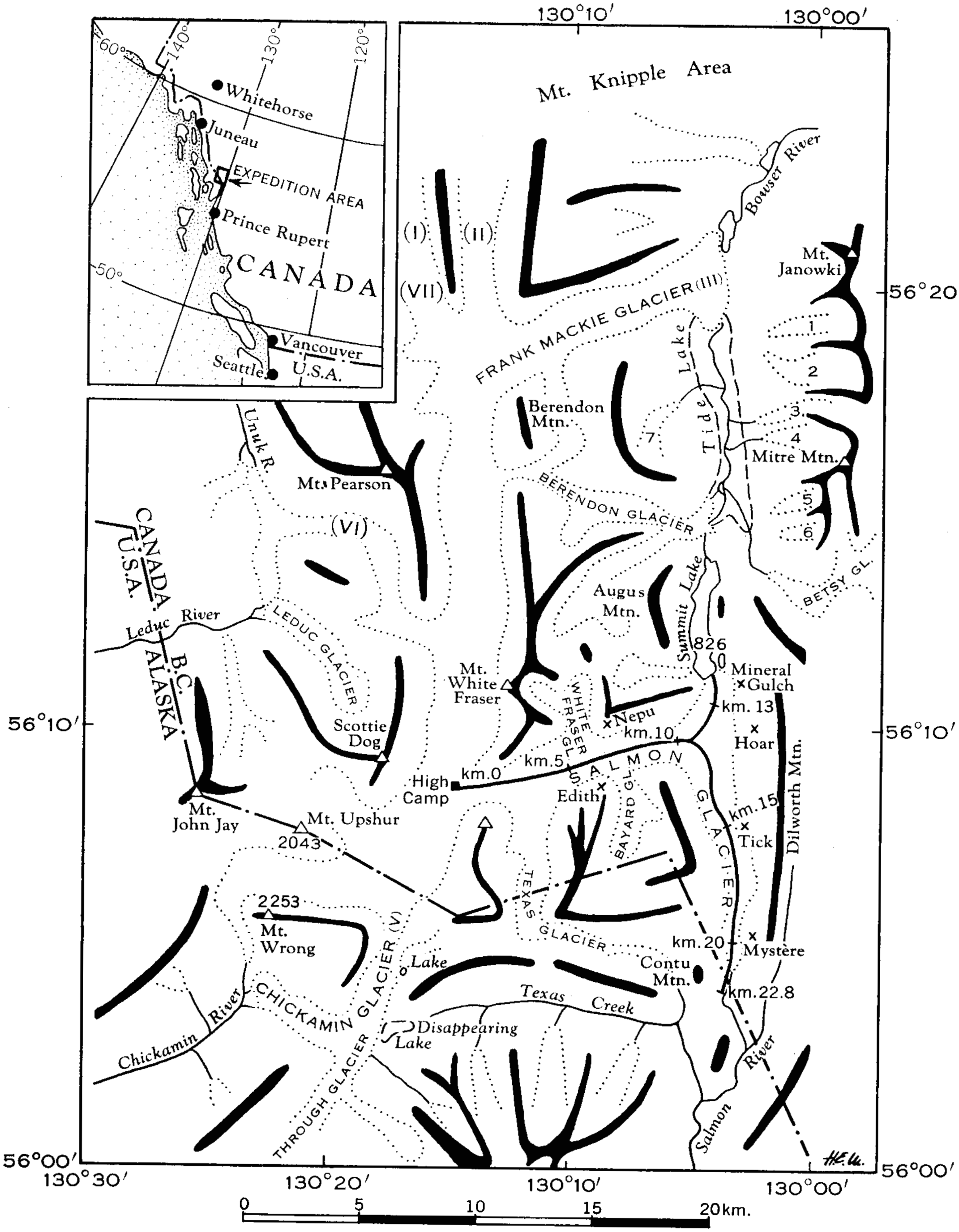


Fig. 1. Sketch map of Salmon Glacier area.

Note added in proof: In Fig. 1 read Janowski for Janowki and in Figs. 1 and 3 read Cantu for Contu.

PHOTOGRAMMETRIC AND GLACIOLOGICAL STUDIES OF SALMON GLACIER

Dieter Haumann*

Introduction

SINCE the middle of the last century extensive studies have been carried out on some glaciers to determine the causes of fluctuations in glaciation. It was soon found that the factors involved are very complex and vary both regionally and locally. Therefore a more statistical approach was taken and glaciological expeditions have been sent all over the world to collect information.

A glacier, product of climate and topography, undergoes rapid changes, often of considerable magnitude, in mass and extent. An exact recording of these changes can best be accomplished by accurate mapping of the glacier and its surrounding terrain at suitable time intervals and at appropriate scales. When studied together with meteorological observations, the map series permit a comprehensive analysis of the behavior of the glacier. An accurate map is an indispensable foundation for all scientific and practical investigations in a glaciated area.

Classical field mapping methods have proved to be quite ineffective. An improved technique was provided by photogrammetrists, who have been using terrestrial stereophotogrammetry in glaciological work for the last fifty years. The results of their work are often masterpieces of photogrammetric engineering. However, little effort has been made to apply aerial photogrammetry to detailed glaciological studies, and it is believed that the Salmon Glacier project and the ablation studies in the Salmon Glacier area represent one of the first attempts to use aerial photogrammetry in a systematic way as a surveying method for glaciers.

It is true that aerial photographs of glaciated regions have been taken before and aerial photogrammetric studies have been made, e.g., of Eastern Greenland in 1932 (Lacmann 1937), near Mount Everest in 1933 (Fellowes 1934), in Norway in 1937 (Finsterwalder 1951), and on Mount Rainier, Washington, U.S.A. in 1951 (Hofmann 1953). Glaciated areas have also been photographed in official mapping surveys in several countries. However, these undertakings were not directed specifically towards the detailed surveying of glaciers and practically no glaciological aims were involved, nor were the results significant for glaciology.

*Photogrammetric Research Section, National Research Council, Ottawa, Canada.

In 1956 and 1957 the University of Toronto organized as part of the I.G.Y. program two expeditions to the Salmon Glacier region in British Columbia. These were concerned primarily with seismic and gravimetric measurements of the Salmon and Leduc Glaciers, but also included hydrological and microclimatological investigations (Adkins 1958). The National Research Council participated in the second expedition by sending the author as geodesist-glaciologist to establish a ground control network and to carry out the field work necessary for the aerial photogrammetric survey of the Salmon Glacier, and also to engage in glaciological observations if time permitted. Some of the triangulation points used on the second expedition were set up by Mr. Keith Arnold during the first expedition.

The expedition area

There are several general maps showing the expedition area. These are (a) Iskut River, Canada, Sheet 104B, National Topographic Series, 1:250,000, (b) USGS Bull. 807, Plate 1, 1928, 1:62,500, Topographic Map of the Hyder District, Alaska, and (c) International Boundary between United States and Canada, 1:250,000, Sheet No. 3, 1927.

Salmon Glacier lies in the Coast Mountains, which occupy a strip 150 to 200 km. wide along the Pacific coast of Alaska and British Columbia. This range terminates in the north in the St. Elias Mountains, which rise in Mt. Logan to a height of 6050 m. (all heights refer to mean sea-level, unless otherwise specified), and continue south in the U.S.A. as the Cascade Ranges, whose average height is about 2300 m. with volcanic peaks (Mt. Rainier) up to 4400 m. (Fig. 1).

The Salmon Glacier region lies in the central lower section of the Coast Mountains along the Alaska-Canada boundary at the southern end of the "Panhandle", the 900-km. long coastal strip of Alaska. The nearest settlements are Stewart, B.C., and Hyder, Alaska, both within 20 km. of the glacier.

The Coast Mountains are not continuous but consist of an intricate system of small mountain groups and chains. The geological composition of the range is complex and the chief types of rock are granite, pegmatite, and slate.

The peak areas are heavily glaciated, and the snow line lies between 1400 and 1700 m. depending on exposure. Valley glaciers attaining lengths of 20 to 30 km. flow from the large accumulation areas, sometimes forming networks of ice streams. Valley floors at altitudes between sea-level and about 500 m. are buried under glacial or glacio-fluvial till.

The lower slopes of the mountains are covered by a dense primeval forest, mostly coniferous. The timber line lies between approximately 500 and 600 m., although isolated wooded areas occur on suitable, relatively flat terrain to about 900 m. Above the timber line lies a belt of scrub that merges into a zone of alpine tundra vegetation at about 1100 m., where Ericaceae, mosses, and lichens are found and even juniper bushes occur in favourable spots.

Field survey

From the start the emphasis in field work was placed on securing a dense and accurate ground control network to guarantee the required accuracy for the photogrammetric processing of the photographs. Furthermore, it was decided that all control points were to be set up so that they would be distinctly visible in the aerial photographs and at the same time would be as durable as possible so that they could be used in subsequent periodic surveys. The relative flying heights were fixed at 2100 to 3000 m., so that a mean elevation error in the photogrammetrically drawn contour lines would not exceed 50-70 cm. This meant that the vertical control points had to be accurate to ±10 cm. Since an inaccuracy in distance measurement introduces an appreciable error in height calculation when steep lines of sight have to be used, the accuracy of the horizontal angular measurement had to be carefully specified. Taking into account the expected conditions, the accuracy requirements for the observation of horizontal angles were determined from the formula for trigonometric height measurement:

$$\Delta h = s \tan\alpha + i - z + \left(\frac{1-k}{2r}\right) s^2, \qquad (1)$$

where s = the distance between two points,
i = the height of the instrument above the station,
z = the height of the signal above the point observed,
α = the vertical angle,
r = the radius of the earth,
k = the refraction coefficient.

All triangulation observations were carried out with a Wild T-2 theodolite, which gives under the field conditions encountered an accuracy of ±2 seconds for the horizontal angles. The extreme difference in height should not exceed 2000 m. and the average length of a side should range between 3 and 5 km. Differentiation of formula (1) gives

$$d(\Delta h) = ds \tan\alpha + \frac{s d\alpha}{\cos^2\alpha} + R + di - dz. \qquad (2)$$

Errors di and dz in the instrument and signal heights were easily kept within a few millimeters and were therefore not considered. R, the error due to refraction, cannot be determined or estimated in a practical way, but it can become very large as it increases with the square of the distance. The fact that lines of sight near the ground do not occur frequently in high mountains favours the results. Good results can be obtained by observing the vertical angles from both ends of a line simultaneously, but this procedure is not practical on expeditions of this kind. However, the vertical angle of nearly all triangulation lines was measured in both directions, but at different times. Disregarding the error R for the present analysis, the following expression remains:

$$d(\Delta h) = ds \tan\alpha + s d\alpha/\cos^2\alpha. \qquad (3)$$

By assuming that $d\alpha = \pm 2$ seconds, as already indicated above, and substituting other quantities: $\triangle h = 2000$ m., $s = 3000$ m., $\alpha = 34°$, and $d(\triangle h) = 10$ cm., the error in distance ds would amount to about 9 cm. This limit of error for the length defines an error of ± 5 cm. in the coordinates.

When it is supposed that every new point is determined by intersection, the following expression can be derived from Fig. 2 for an estimate of the error:

$$m = s d\phi \cos \frac{\gamma}{2} \tag{4}$$

when $m = 5$ cm., $\gamma = 40°$, and $s = 5$ km., then $d\phi \approx 2.2$ seconds.

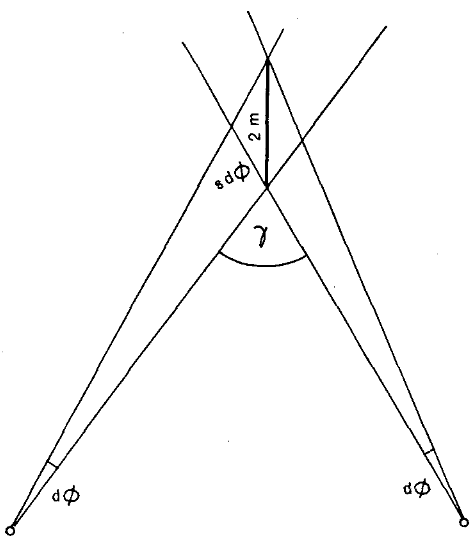


Fig. 2. Derivation of error in length at intersection.

Since these error limits practically demand maximum accuracy of observations under the conditions assumed, particular attention was paid to pointing accuracy and to the types of signals, cairns, and pyramids used in the triangulation net. Whereas aerial surveying requires large flat markers, signals used in triangulation must be vertical, such as cairns, etc., and they must be of a good height. It is desirable to erect the signals so that the points can be occupied and eccentric observations avoided. This permits checking the closure errors in the field and assessing the quality of basic field work on the spot. The best signals were tripods about 2.10 to 2.50 m. high with a yellow flag mounted on the top. As second choice, cairns were erected and painted yellow for easier detection. Quite frequently there was no choice but to set up separate triangulation and photogrammetric control points close to each other. Since cairns are rather difficult to identify in aerial photographs, a circle of flat yellow-painted stones was placed around the cairn. Yellow paint seemed to give best results for both photogrammetric and field surveying.

The size of the control-point targets depends on the scale of the aerial photographs and the contrast between the target and the surrounding terrain. For the Salmon Glacier project 60 × 60 cm. Masonite targets were used, painted with flat white on one side and black on the other. With a photo-scale of 1:14,000 (relative flying height 2200 m.) these targets should produce an image of 0.04 mm. diameter if the geometrical relationship only is considered. Out of 21 targets laid on a dark rocky background 19 were located with certainty on the photographs, although not without difficulty and occasionally only after comparison with pictures from lower flights (1:6500 at 1040 m.). Of 30 targets laid on snow or ice black side up none were located, even on low altitude photographs, because of the halation effect of the strongly reflective surrounding area.

Signals had to be erected over the entire triangulation network before observations were carried out to assure a high accuracy of angular measurements. This is not always possible on high mountain expeditions because of limitations imposed by high altitude and rugged terrain, but at Salmon Glacier no such difficulties were encountered.

The triangulation net was designed to conform to the shape of the glacier (see Fig. 3 and the map). In selecting the triangulation points care

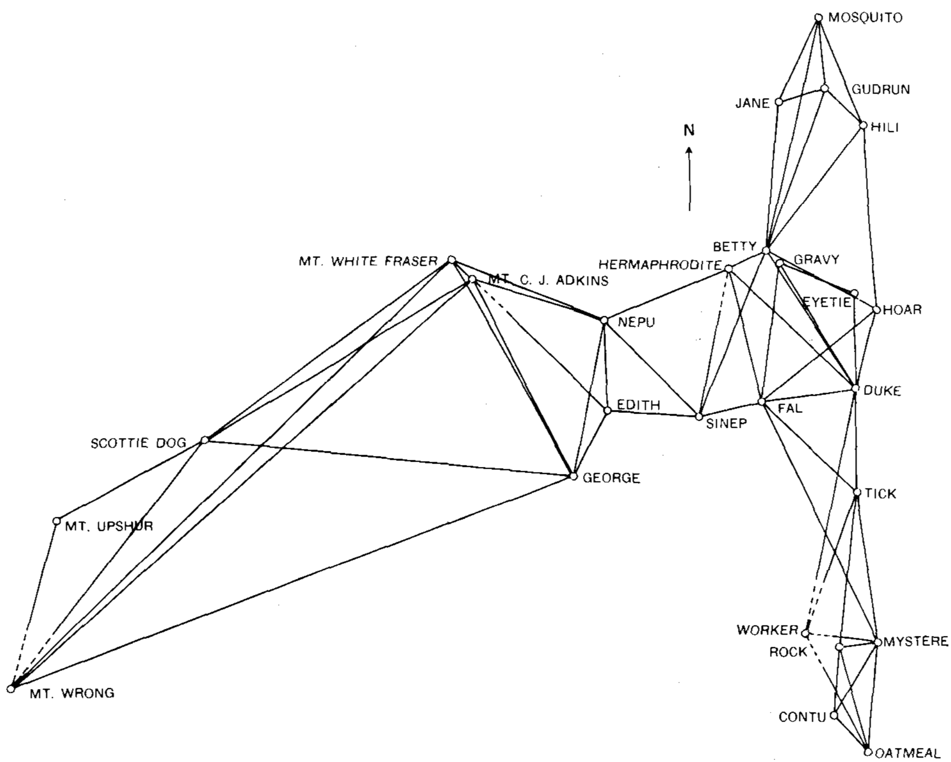


Fig. 3. Triangulation net for Salmon Glacier.

was taken to ensure that at least three triangulation stations could be seen from most of the points within the glacier area. If necessary new points could then be determined by resection.

The photographed region contains several international boundary points and two triangulation points of the British Columbia Topographical Survey. However, since it was doubtful whether these could be located easily and used without extensive local triangulation operations, two base lines were established and measured. Both are in the southern part of the network and showed good agreement with each other and with the available fixed points.

The triangulation net consists of 32 stations, including two B.C. Topographical Survey points, four points of an additional network permitting an extension of the triangulation to the Chickamin Glacier, four base points (only two of which were permanently established) and three secondary points, one of which could not be occupied because the snow bridge leading to the point had melted in the meantime.

Fifty-four additional control points were tied into this system. Thirty of these were situated on the glacier and were determined by resection. The required measurements were carried out on the day of the photo flight to prevent errors in the coordinates and heights caused by glacier movement and ablation. Attractive as this method of determining control points on the glacier may seem, it proved unsuitable in practice. Since the weather, and hence the time of the flight, could not be predicted in advance, the survey parties were compelled to be on constant watch and this involved a considerable loss of time. In this project all 30 points established on snow or ice were useless for plotting purposes.

Despite the good triangulation results (mean errors below 1.5 seconds at individual stations), the mean closure error in triangles amounted to ± 8 seconds. In the main this is caused by centering errors, as an eccentricity of 5 cm. is sufficient to cause an angular error of 10 seconds for a distance of 1 km.

The triangulation net was computed in a local system, with the origin at 56° 00′ N. and 130° 15′ W. (see also Fig. 5). The net was divided into three parts that were adjusted by the method of least squares and then linked together. The additional net was tied in by single-point adjustment. The errors resulting from the adjustment are shown in Table 1 for individual parts of the nets.

Altitude measurements were adjusted by an iterative approximation. The average error of closure of a loop was 9 cm.; the extreme values were 2 and 41 cm. The mean square error of an adjusted altitude point was $\pm$ 11 cm. A list giving full details of all triangulation points can be supplied by the author.

Photogrammetric operations

(A) *Aerial photogrammetry*

Aerial photogrammetry was chosen as the actual surveying and mapping method. Glaciological mapping requires greater accuracy in altitude and horizontal position than regular topographical mapping since it is necessary to determine minute changes of the glacier and to plot certain features with dimensions of the order of a few metres. The fundamental question of picture and mapping scale must be solved accordingly.

Experience of European centres that have carried out glaciological studies in Asia, Africa, South America, and recently in the U.S.A. has shown that scales smaller than 1:25,000 as the publication scale should not be used. The most useful scales have been found to be 1:10,000 and 1:12,500. A scale of 1: 5,000 is rather costly, but it permits a very detailed presentation of recessional moraines, terraces, and other glacial features.

TABLE 1.

	South net	*Summit net*	*Central net*
Mean error of one direction	±2.6″	±4.0″	±3.0″
Average side length (km.)	2.72	3.0	3.32
Mean coordinate error (cm.)	±5.0	±8.0	±7.0

A mean altitude error of 60 cm. was aimed at for the contours. This can be maintained by choosing a relative flying height not exceeding 2500 m. The relative flying height is the crucial factor in aerial photography over mountainous regions since it is impossible to maintain it throughout a project. It determines the number and the pattern of photographic flights. If there are no sharp bends in a valley, the line of flight can be laid out along the valley axis, and then the surrounding mountain slopes will not interfere seriously with the planned flight. If winding valley systems prevail the flight line must be broken accordingly or even careful consideration must be given to the use of terrestrial photogrammetry.

The gradient of a glacier frequently makes it necessary to break up the lines of flight by changing absolute flying heights to keep relative flying heights within acceptable limits and to ensure that the whole width of the glacier is recorded on the pictures. It should be remembered that a sufficiently wide strip of terrain on both sides of the glacier must be included.

Because of the T-shape of the Salmon Glacier two principal flight lines were planned. The north-south line began at the tip of the Salmon Glacier and followed the valley to the tongue of Berendon Glacier. The east-west line extended from the central bend to Mt. Upshur. In addition to these continuous flights, photographs were also made at half the former flying heights carried out in steps to keep relative flying height and picture scale within acceptable limits. The data on individual flights are given in Table 2.

The photographs were taken on August 14, 1957, with a Fairchild F-224 camera with a Metrogon lens supplied by the R.C.A.F. The flights were carried out in an Anson aircraft by the British Columbia Department

TABLE 2.

Flight number	*Picture number*	*Absolute flying height m.*	*Altitude of terrain m.*	*Range of flying height above ground m.*	*Altitude accuracy (0.25°/oo of flying height) cm.*	*Range of picture scale*
1	1- 32	3960	950-1600	2360-3010	60-75	1:15,000-1:19,500
2	33- 54	2500	1180-1520	980-1320	25-30	5700- 8600
3	55- 91	2200	950-1330	870-1250	20-30	5600- 8100
4	92-122	3200	150- 950	2250-3050	55-75	14,500- 20,000
5	123-170	2010	650- 950	1060-1360	25-35	6900- 8800
6	171-209	1710	150- 870	840-1560	20-40	5500- 10,000
7	210-214	1710	200- 450	1260-1510	30-40	8200- 9800

of Lands and Forests. The F-224 camera is considered obsolete, and a modern camera fitted with one of the newest lenses would have produced photographs of superior quality. Previous photographs of the Salmon Glacier region were taken with the same camera type. Basic flight information is contained in Table 3.

TABLE 3.

Date	*Flying height*	*Scale*
26 Sept., 1942	6100 m.	obliques
Sept., 1949	6100 m.	1:40,000
Aug., 1956	6100 m.	1:40,000

(B) *Terrestrial photogrammetry*

Terrestrial photogrammetry has been the only topographical surveying method employed on glaciological expeditions so far. It has been used successfully for many years in the high mountain ranges of Europe, Asia, South America, and in the polar regions (Finsterwalder 1932; Hofmann 1955, 1957; Colcord 1957; Marussi 1957; Hillebrand 1954; Finsterwalder and Schneider 1958). Terrestrial photogrammetry permits the surveying of the most difficult terrain with a minimum outlay for personnel and equipment (Colcord 1957). With suitable instruments it is usually possible to take photogrammetric pictures and to determine the control points simultaneously. By the use of close-range base lines, areas of special interest can be plotted in any desired scale.

On the Salmon Glacier, since aerial photogrammetry was chosen as the principal surveying method, terrestrial photogrammetric work was confined to four photographic base lines and three velocity base lines (Pillewizer 1938 and Finsterwalder 1931). The snout of the glacier was photographed in June and again in August. A comparison of these photographs would have determined the ablation from June to August, but this was not done because of lack of time. Three velocity base lines were laid out at Mystère, Tick, and Mineral Gulch.

Since terrestrial photogrammetry has been dealt with extensively as a surveying method (Zeller 1937, Finsterwalder 1939), only its use for establishing velocity profiles (Colcord 1957) will be discussed in this paper. This use does not require any traverse of the glacier surface and, unlike all other techniques, permits the measuring of the rate of flow at any point.

A base line parallel to the direction of flow of the glacier is laid out with the camera axis perpendicular to it (see Fig. 4). A pair of pictures is taken of the area to be studied. The time of the first picture A_1 is noted

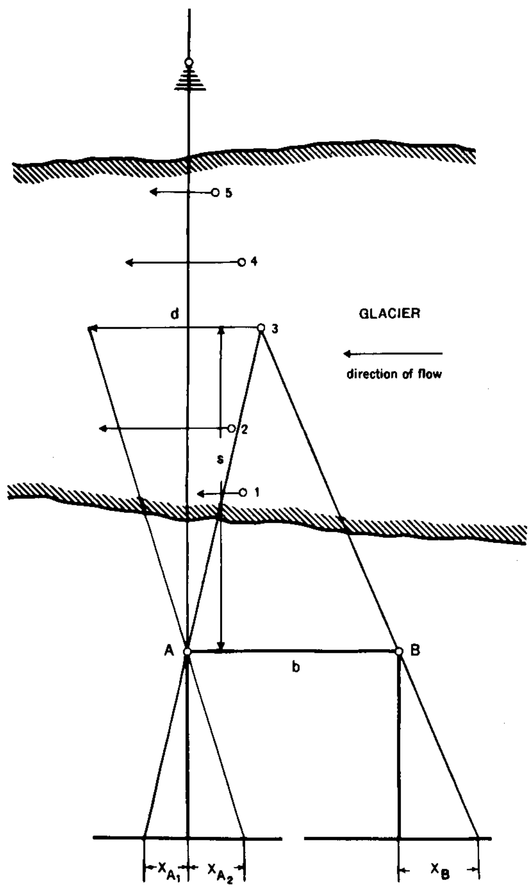


Fig. 4. Method of establishing velocity profiles by terrestial photogrammetry.

as well as the height of the instrument (height of camera lens above the station) and pertinent photographic data (tilt, rotation). Four to fourteen days later another photograph (left) is taken with exactly the same photographic data. On picture pair A_1B_1 salient points (1, 2, 3 . . . n) near the centre of picture A_1 are located and their x-parallaxes $x_{A_1} - x_{B_1}$ are measured. Then pictures A_1 and A_2 are compared and the horizontal and vertical components of glacier motion $x_{A_1} - x_{A_2}$ and $z_{A_1} - z_{A_2}$ are measured. With formulas (5) to (9) the rate of flow d_H and the difference in elevation d_V can be calculated.

$$s = \frac{bf}{(x_{A_1} - x_{B_1})} \tag{5}$$

$$d_H = \frac{(x_{A_1} - x_{A_2})}{f} s \tag{6}$$

$$d_V = \frac{(z_{A_1} - z_{A_2})}{f} s \tag{7}$$

where f = focal length of camera,

$$v = \frac{d_H}{t} \text{ m/day or} \tag{8}$$

$$v = 365 \frac{d_H}{t} \text{ m/year} \tag{9}$$

(In formula (8) the time interval, t, is expressed in days between successive photographs. Since the velocity of glacier flow can vary greatly throughout the year, extrapolations may give wrong results).

The difference in elevation of a given point is composed of a component due to the forward motion and the slope of the glacier, and of another component due to the ablation.

$$d_V = v\ t\ \tan\alpha + A \tag{10}$$

where α = slope of the glacier
A = height difference caused by melting of ice.

In order to obtain reliable results, the slope of the glacier at a given point must be measured very accurately. In consequence, formula (10) is seldom used.

Stereocomparators are the most suitable instruments for this work, although even a simple parallax-bar will suffice.

In laying out velocity profiles it is important to ensure that the entire surface of the glacier is visible from each camera station. To maintain precisely the orientation of photographs taken from Station A aim is generally taken on a distinct point on firm ground on the opposite side of the glacier. Points A and B should be properly marked in order to ensure an exact reoccupation. Comparison of both pictures A_1 and A_2 is facilitated if a narrow strip of solid ground or a few boulders are visible in the foreground of photographs A. The length of the base will of course depend on the width of the glacier. For a width of 1000 m. a base of approximately 60 m. will give the distance to $\pm$ 1.0 m. The time interval between photographs A_1 and A_2 must be chosen according to the expected velocity, but it should not be too long, for ablation will change the glacier surface so much that it will be difficult to locate the corresponding points. Four to fourteen days is an adequate time interval, but on slow moving glaciers even 4 to 8 weeks gave good results.

Photogrammetric evaluation

A Wild Autograph A-7 and a Kelsh Plotter were used for the plotting of the Salmon Glacier photographs. The plotting began with an aerial triangulation of both high altitude strips to make the ground control network denser by additional photogrammetric control points. This work and plotting of some parts of the Salmon and Berendon Glaciers was carried out on the A-7. The main part was mapped on a Kelsh Plotter, with a 500-m. wide gap filled in on Multiplex. A sketch map (Fig. 5) shows the areas mapped on various plotters (see also key diagram on map in pocket).

Plotting was done at a scale of 1: 10,000, with the exception of the south snout plotted at 1: 5,000 and of the outwash plain in front of the snout

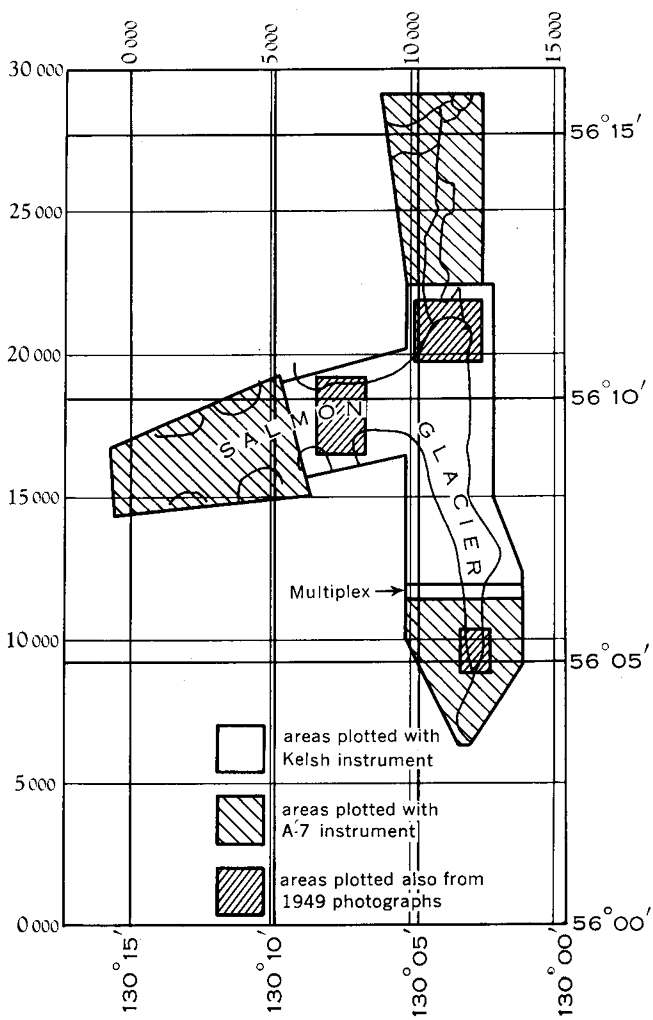


Fig. 5. Sketch map showing how areas were plotted.

plotted at 1:2,500. Because of the steep slopes a 20-m. contour interval was used for solid ground and a 10-m. interval for the surface of the glacier itself. Special attention was given to glacio-morphological features such as moraines, terraces, debris paths, and the character of the glacier surface. The publication scale of the map is 1:25,000.

The A-7 plots of the Salmon and Berendon snouts contained many topographical details. The large, flat, snow-covered glacier areas in the upper part of the central tongue made the drawing of contour lines very difficult, and some could be completed only by interpolation between spot elevations. However, as soon as the serrated firn became visible the contour lines could be drawn with the same accuracy as on solid terrain.

The entire stereogram could not be plotted on the Kelsh Plotter because of the sharp drop in brightness at the edges. The difficulties were increased by the steepness of the valley slopes. The relative difference in height between the glacier and the terrain at the edge of the picture was sometimes as much as 50 per cent of the relative flying height.

Plots were carried out also from photographs taken in 1949, and thus changes that occurred from 1949 to 1957 were determined for the area of the south snout, the north snout, and a part of the central tongue. Control points were selected from the 1957 photographs and transferred to the 1949 photographs. Since the 1949 flying height was 6100 m., the plots of the 1949 photographs are not as accurate as those of 1957, and a mean height error in the contour lines of approximately ±1.50 m. must be expected. This was probably the first time a precise quantitative study was made of the recession of a North American glacier.

Glaciological studies

(A) *General conditions (see Figs. 1 and 6)*

In the Salmon Glacier region the Coastal Ranges are deeply channeled and the crest patterns of the individual chains and mountain groups very complex. The group from which the Salmon Glacier flows has the shape of a reversed "L" and is bounded on the west by the valleys of the Unuk and Leduc rivers and on the east by the Salmon and Bowser rivers. It is separated from the mountain ranges to the south by the Chickamin River valley and by Texas Creek Gorge which leads into the Salmon River valley. In the north it terminates in the flats of the Bell-Irvin River.

The Salmon River valley contains the tongue of Salmon Glacier and continues to the north across Summit Lake to the Bowser River valley, for which Salmon Glacier constitutes the water shed. The same conditions apply for the Leduc and Unuk Rivers, where the ice mass of the Leduc Glacier and Glacier VI occupies the valleys. From this ice mass the South Unuk River flows north and the Leduc River south.

Within these boundaries are three large névés: a northern one around Mt. Knipple, a central one, and a southern one around Mt. John Jay. The latter covers an area of about 30 sq. km. of moderately waved firn plateau and feeds about 10 small glaciers terminating at altitudes between 1000 and 1200 m. The central accumulation area is a large valley about 30 km. long and 2 to 3 km. wide between the Mt. Pearson chain in the west and the Mt. White Fraser and Berendon chain in the east. This "large firn valley" is the accumulation region of seven large valley glaciers, the largest being the Frank Mackie Glacier III, the Salmon Glacier IV, and Glacier VI. The northern accumulation region is similar to the central one, but is not quite as large.

Fig. 6. Mosaic of Salmon Glacier area from aerial photographs taken in 1956. Compare with Fig. 1.

(B) *The large firn valley (see Fig. 7).*

This includes the actual firn valley extending north for 25 km. from High Camp (1593 m.) and two smaller valleys between Scottie Dog and Mt. Upshur and between Mt. Upshur and Mt. Wrong. The last two feed the Chickamin Glacier. From High Camp the terrain ascends at first gently and then somewhat more steeply towards the north, reaching its highest point about 6 km. away somewhere north of Mt. White Fraser at about 1850 m. From there it descends at a slope of 4.7 per cent towards the north and forms the Frank Mackie Glacier. There is a steeper section between Mt. Berendon and Mt. Pearson. Up to that point the east side partly melts away, owing to the increased exposure in that vicinity. Where the snow cover remains intact no crevasses are discernible. However, at about 4.5 and at 5.5 km. north of High Camp there are two groups of very large crevasses that appear on all available aerial photographs, including the obliques taken in 1942.

Fig. 7. The large firn valley photographed from the north peak of Mt. Jefferson Coolidge on June 2, 1957. The peaks are, from left to right: Scottie Dog, Mt. Pearson (pyramidal peak), névé, Mt. Berendon, and Mt. White Fraser (2325.7 m.). Névé in middle background is 30 km. away. Note the big crevasses that were already observed on the oblique aerial photographs of 1942.

Unfortunately, no reliable precipitation data are available. On June 10, 1957, in a trench being dug about 100 m. north of High Camp, a layer of dirt was reached at a depth of 4.70 m., which may indicate the thickness of the snow cover of the previous year. Density measurements in this trench gave a mean value of 0.54 g./cm.^{3}, from which a precipitation of about 2540 mm. of water equivalent at an altitude of 1590 m. was calculated. The meteorological station at Premier, about 18 km. east of the camp at an altitude of only 300 m. above mean sea-level recorded 2210 mm. of precipitation per year. The difference can easily be attributed to differences in altitude and exposure.

These values lie well within the limits expected for the Alaska coast region, but they do seem rather low for the extent of glaciation in the Salmon Glacier area, with its relatively low altitude and warm summer weather.

The accumulation areas of individual glaciers could be defined only very roughly. If the summit of the pass is assumed to be also the ice shed, approximately 60 per cent of the area of the firn valley would be contributory to the Frank Mackie Glacier and the rest to the Chickamin Glacier. Only a very small part appears to feed the Salmon Glacier. About 300 m. west of High Camp part of the firn area begins to descend very definitely towards the south-west and thus defines the reservoir region of the Chickamin Glacier, and another 1500 m. farther crevasses clearly indicate movement towards the Chickamin Glacier.

On the glaciers the snow line shows a very uniform height between 1300 and 1350 m. Only steep, small glaciers with southern exposures melt off at higher altitudes, partly because of loss of snow through avalanches. The snow line over rocky terrain is 200 to 280 m. higher. Here the steepness of the ground together with the exposure produces a greater variation in the snow line, but 1550 m. seems to be the representative height. In protected areas patches of snow were found 150 m. above mean sea-level as late as August 20.

(C) *Salmon Glacier*

After emerging from the large firn valley the Salmon Glacier first flows 12 km. eastward down a valley averaging 2.5 km. in width. When it reaches the Salmon River valley it divides into two ice streams (see Fig. 8). One curves towards the north and discharges another 3 km. farther into Summit Lake (826 m.); the other turns southward and terminates after about 9 km. at an altitude of 160 m. above sea-level. For further positions the distances in kilometres are counted from High Camp (see Fig. 1).

Starting at High Camp the slope of the glacier is as follows. The first part with a gradient of about 8 per cent extends over a distance of 1 km. and blends into a terrace-like flat area, which terminates at kilometre 2. From there the gradient increases to 12 per cent, and at a distance of 3 km. from the camp the second flat area begins and extends to kilometre 5.5, where the slope changes to 6 per cent and continues interrupted by only a short flat step to the bend at kilometre 9.0. In this section Salmon Glacier receives two small glaciers between kilometre 3 and kilometre 5 and a larger tributary glacier from the Mt. White Fraser system at kilometre 6.5 (left side of map). Two other tributary glaciers come from the south, one at kilometre 4 from a snow field that also feeds Texas Glacier, and the other at kilometre 8.2 from a snow field west of Mt. Bayard. At kilometre 11 the glacier splits into a north and a south stream. After the ice fall at Fal (kilometre 11) the south tongue flows at a moderate slope of 4.7 per cent with relatively few crevasses as far as the glacier cataract near Tick, which has a gradient of 17 per cent. From kilometre 16 the gradient decreases to 5 per cent because of the constriction of the glacier bed from 1380 m. at kilometre 17.6 to 650 m. at kilometre 19.1. From here the gradient of 13.5 per cent remains steady as far as the snout at kilometre 20.5. At kilometre 17.6 the south snout at one time received another tributary, the Munro Glacier, which has receded to such an extent that it no longer reaches the Salmon Glacier. However, the 100-metre long lobe-shaped extension of Salmon Glacier still remains in Munro Canyon.

A characteristic of the central tongue of the Salmon Glacier (between kilometres 6 and 11) is the medial moraines that mark the boundary between the tributary glaciers from the Mt. Bayard and Mt. White Fraser area and the main glacier stream. The glaciers carry relatively little debris, because the accumulation areas are not bounded by many steep rocky slopes that could deposit gravel and rocks on the névé. The tributary glaciers from the Mt. White Fraser region are an exception in that these glaciers are fed chiefly by snow and ice avalanches from steep rocky slopes, so that accumulation of debris is heavier on these tributary glaciers and the result is a marked outcropping of moraines (kilometre 11 to 13 north). The right-hand medial moraine reaches considerable dimensions only in the central part of the south tongue (from kilometre 15 southward).

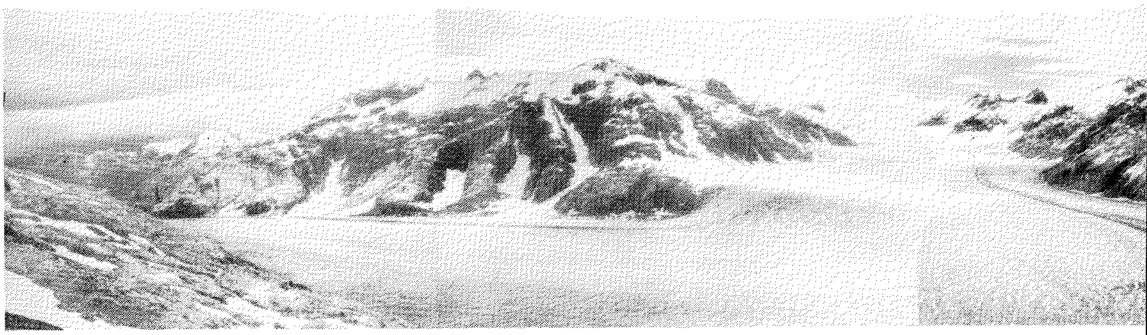
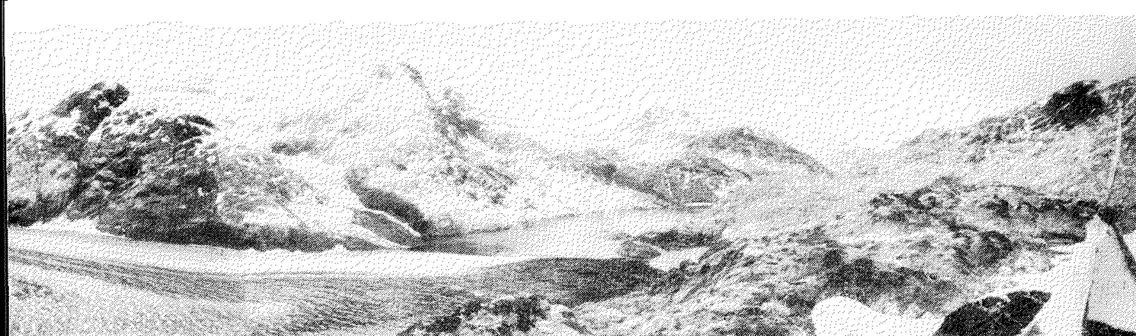


Fig. 8. Panorama of Salmon Glacier from Hoar, taken on July 30, 1957, on infrared film. The field of the right are the north tongue and Summit Lake. Signal Hoar can be seen in the lower right-hand peninsula in Summit Lake indicates the extension of the 1920 glaciation. Note that on

Salmon Glacier with its tributaries occupies the east-west valley which joins the north-south Salmon valley at kilometre 11. At kilometre 10 the glacier has a width of 1580 m., made up of a right-hand ice stream 240 m. wide, a main ice stream 990 m. wide, and a left-hand ice stream, 350 m. wide. The right-hand ice stream is made up of Bayard Glacier (joining at kilometre 8.2) and two minor small glaciers. Since the main ice flow is completely devoid of debris, individual components cannot be distinguished. At the very tip (kilometre 19.2) there is a fairly large medial moraine whose origin could not be definitely established. Judging from the debris it cannot be a ground moraine nor till from a sub-glacial rock obstacle as there is no evidence of polishing or smoothing. The single rock pieces appear to have been freshly broken from a cliff and brought down by the glacier in contact with ice only, thus preserving their sharp edges. The fact that they have melted out so far down indicates that the debris had accumulated in the névé, and the writer suggests that its origin is the bergschrund on the west slope of Mt. White Fraser.

The left-hand ice flow is made up of the White Fraser Glacier and several minor components that are not easy to distinguish from each other because the connecting links between the different medial moraines are covered with snow the whole year round.

From kilometre 11, where the valley widens, the main ice stream, representing the actual Salmon Glacier, continues to move eastward for another kilometre, then makes a 90-degree turn southward. The medial moraines between the main ice stream and the left-hand components follow an S-shaped path, and the left-hand components of the main ice stream follow this motion towards the north for about 500 m., after which they turn abruptly southward. The right-hand ice stream, formed mainly by the Bayard Glacier, makes its turn to the south without showing any special characteristics. It widens out on its bend at the icefall near the triangulation point Fal to 500 m., owing to relaxation of the pressure



view is about 190°. The central tongue divides in the foreground, to the left is the south tongue, and to
corner. To the left of Summit Lake is Augus Glacier surmounted by Augus Mountain. The small
nfrared photographs the bright barren belts show up dark and green vegetation white.

from the main ice flow.

The main ice stream forms a bulb in the bend zone, from which dirt fans flow off to the north and south. At Mineral Gulch the northward motion is clearly established as well as the southward one 500 m. to the south of Eyetie. The north snout, derived mainly from the White Fraser Glacier, ends in Summit Lake, where its wedge-shaped ice front rises up to 35 m. above the water level. On the eastern flank of the wedge two brooks have melted a channel about 100 m. wide between the rock and the glacier, which are now connected only by an ice bridge 120 m. wide. From photographic evidence it is clear that this channel has developed during the last eight years.

Only the main stream of the Salmon Glacier reaches the southern tip at kilometre 20.5, because the right-hand branch is squeezed out shortly before reaching the 18.0-km. mark. The medial moraine formed at kilometre 17.0, a ridge 8 m. high and 200 m. wide, is gradually pushed closer to the right-hand wall of the valley. By the time it reaches the snout it is only 15 m. wide and lies just beside the glacier gate, which was 40 m. wide and 15 m. high in mid-August. Stationary ice masses cover an area of about 500 m. by 250 m. just in front of the actual snout. They were created when the former snout was covered by the debris from the medial moraine, whose outcropping began at kilometre 19.2. On the 1949 photographs this area is part of the active snout, and is covered by a triangular dirt fan. Melting from radiation and erosion by extensive glacier streams creates a complex system of islands and pools, which is constantly changing with the melting process.

The velocity of the glacier was determined by three profiles at kilometres 18.9 (Mystère), 15.0 (Tick), and 13.4 north (Mineral Gulch) (see Fig. 9 and Tables 4-6). The rates of flow, measured at intervals of 69, 22 and 21 days, were extrapolated to one year. The Tick profile gave the maximum velocity of 150 m. per year and shows a parabolic velocity distribution

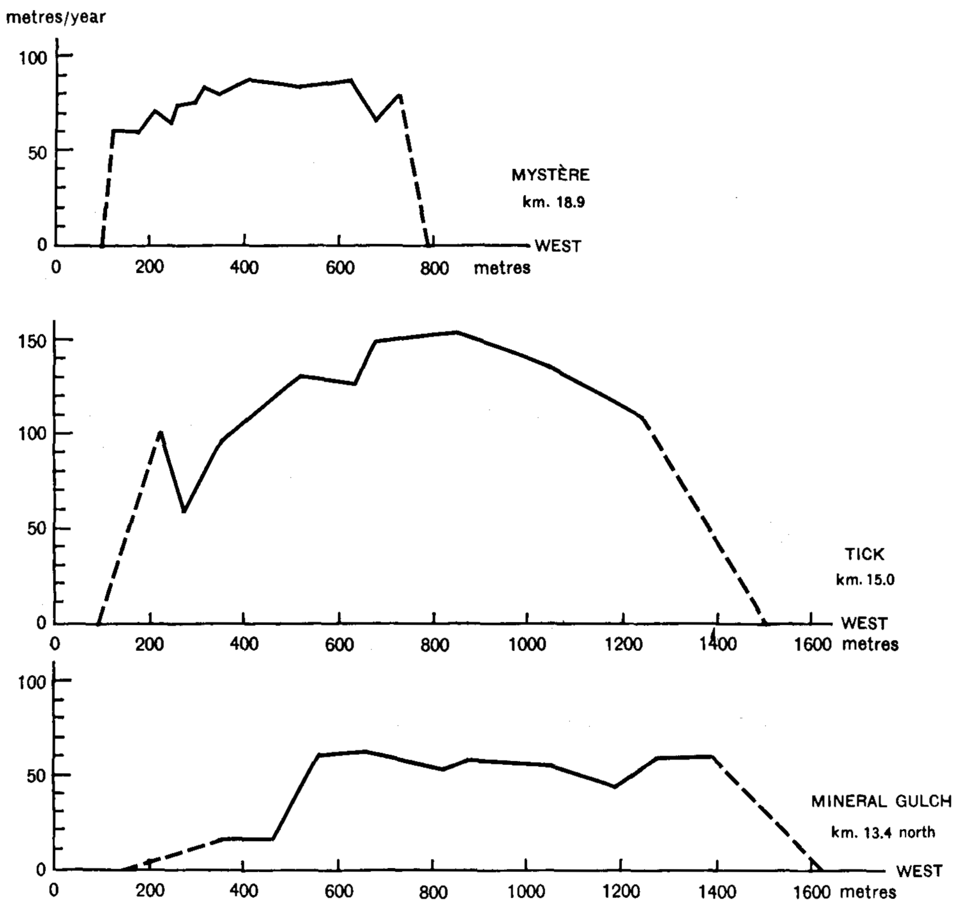


Fig. 9. Three velocity profiles of Salmon Glacier.

over the profile. The high values are explained by an ice fall close by. The Mystère profile, on the other hand, gives the appearance of a block-motion, which is quite possible because at this point the glacier, after the stagnant basin between kilometres 16 and 18.5, is being forced through a gap where the valley narrows to half its former width.

Tables 4-6. Results of the velocity base lines.

Table 4. Base line Mystère (kilometre 18.9).

Distance from glacier margin m.	*Ice flow during observation period (June 15-Aug. 13)* m.	*Velocity* m./day	m./year
36	11.1	0.16	59.3
52	11.1	0.16	59.3
83	11.1	0.16	59.3
113	12.8	0.19	68.4
126	13.4	0.20	71.6
160	12.2	0.18	65.2
176	13.8	0.20	73.8
206	14.0	0.20	74.8
226	15.4	0.23	82.3
256	15.0	0.22	80.2
319	16.3	0.24	87.1
434	15.8	0.23	84.5
536	16.2	0.24	86.6
586	12.2	0.18	65.2
645	15.0	0.22	80.2

Table 5. Base line Tick (kilometre 15.0).

Distance from glacier margin m.	*Ice flow during observation period (July 22-Aug. 17)* m.	*Velocity* m./day	m./year
129	6.0	0.28	102.0
177	3.6	0.17	61.2
181	3.9	0.18	66.3
244	5.3	0.25	90.1
254	5.6	0.26	95.2
328	6.5	0.30	110.5
420	7.5	0.35	127.5
531	7.5	0.35	127.5
580	8.7	0.40	147.9
760	9.0	0.42	153.0
941	7.4	0.34	125.8
1137	5.2	0.24	88.0
1332*	.	.	.

*Point on firm ground on the opposite side of the glacier.

The Mineral Gulch profile clearly shows the slower motion of the ice masses near the edges, where they push up the east-slopes of the Salmon valley and to some extent still share in the rotational motion of the main stream, and the faster motion of the glacier component discharging freely into Summit Lake that is constant over almost the entire profile.

Table 6. Base line Mineral Gulch (kilometre 13.4 north).

Distance from glacier margin m.	*Ice flow during observation period (July 25-Aug. 16)* m.	*Velocity* m./day	m./year
176	0.8	0.04	13.3
226	0.9	0.04	14.9
274	0.9	0.04	14.9
308	0.9	0.04	14.9
418	3.7	0.17	61.4
526	3.8	0.17	63.0
674	3.2	0.15	53.1
718	3.4	0.15	56.4
722	3.4	0.15	56.4
862	3.3	0.15	54.7
902	3.3	0.15	54.7
1038	2.7	0.12	44.8
1126	3.7	0.17	61.4
1233	3.7	0.17	61.4
1472*	.	.	.

*Point on firm ground on the opposite side of the glacier.

There are four morainic mounds in the bend zone. The most prominent one, close to the Mineral Gulch profile, was discernible in the aerial photographs of 1949, and its velocity over the last 8 years could be determined. The velocity decreases towards the edge of the glacier. At distances of 550, 410, and 290 m. from the glacier edge the following velocities were obtained: 44, 31, and 25 m. per year. The total distance covered during the 8-year period was 315, 250, and 200 m. for the same points.

The glaciers of the expedition region are receding at the present time. The conditions are basically the same as in the Alps. There are indications that a glaciation maximum around 1850 was followed by a period of recession, which is still going on. During the nineteen-twenties, however, this recession was interrupted by an advance during which the glacier almost regained its former maximum. After the nineteen-twenties at least two smaller advances, or stagnations, must have occurred, leaving two small moraines. The similarity of conditions in both areas is evident from a comparison of the photographs of the Horn in 1921 and Waxeggkees in 1951 (Finsterwalder 1953) with photographs of glaciers 3 and 4 of the Tide Lake region in 1957 (see Fig. 10). On the Horn and Waxeggkees the lateral moraines of 1850 were practically filled up again in 1921, whereas in 1951 the snouts occupied only about one-tenth of the glacier bed. The picture of the snouts of glaciers 3 and 4 shows the same conditions. Unfortunately, no photograph taken during the nineteen-twenties is available for better evidence.

A characteristic of the glaciers of the expedition region is the barrens that have melted out since the last high point of glaciation and that can be recognized as a bright belt along the tongue extending up into the firn region. The glacier surface has dropped considerably. The vertical extent of these belts is very noticeable on the steep valley slopes (Figs. 11 and 12). At lower altitudes the glacier is surrounded by a coniferous forest whose trees reach heights of 30 m. or so. Then follow zones of dense and intermittent scrub, and finally a zone devoid of vegetation (see Fig. 11). At high locations these vegetation zones are less evident or non-existent. From comparisons with maps of the Boundary Commission from 1903 to 1920, it is concluded that the bare zone was still covered with ice in 1920. The end of the south snout still extended some distance across the border into Alaska and was located at kilometre 22.0. Triangulation

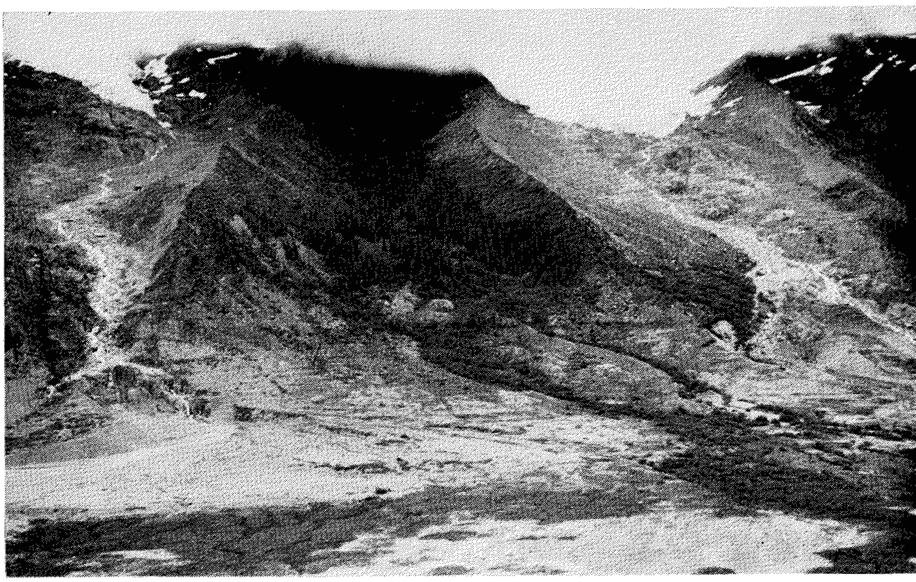


Fig. 10. Snouts of Glacier 3 (left) and Glacier 4 in Tide Lake valley. The big marginal moraines remain from the glaciation maximum around 1850. Trees between the moraines are more than 100 years old. Note minor recessional moraines inside the outermost terminal moraine, and the advance of vegetation. Note also the former shore lines of Tide Lake in mid-picture.

points had been set up around 1905 at kilometre 22.2 (Salmon Glacier north base and Salmon Glacier south base of the Boundary Survey), so this area must have been free of ice at that time. About 1850 the tip of the snout could have reached as far as km. 22.8, because at that point trees whose ages can be estimated as 100 years and older are found on the valley floor (see Fig. 11). There is also a hilly formation that could be a remnant of the terminal moraine from that time.

An accurate picture of the expansion of the glacier is given by the shore line of Summit Lake. Here the data of the Boundary Commission Chart coincide exactly with the recognizable barren (see Figs. 8 and 12). In 1920 the ice front was at the narrowest part of Summit Lake. On our kilometre scale this would be kilometre 15.4 north. The Augus Glacier was then a tributary of the Salmon Glacier and shared a common path with it for about 450 m. This strengthens the assumption that the bare strip of terrain shows the extent of glaciation in 1920. At that time the Salmon Glacier was still holding back Daisy Lake, about 900 m. long and 250 m. wide and 1.8 km. north of point Eyetie. From the shore line a water level of 890 m. is assumed. The glacier level of 1850 at the dividing area (about kilometre 11) cannot have been very much higher than that of 1920, since a few horse trails going back to the time of the Gold Rush in the forties of the last century pass within 10 m. of this small glacial lake north of Eyetie (compare also with map).

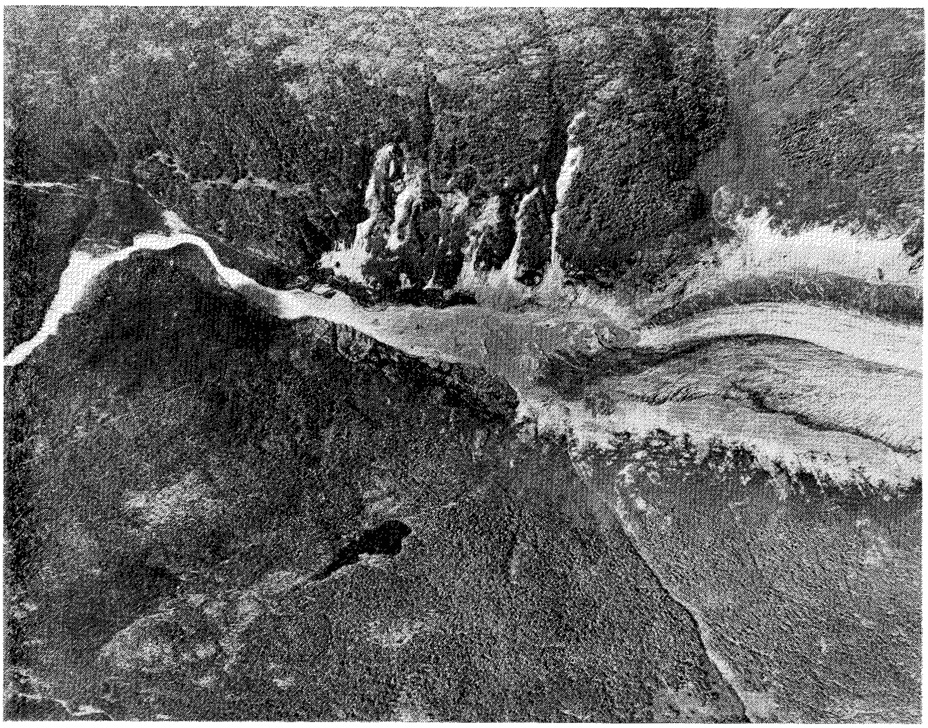


Fig. 11. South terminus of Salmon Glacier in 1957. Note the different vegetation zones. Innermost barren, followed by scattered scrub, dense scrub, and forest. Older trees on valley bottom on the left edge of the picture indicate a possible glaciation maximum of approximately 1850. The cut-line near the left margin is the Canada-Alaska boundary line. An amateur photograph from about 1920 shows the snout still in Alaska. The 1920 snout seems to coincide with the bare rock formation in the left middle ground.

As already stated, the aerial photographs of 1949 could be used for comparative plottings. Three typical glacier regions were selected (see Fig. 5): (a) the south snout (kilometres 19.7 to 21.2), (b) the north snout (kilometre 12.5 north to kilometre 14.3 north), and (c) a part of the central tongue (kilometres 8.5 to 11.2). The annual height losses were determined by Finsterwalder's method (1953). The formulas for this may be given briefly (see Fig. 13) as

$$dh = \frac{\triangle F_1 + \triangle F_2}{F_1 + F_2} \triangle h \qquad (11)$$

$$dV = F_m \, dh \qquad (12)$$

$$\overline{dh} = \frac{dh}{n} \qquad (13)$$

where dh = the loss of height during the observation period,
$\overline{dh}$ = the loss of height for one year,
n = the number of years,
$\triangle h$ = the contour interval,
dV = the loss of volume,
F_1 = $A_2A_3B_3B_2$ = the area at the beginning of the period,
F_2 = $C_1C_2D_2D_1$ = the area at the end of the period,
$\triangle F_1$ = $A_2A_3C_2C_1$ the contour line displacement at the lower limit of the zone,
$\triangle F_2$ = $B_2B_3D_2D_1$ the contour line displacement at the upper limit of the zone,
F_1' = $A_1A_2B_2B_1 + A_3A_4B_4B_3$ the total loss of a zone,
F_1'' = $A_1A_4B_4B_1 = F_1 + F_1'$ the total area at the beginning of the period, and
$F_m = (F_2 + F_1'')/2$.

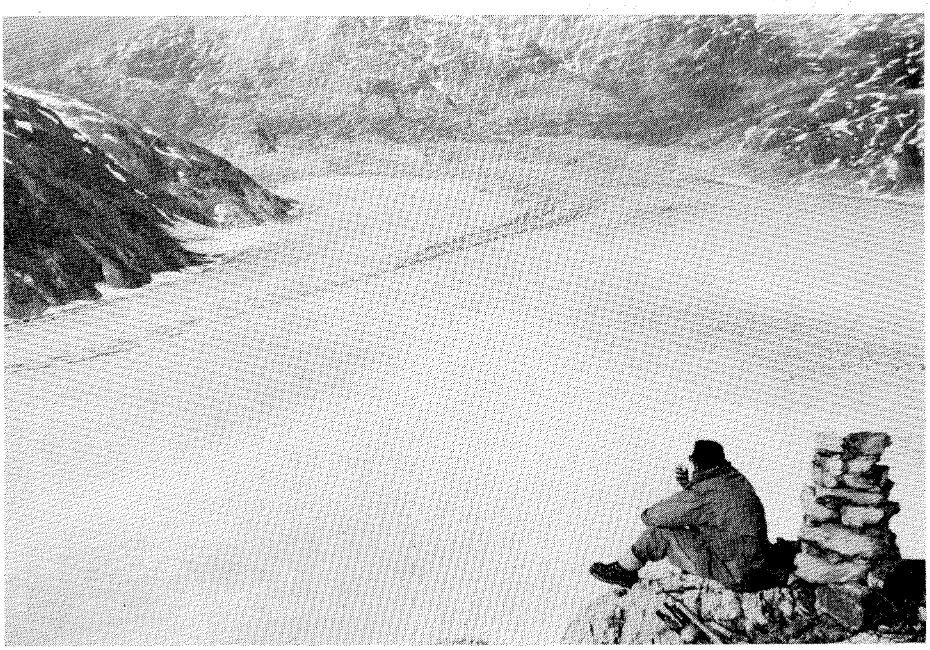


Fig. 12. Dividing area and north snout of Salmon Glacier from triangulation station Sinep (July 29, 1957). The left glacier component widens and forms the north snout discharging into Summit Lake. Note the barren bands along the glacier margin and on the rocky shore of Summit Lake. In the middle ground is the shore line of Daisy Lake, which was dammed up during the high glaciation in the nineteen-twenties.

Tables 7 to 11. Ablation data during the observation period 1949-1957.

Table 7. Salmon glacier south snout

Height zones m.	F_2 1957 ha.	F_1 1949 ha.	F_1' 1949 ha.	F_1'' 1949 ha.	F_m ha.	$\triangle F$ ha.	$\Sigma \triangle F$ ha.	ΣF ha.	dh m.	dV $m.^3 \times 10^6$	$\overline{dh}$ m.	*Height zones* m.
160												160
	10.00*	.	2.15*	2.15*	6.08*		.	10.00*	.	.	.	
180						10.08						180
	3.91	1.36	5.67	7.03	5.47		22.38	5.27	84.60	4.64	10.59	
200						12.30						200
	3.40	3.06	5.21	8.27	5.84		24.78	6.46	76.60	4.47	9.56	
220						12.48						220
	4.46	3.80	4.63	8.43	6.44		25.52	8.26	61.70	3.97	7.71	
240						13.04						240
	5.91	3.68	3.37	7.05	6.48		28.39	9.59	59.20	3.84	7.40	
260						15.35						260
	8.68	4.00	1.89	5.89	7.28		35.40	12.68	55.90	4.06	6.98	
280						20.05						280
	9.30	5.25	2.96	8.21	8.76		44.10	14.55	60.60	5.31	7.56	
300						24.05						300
	9.13	7.55	3.34	10.89	10.01		49.70	16.68	59.60	5.98	7.35	
320						25.65						320
	10.38*	12.03*	.	12.03*	11.20*		49.35*	22.41*	44.00*	4.93*	5.50	
340						23.70*						340
Σ	65.17	40.73	29.22	69.95	67.56	156.70	.	105.90	62.80	37.20	62.65	
Σ*	44.79	28.70	27.07	55.77	50.28	133.00		73.49	65.50	32.27	57.15	
Average									8.19	8.03	8.17	

*Values marked * are not included in Σ*.

Table 8. Salmon glacier north snout.

Height zones m.	F_2 1957 ha.	F_1 1949 ha.	F_1' ha.	F_1'' ha.	F_m ha.	ΔF ha.	$\Sigma\Delta F$ ha.	ΣF ha.	dh m.	dV $m.^3 \times 10^6$	$\overline{dh}$ m.	*Height zones* m.
825						·						825
	·	·	10.73*		·		·	·	·	·	·	
850						19.18						850
	34.47	12.46			23.46		60.75	46.93	25.90	6.075	3.24	
870						41.57						870
	44.75	45.72			45.24		81.96	90.47	18.10	8.196	2.26	
890						40.39						890
	44.19	51.31			47.75		74.03	95.50	15.52	7.403	1.94	
910						33.64						910
	52.81	50.17			51.49		69.38	102.98	13.49	6.938	1.68	
930						35.74						930
Σ	176.22	159.66			167.94				73.01	28.612	9.12	
Average									2.28	2.13	2.28	

*Total losses at the snout. The total losses along the margins are negligible.

Table 9. Salmon glacier central tongue.

Height zones m.	F_2 1957 ha.	F_1 1949 ha.	F_m ha.	ΔF ha.	$\Sigma\Delta F$ ha.	ΣF ha.	dh m.	dV m.$^3 \times 10^6$	$\overline{dh}$ m.	*Height zones* m.
1080				1.12						1080
	121.20	105.58	113.39		17.33	226.78	1.53	1.733	0.19	
1100				16.21						1100
	46.48	55.23	50.86		23.77	101.71	4.66	2.377	0.58	
1120				7.56						1120
	30.89	29.93	30.41		15.96	60.82	5.25	1.596	0.66	
1140				8.40						1140
	47.11	38.67	42.89		25.15	85.78	5.86	2.515	0.73	
1160				16.75						1160
	65.12	69.17	67.14		25.15	134.29	3.74	2.515	0.47	
1180				8.40						1180
1200										1200
Σ	298.58	310.80	304.69	58.44	107.36	609.38	21.04	10.736	2.63	
Average							0.53	0.44	0.53	

Table 10. Bayard glacier (joining area).

Height zones m.	F_2 1957 ha.	F_1 1949 ha.	F_m ha.	ΔF ha.	$\Sigma\Delta F$ ha.	ΣF ha.	dh m.	dV m.$^3 \times 10^6$	$\overline{dh}$ m.	*Height zones* m.
1180				4.52						1180
	6.67	10.20	8.43		5.38	16.87	6.36	0.538	0.80	
1200				0.86						1200
	6.30	5.83	6.06		2.29	12.13	3.77	0.229	0.47	
1220				1.43						1220
	5.68	6.74	6.21		1.68	12.42	2.71	0.168	0.34	
1240				0.25						1240
	11.93	10.05	10.99		2.42	21.98	2.20	0.242	0.27	
1260				2.17						1260
	9.51	9.14	9.32		4.74	18.65	2.54	0.237	0.32	
1270				2.57						1270
Σ	40.09	41.96	41.01	11.80	16.51	82.05	17.58	1.414	2.20	
Average							0.44	0.43	0.44	

Starting from the relation

$$dh = \triangle h \, ds/s \qquad (14)$$

where s is the horizontal distance between two successive contour lines and ds the contour line displacement, the formulas above are easily derived by geometrical considerations or by integration. The values could also be obtained by a point by point method using eq. (14), but many points would have to be determined to eliminate accidental errors. Instead, the areas mentioned are planimetered on suitable contour maps and the calculation is then carried out with these values. Equation (14) constitutes a convenient test. The results are shown in Tables 7 to 10, and the mean values obtained from $dV/F_m = dh$ over the four altitude zones are given in Table 11.

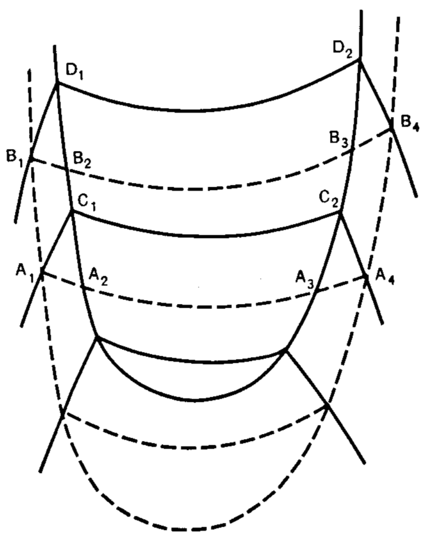


Fig. 13. Derivation of formulas for calculating height losses.

Table 11. Summary of Tables 7-10.

Height zones	*Mean height*	dV	Fm	dh	$\overline{dh}$
m.	m.	$m.^3 \times 10^6$	ha.	m.	m.
180- 320	250	32.27	50.28	64.10	8.03
850- 930	890	28.61	167.94	17.05	2.14
1080-1180	1130	10.74	304.69	3.53	0.44
1180-1270	1225	1.414	41.01	3.45	0.43

The results show the expected ablation decrease with increasing altitude. The values also confirm the assumption that the upper edge of the barren represents the glacier shore line of 1920.

Exact figures for the glacier recession can be given only for the period 1949 to 1957. However, comparison of the present glacier shore lines with the barrens should enable us to draw useful conclusions for the period of 1920 to 1957. The comparison is given in Tables 12 to 14.

Tables 12 to 14. Ablation data derived from comparison of vegetation margins. Observation period approximately 1920-57. All values in metres.

Table 12. Salmon glacier south tongue.

Heights 1920 (*approximately*) *left margin*	*right margin*	*mean*	*1957*	dh	$\overline{dh}$
.	420	420	200	220	5.92
300	400	350	250	100	2.70
410	420	415	300	115	3.10
420	480	450	350	100	2.70
500	510	505	400	105	2.84
540	570	555	450	105	2.84
670	650	660	500	160	4.32
690	650	670	550	120	3.24
750	690	720	600	120	3.24
800	.	800	650	150	4.05
820	.	820	700	120	3.24
860	890	875	750	125	3.37
880	920	900	800	100	2.70
960	.	960	850	110	2.96
960	.	960	900	60	1.62

Table 13. Salmon glacier north tongue.

Heights 1920 (*approximately*) *left margin*	*right margin*	*mean*	*1957*	dh	$\overline{dh}$
950	.	950	825	125	3.37
960	.	960	840	120	3.24
970	960	965	860	105	2.48
980	972	976	880	96	2.60
990	1010	1000	900	100	2.70
1015	980	990	920	78	2.10
1020	.	1020	930	90	2.43

Table 14. Berendon glacier.

Heights 1920 (*approximately*) *left margin*	*right margin*	*mean*	*1957*	dh	$\overline{dh}$
820	.	820	700	120	3.24
840	.	840	750	90	2.42
920	880	900	800	100	2.70
980	930	955	850	105	2.83
990	.	970	900	70	1.88
1070	.	1070	950	120	3.23
1080	.	1089	980	100	2.70

Tables 12-14 show the differences in height between today's glacier and the upper edge of the barren strip above. The shore heights on the left and the right were averaged and the difference in height between this average and the upper edge of the barren strip was divided by 37. These values are not as accurate as those obtained from contour line comparisons, since local exposure can influence the melting, the nature of the ground can affect the advance of vegetation greatly, and the beginning of the period 1920 is only approximate. They are useful, however, when earlier plottings are not available.

All observations are combined in Fig. 14. The values scatter considerably owing to topographical, micro-climatological, and other peculiarities

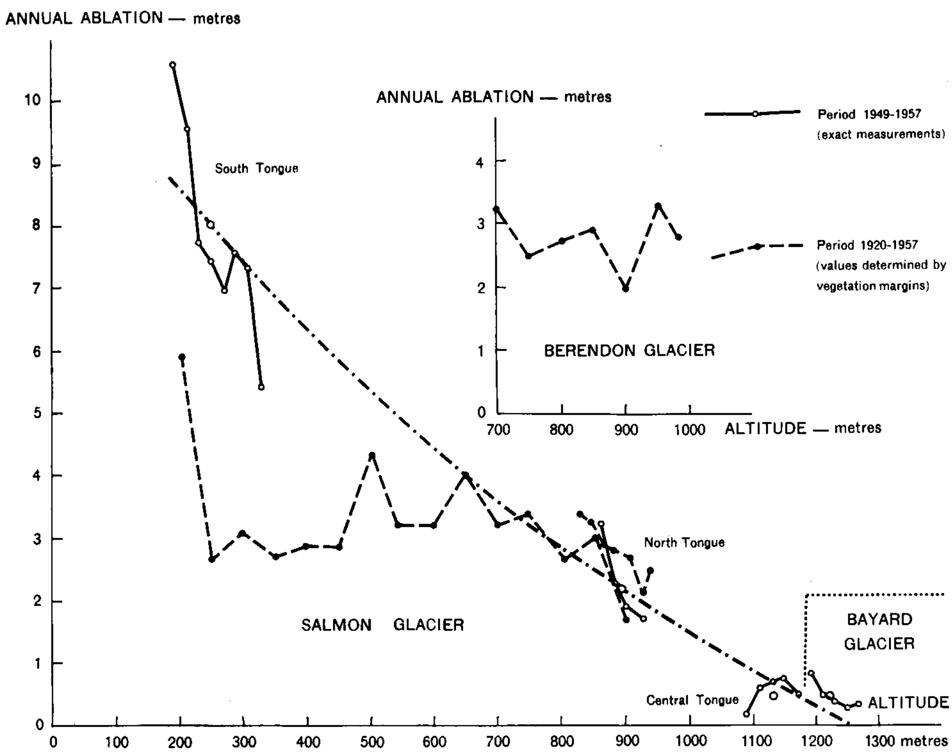


Fig. 14. Ablation values for Salmon, Bayard, and Berendon glaciers.

of altitude zones. Smoothing would produce a hyperbola-like curve. Extrapolation upwards gives an altitude of approximately 1280 m. for dh $= 0$ where ablation is balanced by accumulation, i.e., this should give the snow line. The actual snow line was at 1300 m. at the end of August 1957, close to the end of the ablation period. It should be noted that the loss in height near the snout is greater than expected because of its exposure.

Since the valley slopes are very steep, the loss in glacier area is quite small. In the north snout region a strip of terrain averaging 30 m. in width became free of ice between 1949 and 1957.

In calculating the losses in height, area losses were considered only in the region of the south snout. They are given in Tables 7 and 8.

It was possible to observe the movement of the snow line up the glacier during the expedition. On May 31 the glacier was bare of snow up to kilometre 17.5 (620 m.), except for a few large patches. The snow melted rapidly on solid ground during the first half of June (80 cm. of firn snow melted on the bottom of Daisy Lake (890 m.) between June 5 and 18, but the snow line remained stationary at the upper level of the ice fall (kilometre 15.4) until about June 25. A few patches became then bare between kilometres 15 and 12. The first boulders of the moraine between Eyetie and Gravy (kilometre 12.5 north) melted out, indicating that there was still 1.5 m. of snow at this point. The exposed patches between kilometres 15 and 12 grew slowly, the first patches at kilometre 10 became bare, and the ice on Summit Lake broke up. A firn line also took shape from the direction of the ice front and nearly extended to kilometre 13.5 north on July 1. During the first half of July the entire flat glacier area up to kilometre 9 (1100 m.) was covered with slushy snow, which was knee-deep in some places. A wedge of snow extended to the glacier only at kilometre 11 (see Figs. 8 and 12) and remained until about August 5, meanwhile receding gradually towards the permanent patch of snow to the west of Point Fal (kilometre 11.3). During July it was not possible to obtain a clear picture of the behaviour of the snow line, but toward the end of the month it had reached the Edith-Nepu line (kilometre 6.8) and by mid-August, when the expedition was leaving, it was at kilometre 5.7 (1300 m.).

(D) *The Tide Lake area (see Fig. 10)*

At its maximum the Frank Mackie Glacier blocked the Bowser River valley and held back a lake on an average 8.5 km. long by 1.7 km. wide, which drained intermittently and progressively during the 1930's. Today only two small lakes remain, one at the south end close to the Berendon Glacier snout and the other just in front of the outlet that was eroded through the lateral moraine of the Frank Mackie Glacier. The two remaining lakes are approximately 300 m. $\times$ 300 m. in size, the water level of the southern one being at 647 m. and that of the other at about 550 m. At the time of its maximum size, the water level of Tide Lake stood at 785 m. The shore line is still very well preserved around the entire lake (see Fig. 10), and it is clearest at the mouth of Betsy Creek Gorge. The Bowser River flowing from the southern residual lake meanders northward along the bottom of the Tide Lake basin. The southern residual lake receives the glacial streams from the Berendon and Betsy glaciers as well as those from glaciers 5 and 6 and the drainage of Summit Lake. In the lake basin itself the streams of glaciers 3, 4, and 7 empty into the Bowser River.

From stereophotogrammetric plotting twenty-seven former shore lines could be distinguished on a large crescentic moraine that the Berendon Glacier had deposited on the lake bottom, and twenty-one more shore lines were revealed at a higher point at the entrance to Betsy Creek Gorge. 35-mm. photographs of other points showed as many as thirty-six former shore lines. Some can also be discerned on the marginal moraine of the Frank Mackie Glacier. The maximum distance found between two shore lines was 7.8 m., but most were between 1.5 and 3.0 m. apart.

The glaciers of the Tide Lake area consist of two groups: two large valley glaciers, the Berendon and Frank Mackie, and the seven small valley glaciers that descend from Mt. Janowski and Mitre Mountain (glaciers 1-6 in Fig. 1) and from the Berendon range (Glacier 7 in Fig. 1). The two large glaciers show the characteristic barren bands surrounding the tongue. On the small glaciers snout losses are noteworthy but the barren bands along the margins are not as striking.

Fig. 15. Berendon Glacier photographed from terminal moraines of maximal glaciation of approximately 1850. The joining point of the two ice streams is about 2.8 km. distant. Note the barren in foreground and along the glacier margins. The small recessional moraine in the foreground was deposited during a very recent stage in the nineteen-thirties.

(E) *The Berendon Glacier (see Figs. 15 and 16)*

The Berendon Glacier consists of two branches, each having its own accumulation area fed from the large firn valley. The two branches join 3 km. above the terminus, whose right-hand component runs up against the rock barrier between Summit Lake and Tide Lake and whose left one bends northward and just reaches the flat floor of Tide Lake basin.

With its lateral moraine the Berendon Glacier blocked the present outlet of Summit Lake. This outlet has cut a deep notch into the 1850 moraine dam and disappears into Berendon Glacier from which it emerges after, a sub-glacial run of 1000 m. into a small lake (652 m.). Another stream emerges from a glacier gate 250 m. farther north. In the barren the Summit Lake outlet was dammed up into a small lake that finally vanished about 1950. Three terraces are clearly visible here, from which the size of this lake can be estimated. The bed of the earlier outlet gorge 500 m. to the east is 855 m. high, from which a drop of 29 m. can be calculated to the present water level of 826 m. Further to the east are two more rifts, whose beds lie at 885 m. and 920 m., respectively. If these were still earlier outlets of Summit Lake, another advance than that of the 1850 period is indicated. There is evidence to support this previous advance as, for example, in the Salmon Glacier valley at kilometre 13 and at an altitude of 1200 m., i.e., 350 m. above the present glacier surface, there are glacial striations running parallel to the present glacier flow. However, a definite statement cannot be made for lack of adequate data. Assuredly, Pleistocene glaciation in the expedition area must have reached proportions similar to that in the European Alps.

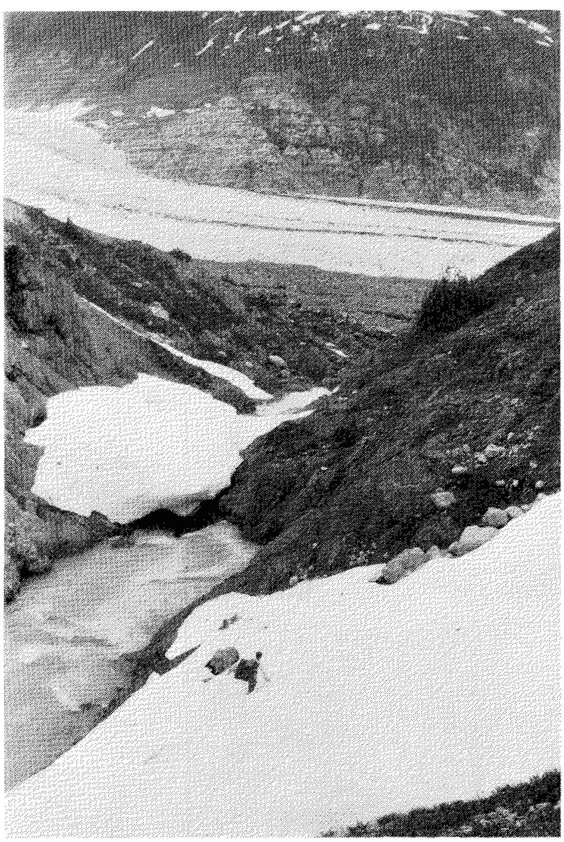


Fig. 16. Present outlet of Summit Lake with Berendon Glacier in background. Note barren on both sides of the glacier. The notch was eroded through the marginal moraine of the glaciation maximum of approximately 1850.

The moraines show very definitely the glaciation of 1850 and 1920, the outermost ones already supporting fairly large trees which grow in rows along the crest of the mounds. The flat ground around them is covered only with small shrubs. Within these large moraine walls is a smaller one about 600 m. to the west of the outlet of Summit Lake inside of which the glacier bed is entirely bare of vegetation. This would indicate the glaciation of 1920. The large medial moraine continues 1450 m. farther to Betsy Creek. The southern residual lake of Tide Lake is enclosed by a smooth, circular ridge which may indicate a still earlier advance of the Berendon Glacier. This assumption is confirmed by the form of the barren on the left side of the glacier, which descends till it reaches this ridge and then merges into the shore line of Tide Lake.

Fig. 17. The 90-degree bend of the Chickamin (left) and Through glaciers, taken at 2250.5 m. from Mt. Wrong on July 17, 1957. Note large moraine mound to the right of middle ground. Rubble has been carried down by Greenpoint Glacier (right), which joins Through Glacier. Little debris is transported by the larger glaciers. In mid-picture is Humming Glacier with its creek flowing into Chickamin Glacier. To the left of Humming Creek is seen the barren of Disappearing Lake. Note also the barren along Greenpoint Glacier.

(F) *The glaciers of the Leduc and Chickamin valleys*

The glaciers of the Leduc and Chickamin valleys show essentially the same conditions as the other glaciers. They are rapidly retreating and also show the characteristic bright barrens indicating the earlier stage of glaciation. During their advance they had often lobes extending into adjoining valleys, where today the bared glacier beds are clearly distinguishable from the surrounding terrain. The Chickamin Glacier (see Fig. 17) pushed one such lobe into the Texas Creek Gorge. When the lobe melted its terminal moraine dammed a small lake, Disappearing Lake.

At its 90-degree bend westward the Chickamin Glacier is met by Through Glacier and they flow then side by side until the smaller Through Glacier is squeezed out just before the end of the Chickamin lobe. The medial moraine dividing these two glaciers decreases in size as it continues down the glacier (see Fig. 18). The moraine material is pushed on to Through Glacier by Greenpoint Glacier that joins it 1 km. south of the large bend. Most of the moraine material is squeezed out eastward at the bend, whence the glaciers themselves flow west. The Chickamin Glacier does not form a glacier gate because melt water seeps out from under the ice lobe into a small lake which is drained by the Chickamin River.

The Leduc and Unuk glaciers still fill their valleys completely and thus form a network of ice streams. Glacier VI divides and its northern arm (2.5 km. long) joins a glacier from the other side of the valley. Its southern arm (3.5 km. long) joins the Leduc Glacier. This ice mass of Glacier VI forms the watershed between the Leduc and Unuk rivers.

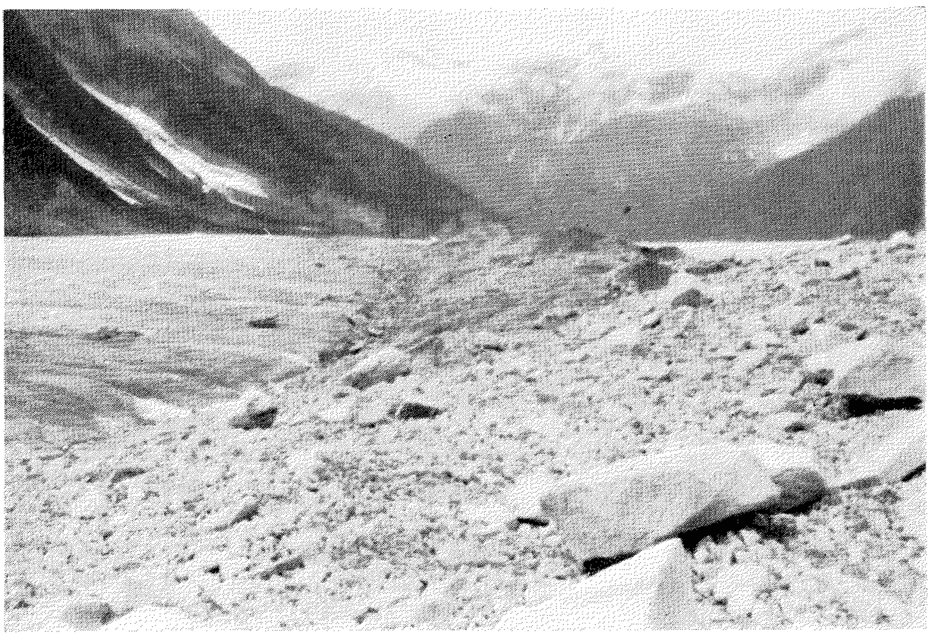


Fig. 18. Looking westward along the medial moraine between the Chickamin (right) and Through (left) glaciers.

Conclusion

On Salmon Glacier aerial photogrammetry was used systematically for glacial studies. A special map (in pocket at back) of the Salmon Glacier at a scale of 1:25,000 was produced from aerial photographs taken from a relative flying height of 2200 to 3000 m. This established an accurate starting-off point for further investigations. The glaciers of the expedition area are retreating in conformity with the world-wide behaviour of glaciers at present. By a study of vegetation zones fluctuations in glaciation since the last advance, approximately during the twenties to the fifties of the last century, were reconstructed. Aerial photographs taken earlier, especially in 1949, were used to prepare plots. They gave accurate indication of ice losses during the period 1949 to 1957 when compared with the 1957 plots. Ground control was established and monumented to simplify future photogrammetric operations. The rate of flow of the glacier was determined at three profiles using terrestrial photogrammetric methods.

In about five years' time, i.e., in 1962, a second mapping should be considered of the whole Salmon Glacier area, the adjoining Leduc Glacier and Glacier VII areas, and the lobe-end areas of the Berendon, Frank Mackie, and Chickamin Glaciers.

Aerial photogrammetry has been most satisfactory. As the error in the altitude of the contour lines should be less than 1 m., relative flying heights should be limited to a 3000 m. maximum and preferably not exceed 2500 m. Superwide-angle cameras are to be avoided. Wide-angle cameras with a focal length of 15 cm. and image size of 23 x 23 cm. with up-to-date lenses, such as the Aviogon or Pleogon, should be used. The flight pattern depends on the terrain and local circumstances. Care must be taken to ensure that a sufficiently wide strip of ice-free ground is covered by the photographs. The slope of the glacier and the shape of the surrounding mountain chains may necessitate breaking up the flight lines and changing the absolute flying height in order to keep the relative flying height within acceptable limits, e.g. 1900 to 2500 m. for the above cameras. Ground control points should be well marked with proper targets. As the scale of the picture ranges from 1:12,500 to 1:16,500, the target size should be at least 0.6 m. square. The rugged terrain in high mountains makes target recognition more difficult than in cultivated areas. Targets on white glacier surfaces, such as ice and snow areas, were not satisfactory. Ablation and glacier flow required a ground survey at the same time as the photo flight, and this complicated the organization of both the field survey and the flight.

Because of accuracy requirements maps must be plotted on precise instruments such as the Wild A-7, Zeiss C-8, or Wild A-8 plotters. Plotters which use the anaglyph principle for stereo-viewing are not recommended because of their limited depth of focus and poor definition of important details, which in glaciated areas are difficult to detect under the best of conditions. As the interpretation requires a comprehensive knowledge of glacial morphology and of the various problems involved in glaciology, the plotting should be done by persons who have practical experience in glacial work, preferably by those who participated in the expedition.

Plotting of snow areas is only possible if there is enough contrast in the snow surface from snow drifts or other objects and glare is absent. These difficulties were encountered on the Salmon Glacier in the area (see map) between the triangulation stations Edith and Nepu and High Camp.

The range of the final publication scale may be given as 1: 10,000 to 1: 25,000. A scale of 1: 50,000 is obviously too small for the presentation of details important from the glaciological point of view.

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