoods, cut sections from them, and later dried and polished these and counted their growth layers. The difference between the number of rings and the number of years since the year when the ice is known to have melted away was assumed to represent the number of years required for the

[12] Lawrence, Estimating Dates of Recent Glacier Advances and Recession Rates (see footnote 5, above).

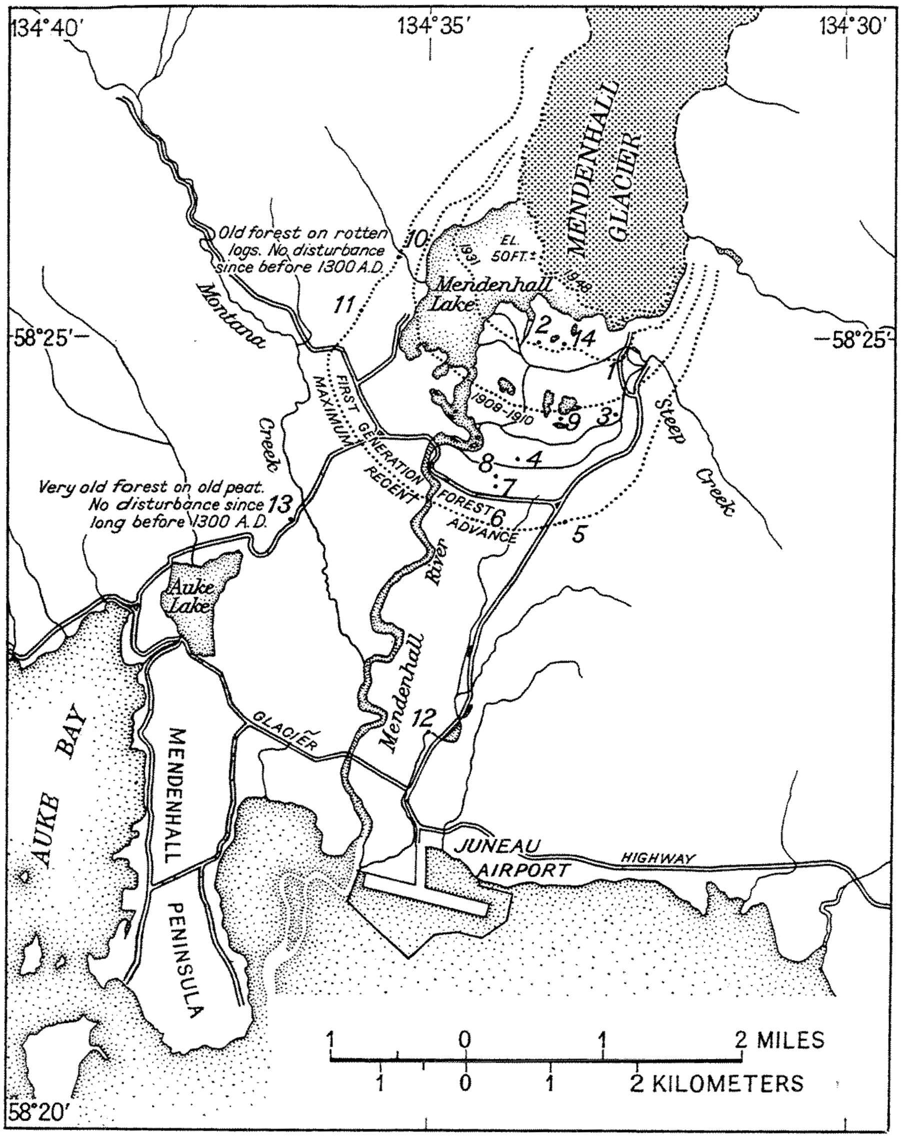


FIG. 5—Sketch map of the Mendenhall Glacier area, showing positions of maximum recent advance and 1948 terminus. The numbers refer to study areas mentioned in the text. From U. S. Navy aerial photographs, 1948. Control from the U. S. Geological Survey's Juneau (B-2) Quadrangle, 1949; 1909–1910 position from its *Bull. 502*, Pl. 2; 1931 position from map by Charles H. Forward, U. S. Forest Service, Juneau.

substratum to become a suitable seedbed. Since the studies on the older modern moraines were of necessity being based on the Sitka spruce, because that is the only woody species present throughout the first 200 years of the forest development, we devoted most attention to this species.

Analysis of our ring counts from the stem bases of the sapling spruces revealed that the usual interval between the melting away of the ice and successful germination was three to five years in the slight depressions and five to seven years on the ridgetops, and these values were applied as corrections to ring counts of spruce throughout the study. The facts that the ring counts so nearly corresponded with the known number of years elapsed since the ice melted away and that in no case was the number of basal rings greater than the number of years of freedom from ice provide good evidence that the rings of the trees of this region are really annually produced and thus may be accepted as a reliable index of time. Two other forms of evidence support this view: (1) all the rings are invariably complete; and (2) cross-dating between trees growing 10 to 25 miles apart is readily possible. Since it is usually impossible with a Swedish increment borer, and often difficult with a saw, to obtain a sample of wood of the larger trees at the very stem base, we were interested in working out also values for correcting ring counts at various heights above the surface of the parent soil material on which the seed germinated. All spruces cut at these stations and some collected at Herbert Glacier station 6 were therefore sectioned at 6, 12, 18, 24, and 30 inches above the stem base as well as at the base. Though we found that there was a good deal of variation in the number of years required for growth to a given height, and that the greatest variation was within the first 6 inches, the usual period for attaining the 6-inch height was 5 years, for 12 inches 7 years, for 18 inches 8 years, for 24 inches 9 years, and for 30 inches 10 years. These values were used in correcting ring counts throughout the study except at Twin Glaciers in the Taku Valley, where the rate of diameter growth had been so rapid that it seemed justifiable to assume that a height of 16 inches was attained in only 3 years instead of 7 or 8.

At Mendenhall, as at Herbert, not every moraine was sampled, so that further field work will be necessary to fill in the details. The similarity to conditions at Herbert was again strong, and there is no reason to believe that the history has been very different. The total recession since the middle eighteenth century has been two miles, and half of that has occurred since the position plotted by Knopf in 1909–1910 (Fig. 5). The 1931 position plotted by C. H. Forward stands about halfway between that of 1909–1910 and that of 1948, an indication of a rather uniform rapid rate for the past 40 years.

The rapidity of this most recent recession is in fact the reason for the guess, rather widely accepted by the local population, that the Mendenhall Glacier terminus has receded from tidewater at Gastineau Channel within the past 200 years. Even Wentworth and Ray[13] believed that both this glacier and Herbert "have only recently retreated from the coast." This guess cannot be true, however, because at station 12 on an outwash surface spruces were growing as early as 1680. More convincing still, at station 13 are living trees at least 630 years old, which would most certainly have been overwhelmed by ice if Mendenhall Glacier had advanced even to within two miles of Gastineau Channel. As a matter of fact, the forest at station 13 presents more convincing evidence of great age than the forests outside the areas of recent glacier disturbance at Herbert and Eagle Glaciers. At Mendenhall station 13 the forest is a mixture of ancient lodgepole pine, hemlock, and occasional spruce; the forest floor consists of waterlogged peat of untested depth. This vegetation seems to be in an intermediate successional stage between old hemlock forest and the muskeg which Zach[14] suggests may be the true regional climax on this gently sloping terrain. The oldest tree sampled here, a Sitka spruce, only 18 inches in diameter at the surface of the peat, was cut to provide a power-line right of way beside the road in 1948. The center ring was formed about A.D. 1319. The extreme narrowness of the growth layers even near the center shows conclusively that this tree cannot possibly have been a member of the first generation of forest which grew on this surface. The species composition and the presence of peat indicate that many forest generations must have passed before the present condition could exist.

Spruces sampled at station 6, in the middle part of the terminal moraine of maximum recent advance, show that deglaciation occurred about 1767–1769, whereas at station 5, near the east margin, the ice remained until 1786–1788 and deposited on top of the 12-foot-high moraine ridge some monstrous boulders, one 24 feet long and 9 feet high. At station 10, on the west lateral moraine just below trimline, deglaciation had occurred by 1772–1774. At station 11 an extensive wind throw about 1882–1883 tilted many trees; the first impression was that they had been tilted by advancing ice, but they were found to occur both above and below the lateral moraine and trimline.

Within the area deglaciated since the modern maximum, the moraine at station 7 was ice-freed about 1832–1834, the next younger moraine at station 8, which unites with the older one at both ends, was ice-freed about 1865–1867. There is evidence in tilted trees at station 7 that a readvance occurred between 1832 and 1865, perhaps overrunning moraines formed in

[13] C. K. Wentworth and L. L. Ray: Studies of Certain Alaskan Glaciers in 1931, *Bull. Geol. Soc. of America*, Vol. 47, 1936, pp. 879–934; reference on p. 885.

[14] L. W. Zach: A Northern Climax, Forest or Muskeg?, *Ecology*, Vol. 31, 1950. (In press.)

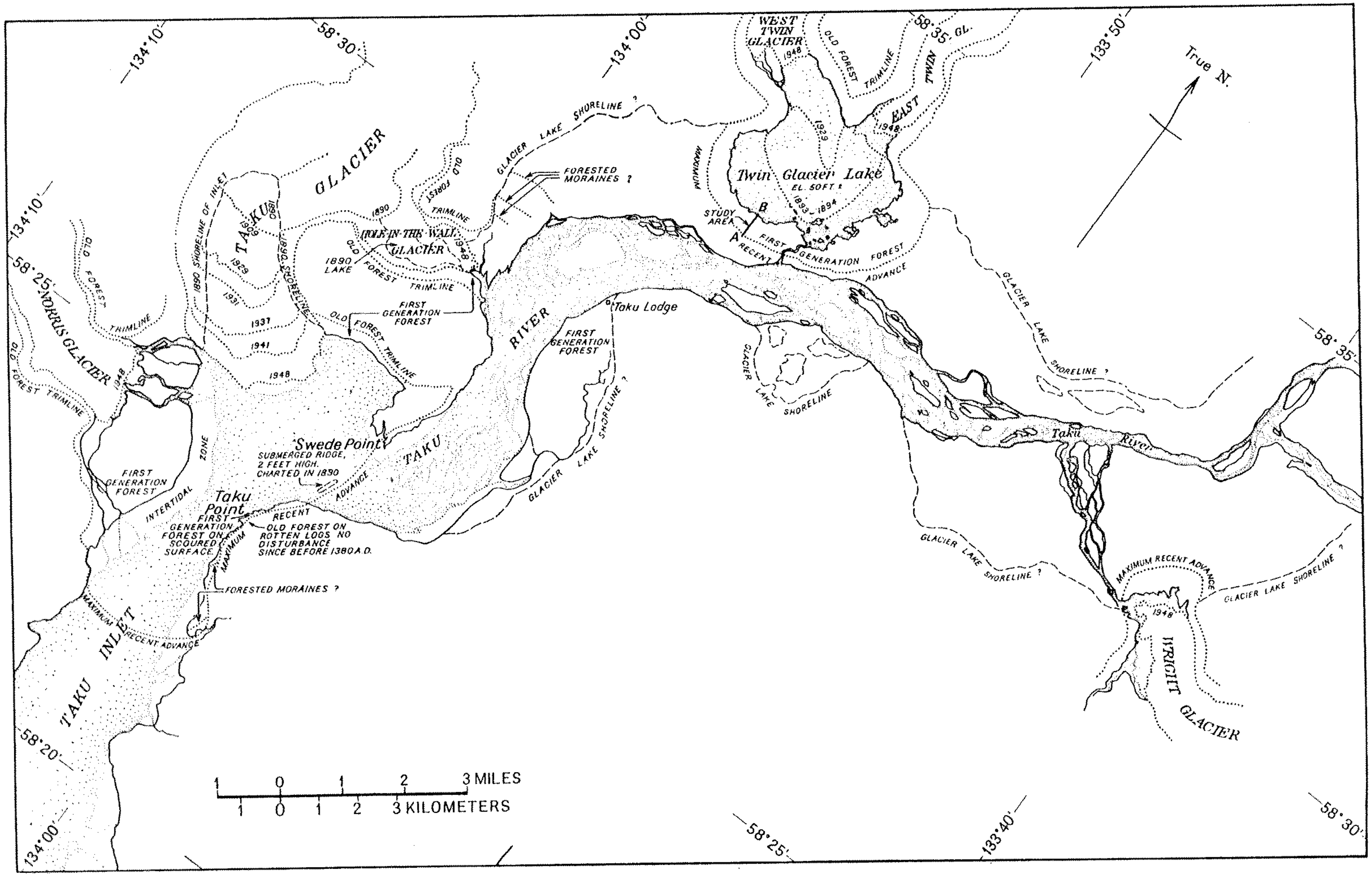


FIG. 6—Sketch map of lower Taku River area showing 1948 positions of several glaciers and positions at other dates estimated from several sources. Note the ice dam of the Taku River formed by advance and coalescence of Norris and Taku Glaciers in the middle 1700's and the extent of the lake thus formed; the strong present readvance of Taku and Hole-in-the-Wall Glaciers; the extensive recession of Norris and the Twin Glaciers; and the minor recession of Wright Glacier. From United States Navy aerial photo-

the interim. The moraines at stations 4 and 9 were freed of ice about 1883–1885 and 1901–1903 respectively.

According to Wentworth and Ray[15] there are at both Mendenhall and Herbert Glaciers, in the area between the present ice fronts and the terminal moraines of maximum recent advance, occasional old stumps, the remains of trees that grew there before the recent advance. If the advance killed them within the past 300 to 500 years, their contemporaries are still alive today above the trimline and farther down the valley, and it may be possible to cross-date the ring patterns of the old stumps with those of the old trees living in the vicinity today and discover just when and at what rate the recent advance took place. If it occurred more than 500 years ago, a fairly close estimate of the date may be obtained by analysis of the radioactive carbon content of the old stumps by the technique described by Arnold and Libby.[16]

Glaciers of the Taku Valley

Fifteen miles above the mouth of Taku Inlet (Fig. 2) a most unusual sight greets the eye (Figs. 6–8). Emanating from the same ice field, and with termini side by side and less than a mile apart in 1948 and 1949, lie two glaciers, Norris and Taku, the first receding, the second advancing. We have sufficient historical data to know that Taku has been advancing since at least 1900 and that Norris, after a period of minor fluctuations, has been receding since about 1916. The activity of Norris Glacier, then, is more nearly normal, to judge from the glaciers already discussed; that of Taku and its distributary arm, Hole-in-the-Wall Glacier (to be considered later), most abnormal.

Norris Glacier

The periglacial terrain features between the Norris ice front and Taku Inlet were studied in 1941, and since tree-ring material was collected at that time, the area was not revisited last summer. The terrain consists chiefly of an extensive outwash apron, parts of which adjacent to the inlet must have been deglaciated as early as 1828–1830. Periodic outbreaks under the ice of a lake along the flank of the glacier above its terminus, which have been occurring at least since 1916 (personal communications from W. S. Cooper and Louis DeFlorian),[17] have kept much of the outwash fan so un-

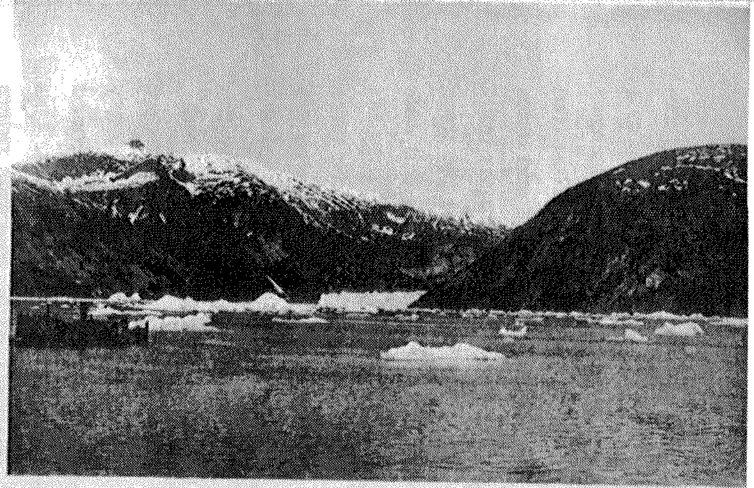
[15] Wentworth and Ray, *op. cit.*, pp. 888, 891.

[16] J. R. Arnold and W. F. Libby: Age Determinations by Radiocarbon Content: Checks with Samples of Known Age, *Science*, Vol. 110, 1949, pp. 678–680.

[17] See also Wentworth and Ray, *op. cit.*, p. 894.

FIG. 7—Norris Glacier (left) and Taku Glacier (right) from Pond cabin just west of Taku Point, as they appeared in August, 1916. (Photographs by William S. Cooper.)

FIG. 8—View from within 100 feet of Pond cabin (see Fig. 7), 33 years later, showing recession of Norris Glacier and advance of Taku Glacier, August, 1949. (Photographs by the author.)



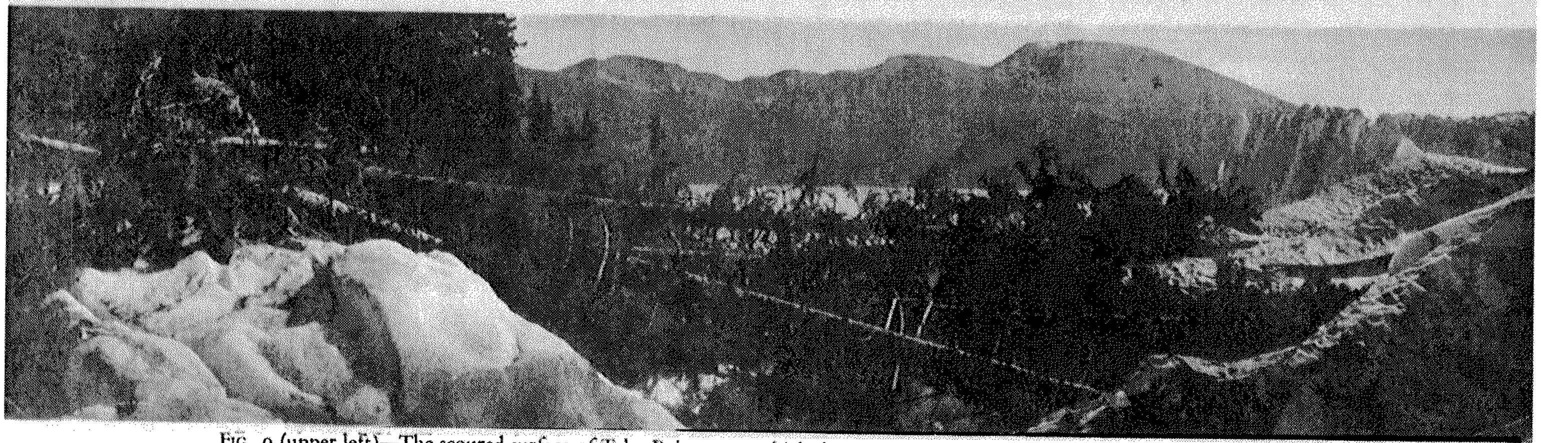


FIG. 9 (upper left)—The scoured surface of Taku Point, over which the Taku River must have poured when the Norris Glacier, out of view at left, and the Taku Glacier, left center, extended across the river to form an ice dam. Old forest at right stands beyond and above the eighteenth-century limit of ice advance. [The altitude of the old forest trimline here is about 100 to 150 feet above sea level.] August, 1949. (Photograph by the author.)

FIG. 10 (upper right)—One of the earliest photographs of Taku Glacier. 1893. (Believed to be from Canadian Boundary Survey.)

FIG. 11—Forest wreckage, uprooted by the advancing ice, along east margin of Taku Glacier. Although these trees are large, the forest is in its first generation and none of the trees sampled predate 1790. August, 1941. (Photographs by the author.)

stable that forest development has not advanced beyond pioneer stages except in a few small areas. The only ridge that has been surely identified as a moraine lies 0.3 to 0.4 mile ahead of the 1948 ice front. This seems to have been formed by a slight advance, the peak of which, estimated from tree rings, must have occurred before 1916–1918 but after 1878–1880. Field states (personal communication) that "a comparison of early photographs indicates that in the 1880's the glacier was close to or in contact with the trees along the margins. In 1906 the Wrights found it advancing and this culminated between 1910 and 1916." A description by Vancouver[18] suggests that the Norris still had a vertical tidal icefront in 1794, since there were then "immense bodies of ice (glaciers) that reached perpendicularly to the surface of the water in the basin which admitted of no landing place for the boats," and that there was a great deal of floating ice, especially at the entrance of the inlet, through which "a passage was with difficulty effected."

Although much more detailed field work should be done here, evidence is already available to indicate that in the middle of the eighteenth century Norris Glacier, in coalescence with its neighbor Taku Glacier, extended across Taku Inlet to Taku Point, three miles beyond its 1948 terminus. This evidence consists of two fragments of what appear to be moraine ridges south of Taku Point (Fig. 6), a forest trimline that stands 100 to 150 feet above tidewater on Taku Point, against which Norris Glacier must have pushed, and a heavily scoured region between that trimline and the inlet, over which the Taku River must have flowed when the tip of the ice dam rested there. At Taku Point (Figs. 6, 9) a first-generation forest that began to grow about 1755–1757 stands immediately below the trimline, and a very old forest perched on rotten logs and surely undisturbed since 1390 or earlier stands above the trimline.

Taku Glacier

For many years before the early 1940's Taku Glacier was probably the best-known glacier in Alaska, because in those days the head of Taku Inlet was still deep enough to admit large tourist ships. More recently, however, as the ice has continued to advance, the inlet has become silted, so that only shallow-draft vessels can approach it closely. In 1890, Taku Inlet was carefully charted by the United States Coast and Geodetic Survey under the supervision of Lieutenant Commander H. B. Mansfield, and the outline of the inlet and the position of the ice front of Taku Glacier as shown on the chart

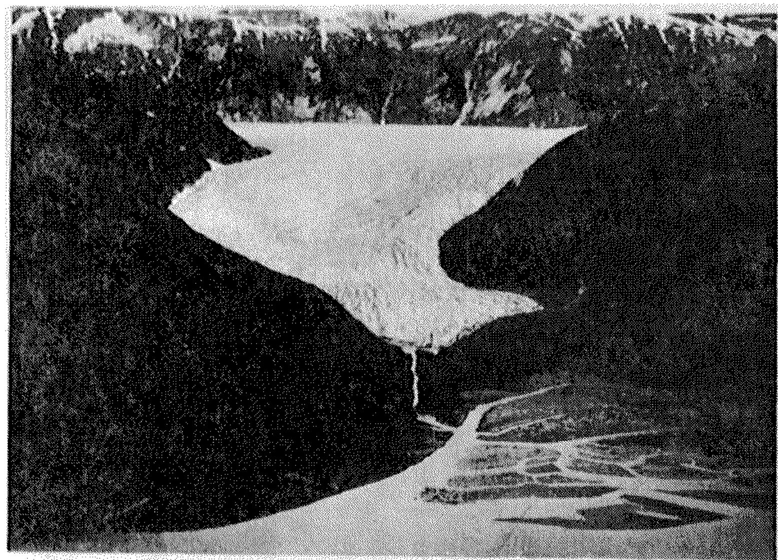
[18] Pacific Coast Pilot: Alaska, Part I, Washington, 1883, p. 170 (citing Vancouver, official edit., Vol. 3, p. 278).

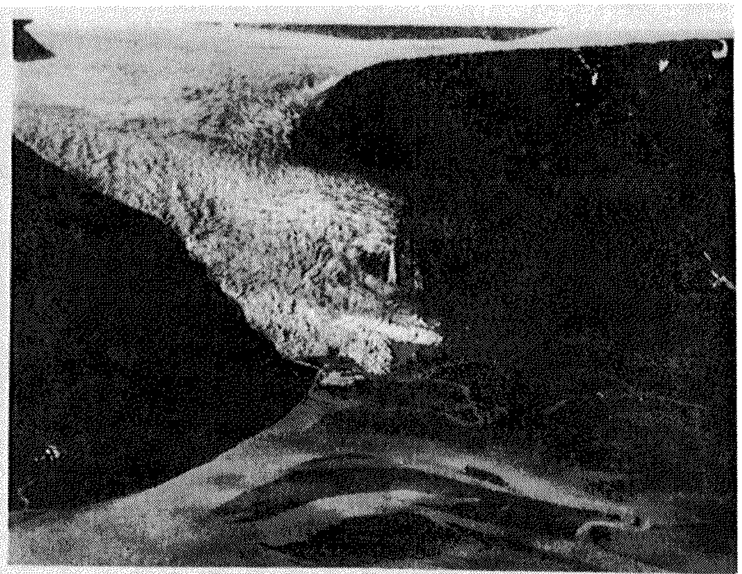
have been transferred to the sketch map (Fig. 6), so that a comparison of the 1890 and 1948 positions can be readily made. Photographic confirmation of the great advance since the 1890's is seen in Figure 9. According to Field (personal communication) "in 1890 I. C. Russell visited Taku Glacier and recorded the impression that it was retreating. In 1903 H. F. Reid referred to a report that the glacier had been greatly affected by the earthquake of 1899 but that the resulting losses were then being made up. By 1904 a net advance had occurred. I know of no evidence that the present advance began before 1899 and I believe if it did, that it is quite possible that the loss of ice in the earthquake in that year nullified the advance so that it started again from the 1890 position about 1900." It is estimated, therefore, that Taku has advanced about 3½ miles in 48 years. If this rate is continued for another 32 years, the remaining two-mile gap between the terminus and Taku Point will be closed up, and again an ice dam will block the Taku River as it must have in the middle eighteenth century. It has been stated in the literature[19] that Taku Glacier was in a more advanced position in 1935 than it had been for many centuries, and indeed the large size of the individual trees at the edge of the ice led me to the same conclusion after superficial observation in 1941. But now I must contradict that idea; for careful sampling of the forest, into which the ice was plowing (Fig. 11) along its north margin last summer, revealed that it is a first-generation forest of spruces and hemlocks without rotten logs and stumps, and that the time when the ice of the last recent advance melted away in that area must have been as recent as about 1771.

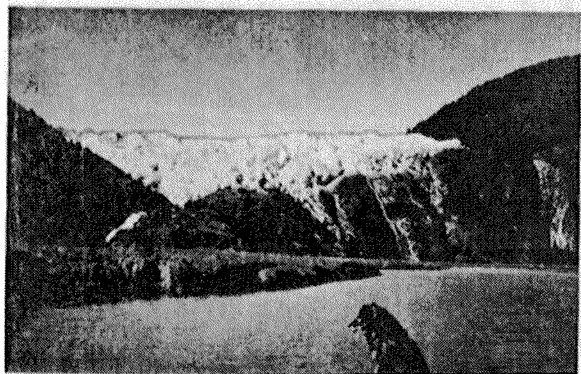
The evidence on Taku Point described for Norris Glacier holds for Taku Glacier also. The whole tip of Taku Point below an altitude of 100–150 feet is heavily scoured (Fig. 9), and it seems to have formed both abutment and spillway of a gigantic ice dam derived from both Taku and Norris. Additional confirmatory evidence of the extent of that recent advance by Taku is found in the submerged ridge (Fig. 6) lying across the mouth of the Taku River north of Taku Point in 1890,[20] since this is assumed to have constituted a part of the terminal moraine of the middle eighteenth century. The oldest trees immediately below the trimline show that overflow from the ice-dammed Taku Lake must have begun to cross the higher scoured parts of Taku Point by about 1755–1757. The lake surface must have been lowered below an altitude of some 50 feet above sea level by about 1775, because by

[19] Matthes, *op. cit.* (see footnote 1, above), p. 201.

[20] "Taku Inlet, S. E. Alaska. By the party unter [*sic*] the charge of Lieut. Comdr. H. B. Mansfield . . . 1890." 1 : 40,000. U. S. Coast and Geodetic Survey hydrographic survey, photostatic reproduction.







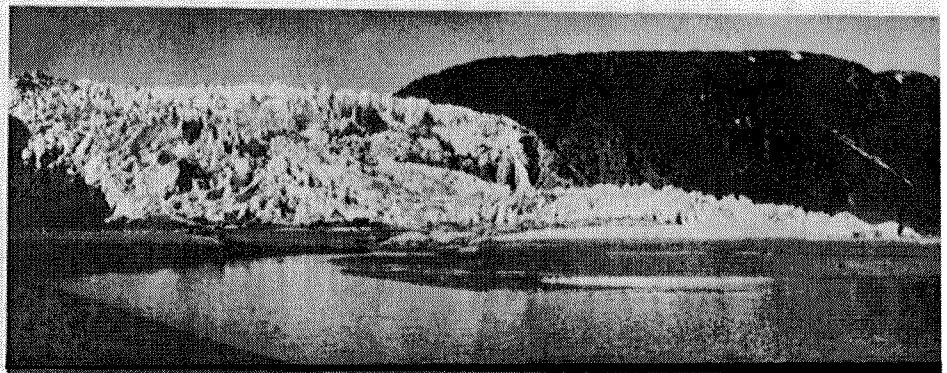


FIG. 12 (upper left)—Hole-in-the-Wall Glacier in August, 1934. Still visible at the tip of the ice is remnant of the lake which was 1.2 miles long in the 1890's, before the present glacier advance occurred. Taku Glacier flows from right to left in background; Taku River and tidal flats in foreground. (U. S. Navy aerial photograph.)

FIG. 13 (upper right)—Hole-in-the-Wall Glacier in 1949, showing 15-year advance. (Photograph by the author.)

FIG. 14 (lower left)—Hole-in-the-Wall Glacier in August, 1941. (Photograph by the author.)

FIG. 15 (lower right)—View from approximately the same position as Figure 14. August, 1949. The glacier has advanced over the 200-foot cliff onto the tide flat. (Photographs by the author.)

then trees had begun to grow 10 miles upstream on parts of the terminal moraine of Twin Glaciers, which had apparently been deposited below the lake surface. The shore line of the glacier lake as roughly identified from the aerial photographs is shown in Figure 6, and it will be noted that the whole terrace on which Taku Lodge is built was then lake floor. The forest on that terrace is in a young stage of the first generation.

To review the complex history of Taku Glacier, then, we may infer that it advanced along with all the others already described, to a maximum sometime in the middle eighteenth century, and then began to recede along with the others. This part of its history was normal, but by 1900 at the latest a readvance began that has continued to the present time. The total recession from the position of maximum recent advance must have amounted to more than five miles, before the readvance began. Just what caused this glacier to begin advancing after receding extensively is not fully known. The extent to which its readvance may have hastened the recession of the other glaciers feeding from the same ice field, through "snow piracy," may be discovered at higher levels by study of the degree of competition among these glaciers for snow from a source that is shared by the Taku.

Hole-in-the-Wall Glacier

Sometime between 1888 and 1906, when the surveying was done for United States Coast and Geodetic Survey Chart 8300,[21] Hole-in-the-Wall Glacier did not exist at all (Fig. 6), and its present bed was occupied by a lake about 1.2 miles long. Since then it has advanced onto the tide flats of the lower Taku River. Any satisfactory explanation of the recent readvance of Taku Glacier would serve to explain the behavior of Hole-in-the-Wall, since it is a distributary arm of Taku. Figures 12 to 15 show various stages in its advance since 1934. As far as can be judged from the trees growing along its margin today, its history is one of advance to a maximum in the middle eighteenth century followed by normal recession. At an unknown time it began readvancing. It is advancing today into a very sparse first-generation forest, the age of whose individuals indicates that recession from the last maximum was in progress by about 1790–1792. Just how far it advanced in the middle eighteenth century is not yet known, but three parallel forested ridges rising out of the tide flats 1.5, 1.0, and 0.7 miles beyond the 1948 ice front (Fig. 6) appear much like moraines on the aerial photographs.

[21] "Lynn Canal and Stephens Passage, S.E. Alaska," 1 : 200,000, *U. S. Coast and Geodetic Survey Chart No. 8300*, 1906.

Twin Glaciers

Perhaps the most spectacular glaciers of the lower Taku Valley are the Twin Glaciers (Fig. 6), which end in a lake three miles across. Their history is obviously similar to that of Herbert and Mendenhall and is not complicated by present readvance, as in the case of the Taku. The total recession since the stage of maximum recent advance in the middle eighteenth century, when there was a large semicircular terminal lobe, had amounted by 1948 to 3.3 miles for West Twin and 2.5 miles for East Twin. The difference may reflect effects of recent snow piracy by the Taku, whose feeding ground is much more closely associated with West Twin than East. Twin Glaciers Lake was found to be at least 447 feet in depth, and according to historical records[22] it was still completely filled with ice in 1893–1894. The position of the edge of the ice as recorded then is shown in Figure 6, though a large area which must have been debris-covered ice has since melted out and increased the size of the lake. I saw evidence in 1941 that melting was still going on—small islands recently sunk below the surface of the lake bearing drowned young spruces. In a photograph taken in 1923, East and West Twins are still joined in a common bulbous tip, with giant bergs, some apparently more than a mile long, floating in the lake. According to Field (personal communication), the two glaciers were still joined at their termini when he visited the area briefly in 1926, but an aerial photograph taken by the United States Navy in 1929 shows two termini separated by a distance estimated at a few hundred feet.[23]

Detailed work on the age of moraines formed since the maximum recent advance was carried on last summer along the line *A–B* in Figure 6. The trees on the terminal moraine had grown to very large size, some as much as 46 inches in diameter at breast height, so that a special technique using a socket-wrench extension to our borers was devised by Hulbert for collecting cores all the way to the center. The oldest trees tested in this way showed that the 14-foot-high terminal moraine must have been freed of ice by about 1775–1777. The ridgetop here bore a mantle of what seemed to be lake silt; a machete blade could be thrust into it to a depth of six to eight inches below the bottom of the organic layer without striking any pebbles. Since we studied the Twin Glaciers area before the Taku Glacier and Taku Point areas, this was our first intimation that the Twin Glaciers moraine must have been formed under the surface of a water body; investigation of the Taku

[22] Boundary Atlas of Alaska, 1893–1895, Survey Sheet No. 12.

[23] Wentworth and Ray, *op. cit.*, p. 895.

Lodge terrace disclosed further evidence that sent us on to Taku Point in search of final confirmation. Later we learned of a local Indian legend that mentioned a lake formed by a dam across the river near Taku Point.

At the Twin Glaciers study area all the moraines along the line *A–B* were sampled, and the years of deglaciation were found to be 1775–1777, 1788–1790, 1800–1802, 1835–1837, 1844–1846, 1857–1859, 1869–1871, and 1877–1879. The oldest trees that could be found on the level shore of the lake indicate that the subaerial history of that surface does not precede about 1881–1883.

Wright Glacier

We did no ground work on the terrain in front of Wright Glacier. To judge from the aerial photographs, its position of maximum advance was only 0.7 mile beyond the 1948 ice front, and the position of the apparent shore line would suggest that the terminal moraine was formed under water, as it was at the Twins. Much difficult ground work will need to be done here before we can arrive at any sound conclusions regarding the history of this glacier, which emanates not from the Juneau Ice Field but from an entirely different ice field to the south of the Taku Valley (Fig. 2).

A Tentative Hypothesis on Recent Glacier Periodicity in Northwestern North America

In the results that have been presented here, one notable feature stands out. That is the synchronism, for all the glaciers studied, of an advance of the termini to positions of maximum extent in the early or middle eighteenth century and the beginning of recession by about 1765. It is true, of course, that these glaciers all emanate from the same broad ice field, so that uniformity of behavior in this respect would be expected. But the synchronism with the glaciers of the Glacier Bay area, 65 miles to the northwest,[24] those of Garibaldi Park (W. H. Mathews, personal communication), 800 miles to the southeast, and of Eliot Glacier on Mt. Hood,[25] 1100 miles to the southeast, and even glaciers of Norway and Iceland,[26] can hardly be assumed to be merely coincidental. The similarity reported in the periglacial features of Nisqually Glacier on Mt. Rainier (Arthur Johnson, personal communication) and Coleman Glacier on Mt. Baker (K. N. Phillips, personal communication) leads me to believe that their histories have been similar also. Even the

[24] Cooper, *op. cit.* (see footnote 3, above), p. 47.

[25] Lawrence, Mt. Hood's Latest Eruption (see footnote 4, above).

[26] Matthes, *op. cit.* (see footnote 1, above), pp. 207–208.

morainal features of North Iliamna Glacier on Iliamna Volcano, 700 miles northwest of the Juneau Ice Field, seem similar (Bradford Washburn, personal communication)[27] to those just examined. Only some of the glaciers of the Prince William Sound region, 500 miles northwest of the Juneau Ice Field, and of a few other areas on this continent, have behaved in a significantly different way (W. O. Field, personal communication; see also footnotes 39 and 40, below). Surely some widespread climatic event must have been the reason for the concordant behavior of glaciers so widely spaced geographically.

Unfortunately, no weather records for this region extend back far enough to be useful for comparison with glacier behavior at the time of the maximum recent advance in the middle eighteenth century. There are, however, well-documented records of relative sunspot numbers extending back to 1610, when careful systematic observations of the sun's surface through telescopes began.[28] Many workers have pointed to close correlations between visible evidences of solar activity (relative number and position of sunspots) and the incidence of various terrestrial phenomena. Best known of the correlations occur between relative sunspot number, particularly below a certain solar latitude, and magnetic disturbances, auroras, and radio transmission. Sunspot curves and curves of annual growth in trees have also been shown to be related. Correlations with weather have been convincingly demonstrated, but apparently these have been particularly perplexing to the layman because the sign and the closeness of the correlation for at least some of the elements of weather seem to depend on the latitude and longitude of the part of the earth under consideration. Clayton[29] has been most careful to emphasize this; he has indicated that in the North Pacific coastal region of North America the correlation between sunspot number and winter barometric pressure is high and positive. Consequently, during periods of high sunspot number, glaciers should shrink through the operation of the following meteorological conditions, particularly on south-facing slopes that receive insolation most efficiently: increased frequency of northerly winds bringing clear skies, admitting a greater amount of sunshine—presumably most intense at this stage of the cycle—to the ice fields and glaciers, and

[27] See also Washburn's aerial photograph of this glacier on page 669 of F. B. Colton: Weather Fights and Works for Man, *National Geogr. Mag.*, Vol. 84, 1943, pp. 641–670.

[28] The Chinese, however, had been observing sunspots with the naked eye since 28 B.C. See Co-Ching Chu: Climatic Pulsations during Historic Time in China, *Geogr. Rev.*, Vol. 16, 1926, pp. 274–282; reference on p. 280, footnote 5.

[29] H. H. Clayton: Solar Relations to Weather and Life, 2 vols., Canton, Mass., 1943; reference in Vol. 2, p. 367 (Fig. 12).

thereby increasing ablation while at the same time decreasing the amount of snowfall. Conversely, during periods of low sunspot number, the frequency of southerly winds should increase, bringing greater cloudiness and thus decreased ablation and increased snowfall, causing glaciers to accumulate more rapidly than they melt, with a resultant net advance at the terminus, or perhaps merely a cessation in shrinkage or a reduction in the rate of recession. It was with great interest therefore that while reading

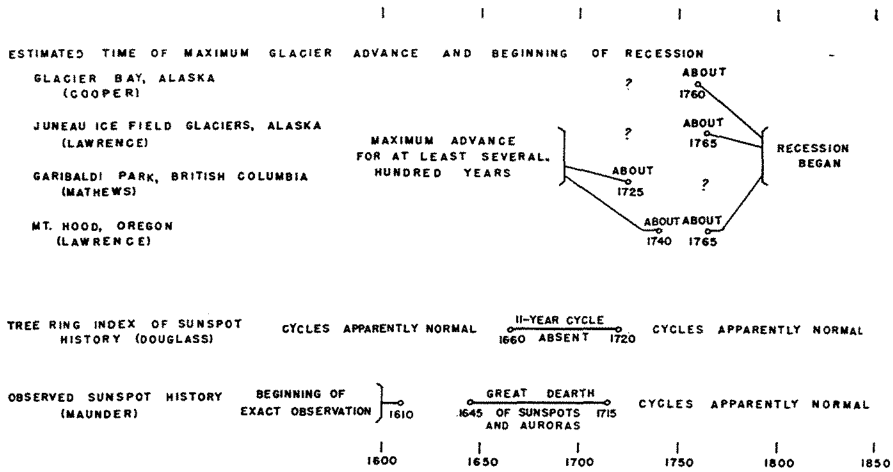


FIG. 16—Relation of the strongest glacier advances in northwestern North America for at least the past six centuries to the period of great sunspot dearth, 1645–1715.

Stetson's "Sunspots in Action"[30] I stumbled on the fact that two workers, Maunder and Douglass,[31] had independently assembled evidence pointing to a period of great sunspot dearth 60–70 years long that closely preceded the time of maximum recent glacier advance in Alaska, Oregon, and British Columbia. The concordant results of the Juneau Ice Field studies reported here are strong evidence of the significance of this interesting correlation (Fig. 16).

THE PROLONGED SUNSPOT MINIMUM OF 1645–1715

The most comprehensive, though not the earliest, report of this phenomenon was prepared by the late Professor E. Walter Maunder[32] of the

[30] H. T. Stetson: Sunspots in Action (Humanizing Science Ser.), New York, 1947.

[31] E. M. Maunder: The Prolonged Sunspot Minimum, 1645–1715, *Journ. British Astronom. Assn.*, Vol. 32, 1921–1922, pp. 140–145; *idem:* The Sun and Sunspots, 1820–1920, *Monthly Notices Royal Astronom. Soc.*, Vol. 82, 1922, pp. 534–543.

A. E. Douglass: Climatic Cycles and Tree-Growth, 3 vols., *Carnegie Instn. Publ. No. 289*, 1919–1936.

[32] The Prolonged Sunspot Minimum (*op. cit.*). Maunder's articles (see footnote 31) mention early reports by Rudolf Wolf (no date), F. W. G. Spoerer in 1889, and his own brief notes of 1890, 1894, and 1896 commenting on the Spoerer articles.

Royal Observatory, Greenwich, England. He pointed out that for the first 35 years after 1610, when sunspots were first seen by Galileo through his new telescope and a careful systematic record of their numbers was begun by Galileo and Scheiner (1611), the periodicity of spottedness seems to have been normal, with minima in 1619 and 1634 and maxima in 1625 and 1639. But from 1645 to 1713 almost no spots were observed, and those seen were all in the sun's southern hemisphere.[33] In 1714–1715 many spots appeared in high latitudes in the northern hemisphere, and in 1716 spots were plentiful. In Maunder's own words:

> Thus for close upon 70 years, the ordinary progress of the solar cycle, as we have been accustomed to it was in abeyance—in abeyance to such a degree that the entire records of those 70 years combined together would scarcely supply sufficient observations of sunspots to equal one average year of ordinary minimum such as we have been accustomed to during the past century.

He pointed out that the dearth must have been real and not due to inadequate equipment, because the telescopes then were more powerful than those used by Galileo and Scheiner in their discovery. Nor were observers few: sixteen qualified men were watching for sunspots during this period. Maunder further emphasized:

> It ought not to be overlooked that, prolonged as this inactivity of the Sun certainly was, yet the few stray spots noted during the seventy years' dearth,—1660, 1671, 1684, 1695, 1707, 1718,—correspond, as nearly as we can expect, to the theoretical dates of maximum . . . so the above-mentioned years seem to be marked out as the crests of a sunken spot-curve.

He quoted from Miss Agnes Clarke's report that there was strong but indirect evidence that the prolonged sunspot minimum was attended by a profound magnetic calm; for in England not an auroral glimmer was chronicled in the whole seventeenth century, and even in Iceland and Norway they became so rare as to be considered portentous, and their reappearance at Copenhagen in 1709 was greeted with consternation and amazement.

Meanwhile, unaware of Wolf's or Spoerer's reports (1889) and Maunder's publications of 1890, 1894, and 1896, A. E. Douglass of the University of Arizona had been having more trouble over the interval 1660–1720 than over any other in working out the action of the sunspot cycle in the growth layers of yellow pines. Nevertheless, in 1919 he published his results,[34] with mention that "for the next 60 years [following 1660] the curve flattens out in a striking manner." He finally concluded that, "taking the evidence as a whole, it seems likely that the sunspot [11-year] cycle has been operating since

[33] I do not know whether this marked asymmetry of solar activity has any bearing on the case; it is given merely as a matter of record.

[34] Douglass, *op. cit.* (see footnote 31, above), Vol. 1, p. 102.

1400 A.D., with some possible interference for a considerable interval about the end of the seventeenth century." In 1928[35] he described with enthusiasm the historical confirmation of his period of sunspot dearth. He stated that in 1914 he had nearly given up the idea that the trees showed the 11-year cycle. The first confirmation came in 1922, in the form of a letter from Professor Maunder "calling attention to the prolonged dearth of sunspots between 1645 and 1715, and saying that if there were a connection between solar activity and the weather and tree-growth, this extended minimum should show in the weather and in the trees." Douglass immediately recognized this interval as the one in which "there was entire failure in attempting to trace effects of the well-known solar cycle." He subsequently found that further confirmation existed in the sequoia record and also in the Vermont hemlocks and in other tree records, and that nothing similar to this dearth period had occurred "for hundreds of years" before the seventeenth century.

Confirmatory evidence of this period of abnormal conditions of sun and weather is found in a graph[36] of the frequency of severe winters based on old historical records, which indicates that the greatest frequency from the beginning of the record in about A.D. 300 to about 1760 occurred in the seventeenth century.

MORAINE FORMATION AND SUNSPOT MINIMA OF THE "11-YEAR CYCLE"[37]

Figure 17 shows a most interesting correlation between the dates of deglaciation as worked out from the oldest trees sampled on the moraines and the years of observed sunspot minima. The correlation at Herbert Glacier seems most exact. Further work, particularly on the Herbert moraines, where the record seems most regular and complete, may confirm my supposition that during each sunspot minimum in a general period of recession the glacier terminus hesitated long enough to deposit a ridge of till. A less exact correlation is apparent for the sampled Mendenhall moraines. The correlation at Twin Glaciers is high if we assume, as mentioned in the discussion of Mendenhall Glacier, that the young trees grew to the sampling height four years faster than at Herbert and Mendenhall, thereby in effect sliding the estimated dates of deglaciation four years to the left for all (correction made before plotting).

---

[35] *Ibid.*, Vol. 2, pp. 125–126.

[36] H. W. Clough: The 11-Year Sun-Spot Period, Secular Periods of Solar Activity, and Synchronous Variations in Terrestrial Phenomena, *Monthly Weather Rev.*, Vol. 61, 1933, pp. 99–108, Fig. 2 (on p. 102).

[37] I place the length of the cycle in quotation marks because this value is merely an approximate average; the length between minima has ranged from 9 years to 14 years within the period of most careful observation, which began in 1749 (see Stetson, *op. cit.*).

The 20-year moving mean of sunspot numbers is plotted across the middle of Figure 17 in order to smooth the curve and give some idea of the trend of spottedness during the period of observation. It will be noted that there are general lows in the early and late nineteenth century and the early twentieth, and one would therefore expect the frequency of occurrence of

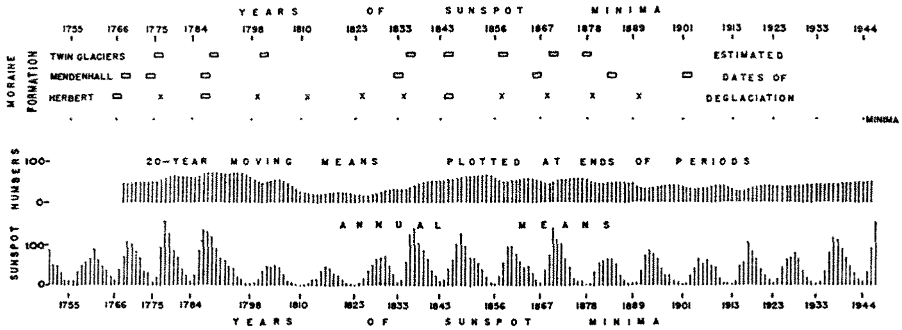


FIG. 17—Suggested relation of moraine formation to time of sunspot minima. Sunspot numbers are graphed at the base as annual means, from H. T. Stetson's tables published in "Sunspots in Action," and in the middle as moving 20-year means calculated by Elizabeth G. Lawrence from the Stetson data. The estimated times of deglaciation of the moraines studied, based on oldest trees found on each, are plotted above as open rectangles; x's indicate the suspected time of deglaciation of existing but unsampled moraines. It is notable that the number of existing moraines does not exceed the number of sunspot minima and that the estimated times of deglaciation usually coincide with, or shortly follow, the years of sunspot minima.

slight glacier advances to be higher toward the ends of those periods than at other times, but the correctness of this assumption must also await further field study.

The history of the places sampled at both Mendenhall and the Twins is obviously complicated by advances in the nineteenth century, but the history at Herbert does not seem to be complicated in that way. My interpretation of the morainal history of these three glaciers, based on the field work done so far, is shown diagrammatically in Figure 18, in which the assumption is made that a moraine would be produced for each occurrence of sunspot minima. Unfortunately, there still seem to be more question marks than known facts, but I present it as a framework for testing the tentative hypothesis that, for this general region and during a period of general recession such as we have experienced since the maximum recent advance of the middle eighteenth century, moraine formation is related to the occurrence of sunspot minima.

Since all the moraine dating reported here is based on the time of germination of woody plants, particularly Sitka spruce, on surfaces just freed of ice, it might be argued that the periodicity of moraine formation shown in Figures 17 and 18 could be due entirely to a periodicity in production of seed crops, which might in turn depend on the "11-year" solar cycle. But data provided by United States Forest Service personnel indicate that this objection is not justified. Dr. R. F. Taylor of the Forest Research Center in Juneau indicates (personal communication) that some Sitka spruce seed is

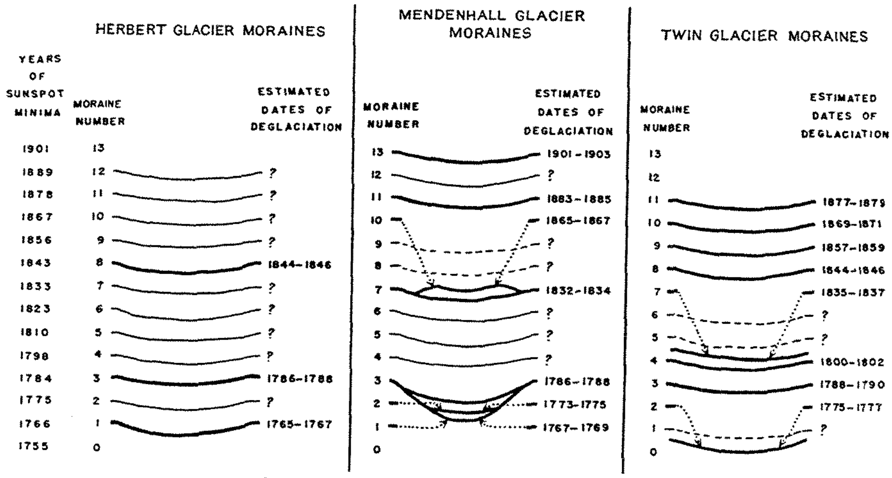


FIG. 18—Interpretation of periodicity in the formation of moraines of Herbert, Mendenhall, and Twin Glaciers, assuming a moraine to be formed at each sunspot minimum of the "11-year" cycle during a period of general glacier recession. Heavy lines are sampled moraines, light lines are visible but unsampled moraines, broken lines are moraines presumably buried or destroyed by a subsequent readvance. See text (on Herbert and Mendenhall Glaciers) for description of technique of estimating age of moraines.

produced there every year, and that the usual interval between heavy seed crops is three to four years; heavy crops occurred in 1945 and 1949, and a particularly light crop in 1948. Mr. Leo A. Isaac of the Pacific Northwest Forest Experiment Station states (personal communication) that the usual interval between heavy seed crops of Sitka spruce in coastal Oregon and Washington is about seven years, and that particularly heavy seed crops were noted there in 1929, 1933, 1937, and 1949, whereas in 1948 the crop was a failure. We may conclude, therefore, that although more seeds are available in some years than others, some seeds are available in most years, and the usual interval between heavy crops is much less than the interval suggested here between the formation of successive moraines.

PROPOSED FURTHER TESTS OF THE HYPOTHESIS

Now that the framework of the hypothesis has been presented and the evidence so far collected has been fitted into it, I should like to point out what kind of evidence is needed for testing it further.

First of all, we need to know for many glaciers of northwestern North America how greatly shrunken the glaciers were before the maximum recent advance, for how long a time they were in that shrunken condition before the advance began, when it began, its rate of advance, and when the peak occurred. Careful study of both the living forest trees and the interstadial fossil forest remains should supply this information. Work has already been carried on for many years by Cooper[38] for the Glacier Bay region, but more work is needed even there.

Secondly, we need to study in much more detail all the moraines available for a given glacier; those of Herbert seem most promising because of their apparent regularity and completeness.

Thirdly, there are several strong moraines that have been formed by various glaciers of this general region at known dates since 1900. The times at which these were formed should be compared with the years of sunspot minima shown in Figure 17 to see whether they fit into the scheme.

Fourthly, we need to compare distances of recession from position of maximum recent advance to present ice front for many north-facing and south-facing glaciers. Among glaciers with comparable nutrition and exposed to comparable amounts of clear and cloudy weather, the south-facing glaciers should have receded much greater distances than the north-facing ones, if differences in amount of solar energy impinging on the ice fields and their glaciers have been basically responsible for the variations we observe. Glaciers of symmetrical volcanic cones should be most useful for this test.

Finally, we need to study carefully through at least two cycles of sunspot minima and maxima the various elements of weather at a series of stations located at different altitudes in this region, so that the mechanics by which the glacier economy is altered by variation in solar activity may be learned.

THE PRINCE WILLIAM SOUND ENIGMA[39]

As I have pointed out earlier in this report, the recent glacier history of the Prince William Sound region does not correspond with that of the region as a whole. Cooper[40] and other investigators have found that within

[38] W. S. Cooper: The Recent Ecological History of Glacier Bay, Alaska: I, The Interglacial Forests of Glacier Bay, *Ecology*, Vol. 4, 1923, pp. 93–128; *idem:* A Fourth Expedition to Glacier Bay, Alaska, *ibid.*, Vol. 2c, 1939, pp. 130–155.

[39] Field (personal communication) points out that there are a few other enigmas, such as the Lituya Bay area on the west slope of the Fairweather Range where the two big glaciers have been advancing slowly for some decades and are now far in advance of their position in 1786.

[40] W. S. Cooper: Vegetation of the Prince William Sound Region, Alaska; With a Brief Excursion into Post-Pleistocene Climatic History, *Ecological Monographs*, Vol. 12, 1942, pp. 1–22.

the past 40 years some of the glacier termini here have advanced much farther than at any other time within at least 500 years. Field reports (personal communication based on information received from Douglas N. Brown) that advances are even now in progress. I have little explanation to offer at present except that this region has much higher annual snowfall at sea level than any other part of Alaska. It is reported that Whittier has a mean annual snowfall of 175 inches, and Valdez 266 inches.[41] Fort Liscum, five miles southwest of Valdez, has 369 inches a year and has had as much as 691 inches in one season. The Prince William Sound region must therefore be also one of great cloudiness, which should screen out direct influences of variation in solar activity on glacier ablation rates. At Juneau the mean annual snowfall amounts to only 114 inches. Field (personal communication) states also that the névé line in Prince William Sound, at least in the northwestern part, at Harriman Glacier and in Blackstone Bay, is much lower than at most other places along the coast. In this connection it is important to point out that with increase in temperature, which has been noted since 1900 especially, the altitude at which maximum precipitation occurs in the form of snow should rise.[42] Simple computations show that it should rise about 280 feet per degree Fahrenheit rise in temperature. If the zone of maximum precipitation in the form of snow was already at a very low altitude in the early 1600's, as it seems to be today, perhaps the reduction of temperature which apparently occurred in the late seventeenth and early eighteenth centuries would not have had much effect. It should also be true that for ice fields nourished rather uniformly over a wide altitude range because of the precipitousness of the surfaces of accumulation, as seems to be the case in the Prince William Sound region, increase in temperature of even several degrees over a period of years should make little difference in the amount of snow that reaches the glaciers; though the altitude of maximum precipitation as snow would rise, nourishment should still be about the same. Consideration of these ideas would lead us to expect local reduced sensitivity of the Prince William Sound glaciers to changes in solar activity.

The greatest sensitivity to solar changes should be shown by glaciers nourished by ice fields lying mainly at a critical low altitude without numerous high peaks to draw from, such as the Juneau Ice Field, where, as has been noted, the firn line now lies just a few hundred feet below the general level of its snow accumulation surface. A general rise in temperature of

---

[41] "Climate and Weather of Alaska" prepared by Weather Central, 7th Weather Group, Ft. Richardson, Alaska, U. S. Army, 1947. (Mimeographed.)

[42] W. O. Field, Jr.: Glacier Recession in Muir Inlet, Glacier Bay, Alaska, *Geogr. Rev.*, Vol. 37, 1947, pp. 369–399; reference on p. 397.

only a few degrees would expectably cut off the whole ice field from much of its source of snow and perhaps replace it with an equivalent amount of rain, which would cause ablation rather than accumulation and result in rapid shrinkage. It is quite possible that the extensive recession in Glacier Bay, where the accumulation surfaces lie at altitudes much lower than those of the Juneau Ice Field, has been brought about by this mechanism, emphasized of course by the palmate valley system noted by Cooper.[43]

To summarize, the glaciers emanating from the southern part of the Juneau Ice Field, including Eagle, Herbert, Mendenhall, Norris, Taku and its distributary arm, Hole-in-the-Wall, and Twin Glaciers, seem to have advanced in unison to a maximum sometime in the early or middle eighteenth century, which surely had not been exceeded since before the 1300's, and from which recessions of 1.3 miles to 5 miles beginning by 1765 at the latest subsequently occurred. The same chronology has been reported from Glacier Bay, Alaska, from Garibaldi Park, British Columbia, from Mt. Hood, Oregon, and even from Norway and Iceland. A close correlation is noted between the time of this glacier maximum and the end of the 70-year period of great sunspot dearth which extended from 1645 to 1715. The few spots observed then were all in the sun's southern hemisphere, but whether this fact has any bearing on the case is not known. The dearth period was independently reported by Maunder from historical records and Douglass from living pine-tree growth curves in Arizona. The hypothesis is offered that reduction of solar energy inflow to the earth and the various weather alterations attendant upon that great and prolonged sunspot dearth resulted in the general glacier advance that had its climax in the middle eighteenth century. The relatively high positive correlation that exists between winter atmospheric pressure and sunspot number in the latitude and longitude represented by the northwestern part of North America, as reported by Clayton, is offered as one evidence that glacier advance at times of low sunspot numbers is to be expected here. Further evidence is the relation between times when recessional moraines have been formed since the middle eighteenth century by Herbert, Mendenhall, and Twin Glaciers and the years when sunspot minima of the "11-year cycle" occurred. The need for further detailed information for testing this hypothesis is emphasized. The trend since 1765 has been one of general recession except for occasional slight temporary readvances such as observed in the Norris in the 1880's and from 1906 to 1916. For the past third of a century almost all of the glaciers emanating

[43] Cooper, The Problem of Glacier Bay, Alaska (see footnote 3, above).

from the southern half of the Juneau Ice Field have receded at an accelerated rate. The Taku and Hole-in-the-Wall Glacier system constitutes the one notable exception. Its strong advance, continuing from about 1900 to the present, is still in need of adequate explanation.

If further work confirms the relation suggested here between reduced solar activity and glacier advance, we may have new evidence for testing old theories regarding the causes of Pleistocene glaciation. In closing I should like to quote from a recent article by Donald H. Menzel[44] that is particularly apropros.

> We are now in a scientific period where intensive study of the sun, together with simultaneous study of many types of terrestrial phenomena, should lead to discoveries of vital interest and practical value. . . .
>
> Geologists and meteorologists have hesitated to ascribe the variability of terrestrial climate to a solar cause. But many have gradually come to the conclusion that a solar origin is the only remaining acceptable hypothesis. A million years is only a small amount of time in terms of the age of the sun or earth. Any variations in the output of solar heat cannot be attributed to evolution. But we cannot disprove, at the present time, the suggestion that the sun may have a long-range variability in addition to its 11-year cycle.

---

[44] D. H. Menzel: The Sun and the Earth, *Science*, Vol. 108, 1948, pp. 590–591.