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Glacier surveys by the Water Survey of Canada

I.A. Reid

Water Survey of Canada, Water Management Service, Department of the Environment, Ottawa, Ontario

ABSTRACT: Glaciers act as natural regulators, storing water in winter and releasing it in summer. To gain some understanding of this phenomenon and the contribution which glaciers make to streamflow, the predecessors of the Water Survey of Canada began glacier surveys in 1945. The earlier surveys offered some clue to the role of the glacier but the data collected were not sufficient to provide the overall picture. Following adoption of photogrammetric survey techniques, however, the glacier surveys have evolved to the extent that it is now feasible to produce a series of maps from which the linear, areal, directional and volumetric changes can be determined.

This paper traces the glacier survey work from its inception in 1945. In addition, the results of two methods for determining the average contribution of a glacier to streamflow are summarized. The surveys have revealed that the glaciers, in general, are becoming smaller in size; hence, the regulation effect is diminishing.

RESUME: Les glaciers jouent un rôle de régularisation naturelle, emmagasinant l'eau pendant l'hiver et la laissant s'écouler durant l'été. Pour arriver à comprendre quelque chose à ce phénomène et aussi à la contribution que les glaciers apportent au ruissellement, les prédécesseurs de la Direction des levés hydrologiques avaient commencé en 1945 une étude des glaciers. Ces études premières apportèrent certains indices quant au rôle des glaciers mais les observations compilées n'étaient pas suffisantes pour donner une idée d'ensemble. A la suite de l'adoption de relevés photogrammétriques, cependant, l'étude des glaciers a évolué au point qu'il est maintenant possible de produire une série de cartes à partir desquelles les changements linéaires, directionnels et de volume peuvent être déterminés.

Ce rapport retrace les travaux accomplis dans l'étude des glaciers à partir du début en 1945. De plus, on résume les résultats obtenus au moyen de deux méthodes pour déterminer en moyenne la contribution des glaciers au ruissellement des cours d'eau. Les études ont révélé, qu'en général, le volume des glaciers diminue et que de ce fait, l'effet de régularisation est aussi diminué.

INTRODUCTION

In connection with studies of the water resources of the mountainous rivers of British Columbia and Alberta, the Dominion Water and Power Bureau in 1945 initiated an annual survey of certain glaciers in the Canadian Cordillera. In addition to obtaining glacier information of general scientific value, the ultimate purpose was the determination of the effect of glacier variation on runoff, particularly the amount of runoff which could be expected in subsequent years from Canadian glacier sources.

Eight glaciers in British Columbia and seven in Alberta were selected for study (*Fig. 1*). The criteria for selection were easy accessibility, representativeness of the general area, and the availability of records obtained by private individuals or clubs such as the Alpine Club of Canada. The goal of the surveys was to determine the snout movement — advance or retreat — with respect to a fixed point on the ground, the volumetric change, (the surface movement of glacier tongues) and the amount of water which glaciers contribute to streamflow. [1] [2] As will be seen, this goal was not entirely met in the earlier years.

Since glaciers supply a considerable portion of the summer flow to many Canadian rivers, their size and behaviour are an important factor in streamflow investigations of glacier-fed streams. Such streams reach their seasonal peak flow during the period of maximum temperature (July or August), while the peak flow of streams of non-glacial origin usually occurs in May when snowmelt contributes much of the spring runoff.

There are not many large natural reservoirs in the headwaters of streams in the Canadian Cordillera. Fortunately, however, the flow regulation role normally played by reservoirs is taken up by glaciers and snow fields. [3] As the glaciers shrink the regulation effect decreases. If the glaciers disappear, the regulation effect becomes nil. The effect of this would be twofold. First, because of the lack of runoff retention otherwise exercised by the glaciers, the peak discharge would occur nearer to the time of the melting of the snow in May or early June, increasing the possibility of floods. Second, there would be no runoff from ice or snowmelt to sustain flow in the rivers during the hot summer months and this could be catastrophic, especially on the prairies. To overcome the lack of storage normally provided by the glaciers, reservoirs would have to be constructed in the headwaters and this in terms of cost would be a major undertaking.

When initiated in 1945, the survey of each glacier was made annually near the end of the melt season by District field staff. It was found subsequently that yearly changes in the glacier snout were comparatively small; thus, after 1950 the frequency of surveys was reduced to one every two years.

The surveys by the Districts generally included the following: [1, 2].

1. The establishment of fixed reference marks near the toe of each glacier in relation to permanent topographical features.
2. The measurement of the distance from the tongue to a reference point or baseline, or alternatively the mapping of the forefoot. In the latter case, successive plottings clearly show the average advance or recession across the whole forefoot.
3. The setting up of camera stations from which single photographs are taken at each survey to show prominent change in the glaciers.
4. The estimation of the amount of water discharged from each glacier at time of visit.

In 1947, glacier surveys were expanded to include the following: [3]

a) The rate of glacier surface movement near the toe. This was determined using plaques or markers set out on the ice, along a reference line crossing the glacier.
b) The surface lowering. This was measured by means of surface cross-section and profile lines.

Attention was again focussed on Canada's glaciers during the late 1950's, largely due to the International Geophysical Year

(1957-58). In assessing the data collected by District Office Staff, it was decided that more information pertaining to the upper part of the glacier was needed. This could not be easily done by transit-stadia methods. Photogrammetry was the answer.

In 1959, personnel from the Division's Head Office in Ottawa carried out, as a pilot project, a precise aerial photogrammetric survey of the Athabasca Glacier in Jasper National Park. At the time, the Division's intention was to carry out aerial photogrammetric surveys every three years on this and other glaciers. [4] The survey was carried out again in 1962. From a series of maps prepared from the photographs, linear, aerial and volumetric changes can be determined.

The International Association of Scientific Hydrology Commission on Snow and Ice met in Helsinki in August, 1960. During the General Assembly at Helsinki, the Commission on Snow and Ice made the following resolutions:

a) The Commission shall undertake the permanent task of recording the variation of existing glaciers. To do this, a Sub-Committee on Variations of Existing Glaciers was formed. The terms of reference of the Sub-Committee were: To prepare a document detailing the measurements to be made on existing glaciers in all countries so as to record their variations from time to time, and to recommend the various means by which this work could be accomplished, and the results collected together and published.
b) The International Committee on Geophysics (C.I.G.) may wish to consider using the existing World Data Centres (Glaciology) for assembling the data arising from item (a) above when their present task with the I.G.Y. is complete.

The Sub-Committee on Variations of Existing Glaciers prepared a report which was sent to the Canadian Sub-Committee on Glaciers: The Canadian Sub-Committee changed the recommendations slightly to fit Canadian conditions. The Water Survey of Canada Division adopted stereoscopic terrestrial photogrammetric survey methods to fulfil most of the Sub-Committee's recommendations.

Terrestrial photogrammetry has certain advantages over aerial photogrammetry for mapping relatively small glaciers. Terrestrial photogrammetry does not require a chartered aircraft and weather conditions do not play as large a role in determining its success, moreover, terrestrial photography can be successfully carried out under a heavy cloud cover which would prohibit aerial photography. Terrestrial surveys require fewer control points and the placing of the control points is less critical than is the case for aerial photogrammetry. All in all the terrestrial survey is more likely to be successful and requires a smaller party to carry out the complete survey.

These advantages influence cost which is much smaller with terrestrial surveys. The cost of aerial photography is largely in the chartering of a suitable aircraft; such costs can be considerable, depending on the plane's distance from home base or if poor flying weather keeps it standing-by for long periods.

The accuracy of terrestrial and aerial photography is comparable provided that similar base ratios are used. Because of the larger areas covered in terrestrial photographs, however, care has to be taken that the recommended mapping limits are not exceeded.

In 1963, the Saskatchewan Glacier was surveyed jointly by the University of New Brunswick and the Water Survey of Canada using terrestrial methods. [5] This afforded members of the Water Survey an excellent opportunity for becoming competent in the science of terrestrial photogrammetry. In 1964, and biennially since, the Water Survey carried out a terrestrial photogrammetric survey of the Bugaboo, Kokanee, Sentinel, Sphinx and Nadahini Glaciers. [6] To ensure the success of the 1964 survey, the Water Survey hired a consultant from the Department of Surveying Engineering, University of New Brunswick. In 1965, and biennally since, the Water Survey carried out a terrestrial photogrammetric survey of the Athabasca and Saskatchewan Glaciers. [7]

FIELD WORK

Standard procedures [8, 9] were followed in carrying out the terrestrial survey of the seven glaciers. (Fig. 1). Generally, horizontal and vertical control points are established on bedrock around the glacier's periphery as well as on the ice surface. The position of control points on ice are determined during (or near to) the day of photography. Where possible, the photographic stations are established on a high ridge overlooking the glaciers. Generally, two photo bases are established - a short base to map the near areas of the glacier and a long base to plot the far areas.

Theodolites reading to the nearest second are used to carry out the triangulation. A phototheodolite is used to take the photographs and to do some triangulation, while a high quality subtense bar is used to measure base line distances. Kodax Spectroscopic type glass plates are used for the photography. These plates are of good quality with high resolution.

On arriving at the glacier, the party first carries out a reconnaissance to locate the best possible area to establish the photo stations. The simplest case is to have one photo base on top of a ridge so that the closest part of the area to be mapped is at least four times the base length away, while the most distant area to be mapped is not more than twenty times the base length away. In equation form this can be expressed as:

$$\frac{D\ max}{20} < b < \frac{D\ min}{4}$$

where b is the base length and D is the distance from the base to the area being mapped.

The ends of the base line are identified by bronze plugs cemented in rock (Fig. 2). The next simplest case is to have two photo bases on the same ridge, the second photo base being a projection of the first base. If some of the area to be mapped cannot be seen in the stereo overlap, then additional bases must be established on the same ridge or on another ridge.

The location of the cairns is important. Figure 3 illustrates the control stations for Sentinel Glacier. In practice, each stereo overlap requires four to six well chosen control points. [9] These should be situated as follows: a) one near the centre (top) of the stereo overlap at roughly the farthest area to be mapped; b) one midway up either side of the area near the extreme outer limits of stereo view, and c) one or two points in the nearest area (bottom) to be plotted.

The photo bases and cairns are tied-in by triangulation. Only one distance in the triangulation network needs to be accurately measured; the lengths of the other sides are computed using trigonometry. These measurements could be carried out with one of the newer electro-optical distance measuring instruments, a subtense bar or a steel tape.

The triangulation should be carried out to give third order accuracy. This generally requires taking two or three rounds of vertical and horizontal directions with a theodolite reading to seconds. The directions should be read on to a pole centred upright in the cairns.

Complete notes should be taken. For determining elevations, the notes should include the height of instrument and describe the part of the object being sighted on, such as the top, middle or bottom of a cairn. Generally speaking the x, y and z co-ordinates should refer to the bronze plugs or the base of the cairn. Cairns can be knocked over or torn down very easily.

The photographs should be taken with extreme care. It is important to a) record the height of camera, b) have bubbles centered, c) set and record the camera aversions and inclinations accurately, and d) make complete sketches or take polaroid pictures of control points and other noteworthy features of the area being mapped. Attention to all these details pays real dividends when the map is compiled on the plotter.

REDUCTION OF FIELD DATA

The co-ordinates for these glacier maps were computed in a plane rectangular co-ordinate system. In this local system the sea level surface can be assumed to be a plane, the meridians of longitude and parallels of latitude can be represented by straight lines, and the co-ordinates of the triangulation stations can be determined by plane trigonometry. This procedure was considered to be adequate for the relatively small areas being mapped.

One of the stations, usually a photo station, was assigned the value x = 100,000 and y = 100,000. The azimuth of one of the sides of a quadrilateral (usually a photo base) was found from a topographic map. The orientation of the glacier map was therefore referenced to approximate true north.

The x and y co-ordinates for the other control stations were determined by plane trigonometry, using seven-place trigonometric tables and a desk calculator. In the main triangulation net, the co-ordinates for each station should be the mean of the values computed from two bases. A control point on ice is normally only observed from one base and therefore there is only one value obtained. To eliminate errors in calculation a system of checks should be employed throughout.

The approximate elevation of one of the control points is determined from a topographic map. The elevations of the other stations are calculated from this one point by trigonometry using five-place trigonometric tables. The elevation of each station should be computed from other stations in the triangulation net. The mean elevation is accepted as correct.

In the future, if warranted, these glacier surveys can be related to the National Topographic Mapping System. This would entail much work and a considerable expenditure of money. At this time, the benefits do not appear to warrant such an outlay of time, effort and money.

PLOTTING

The plotting of maps was carried out by means of a Wild A-5 or Wild A-7 Universal Autograph belonging to the Department of Energy, Mines and Resources. For this work, it has been common practice to have the photogrammetrist accompany the field party. In this way, he becomes familiar with the terrain and particularly with the control points. It seems that if the control points are positively identified, then the plotting can proceed with relatively little trouble. The task of plotting can be very satisfying if the field and office work have been done with care. The plotting can be very frustrating and very unsatisfactory if one is working with an inferior product. The results can only be as good as the field and office work; if a job like this is worth doing, it has to be done to sufficient precision to allow results to be used for valid glaciological interpretation.

Map Scale and Contour Interval - One should strive to present the glacier at a relatively large scale 1:10,000 or better commensurate with the accuracy of the field work and the precision of the plotter.

The contour interval should be chosen to give a good representation of the glacier. The contour interval is dependent on the slope of the surface of the glacier and the accuracy of the survey and plotter. For best visual effect the contours should not be closer than 3 mm on the steeper parts of the glacier. It is possible that more than one contour interval should be used to portray a glacier.

From one map it is possible to measure linear distances and areas and to scale directions. From a series of maps of the same glacier, it is possible to measure or determine linear, areal, directional, and volumetric changes. The determination of linear, areal and directional changes are relatively simple. The determination of volumetric changes is more complex.

A.J. Brandenberger and C. Bull described four methods for computing volumetric change. [12] In 1966, Messrs. R.O.N. Lyons and J. Shastal developed another method in which the desired portion of the glacier was completely enclosed by fixed co-ordinates. [6] The map was divided into squares (grid pattern). The co-ordinates in the grid system were selected and joined in such a manner that snow areas could be eliminated. In the resulting enclosure, only the ice and snow were variable and could change the volume: the rock was stable. The volumetric change is computed on the basis of height zones, a height zone being defined as the surface area measured between two contours. The volumetric change of a height zone is computed as the mean of two areas, one produced by the horizontal displacement of the lower contour during the time period under consideration and the other produced by the horizontal displacement of the upper contour during the same time period, multiplied by the difference in elevation between the two contours. The sum of the volumetric changes in the series of height zones which comprise the ice area under study represent the total surface change for the period between surveys.

The advantages of this method are:

a) the visible rock-ice edge need not be defined;
b) maps compared need not be at the same scale;
c) printout maps can be used whereas with other methods, one map had to be transparent, so that it could be superimposed

on the other;

d) it takes lateral as well as longitudinal ice growth or loss into consideration.

Since the start of the surveys in 1945, the Survey's aim has been to determine the amount of water which glaciers contribute to streamflow. Various estimates have been made and various deductions made from discharge stations located near the glacier toe. It was not until 1967 that Reid and Paterson[1], independently and by different methods, measured the average amount of water produced annually by the melting of ice on a glacier. [10] The method used by Reid is applicable for geometrically simple glaciers whereas that of Paterson is applicable for complex glaciers. Both methods assume that the glacier remains in a steady state, that is, one whose dimensions do not change from year to year.

The method used by Reid states: the amount of ice flowing in one year through the cross-section of the glacier at the equilibrium line equals the annual loss of ice from the ablation area. The method used by Paterson states: at each point in the ablation area, the component of velocity perpendicular to the glacier surface (the "emergence velocity") equals the annual ablation (expressed in this case as volume of ice per unit area per year measured perpendicular to the glacier surface). These methods were employed on the Athabasca Glacier in the manner described in the following paragraphs.

The Athabasca Glacier is one of the main outlet glaciers from the Columbia Icefields in the Rocky Mountains. The outlet stream (Sunwapta River) has been gauged since 1948 at a point just downstream from a small lake, located near the toe of the glacier. Of the 33.8 km^2 drainage basin above the gauging station, the Athabasca Glacier occupies 18.7 km^2, three other glaciers occupy a total of 4.3 km^2, and the remaining 10.8 km^2, is unglacierized. The streamflow is measured from mid-May to the end of October (open water season). The runoff for this period, averaged over the 20 years of record, is 35.1 x $10^6 m^3$. The runoff for the remainder of the year was estimated by assuming that the average runoff for the first and last weeks of record was maintained throughout the winter. This gave a value of 2 x $10^6 m^3$.

The ice discharge through a section just below the lowest of the three ice falls was 10.8 x $10^6 m^3 a^{-1}$ by the Reid method. The ice discharge through the same section was 10.6 x $10^6 m^3 a^{-1}$ by the Paterson method.

Since the equilibrium line lies in the highest of three ice falls, it was necessary to compute the volume of ice lost between the ice discharge measuring section and the equilibrium line. The amount of ice melted from the upper part of the ablation area, where no measurements were made, was estimated in the following way. In a glacier in a steady state, the emergence velocity at the equilibrium line is zero. It is assumed, therefore, that the emergence velocity decreases linearly, with increase of elevation, from the measured value of 3.7 ma^{-1} at the foot of the lowest ice fall to zero at the equilibrium line. On this assumption, contours of elevation are also contours of emergence velocity. Thus, by the second method, an average loss of 3.0 x $10^6 m^3 a^{-1}$ of ice from this area was determined. Hence, a figure of 13.6 x $10^6 m^3$ is obtained for the

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[1] Dr. W.S.B. Paterson, Polar Continental Shelf Project, Department of Energy, Mines and Resources, Ottawa, Ontario.

average annual loss of ice from the Athabasca Glacier.

There were not enough ablation measurements, even in the area below the ice falls, for a direct calculation of the amount of ice lost annually. However, as the glacier has been mapped five times between 1959 and 1968, it was possible to determine whether the glacier is close to a steady state. Over this period the ice in the area in question, has grown thinner at an average rate of 0.32 m a^{-1}. This is equivalent to a loss of volume of 1.1 x $10^6 m^3 a^{-1}$ or about 10 percent of the calculated discharge. This is the amount by which the methods will underestimate the average amount of ice melted in a year.

Thus, on the average, 14.7 x $10^6 m^3$ of ice is lost from the Athabasca Glacier each year. This will annually contribute 13.4 x $10^6 m^3$ of water or about 35 percent of the average annual streamflow at the gauging station. [11]

CONCLUSIONS

Surveys by the Water Survey of Canada indicate that the glaciers in Western Canada are generally receding. If this trend continues, the glaciers will exert a progressively smaller influence on the regimen of rivers; the regulation effect will diminish, along with the retardation effect on the spring runoff. In addition, there will be a gradual lessening of melt water released during the summer seasons and thus smaller summer flows can be expected on rivers of glacial origin.

Terrestrial photogrammetry is an excellent method to systematically map the changes in the ablation area of relatively short glaciers. The method is less suitable for mapping glaciers of, say, over five kilometres in length and for mapping the source areas. The shape and size do not lend themselves to terrestrial photogrammetry. However, the possibility exists for mapping sample portions of the source areas from, say, one or two photo bases. These sample portions could serve as an index of loss or gain within the source area.

ACKNOWLEDGMENTS

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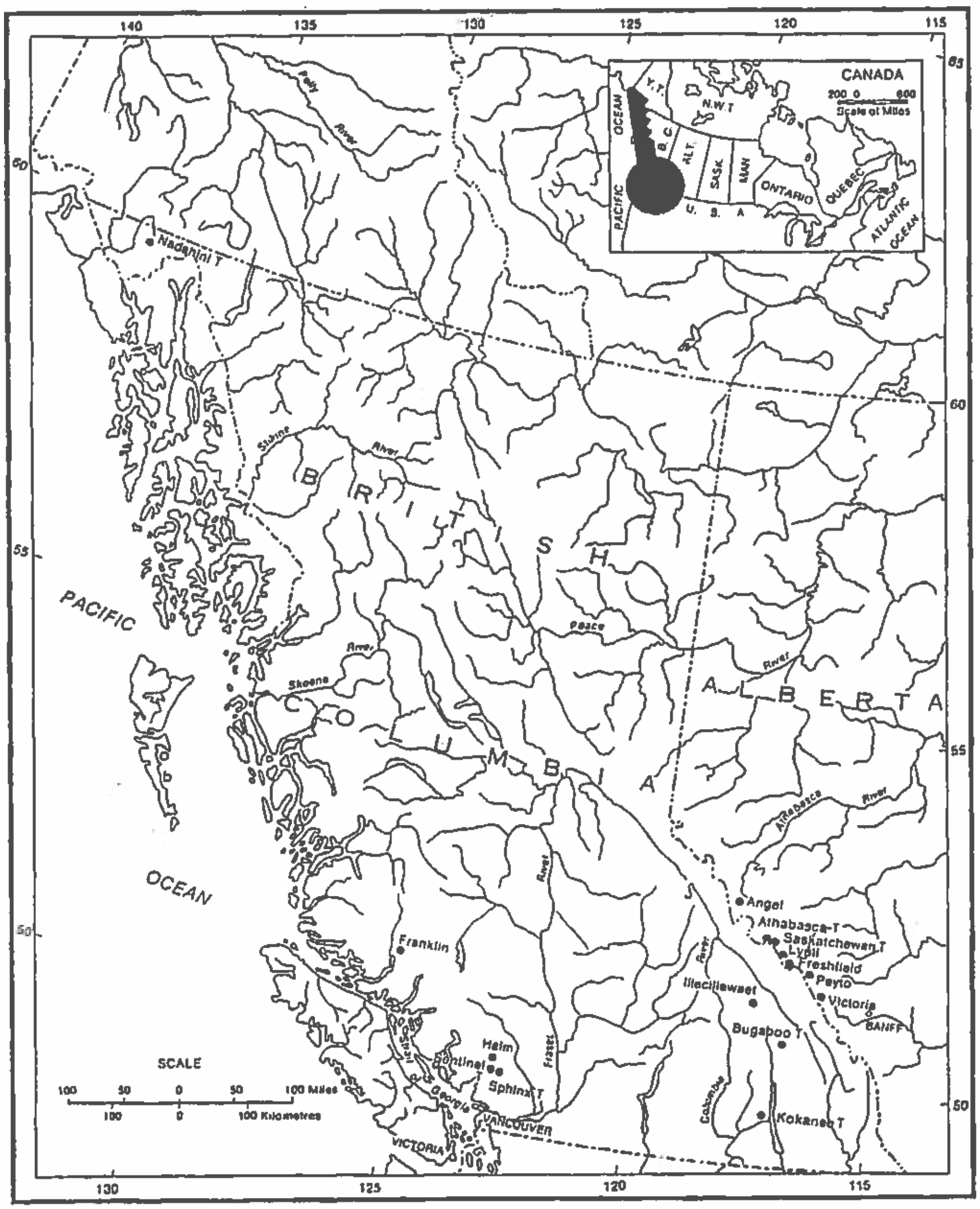

Fig. 1. Glaciers surveyed by the Water Survey of Canada.
(T indicated Terrestrial Surveys)

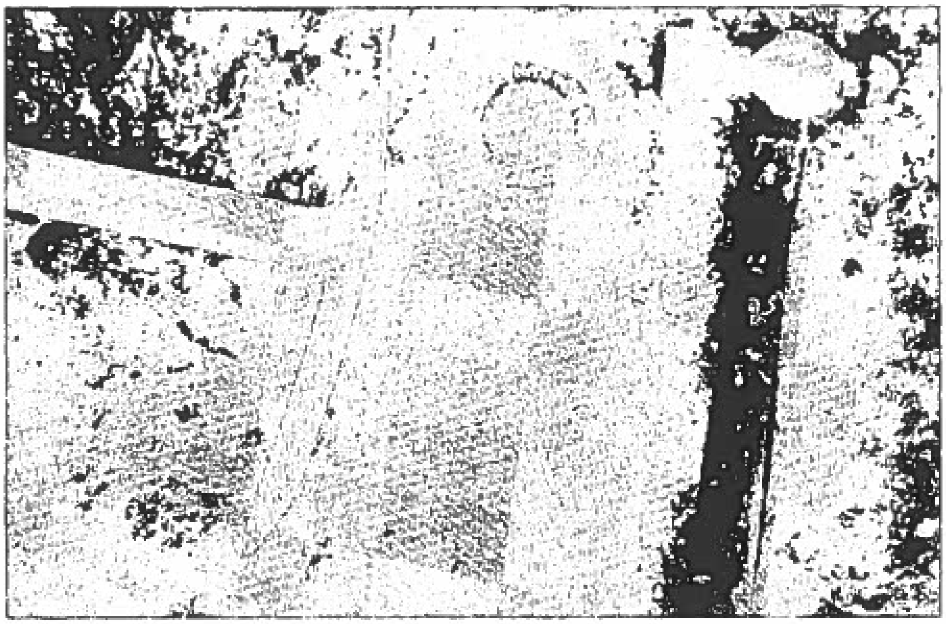

Fig. 2. Photograph showing the standard W.R.B. plugs used to locate the photographic stations

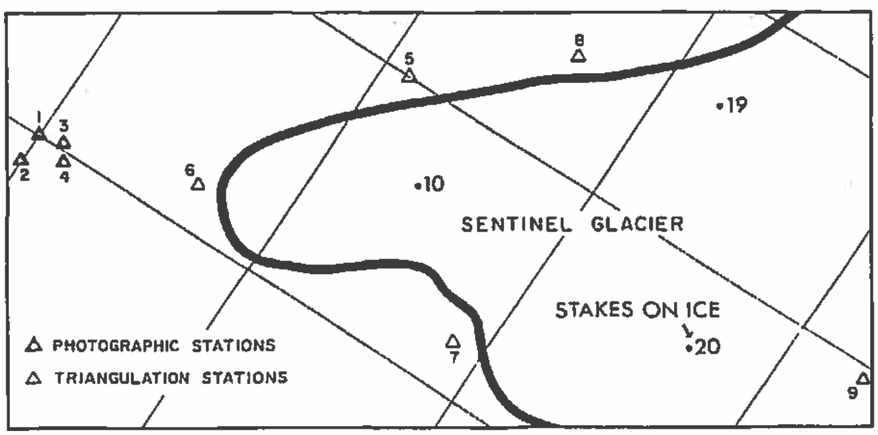

Fig. 3. Sketch showing distribution of photographic and triangulation stations - Sentinel Glacier

There was no discussion of this paper.