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Glacier Surveys in British Columbia — 1970

I.A. Reid and J.O.G. Charbonneau

REPORT SERIES NO. 32
(Résumé en français)

INLAND WATERS DIRECTORATE,
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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.

The surveys have revealed that the glaciers, in general, are becoming smaller in size; hence the regulation effect is diminishing.

Résumé

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 Division des relevés hydrologiques du Canada avaient commencé en 1945 une étude des glaciers. Ces premières études apportèrent certains indices quant au rôle des glaciers mais les observations compilées n'étaient pas suffisantes pour donner une idée d'ensemble. À 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 on peut déterminer les changements linéaires, directionnels de superficie et de volume.

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

An important function of the Water Resources Branch is the systematic collection of water resource data throughout Canada. This work is of vital importance in the development of Canada's water resources because the feasibility, safety and cost of water use or water control projects depend largely on the availability and reliability of such information.

Since glaciers form part of Canada's water resources, some glaciers are surveyed on a continuing basis by the Applied Hydrology and Water Survey of Canada Divisions in an effort to determine the extent and pattern of a glacier's influence on surface water runoff. Of the large number of glaciers in Canada, however, only a few are surveyed.

This report summarizes the history of glacier surveys conducted in Canada by these Divisions and describes present glacier survey practices. Tables of results for the period of record, some interpretation of these results and the most recent glacier maps are also included. Only those surveys conducted partially by or under the supervision of the Applied Hydrology Division are described in detail; brief reference, however, is made to surveys conducted entirely by Water Survey of Canada District Office staff to make the historical summary coherent and the Tables of data as complete as possible.

In response to a directive recommending greater use of the metric system, the Applied Hydrology Division decided to change from English to SI units in the determination of biennial glacier variations. In 1968, the year of the changeover, it was necessary to compile separate sets of maps using both English and SI units in order that data produced prior to 1968 might be compared to data obtained after 1968. To assist the reader in converting units, a table of equivalents follows:

SI units	English units
1 metre (m)	3.2808 feet (ft)
1 square metre (sq m)	10.7639 square feet (sq ft)
1 cubic metre (cu m)	35.3147 cubic feet (cu ft)

HISTORICAL SUMMARY

Surveys of selected glaciers in the Rocky, Columbia and Coast Mountains were begun in 1945. The surveys of glaciers located in the Rocky Mountains were carried out by WSC Calgary staff, and the Columbia and Coast Mountain surveys were performed by the WSC Vancouver staff. These surveys, in general, were designed to determine the position of the glacier toe, to define the movement of a plaque line on the glacier's surface and to provide a transverse and a longitudinal profile for the lower portion of the glacier. Reports describing the 1945 survey and subsequent surveys conducted by the District Offices are available from

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V6E 2M9

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Water Survey of Canada,
Inland Waters Directorate,
Department of the Environment,
110-11th Avenue, S.W.,
Calgary, Alberta.
T2R 0B8

More information concerning the evolution of the glacier surveys may be obtained from "Glacier Surveys by the Water Survey of Canada," a paper by I.A. Reid in the *Proceedings* of the Banff Symposia on "The Role of Snow and Ice in Hydrology," held in September 1972.

A glacier's contribution to the volume of runoff can be calculated if two quantities are known: 1) the change in volume of a glacier during a given period of time and 2) the amount of ice that flows from the source icefield to the glacier during the same period of time. Surveys have been designed to measure the first quantity directly, but since no direct method of measuring the second quantity was known

until recently, it has been determined only indirectly.

A paper entitled "A Simple Method of Measuring the Average Amount of Water Produced Annually by Melting of Ice on a Glacier" by I.A. Reid and W.S.B. Paterson was presented at the Symposium on "Hydrology of Glaciers" at Cambridge, England, in September 1969. The Symposium's *Proceedings* were published by the Glaciological Society, Cambridge, in 1974.

Since the information obtained for each glacier by District Office staff was applicable only to the lower portion of the glaciers, volumetric and linear changes could be obtained for only the lower portion. In an effort to increase the areal coverage of the glaciers surveyed, an aerial photogrammetric survey of the Athabasca Glacier was undertaken as a pilot project in July 1959. Permanent survey plugs were established around the perimeter of the glacier and tied-in by means of a triangulation survey. From the aerial photographs, a topographic map was prepared using a high-precision plotter. This was the first time that a topographical map of high quality was prepared by the Branch, and the precedent was set for later maps.

During the summer of 1964, high-quality maps of five selected glaciers in British Columbia were prepared by stereoscopic terrestrial photogrammetric methods. It was found by study that for the survey of glaciers, stereoscopic terrestrial survey methods have certain advantages over aerial surveys.

This method is now used to map glaciers in British Columbia in even-numbered years and to map glaciers in Alberta in odd-numbered years. From the maps, linear and volumetric changes in the glaciers are determined.

The continuation of these surveys, apart from more fundamental scientific observations made by the Branch's Glaciology Division, is an important aspect of Branch activities for two reasons: 1) the surveys provide a basis for obtaining greater knowledge of Canada's freshwater resources and 2) they fulfil our announced commitment to the International Association of Scientific Hydrology (IASH) to monitor glacial changes as part of a world-wide surveillance of glacier trends. We can only speculate on the ultimate usefulness of the information being collected. It could well be, however, that the trends of a glacier's behaviour over a period of time will prove to be a very useful prediction tool in hydrological studies of the future.

These glacier surveys are closely co-ordinated with other activities of the Water Resources Branch. The information contained in these survey reports is provided to individuals, scientific agencies and to various libraries throughout the world.

Description of Glaciers

SENTINEL GLACIER

Sentinel Glacier is located at latitude 49° 53′, longitude 122° 58′, in Garibaldi Provincial Park, British Columbia. This glacier was selected because of its accessibility. The Branch has made periodic surveys around the toe since 1945. Meltwater from the glacier flows into Howe Sound via Garibaldi Lake, Rubble Creek and Cheakamus River (Fig. 1).

SPHINX GLACIER

Sphinx Glacier is located at latitude 49° 53′, longitude 123° 06′, in Garibaldi Provincial Park, British Columbia. This glacier was selected on account of its accessibility. The Branch has made periodic surveys around the toe area since 1945. Meltwater from the glacier flows into Howe Sound via Garibaldi Lake, Rubble Creek and Cheakamus River (Fig. 2).

NADAHINI GLACIER

Nadahini Glacier is located in northern British Columbia at latitude 59° 44′, longitude 136° 41′. This glacier was selected due to its accessibility. Meltwater flows via West Nadahini Creek into Tatshenshini River and then into the Pacific Ocean via Alsek Creek (Fig. 3).

KOKANEE GLACIER

Kokanee Glacier is located at latitude 49° 45′, longitude 117° 08′ in Kokanee Glacier Provincial Park, British Columbia. This glacier was selected because of its accessibility. The Branch has made periodic surveys around the toe area from 1945 to 1962. Meltwater from the glacier flows into Kootenay Lake via Keen Creek and Kalso River (Fig. 4).

BUGABOO GLACIER

Bugaboo Glacier is located at latitude 50° 40′, longitude 116° 45′, in British Columbia. The Branch made a reconnaissance survey of the toe area of this glacier in 1946. Meltwater from the glacier flows into the Columbia River via Bugaboo Creek (Fig. 5).

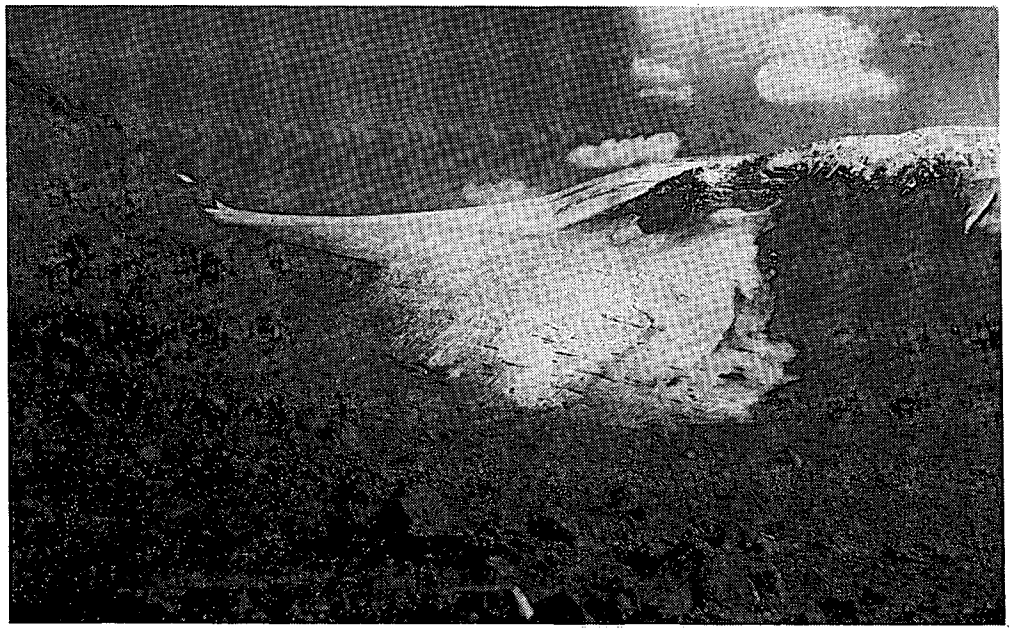


Figure 1. Sentinel Glacier – September 11, 1970.

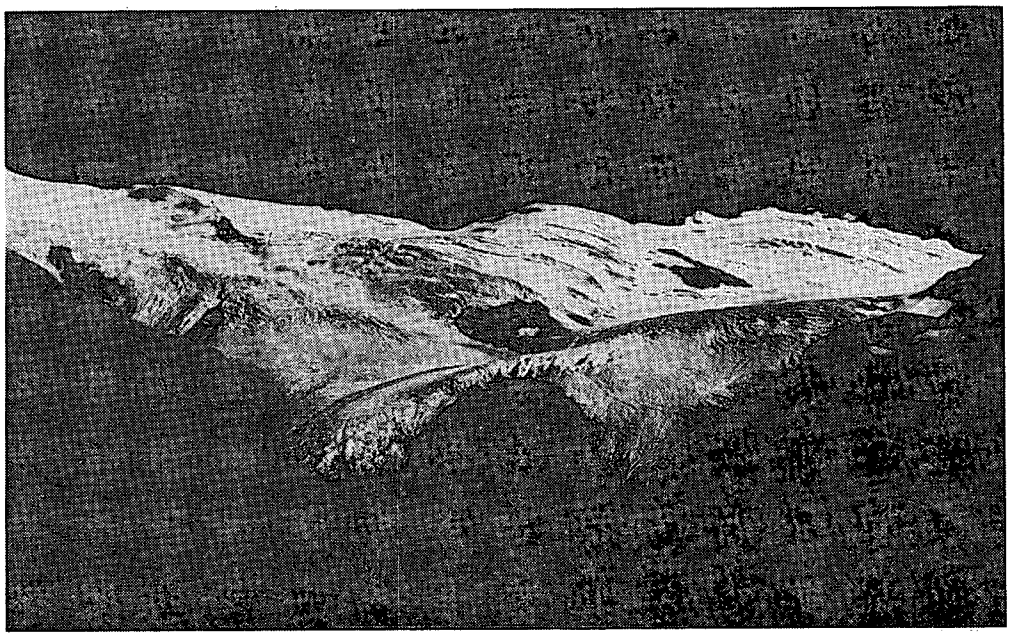


Figure 2. Sphinx Glacier – September 9, 1970.

Figure 3. Nadahini Glacier – September 3, 1970.

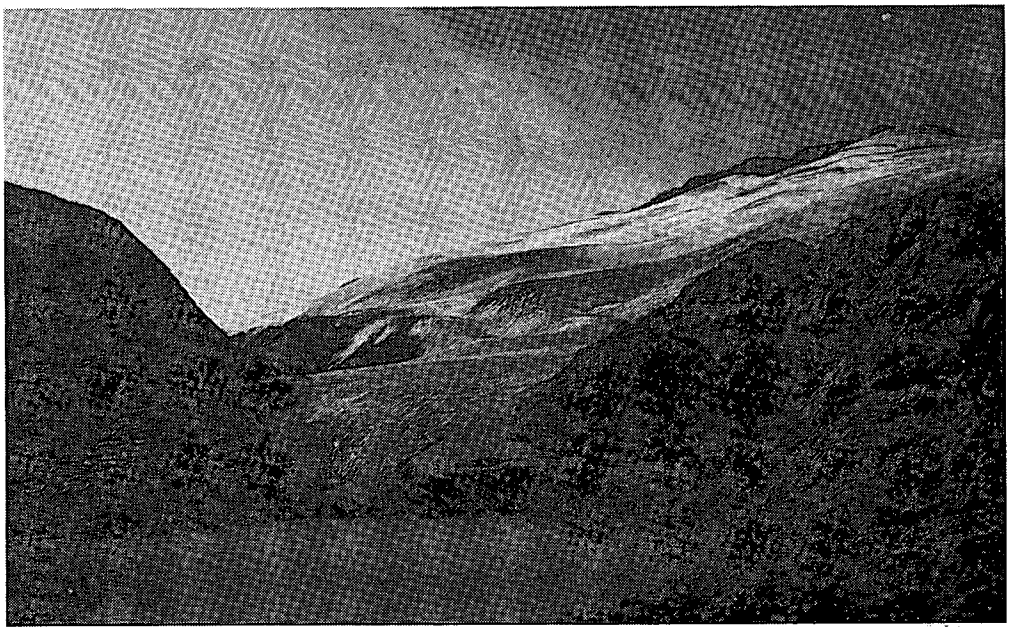


Figure 4. Kokanee Glacier – August 26, 1970.

Figure 5. Bugaboo Glacier – August 18, 1970.

Field Work

The general procedure followed in conducting the survey of the five glaciers was in accordance with the *Text Book of Photogrammetry* (Zeller, 1952).

Generally, horizontal and vertical control points are located on rock around the glacier periphery as well as on the ice surface. The positions of the control points on the ice are established during the day of photography. Photographic stations are situated, where possible, on a high ridge facing and overlooking the toe of the glacier; stereoscopic terrestrial photographs are taken from these stations.

Since the surveys for all the glaciers are essentially the same, a detailed description is given for Sentinel Glacier only. The horizontal, vertical and photographic control points are shown on the maps.

The control net for Sentinel Glacier, as for the other glaciers, is local and not connected to any other triangulation net.

CONTROL

A schematic sketch of the control net is shown in Figure 6.

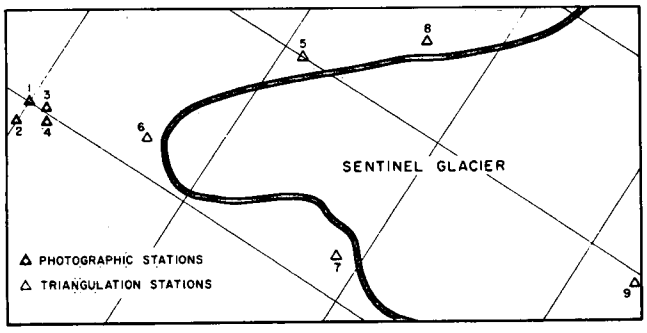


Figure 6. Sketch showing distribution of photographic and triangulation stations – Sentinel Glacier.

Triangulation stations, numbers 5, 6, 7, 8 and 9, are rock cairns located just outside of the glacier's periphery.

The photography stations, numbers 1, 2, 3 and 4, were marked by standard Water Resources Branch benchmark plugs cemented in bedrock (Fig. 7). Small rock cairns were built close to each plug for ease in locating them in the field.

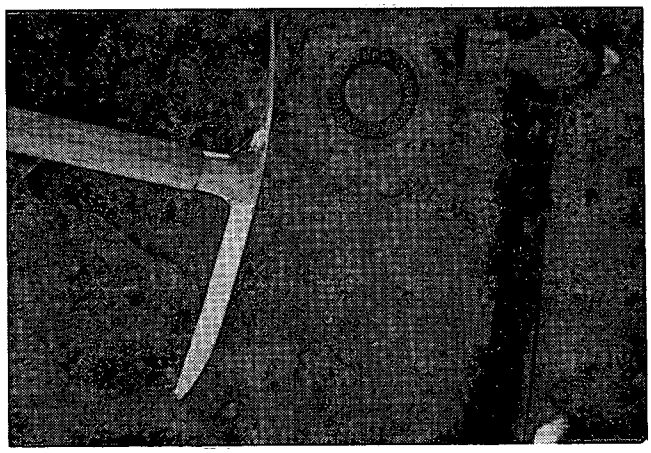


Figure 7. Photograph showing the standard WRB plugs used to locate the photographic stations.

INSTRUMENTS AND EQUIPMENT

A Wild T-2 theodolite and a Wild P-30 phototheodolite were used to measure all horizontal and vertical angles. All readings were to the nearest second.

A Wild invar subtense bar was used to measure the base-line distances. The subtense bar was calibrated optically by the manufacturer. Prior to the survey, the accuracy of the subtense bar was checked against a fixed distance that was accurately chained with a calibrated invar tape.

The Wild P-30 phototheodolite was used to photograph the glaciers. The internal adjustments of the camera were calibrated at the National Research Council, Division of Applied Physics, before plotting the glacier maps. This calibration needs to be done only once unless the camera sustains a violent shock. Kodak spectroscopic type plates were used for the photography.

BASE LINE

The distances between control stations 1 and 2, 2 and 4, and 3 and 4 were measured with the subtense bar

according to the manufacturer's general instructions provided with the instrument. This procedure involves measuring the angle subtended by the subtense bar. To ensure a high order of accuracy, the horizontal angle was read with the telescope in a direct and an inverted position. The horizontal circle was turned about 60 degrees before the second reading and a further 60 degrees before the third. Notes of sample subtense bar readings are shown on Table 1. Horizontal distances corresponding to the mean observed parallax (subtended angle) were determined from the appropriate Tables and used for computing distances in the triangulation net.

TRIANGULATION

The party, on arriving at the glacier, first made a reconnaissance survey of the toe area to locate the best possible locations for the photographic stations. The locations of the photographic stations should be at about the same elevation and on a high ridge facing the glacier. The ratio between the distance separating the base-line stations and the distance to the area to be stereoscopically photographed should not be less than 1:4 nor greater than 1:20. To meet this criterion, measurements were made from the best general area for the photographic stations to the toe area of the glacier and the upper limit of the glacier. When these distances were known, the party established the photographic stations on a ridge to give the best possible results.

Table 1. Sample Field Notes for Using a Subtense Bar– Sentinel Glacier Survey

⅄ @ Stn. 1		Cloudy and cool with sunny periods		Date ⅄
Subtense bar @ stn. 2		Reading	Angle	Distance
L_1	252° 29′ 59″	72° 29′ 59.5″	00° 00′ 00″	
L_2	72° 30′ 00″			
R_1	253° 56′ 44″	73° 56′ 42.5″	01° 26′ 43″	260.12
R_2	73° 56′ 41″			
L_1	252° 30′ 01″	72° 30′ 01″	00° 00′ 00″	
L_2	72° 30′ 01″			
R_1	253° 56′ 45″	73° 56′ 45.5″	01° 26′ 44.5″	260.04
R_2	73° 56′ 46″			
L_1	179° 34′ 30″	179° 34′ 30″	00° 00′ 00″	
L_2	359° 34′ 30″			
R_1	181° 01′ 14″	181° 01′ 13″	01° 26′ 43″	260.12
R_2	01° 01′ 12″			
L – Left end of subtense bar R – Right end of subtense bar			Mean distance	260.09

Cairns were built around the glacier periphery on bedrock whenever possible, and their positions were determined by triangulation. A one-inch by one-inch stake, four feet long, was centred upright and anchored in each cairn.

The stakes were flagged with brightly coloured cotton for ease in locating, and sightings were taken on the stakes

Table 2. Sample Field Notes for Triangulation – Sentinel Glacier Survey

⅄ @ Stn. 3 H.I. = 5.13 ft Overcast, cold, sunny intervals and windy Date ⅄

Stn.	Horizontal angle	Mean	Reduced mean	Vertical angle	Mean	Remarks
4	00° 05′ 48″ 180° 05′ 49″	00° 05′ 48.5″	00° 00′ 00″	97° 40′ 50″ 262° 20′ 07″	97° 40′ 21.5″	Top of tribrach
1	110° 32′ 50″ 290° 32′ 52″	110° 32′ 51″	110° 27′ 02.5″	88° 33′ 39″ 271° 27′ 40″	88° 32′ 59.5″	Top of ⅄
4	60° 00′ 35″ 240° 00′ 41″	60° 00′ 38″	00° 00′ 00″	97° 41′ 05″ 262° 19′ 53″	97° 40′ 36″	Top of tribrach
1	170° 27′ 42″ 350° 27′ 53″	170° 27′ 47.5″	110° 27′ 09.5″	88° 33′ 40″ 271° 27′ 36″	88° 33′ 02″	Top of ⅄
4	120° 09′ 48″ 300° 09′ 56″	120° 09′ 52″	00° 00′ 00″			
1	230° 36′ 56″ 50° 37′ 05″	230° 37′ 00.5″	110° 27′ 08.5″			

Table 3. Sample Field Notes for Taking Photographs with a Phototheodolite – Sentinel Glacier Survey

		Phototheodolite @ Stn. 4 Backsight on Stn. 3 H.I. = 4.46 ft	Began 10.30 a.m. Finished 10.50 a.m.	clear, cool and windy	Date	
Angle	Aversion (rt.)	Inclin. (grad)	Plate no.	Photo no.	Exp. time (sec)	Remarks
263° 00′	7°	+7	2	1	0.5	very bright sun
263° 00′	7°	+7	3	2	0.2	no clouds
263° 00′	7°	+7	4	3	0.1	no clouds
257° 00′	13°	+7	5	4	0.1	no clouds
257° 00′	13°	+7	6	5	0.2	no clouds
257° 00′	13°	+7	7	6	0.5	no clouds

to obtain the angles in the triangulation net.

The triangulation was carried out using a Wild T-2 theodolite or a Wild P-30 phototheodolite. Each horizontal and vertical angle was observed three times with the telescope in a direct position and three times in an inverted position. The horizontal circle was turned in most cases by about 60 degrees for the second reading and a further 60 degrees for the third. Sample field notes for triangulation are shown in Table 2.

PHOTOGRAPHY

The photographs taken from stations 1 and 2 were used to plot distant areas of the glacier, and photographs taken from stations 3 and 4 were used to plot near areas. Sample field notes for taking photographs using a phototheodolite are shown in Table 3.

Instructions for carrying out photography are outlined in the booklet accompanying the phototheodolite. These instructions, as well as those contained in the *Text Book of Photogrammetry*, were followed closely.

Whenever feasible the exposed photographic plates were developed, and a print of each plate was made by a reputable firm as soon as possible. On receipt of the prints, members of the party identified the control points and other noteworthy features. By doing this, it was possible to see the quality of the prints at an early date and, if necessary, repeat the photography before leaving the area.

Office Work

The method of determining co-ordinates for glacier maps is known as the "plane rectangular co-ordinate system." In this system, the area surveyed is assumed to be perfectly level, i.e., the earth's curvature is not taken into consideration. The meridians of longitude and parallels of latitude are represented by equidistant straight lines. The co-ordinates of the triangulation stations are determined by plane trigonometry. This procedure is considered to be ideal for the relatively small areas being mapped.

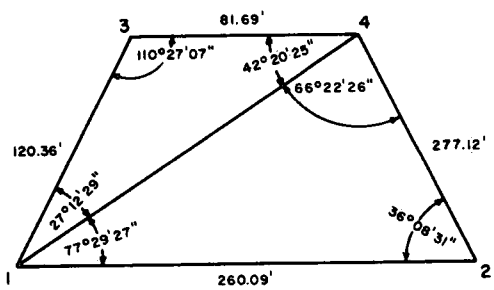
Since the reduction of data for all of the glaciers is essentially the same, a detailed description is given for Sentinel Glacier only.

COMPUTATIONS

The computations of co-ordinates were carried out using a basic calculator with seven-place natural trigonometric functions.

BASE LINE

Subtense bar measurements were made between control stations 1 and 2, 2 and 4, and 3 and 4. The field



Δ1, 3, 4	Δ1, 2, 4		
Observed angles	Observed angles	Correction	Adjusted angles
∠1 = 27° 12′ 29″	∠1 = 77° 29′ 27″	−8″	77° 29′ 19″
∠3 = 110° 27′ 07″	∠2 = 36° 08′ 31″	−8″	36° 08′ 23″
∠4 = 42° 20′ 25″	∠4 = 66° 22′ 26″	−8″	66° 22′ 18″
180° 00′ 01″	180° 00′ 24″	−24″	180° 00′ 00″

Using the sine law $\frac{\text{Sin A}}{a} = \frac{\text{Sin B}}{b} = \frac{\text{Sin C}}{c}$

For Δ 1, 2, 4:

$$\frac{(1\text{-}4)}{\text{Sin}\angle 2} = \frac{(1\text{-}2)}{\text{Sin}\angle 4} \quad \text{therefore} \quad (1\text{-}4) = \frac{(260.09)\ (0.58975638)}{(0.91616464)} = 167.42 \text{ ft}$$

$$\frac{(1\text{-}4)}{\text{Sin}\angle 2} = \frac{(2\text{-}4)}{\text{Sin}\angle 1} \quad \text{therefore} \quad (1\text{-}4) = \frac{(277.12)\ (0.58975638)}{(0.97625297)} = 167.41 \text{ ft}$$

For Δ 1, 3, 4:

$$\frac{(1\text{-}4)}{\text{Sin}\angle 3} = \frac{(3\text{-}4)}{\text{Sin}\angle 1} \quad \text{therefore} \quad (1\text{-}4) = \frac{(81.69)\ (0.93696559)}{(0.45722297)} = 167.40 \text{ ft}$$

$$\frac{(1\text{-}4)}{\text{Sin}\angle 3} = \frac{(1\text{-}3)}{\text{Sin}\angle 4} \quad \text{therefore} \quad (1\text{-}4) = \frac{(120.36)\ (0.93696559)}{(0.67353229)} = 167.43 \text{ ft}$$

} 167.42 ft

Figure 8. Computations for distance using the sine law.

notes were reduced and distances read as shown on Table 1. The distance between stations was found in the booklet entitled *Tables of Distance for Use in Connection with the Wild Precise Invar Stadia Giving the Distances in English Feet* (Wild of Canada).

HORIZONTAL ANGLE

When the notes for all stations were reduced, the horizontal co-ordinate for control station no. 1 was assigned the value, x = 100,000 and y = 100,000.

The azimuth of line 1 to 2 was assumed to be 270° 00′ 00″ and was determined by scaling from a topographic map. The orientation of the glacier is therefore referenced to an approximate true north. Computations showing an example of the use of the sine law to compute distances are shown in Figure 8, and the computations necessary to obtain the horizontal co-ordinates (x, y) for station 4 are shown in Table 4. The co-ordinates for other reference (cut-in) points were computed, as shown in Table 4, from at least two bases, and the mean position was used for those co-ordinates.

Table 4. Sample Calculations for Obtaining Co-ordinates from a Known Point–Sentinel Glacier Survey

Stn.	Angle	Azimuth	Side	Sine α	Cosine α	Δx	Δy	X	Y
1								100,000.00	100,000.00
	77°29′19″	270°00′00″	260.09	−1.0000000	+0.0000000	−260.09	–		
2								99,739.91	100,000.00
	36°08′23″	126°08′23″	277.12	+0.80758121	−0.58975638	+223.80	−163.43		
4								99,963.71	99,836.57
	66°22′18″	12°30′41″	167.42	+0.2166337	+0.9762530	+ 36.27	+163.44		
1								99,999.98	100,000.01

Table 5. Typical Calculations for Elevations–Sentinel Glacier Survey

⊼ @ Stn. 1 H.I. = 4.5 ft Assumed elevation Stn. 1 = 5,000 ft

Stn.	Distance	Vertical angle from stn. 1	Diff. of elev.	Ref.*	Total diff. of elev.	Ht. of target	Mean diff. of elev.§	Elev. (Z)
4	167.42	−5° 14′ 22″	− 15.35	–	− 15.4	3.3†	− 14.2	4,985.8
2	260.09	−9° 30′ 11″	− 43.54	–	− 43.5	on plug	− 39.0	4,961.0
5	1,472.37	+2° 57′ 02″	+ 75.89	–	+ 75.9	on plug	+ 80.4	5,080.4
8	2,155.26	+7° 14′ 30″	+273.87	+0.1	+274.0	4.0‡	+274.5	5,274.5

*In the column marked Ref., corrections are obtained from Tables of Earth's Curvature and Refraction (Breed and Hosmer, 1947)
†Top of tripod
‡Top of cairn
§This column takes into consideration the height of instrument as well as the height of the object sighted for example:
Stn. 8, total difference of elevation = 274.0 ft
Correction is H.I. = 4.5 ft and ht. of cairn = 4.0 ft
Therefore, mean difference in elevation = 274.0 + 4.5 − 4.0 = 274.5 ft

Table 6. Co-ordinate Summary Sheet–Sentinel Glacier Survey

Stn.	From base	X Computed	X Final	Y Computed	Y Final	From stn.	Z Computed	Z Final
6	5-7	100,215.21	100,214.98	99,347.03	99,347.68	1	4,964.0	4,963.3
	1-4	100,214.75		99,348.34		4	4,963.4	
						5	4,962.8	
						7	4,963.1	
8	1-7	101,443.35	101,443.37	98,399.50	98,399.48	1	5,274.5	5,274.6
	4-7	101,443.39		98,399.46		4	5,274.2	
						7	5,275.0	
9	1-7	100,974.48	100,974.42	96,696.83	96,696.92	1	5,630.5	5,630.3
	5-7	100,974.36		96,697.01		5	5,629.9	
						7	5,630.5	

ELEVATIONS

The elevation for station 1, as scaled from a topographic map, was assumed to be 5000 feet above sea level. The elevations for the other stations were calculated by trigonometry using five-place trigonometric tables and the "tangent law for right angle triangles." The mean vertical angle was calculated from the field notes. Typical computations are shown in Table 5.

The computational results for both the horizontal and vertical positions were then compiled and meaned in the type of table depicted in Table 6.

PLOTTING

The plotting of maps was carried out using a Wild A-7 plotter located at the Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa.

Volumetric Change of Glaciers

The only means of determining the change in the quantity of water held in storage by a glacier is by computing the volumetric change (Tables 7 to 41). Several methods for computing the volumetric change are possible. Four methods are described in the *Canadian Journal of Earth Sciences* (Brandenberger and Bull, 1966). Two methods are by Davey, one by Finsterwalder and one by Haumann, but none was found adequate for our particular needs. In 1963, R.O'N. Lyons[1] and I.A. Reid[2] modified the Haumann method by relating the contours to a fixed vertical plane oriented perpendicularly to the general direction of flow of the glacier. In 1966, the concept of completely enclosing the desired portion of the glacier by fixed co-ordinates was devised by R. O'N. Lyons and J. Shastal.[3] This method was used to determine the volumes listed in this report and is described here.

The advantages of this method are

1) the visible rock-ice edge does not need to be defined,
2) the maps compared do not need to be of the same scale,
3) the changes in moraine-covered ice can be detected,
4) the original manuscripts can be used, whereas with other methods one map had to be transparent,
5) the surface of the glacier at time of survey need not be assumed to be parallel to the surface at time of previous surveys,
6) it takes lateral, as well as longitudinal ice growth or loss into consideration, and
7) it provides an excellent positive check of the areas planimetered.

The basic equation of this method is: area multiplied by average height equals volume.

In Figure 9, the glacier ice edge is represented by the dashed line, and the contours are shown by the solid lines A,B,C, etc. The map is divided into squares (grid pattern). Points 1, 2, 3, etc. are co-ordinates in the grid system which are selected and joined in such a manner that snow areas can be eliminated. In the resulting enclosure, only the ice and snow are variable and can change the volume—the rock is stable. Once the co-ordinates are selected, the area in the enclosure can be determined by trigonometry and is called the computed area. The next step is to planimeter the area between contours.

In year "X", the area formed between contour "A" and the enclosure near the contour is planimetered (dA_{LL}). Next, the area formed between contour "A" and contour "B" in the enclosure is planimetered (dA_B). The process is continued for contours "B" and "C", etc. until contour "F" is reached. The area formed between contour "F" and the enclosure near contour "F" is called dA_{UL}. The total area of the enclosure is then equal to $dA_{LL} + dA_B + dA_C + \ldots dA_{UL}$ or

$$\text{Total planimetered area} = \sum_{\text{lower limit}}^{\text{upper limit}} dA$$

where lower limit = enclosure in the vicinity of contour A
upper limit = enclosure in the vicinity of contour F.

If the areas are carefully planimetered, the difference between the computed area and planimetered area should be less than one percent of the total area. Any resulting difference is proportionally distributed throughout the partial areas dA_{LL}, dA_B etc. until the planimetered area exactly equals the computed total area. This same procedure is repeated for the year "X + A".

Refer to Figure 9 and assume grid line 1000 is the centre line of the longitudinal section. The resulting profiles are shown in Figure 10.

The enclosures from Figure 9 are shown in Figure 10 as the lower and upper limits and are in the same positions for both years. The locations of the intersections of contours and the centre line of the longitudinal profile are shown as A', A", B', B" . . . F' F". The horizontal plane is located at the same elevation as the lowest contour, i.e., contour "A" and is called "datum." This elevation is

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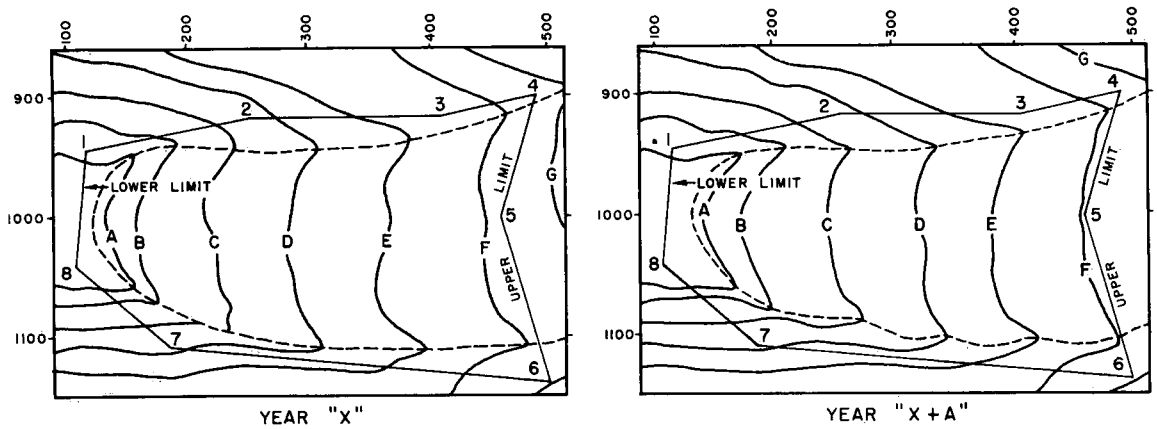

Figure 9. Representations of glacier at different dates.

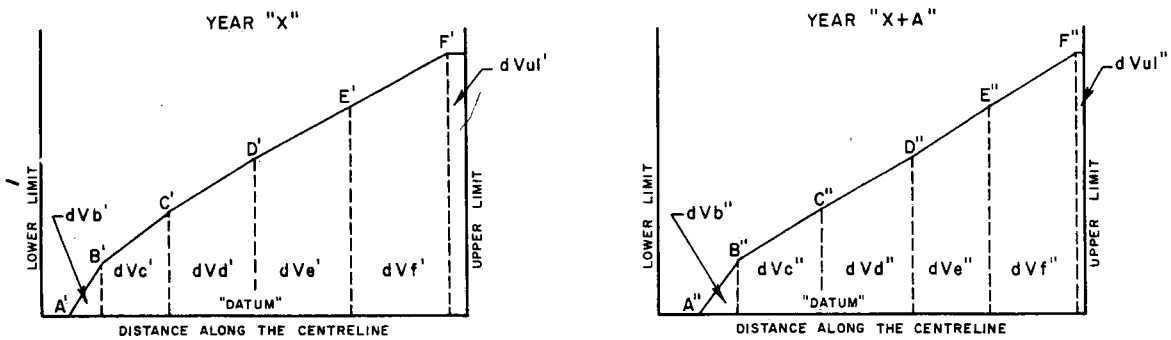

Figure 10. Longitudinal profiles of glacier.

identical for both years. In this method, the area from the lower limit to contour "A" is considered to be level. It is also assumed that the area from contour "F" to the upper limit is level. With these assumptions a hypothetical volume can be computed. The partial volume between contour A' and contour B' (year "X") is the corrected area $dA_{B'}$ multiplied by:

$$\frac{\text{contour A}' - \text{datum} + \text{contour B}' - \text{datum}}{2}$$

or

$$dV_{B'} = dA_{B'} \left[\frac{(\text{contour A}' - \text{datum})}{2} + \frac{(\text{contour B}' - \text{datum})}{2} \right]$$

Since datum = contour A'

then

$$dV_{B'} = dA_{B'} \frac{(\text{contour B}' - \text{datum})}{2}$$

It may be noted that there is no volume between the lower limit and contour A' because it is considered level:

$$dV_{C'} = dA_{C'} \left[\frac{(\text{contour B}' - \text{datum})}{2} + \frac{(\text{contour C}' - \text{datum})}{2} \right]$$

The partial volumes are computed for each pair of contours in this manner until the highest contour is reached (in this case contour F', which is treated in this manner):

$$dV_{UL'} = dA_{UL'} \left[\frac{(\text{contour F}' - \text{datum})}{2} + \frac{(\text{elevation of the upper limit} - \text{datum})}{2} \right]$$

where $dA_{UL'}$ = area (corrected) formed by contour "F" and the enclosure, but since the glacier is considered level from contour F' to the upper limit, the equation is reduced to:

$$dV_{UL'} = dA_{UL'} \left[\frac{(\text{contour F}' - \text{datum})}{2} + \frac{(\text{contour F}' - \text{datum})}{2} \right]$$

$$= dA_{UL'} \ (\text{contour F}' - \text{datum})$$

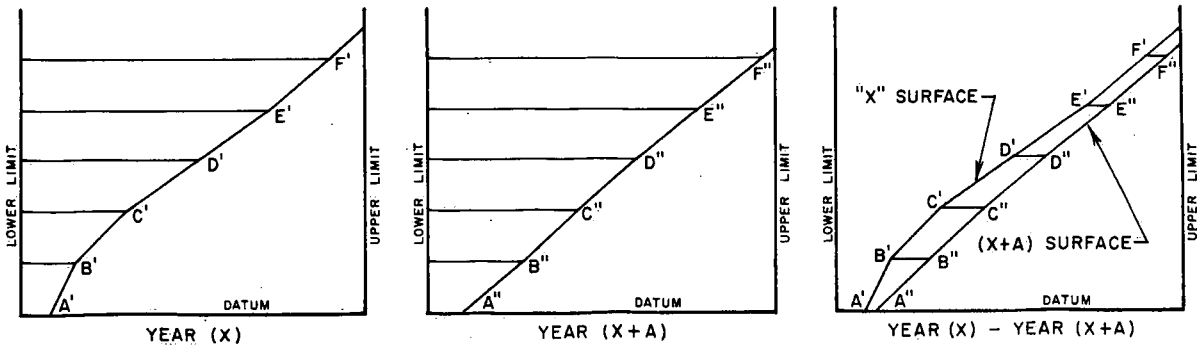

Figure 11. Profiles for computing volumetric changes in height zones.

The sum of all the partial volumes is the total hypothetical volume for year "X".

$$\text{Total volume} = \sum_{\text{lower limit}}^{\text{upper limit}} dV$$

The procedure is repeated for year "X + A", and the difference between the two volumes is the volumetric change:

Volumetric change

$$= \sum_{\text{lower limit}}^{\text{upper limit}} dV \text{ (year "X")} - \sum_{\text{lower limit}}^{\text{upper limit}} dV \text{ (year "X + A")}$$

To ascertain where loss or gain in storage is occurring, it is necessary to compute the volumetric change between various elevations. The term "height zone" is defined as the space between a pair of contours, i.e., height zone A-B is that space between contours A and B. Using the profiles of Figure 10, volumetric changes in height zones can be represented as shown in Figure 11.

The formula used for computing volumetric changes in the various height zones is that of Finsterwalder and Haumann, but the procedure is slightly different. The theory in this work is as follows. The volumetric change of a height zone is the mean of the two areas, one produced by the horizontal movement of the lower contour and the other by the horizontal movement of the upper contour multiplied by the difference in elevation of the two contours. Referring to Figure 11:

height zone "C–D", dV

$$= \left[\frac{(\text{Area } C'-C'') + (\text{Area } D' - D'')}{2}\right]$$

(contour D – contour C)

where Area C'–C" = (the area formed between the lower limit and C') – (the area formed by the lower limit and C")

Therefore Area C'–C" = $(dA_{LL'} + dA_{B'} + dA_{C'}) - (dA_{LL''} + dA_{B''} + dA_{C''})$ from Figure 9

and Area D'–D" = $(dA_{LL'} + dA_{B'} + dA_{C'} + dA_{D'}) - (dA_{LL''} + dA_{B''} + dA_{C''} + dA_{D''}$

Since the volumetric change figures are quite large and difficult to conceive, an abstract dimension called the "effective change in surface" was created. This is simply a way of expressing volumes in terms of one dimension.

Volumetric change = $Vol_{(X)} - Vol_{(X+A)}$

but volume = area x height.

Thus volumetric change = $(Area_X)(ht_X) - (Area_{X+A})(ht_{X+A})$

By taking the mean of $Area_{(X)}$ and $Area_{(X+A)}$

we obtain Area (mean) = $\dfrac{Area_{(X)} + Area_{(X+A)}}{2}$

Now volumetric change

$= [\text{Area (mean)}][ht_X] - [\text{Area (mean)}][ht_{X+A}]$

$= [\text{Area (mean)}][ht_X - ht_{X+A}]$

Volumetric change = $ht_{(X)} - ht_{(X+A)}$ = effective change change in surface area (mean).

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Table 7. Sentinel Glacier – Volumetric Change Co-ordinates for the 1964 and 1966 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	100,500	99,400	N	100,800	97,200
B	100,200	99,300	O	100,900	97,700
C	100,000	99,000	P	101,100	97,300
D	100,200	98,600	Q	101,300	97,300
E	100,400	98,100	R	101,400	97,500
F	100,200	97,900	S	101,600	97,300
G	100,200	97,700	T	101,600	97,400
H	100,400	97,500	U	101,700	97,400
J	100,400	97,300	V	101,800	97,500
K	100,500	97,000	W	101,700	97,900
L	100,600	97,000	X	101,200	98,400
M	100,700	97,200	Y	101,000	98,700

Table 8. Sentinel Glacier – Summary of Changes for 1964 vs 1966 Maps

Height zone (ft)	dV (cu ft)	Mean 64 & 66 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
4,960–4,980	-1,317,820	90,583	-14.55	- 7.28
4,980–5,000	-1,578,660	74,872	-21.08	-10.54
5,000–5,020	-1,718,620	75,728	-22.69	-11.35
5,020–5,040	-1,822,130	73,642	-24.73	-12.36
5,040–5,060	-1,952,390	80,058	-24.39	-12.20
5,060–5,080	-1,942,670	95,030	-20.44	-10.22
5,080–5,100	-1,947,640	90,660	-21.48	-10.74
5,100–5,120	-2,069,130	95,278	-21.72	-10.86
5,120–5,140	-2,081,000	98,728	-21.09	-10.55
5,140–5,160	-2,089,900	107,571	-19.43	- 9.71
5,160–5,180	-2,026,290	107,544	-18.84	- 9.42
5,180–5,200	-1,911,300	111,008	-17.22	- 8.61
5,200–5,220	-1,848,890	114,462	-16.15	- 8.08
5,220–5,240	-1,790,870	111,656	-16.04	- 8.02
5,240–5,260	-1,671,990	110,562	-15.12	- 7.56
5,260–5,280	-1,535,400	107,768	-14.25	- 7.13
5,280–5,300	-1,324,780	104,715	-12.65	- 6.33
5,300–5,320	-1,091,650	97,204	-11.23	- 5.61
5,320–5,340	- 990,820	89,883	-11.02	- 5.51
5,340–5,360	- 806,620	80,570	-10.01	- 5.00
5,360–5,380	- 482,430	50,070	- 9.64	- 4.82
5,380–5,400	- 183,060	33,373	- 5.48	- 2.74
5,400–5,420	+ 8,210	13,028	+ 0.63	+ 0.31
5,420–5,440	+ 62,250	8,312	+ 7.49	+ 3.75
5,440–5,460	+ 61,180	5,940	+10.30	+ 5.15
5,460–5,480	+ 64,680	5,943	+10.88	+ 5.44
5,480–5,500	+ 57,350	3,662	+15.66	+ 7.88

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1964 \& 1966 areas}} = \text{Effective change in surface elevation}$$

Table 9. Sentinel Glacier – Volumetric Change Co-ordinates for the 1966 and 1968 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	99,300	100,500	I	97,300	101,200
B	98,800	101,000	J	98,000	100,500
C	98,600	101,000	K	98,200	100,500
D	98,100	101,100	L	98,400	100,400
E	98,100	101,300	M	98,400	100,200
F	97,900	101,500	N	98,900	100,000
G	97,800	101,500	O	99,100	100,000
H	97,600	101,800			

Table 10. Sentinel Glacier – Summary of Changes for 1966 vs 1968 Maps

Height (ft)	dV (cu ft)	Mean 66 & 68 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
4,960–4,980	- 79,660	128,729	- 0.62	- 0.31
4,980–5,000	- 942,090	90,378	-10.42	- 5.21
5,000–5,020	-1,124,880	87,701	-12.83	- 6.42
5,020–5,040	-1,291,410	93,360	-13.83	- 6.92
5,040–5,060	-1,581,880	104,137	-15.19	- 7.60
5,060–5,080	-1,529,520	82,722	-18.49	- 9.24
5,080–5,100	-1,323,710	66,230	-19.99	-10.00
5,100–5,120	-1,339,630	68,936	-19.43	- 9.72
5,120–5,140	-1,302,210	63,564	-20.49	-10.24
5,140–5,160	-1,168,350	61,404	-19.03	- 9.52
5,160–5,180	-1,050,440	55,206	-19.03	- 9.52
5,180–5,200	-1,002,830	48,234	-20.79	-10.40
5,200–5,220	- 987,920	50,937	-19.39	- 9.70
5,220–5,240	- 972,800	51,959	-18.72	- 9.36
5,240–5,260	- 935,880	53,041	-17.64	- 8.82
5,260–5,280	- 904,320	53,311	-16.96	- 8.48
5,280–5,300	- 867,380	52,230	-16.61	- 8.30
5,300–5,320	- 857,460	54,120	-15.84	- 7.92
5,320–5,340	- 831,040	59,535	-13.96	- 6.98

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1966 \& 1968 areas}} = \text{Effective change in surface elevation}$$

Table 11. Sentinel Glacier– Volumetric Change Co-ordinates for the 1968 and 1970 Maps, Rectangular Co-ordinate Grid System (m)

	North-South	East-West		North-South	East-West
A	30,175	30,570	H	29,750	31,030
B	30,175	30,630	I	29,655	30,845
C	30,055	30,785	J	29,870	30,630
D	29,900	30,815	K	29,930	30,630
E	29,900	30,875	L	29,990	30,600
F	29,840	30,935	M	30,115	30,540
G	29,810	30,935	N	30,145	30,540

Table 12. Sentinel Glacier–
Summary of Changes for 1968 vs 1970 Maps

Height zone (m)	dV (cu m)	Mean 68 & 70 areas (sq m)	Effective surface change (m)	Effective surface change (m/yr)
1,515–1,520	−22,247	4,645	−4.79	−2.39
1,520–1,525	−32,279	4,645	−6.95	−3.47
1,525–1,530	−38,407	4,705	−8.16	−4.08
1,530–1,535	−43,135	5,125	−8.42	−4.21
1,535–1,540	−45,562	5,045	−9.03	−4.52
1,540–1,545	−46,388	5,365	−8.65	−4.32
1,545–1,550	−47,445	5,039	−9.42	−4.71
1,550–1,555	−47,200	4,864	−9.70	−4.85
1,555–1,560	−44,466	4,695	−9.47	−4.73
1,560–1,565	−40,272	4,315	−9.33	−4.67
1,565–1,570	−36,268	3,857	−9.40	−4.70
1,570–1,575	−31,933	3,630	−8.80	−4.40
1,575–1,580	−29,695	3,569	−8.32	−4.16
1,580–1,585	−30,574	3,649	−8.38	−4.19
1,585–1,590	−30,849	3,810	−8.10	−4.05
1,590–1,595	−30,017	3,790	−7.92	−3.96
1,595–1,600	−29,227	3,922	−7.45	−3.73
1,600–1,605	−28,149	3,888	−7.24	−3.62
1,605–1,610	−26,639	3,768	−7.07	−3.54
1,610–1,615	−25,932	3,928	−6.60	−3.30
1,615–1,620	−25,714	4,072	−6.32	−3.16

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1968 \& 1970 areas}} = \text{Effective change in surface elevation}$$

Table 13. Sentinel Glacier–
Summary of Volumetric Changes in the Period 1964-70

Period	Total volumetric change (cu m)	No. of yr	Vol. change/yr (cu m)	Effective surface change/yr (m)
1964-66	−962,000	2	−481,000	−2.45
1966-68	−569,000	2	−284,000	−2.15
1968-70	−732,000	2	−366,000	−3.63

Table 14. Sphinx Glacier–
Volumetric Change Co-ordinates for the 1964 and 1966 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	103,000	103,200	H	105,000	102,700
B	103,000	102,700	J	104,900	103,000
C	103,400	101,800	K	104,900	103,400
D	104,000	101,700	L	104,700	104,000
E	105,000	101,700	M	104,100	104,500
F	105,300	101,800	N	104,000	104,500
G	105,300	102,000	O	103,700	104,000

Table 15. Sphinx Glacier–
Summary of Changes for 1964 vs 1966 Maps

Height zone (ft)	dV (cu ft)	Mean 64 & 66 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
4,900–4,950	−1,617,650	193,058	− 8.38	−4.19
4,950–5,000	−1,493,550	146,722	−10.18	−5.09
5,000–5,050	−1,054,250	167,618	− 6.29	−3.15
5,050–5,100	− 732,800	173,268	− 4.23	−2.11
5,100–5,150	− 292,850	167,177	− 1.75	−0.88
5,150–5,200	− 14,375	214,204	− 0.07	−0.04
5,200–5,250	+ 127,525	289,716	+ 0.44	+0.22
5,250–5,300	+ 700,100	343,314	+ 2.04	+1.02
5,300–5,350	+1,465,125	426,212	+ 3.44	+1.72
5,350–5,400	+2,335,275	478,498	+ 4.88	+2.44
5,400–5,450	+3,461,050	557,949	+ 6.20	+3.10

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1964 \& 1966 areas}} = \text{Effective change in surface elevation}$$

Table 16. Sphinx Glacier–
Volumetric Change Co-ordinates for the 1966 and 1968 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	103,200	103,000	K	103,200	105,300
B	107,700	103,000	L	103,200	105,200
C	101,800	103,400	M	103,500	105,000
D	101,700	104,000	N	103,900	104,800
E	101,700	105,000	O	104,100	104,800
F	102,100	105,000	P	104,500	104,300
G	102,200	104,900	Q	104,300	104,300
H	102,400	104,900	R	104,400	104,100
I	102,600	105,000	S	104,000	103,700
J	102,700	105,300			

Table 17. Sphinx Glacier–
Summary of Changes for 1966 vs 1968 Maps

Height zone (ft)	dV (cu ft)	Mean 66 & 68 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
4,875–4,900	+ 245,075	81,102	+ 3.02	+1.51
4,900–4,950	+ 152,025	194,596	+ 0.78	+0.39
4,950–5,000	+ 319,900	140,522	+ 2.28	+1.14
5,000–5,050	+ 601,700	160,052	+ 3.76	+1.88
5,050–5,100	+ 825,575	171,904	+ 4.80	+2.40
5,100–5,150	+ 940,775	164,376	+ 5.72	+2.86
5,150–5,200	+1,160,650	206,488	+ 5.62	+2.81
5,200–5,250	+1,766,350	281,638	+ 6.27	+3.14
5,250–5,300	+2,492,725	327,010	+ 7.62	+3.81
5,300–5,350	+3,698,150	405,748	+ 9.11	+4.56
5,350–5,400	+4,840,550	459,702	+10.53	+5.26
5,400–5,450	+4,902,650	479,197	+10.23	+5.12
5,450–5,500	+4,745,425	561,212	+ 8.46	+4.23
5,500–5,550	+3,288,500	567,680	+ 5.79	+2.90
5,550–5,600	+1,147,825	162,948	+ 7.04	+3.52

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1966 \& 1968 areas}} = \text{Effective change in surface elevation}$$

Table 18. Sphinx Glacier–
Volumetric Change Co-ordinates for the 1968 and 1970 Maps,
Rectangular Co-ordinate Grid System (m)

	North-South	East-West		North-South	East-West
A	31,450	31,400	K	31,450	32,100
B	31,300	31,400	L	31,450	32,050
C	31,150	31,500	M	31,550	32,000
D	31,000	31,650	N	31,650	31,950
E	31,000	32,000	O	31,750	31,950
F	31,100	32,000	P	31,850	31,800
G	31,150	31,950	Q	31,800	31,800
H	31,200	31,950	R	31,800	31,750
I	31,250	32,000	S	31,700	31,600
J	31,300	32,100			

Table 19. Sphinx Glacier–
Summary of Changes for 1968 vs 1970 Maps

Height zone (m)	dV (cu m)	Mean 68 & 70 areas (sq m)	Effective surface change (m)	Effective surface change (m/yr)
1,500–1,510	- 4,357	10,766	−0.40	−0.20
1,510–1,520	- 2,975	7,851	−0.38	−0.19
1,520–1,530	- 2,378	8,904	−0.27	−0.13
1,530–1,540	- 3,425	9,794	−0.35	−0.18
1,540–1,550	- 4,493	10,523	−0.43	−0.21
1,550–1,560	- 6,609	9,689	−0.68	−0.34
1,560–1,570	- 8,842	10,025	−0.88	−0.44
1,570–1,580	- 8,430	11,707	−0.72	−0.36
1,580–1,590	- 7,763	14,551	−0.53	−0.27
1,590–1,600	- 6,139	16,976	−0.36	−0.18
1,600–1,610	+ 4,143	18,327	+0.23	+0.11
1,610–1,620	+10,926	21,476	+0.51	+0.25
1,620–1,630	+10,875	24,272	+0.45	+0.22
1,630–1,640	+ 7,205	26,612	+0.27	+0.14
1,640–1,650	+ 7,028	27,531	+0.26	+0.13
1,650–1,660	+18,472	27,289	+0.68	+0.34
1,660–1,670	+29,480	30,962	+0.95	+0.48
1,670–1,680	+31,839	36,056	+0.88	+0.44
1,680–1,690	+15,525	34,120	+0.46	+0.23
1,690–1,700	+ 1,210	20,857	+0.06	+0.03

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1968 \& 1970 areas}} = \text{Effective change in surface elevation}$$

Table 20. Sphinx Glacier–
Summary of Volumetric Changes in the Period 1964-70

Period	Total volumetric change (cu m)	No. of yr	Vol. change/yr (cu m)	Effective surface change/yr (m)
1964-66	+150,000	2	+ 75,200	+0.19
1966-68	+880,000	2	+439,000	+1.06
1968-70	+ 81,300	2	+ 40,600	+0.10

Table 21. Nadahini Glacier–
Volumetric Change Co-ordinates for the 1964 and 1966 Maps,
Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	101,300	97,700	H	99,900	97,900
B	101,300	98,200	J	100,100	98,100
C	100,500	98,600	K	100,200	98,000
D	99,100	98,500	L	100,300	97,800
E	98,900	98,300	M	100,500	97,800
F	99,000	98,200	N	100,500	97,500
G	99,400	97,900	O	101,000	97,600

Table 22. Nadahini Glacier–
Summary of Changes for 1964 vs 1966 Maps

Height zone (ft)	dV (cu ft)	Mean 64 & 66 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
3,840–3,860	- 459,880	61,149	- 7.52	- 3.76
3,860–3,880	-1,135,650	55,712	-20.38	-10.19
3,880–3,900	-1,728,770	63,976	-27.02	-13.51
3,900–3,920	-2,359,050	87,726	-26.89	-13.45
3,920–3,940	-2,860,480	101,681	-28.13	-14.06
3,940–3,960	-3,242,750	115,404	-28.10	-14.05
3,960–3,980	-3,601,260	130,649	-27.56	-13.78
3,980–4,000	-3,580,910	120,892	-29.62	-14.81
4,000–4,020	-3,230,560	114,149	-28.30	-14.15
4,020–4,040	-2,873,210	92,996	-30.90	-15.45
4,040–4,060	-2,573,410	100,861	-25.51	-12.75
4,060–4,080	-2,663,820	122,146	-21.81	-10.90
4,080–4,100	-2,821,730	127,876	-22.07	-11.04
4,100–4,120	-2,939,480	131,084	-22.42	-11.21

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1964 \& 1966 areas}} = \text{Effective change in surface elevation}$$

Table 23. Nadahini Glacier–
Volumetric Change Co-ordinates for the 1966 and 1968 Maps,
Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	98,000	101,100	I	95,000	97,700
B	98,400	101,000	J	94,500	97,900
C	98,600	99,400	K	94,300	98,100
D	97,900	98,300	L	94,300	98,300
E	96,500	97,300	M	95,200	98,900
F	95,500	96,900	N	95,500	99,000
G	95,500	97,000	O	96,500	100,000
H	95,300	97,500	P	97,700	101,100

Table 24. Nadahini Glacier–
Summary of Changes for 1966 vs 1968 Maps

Height zone (ft)	dV (cu ft)	Mean 66 & 68 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
3,860–3,880	- 980,900	66,601	-14.73	- 7.36
3,880–3,900	- 1,973,560	88,949	-22.19	-11.09
3,900–3,920	- 2,622,770	109,708	-23.91	-11.96
3,920–3,940	- 3,261,160	115,358	-28.27	-14.14
3,940–3,960	- 4,039,750	132,888	-30.40	-15.20
3,960–3,980	- 4,351,710	160,302	-27.15	-13.58
3,980–4,000	- 4,688,010	172,736	-27.14	-13.57
4,000–4,020	- 5,618,630	216,968	-25.90	-12.95
4,020–4,040	- 6,463,690	233,138	-27.72	-13.86
4,040–4,060	- 7,052,860	272,988	-25.84	-12.92
4,060–4,080	- 7,483,470	297,258	-25.17	-12.58
4,080–4,100	- 8,216,760	320,462	-25.64	-12.82
4,100–4,120	- 9,750,540	354,422	-27.51	-13.76
4,120–4,140	-10,204,470	350,681	-29.10	-14.55
4,140–4,160	-10,862,560	402,500	-26.99	-13.50
4,160–4,180	-12,378,870	495,664	-24.97	-12.48
4,180–4,200	-14,479,110	487,784	-29.68	-14.84
4,200–4,220	-16,131,430	483,546	-33.36	-16.68
4,220–4,240	-15,201,610	506,734	-30.00	-15.00
4,240–4,260	-13,922,210	477,252	-29.17	-14.58
4,260–4,280	-13,112,060	455,174	-28.81	-14.40
4,280–4,300	-14,417,730	511,808	-28.17	-14.08
4,300–4,320	-16,814,610	560,412	-30.00	-15.00
4,320–4,340	-16,338,550	493,496	-33.11	-16.56
4,340–4,360	-13,621,950	469,484	-29.01	-14.50

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1966 \& 1968 areas}} = \text{Effective change in surface elevation}$$

Table 25. Nadahini Glacier–
Volumetric Change Co-ordinates for the 1968 and 1970 Maps,
Rectangular Co-ordinate Grid System (m)

	North-South	East-West		North-South	East-West
A	29,870	30,815	I	28,955	29,780
B	29,990	30,785	J	28,805	29,840
C	30,055	30,295	K	28,745	29,900
D	29,840	29,960	L	28,745	29,960
E	29,415	29,665	M	29,015	30,145
F	29,110	29,535	N	29,110	30,175
G	29,110	29,565	O	29,415	30,480
H	29,045	29,720	P	29,780	30,815

Table 26. Nadahini Glacier–
Summary of Changes for 1968 vs 1970 Maps

Height zone (m)	dV (cu m)	Mean 68 & 70 areas (sq m)	Effective surface change (m)	Effective surface change (m/yr)
1,175–1,180	- 13,364	9,259	-1.44	-0.72
1,180–1,185	- 31,580	8,533	-3.70	-1.85
1,185–1,190	- 44,170	10,546	-4.19	-2.09
1,190–1,195	- 54,756	9,901	-5.53	-2.77
1,195–1,200	- 60,920	11,269	-5.41	-2.70
1,200–1,205	- 61,857	10,946	-5.65	-2.83
1,205–1,210	- 61,995	12,074	-5.14	-2.57
1,210–1,215	- 68,988	13,121	-5.26	-2.63
1,215–1,220	- 75,606	16,822	-4.49	-2.25
1,220–1,225	- 81,056	19,640	-4.13	-2.06
1,225–1,230	- 87,730	19,640	-4.47	-2.23
1,230–1,235	- 90,385	20,444	-4.42	-2.21
1,235–1,240	- 96,677	22,297	-4.34	-2.17
1,240–1,245	-113,072	27,288	-4.14	-2.07
1,245–1,250	-137,162	30,428	-4.51	-2.25
1,250–1,255	-134,091	27,724	-4.84	-2.42
1,255–1,260	-124,782	27,411	-4.55	-2.28
1,260–1,265	-152,087	36,414	-4.18	-2.09
1,265–1,270	-165,564	36,607	-4.52	-2.26
1,270–1,275	-192,862	43,746	-4.41	-2.20
1,275–1,280	-208,231	41,759	-4.99	-2.49
1,280–1,285	-179,104	35,970	-4.98	-2.49
1,285–1,290	-174,588	35,221	-4.96	-2.48
1,290–1,295	-165,361	33,357	-4.96	-2.48
1,295–1,300	-151,861	32,276	-4.70	-2.35
1,300–1,305	-179,437	39,731	-4.52	-2.26
1,305–1,310	-205,594	46,582	-4.41	-2.21
1,310–1,315	-180,351	40,019	-4.51	-2.25
1,315–1,320	-135,842	33,351	-4.07	-2.04
1,320–1,325	-115,729	30,144	-3.84	-1.92

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1968 \& 1970 areas}} = \text{Effective change in surface elevation}$$

Table 27. Nadahini Glacier–
Summary of Volumetric Changes in the Period 1964-70

Period	Total Volumetric change (cu m)	No. of yr	Vol. change/yr (cu m)	Effective surface change/yr (m)
1964-66	-1,090,000	2	- 540,000	-3.78
1966-68	-6,630,000	2	-3,310,000	-3.99
1968-70	-3,760,000	2	-1,880,000	-2.26

Table 28. Kokanee Glacier –
Volumetric Change Co-ordinates for the 1964 and 1966 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	99,800	98,800	L	100,300	97,400
B	100,300	98,800	M	100,200	97,500
C	100,400	98,400	N	100,200	97,900
D	100,500	98,200	O	100,100	98,000
E	100,600	97,600	P	100,100	98,200
F	100,600	97,500	Q	100,000	98,400
G	100,500	97,100	R	99,900	98,500
H	100,500	96,400	S	99,700	98,600
J	100,400	96,400	T	99,700	98,700
K	100,300	96,700			

Table 29. Kokanee Glacier –
Summary of Changes for 1964 vs 1966 Maps

Height zone (ft)	dV (cu ft)	Mean 64 & 66 area (sq ft)	Effective Surface change (ft)	Effective Surface change (ft/yr)
7,240–7,260	-286,090	15,446	-18.52	-9.26
7,260–7,280	- 660	20,420	- 0.03	-0.01
7,280–7,300	+280,460	15,661	+17.91	+8.85
7,300–7,320	+408,270	22,734	+17.96	+8.98
7,320–7,340	+417,370	24,466	+17.06	+8.53
7,340–7,360	+416,790	25,280	+16.49	+8.25
7,360–7,380	+398,320	26,601	+14.97	+7.49
7,380–7,400	+356,470	29,738	+11.99	+6.00
7,400–7,420	+329,310	30,800	+10.69	+5.35
7,420–7,440	+300,980	31,845	+ 9.45	+4.73
7,440–7,460	+270,490	35,018	+ 7.72	+3.86
7,460–7,480	+264,670	33,078	+ 8.00	+4.00
7,480–7,500	+245,420	36,512	+ 6.72	+3.36
7,500–7,520	+156,450	45,608	+ 3.43	+1.71
7,520–7,540	- 35,700	56,456	- 0.63	-0.31
7,540–7,560	-147,950	53,930	- 2.74	-1.37
7,560–7,580	-153,820	46,624	- 3.30	-1.65
7,580–7,600	-149,030	49,704	- 3.00	-1.50
7,600–7,620	-120,850	33,944	- 3.56	-1.78
7,620–7,640	- 85,400	27,560	- 3.10	-1.55

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1964 \& 1966 areas}} = \text{Effective change in surface elevation}$$

Table 30. Kokanee Glacier–
Volumetric Change Co-ordinates for the 1966 and 1968 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	98,800	99,800	J	98,000	100,300
B	98,800	100,300	K	98,100	100,300
C	98,600	100,300	L	98,100	100,200
D	98,200	100,400	M	98,300	100,100
E	98,200	100,500	N	98,500	99,900
F	97,800	100,500	O	98,500	99,800
G	97,700	100,600	P	98,600	99,700
H	97,500	100,600	Q	98,700	99,700
I	97,800	100,400			

Table 31. Kokanee Glacier–
Summary of Changes for 1966 vs 1968 Maps

Height zone (ft)	dV (cu ft)	Mean 66 & 68 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
7,245–7,260	−338,715	13,210	−25.64	−12.82
7,260–7,280	−604,350	11,566	−52.25	−26.12
7,280–7,300	−595,480	12,093	−49.24	−24.62
7,300–7,320	−457,920	14,242	−32.15	−16.08
7,320–7,340	−326,450	19,898	−16.41	− 8.20
7,340–7,360	−286,770	19,368	−14.81	− 7.40
7,360–7,380	−284,800	19,644	−14.50	− 7.25
7,380–7,400	−326,170	22,072	−14.78	− 7.39
7,400–7,420	−308,650	22,588	−13.56	− 6.83
7,420–7,440	−258,160	16,674	−15.48	− 7.74
7,440–7,460	−239,110	15,058	−15.88	− 7.94
7,460–7,480	−198,460	12,909	−15.37	− 7.68
7,480–7,500	−211,790	14,536	−14.57	− 7.28

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1966 \& 1968 areas}} = \text{Effective change in surface elevation}$$

Table 32. Kokanee Glacier–
Volumetric Change Co-ordinates for the 1968 and 1970 Maps, Rectangular Co-ordinate Grid System (m)

	North-South	East-West		North-South	East-West
A	30,115	30,420	J	29,870	30,570
B	30,115	30,570	K	29,900	30,570
C	30,055	30,570	L	29,900	30,540
D	29,930	20,600	M	29,960	30,510
E	29,930	30,630	N	30,020	30,450
F	29,810	30,630	O	30,020	30,420
G	29,780	30,660	P	30,055	30,390
H	29,720	30,660	Q	30,085	30,390
I	29,810	30,600			

Table 33. Kokanee Glacier–
Summary of Changes for 1968 vs 1970 Maps

Height zone (m)	dV (cu m)	Mean 68 & 70 areas (sq m)	Effective surface change (m)	Effective surface change (m/yr)
2,210–2,215	− 5,843	1,470	− 3.98	−1.99
2,215–2,220	− 7,419	906	− 8.19	−4.09
2,220–2,225	− 8,603	745	−11.55	−5.77
2,225–2,230	− 9,381	1,067	− 8.79	−4.40
2,230–2,235	− 9,748	1,348	− 7.22	−3.61
2,235–2,240	− 9,505	1,470	− 6.46	−3.23
2,240–2,245	− 9,461	1,470	− 6.44	−3.22
2,245–2,250	−11,035	1,669	− 6.61	−3.31
2,250–2,255	−10,511	1,652	− 6.36	−3.18
2,255–2,260	− 7,986	1,349	− 5.92	−2.96
2,260–2,265	− 6,771	1,229	− 5.51	−2.76
2,265–2,270	− 5,557	1,108	− 5.02	−2.51
2,270–2,275	− 4,847	967	− 5.01	−2.51
2,275–2,280	− 5,849	1,168	− 5.01	−2.50

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1968 \& 1970 areas}} = \text{Effective change in surface elevation}$$

Table 34. Kokanee Glacier–
Summary of Volumetric Changes in the Period 1964-70

Period	Total volumetric change (cu m)	No. of yr	Vol. change/ yr (cu m)	Effective surface change/yr (m)
1964-66	+ 81,000	2	+41,000	+0.54
1966-68	−126,000	2	−63,000	−1.80*
1968-70	−119,000	2	−59,000	−1.71*

*These figures are misleading as the total volume change is distributed over the pond at the foot of the glacier as well as the ice surface.

Table 35. Bugaboo Glacier – Volumetric Change Co-ordinates for the 1964 and 1966 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	99,100	98,900	E	96,800	97,900
B	99,100	99,100	F	97,700	97,000
C	98,400	99,200	G	98,000	97,300
D	96,800	98,000	H	98,400	98,100

Table 36. Bugaboo Glacier – Summary of Changes for 1964 vs 1966 Maps

Height zone (ft)	dV (cu ft)	Mean 64 & 66 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
6,350–6,400	+ 284,825	30,360	+ 9.38	+ 4.19
6,400–6,450	+ 823,275	31,506	+26.13	+13.06
6,450–6,500	+1,080,925	31,284	+34.55	+17.28
6,500–6,550	+1,417,600	51,224	+27.67	+13.84
6,550–6,600	+1,737,250	61,549	+28.22	+14.11
6,600–6,650	+1,808,875	75,736	+23.88	+11.94
6,650–6,700	+1,959,775	85,196	+23.00	+11.50
6,700–6,750	+2,069,075	84,756	+24.41	+12.20
6,750–6,800	+1,613,850	86,549	+18.65	+ 9.33
6,800–6,850	+1,285,025	82,228	+15.63	+ 7.81
6,850–6,900	+1,575,925	96,328	+16.36	+ 8.18
6,900–6,950	+1,721,675	112,110	+15.36	+ 7.68
6,950–7,000	+1,796,400	136,849	+13.13	+ 6.56
7,000–7,050	+1,876,650	155,471	+12.07	+ 6.04
7,050–7,100	+2,186,500	167,862	+13.03	+ 6.51
7,100–7,150	+2,108,350	163,668	+12.88	+ 6.44
7,150–7,200	+1,962,400	154,037	+12.74	+ 6.37
7,200–7,250	+2,032,750	179,330	+11.34	+ 5.67
7,250–7,300	+1,815,825	179,334	+10.12	+ 5.06
7,300–7,350	+1,841,800	201,889	+ 9.12	+ 4.56

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1964 \& 1966 areas}} = \text{Effective change in surface elevation}$$

Table 37. Bugaboo Glacier– Volumetric Change Co-ordinates for the 1966 and 1968 Maps, Rectangular Co-ordinate Grid System (ft)

	North-South	East-West		North-South	East-West
A	99,000	99,200	F	98,000	96,800
B	99,100	99,200	G	97,000	97,600
C	99,200	99,100	H	97,500	91,800
D	99,200	98,500	I	98,100	98,400
E	98,800	97,800			

Table 38. Bugaboo Glacier– Summary of Changes for 1966 vs 1968 Maps

Height zone (ft)	dV (cu ft)	Mean 66 & 68 areas (sq ft)	Effective surface change (ft)	Effective surface change (ft/yr)
6,350–6,400	+ 970,850	32,890	+29.52	+14.76
6,400–6,450	+1,361,900	32,720	+41.62	+20.81
6,450–6,500	+1,428,450	37,745	+37.84	+18.92
6,500–6,550	+1,533,300	47,530	+32.26	+16.13
6,550–6,600	+1,678,800	62,862	+26.70	+13.35
6,600–6,650	+1,714,825	68,564	+25.01	+12.52
6,650–6,700	+1,768,100	78,867	+22.41	+11.20
6,700–6,750	+1,684,000	86,342	+19.50	+ 9.75
6,750–6,800	+1,449,650	99,627	+14.55	+ 7.28
6,800–6,850	+1,044,425	85,084	+12.27	+ 6.14
6,850–6,900	+ 868,450	93,952	+ 9.24	+ 4.62
6,900–6,950	+1,081,025	114,460	+ 9.44	+ 4.72
6,950–7,000	+1,467,175	132,532	+11.07	+ 5.54
7,000–7,050	+1,945,975	154,656	+12.58	+ 6.29
7,050–7,100	+1,966,400	169,809	+11.58	+ 5.79
7,100–7,150	+1,615,050	179,630	+ 8.99	+ 4.50
7,150–7,200	+1,407,300	149,456	+ 9.41	+ 4.70
7,200–7,250	+1,172,850	181,256	+ 6.47	+ 3.24
7,250–7,300	+ 952,175	171,336	+ 5.56	+ 2.73
7,300–7,350	+1,099,300	185,912	+ 5.91	+ 2.96

$$\frac{\text{Volumetric change of height zone (dV)}}{\text{Mean of 1966 \& 1968 areas}} = \text{Effective change in surface elevation}$$

Table 39. Bugaboo Glacier– Volumetric Change Co-ordinates for the 1968 and 1970 Maps, Rectangular Co-ordinate Grid System (m)

	North-South	East-West		North-South	East-West
A	30,250	30,275	J	29,750	29,500
B	30,275	30,250	K	29,650	29,525
C	30,250	30,200	L	29,500	29,675
D	30,250	29,975	M	29,475	29,700
E	30,050	29,750	N	29,550	29,750
F	30,000	29,675	O	29,750	29,925
G	29,875	29,500	P	29,925	30,000
H	29,850	29,475	Q	30,000	30,075
I	29,775	29,500	R	30,175	30,250

Table 40. Bugaboo Glacier–
Summary of Changes for 1968 vs 1970 Maps

Height zone (m)	dV (cu m)	Mean 68 & 70 areas (sq m)	Effective surface change (m)	Effective surface change (m/yr)
1,930–1,940	+11,990	2,194	+5.46	+2.73
1,940–1,950	+15,161	2,131	+7.11	+3.56
1,950–1,960	+14,568	2,069	+7.04	+3.52
1,960–1,970	+12,726	2,570	+4.95	+2.48
1,970–1,980	+11,469	2,691	+4.26	+2.13
1,980–1,990	+10,164	3,067	+3.31	+1.66
1,990–2,000	+10,730	3,317	+3.24	+1.62
2,000–2,010	+11,640	4,095	+2.84	+1.42
2,010–2,020	+10,705	4,627	+2.31	+1.16
2,020–2,030	+11,426	5,199	+2.20	+1.10
2,030–2,040	+12,873	5,637	+2.28	+1.14
2,040–2,050	+14,961	6,076	+2.46	+1.23
2,050–2,060	+11,118	6,732	+1.65	+0.83
2,060–2,070	+ 5,343	6,583	+0.81	+0.41
2,070–2,080	+ 1,587	5,883	+0.27	+0.13
2,080–2,090	- 3,837	5,351	-0.72	-0.36
2,090–2,100	- 4,561	5,288	-0.86	-0.43
2,100–2,110	- 4,920	6,377	-0.77	-0.39
2,110–2,120	- 8,980	6,784	-1.32	-0.66
2,120–2,130	- 7,725	7,784	-0.99	-0.50
2,130–2,140	- 6,782	8,441	-0.80	-0.40
2,140–2,150	-11,466	9,347	-1.23	-0.61
2,150–2,160	- 9,272	10,129	-0.92	-0.46
2,160–2,170	- 3,638	11,067	-0.33	-0.16
2,170–2,180	- 2,069	10,535	-0.20	-0.10
2,180–2,190	-15,505	10,254	-1.51	-0.76
2,190–2,200	-27,378	9,879	-2.77	-1.39
2,200–2,210	-23,307	11,035	-2.11	-1.06
2,210–2,220	-19,862	10,067	-1.97	-0.99
2,220–2,230	-22,669	11,223	-2.02	-1.01
2,230–2,240	-20,474	11,879	-1.72	-0.86
2,240–2,250	-23,100	13,081	-1.77	-0.88
2,250–2,260	-25,765	15,064	-1.71	-0.86
2,260–2,270	-26,272	16,554	-1.59	-0.79

Table 41. Bugaboo Glacier–
Summary of Volumetric Changes in the Period 1964-70

Period	Total volumetric change (cu m)	No. of yr	Vol. change/yr (cu m)	Effective surface change/yr (m)
1964-66	+935,000	2	+467,000	+2.19
1966-68	+799,000	2	+400,000	+1.85
1968-70	+405,000	2	+203,000	+0.76

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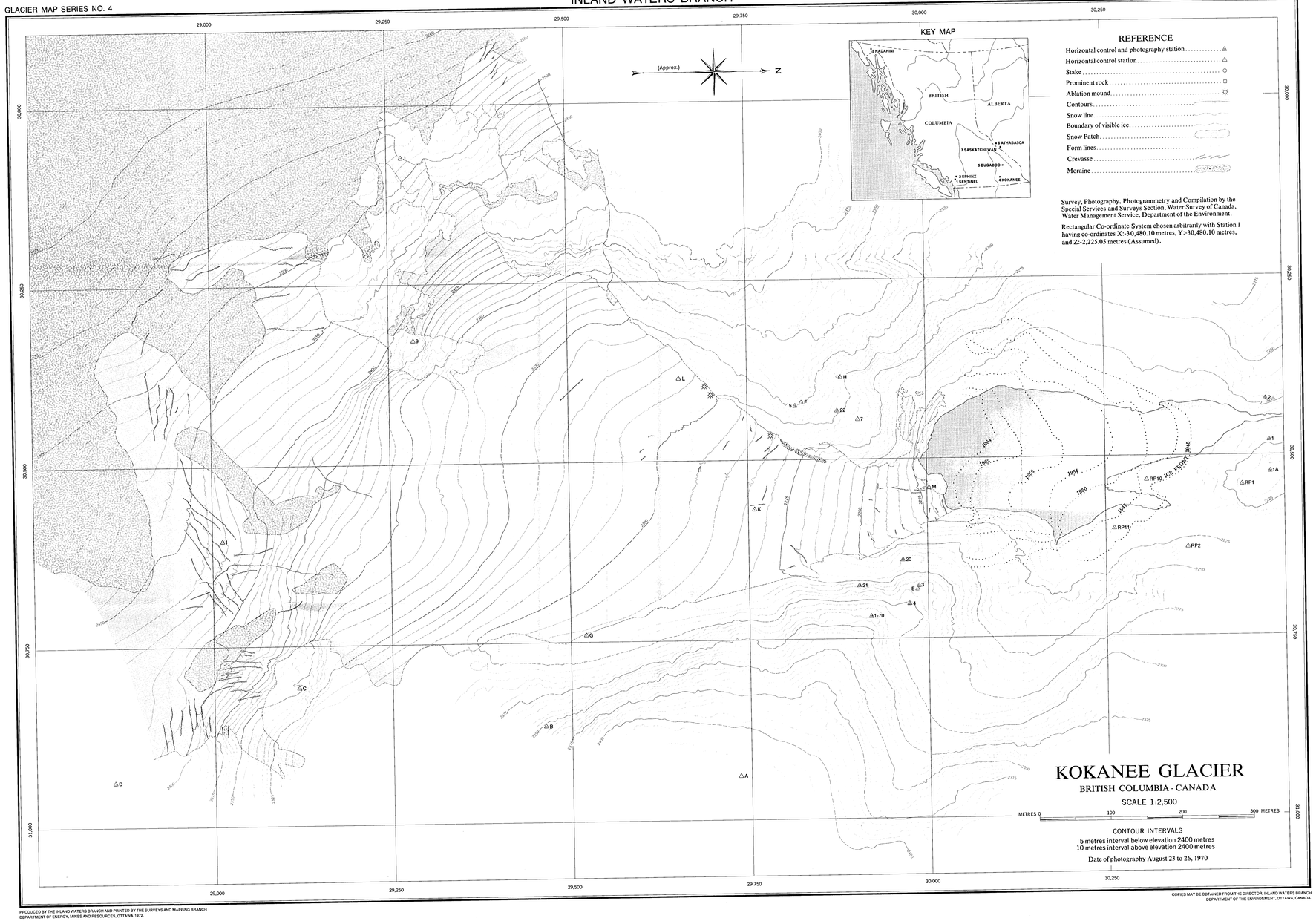

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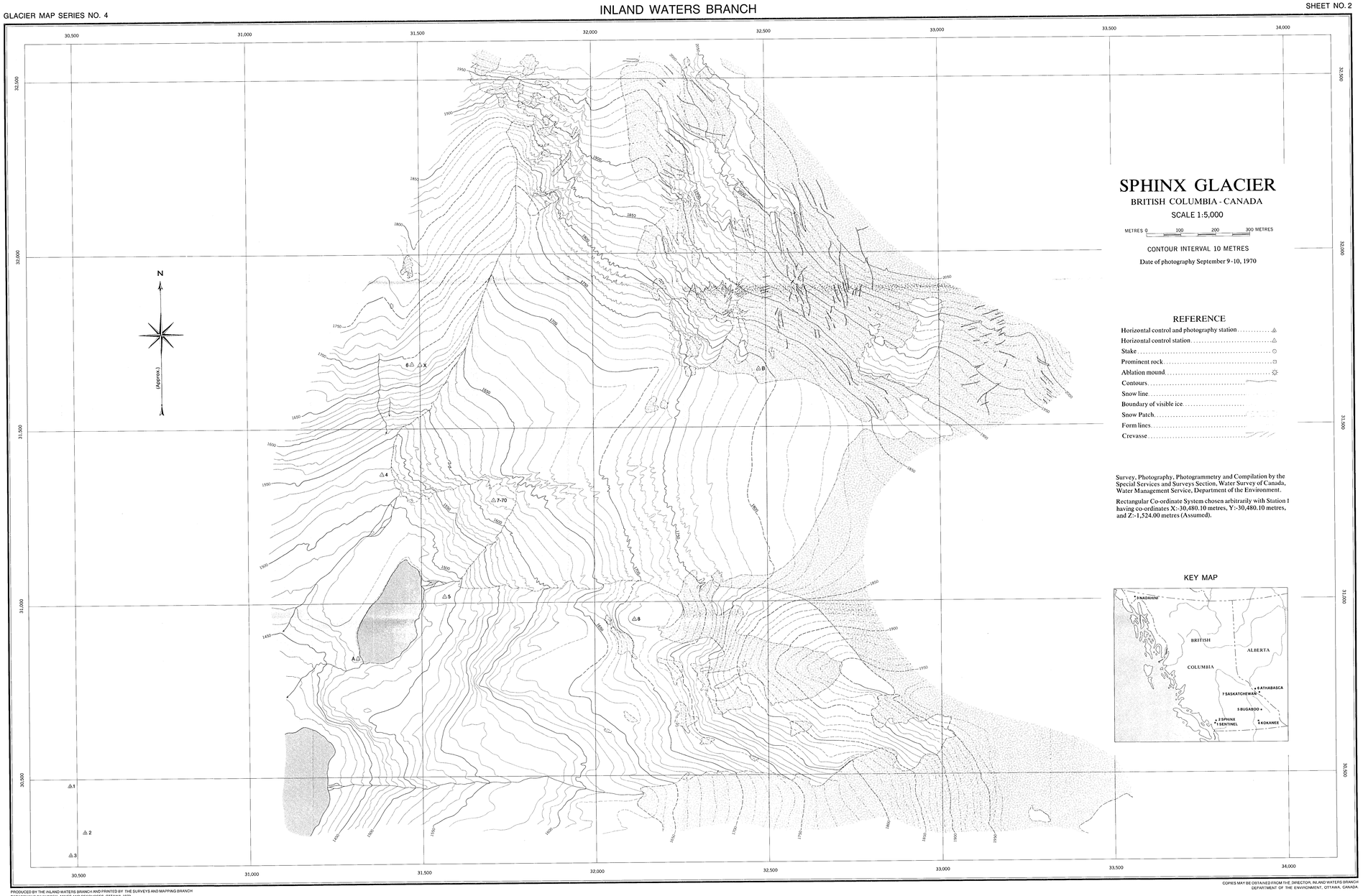

SPHINX GLACIER

BRITISH COLUMBIA - CANADA

SCALE 1:5,000

METRES 0 100 200 300 METRES

CONTOUR INTERVAL 10 METRES

Date of photography September 9-10, 1970

REFERENCE

Horizontal control and photography station
Horizontal control station
Stake
Prominent rock
Ablation mound
Contours
Snow line
Boundary of visible ice
Snow Patch
Form lines
Crevasse

Survey, Photography, Photogrammetry and Compilation by the Special Services and Surveys Section, Water Survey of Canada, Water Management Service, Department of the Environment.

Rectangular Co-ordinate System chosen arbitrarily with Station I having co-ordinates X:-30,480.10 metres, Y:-30,480.10 metres, and Z:-1,524.00 metres (Assumed).

KEY MAP

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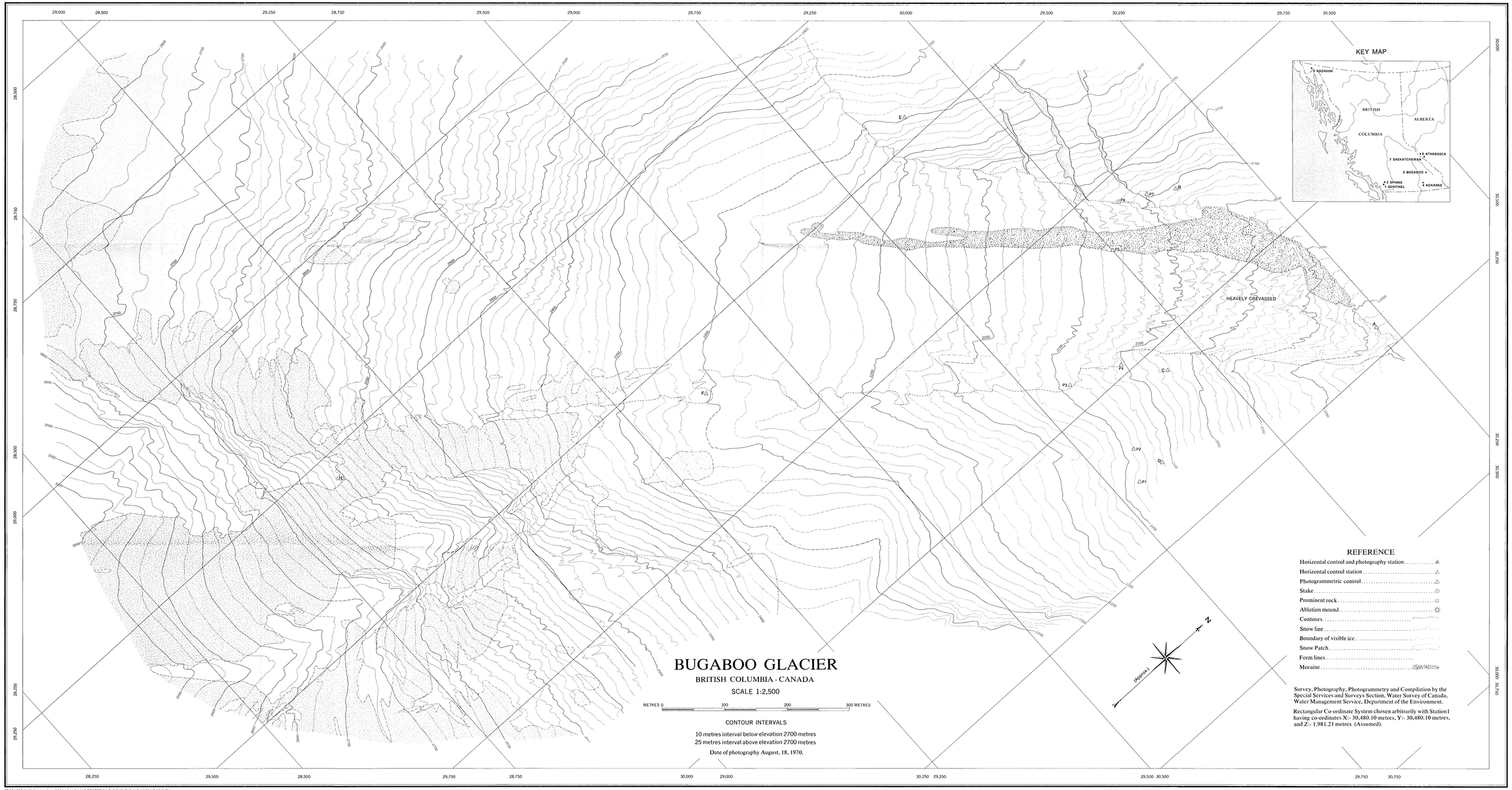

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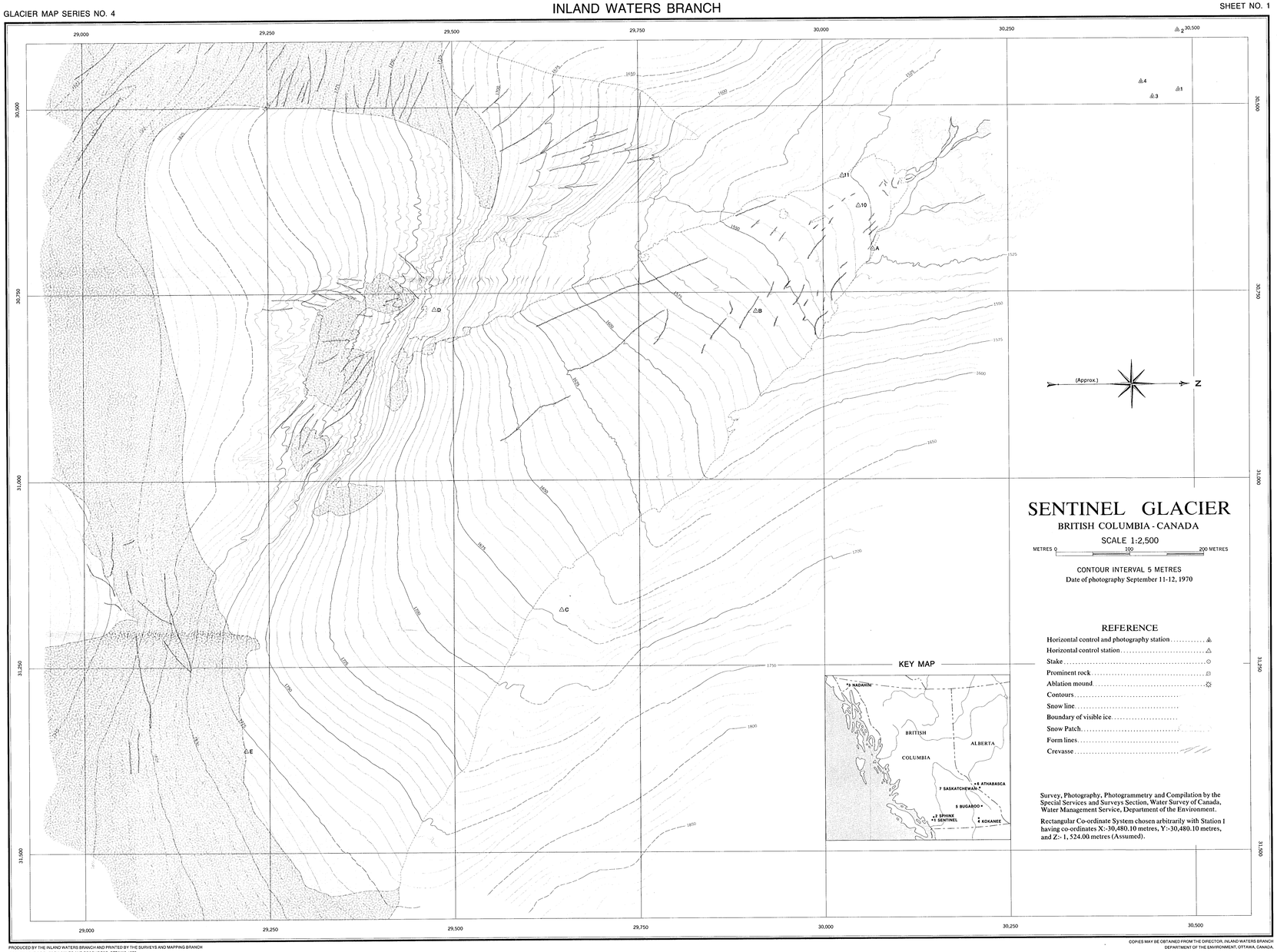
SHEET NO. 1



SENTINEL GLACIER

BRITISH COLUMBIA - CANADA

SCALE 1:2,500

METRES 0 100 200 METRES

CONTOUR INTERVAL 5 METRES

Date of photography September 11-12, 1970

REFERENCE

- Horizontal control and photography station
- Horizontal control station
- Stake
- Prominent rock
- Ablation mound
- Contours
- Snow line
- Boundary of visible ice
- Snow Patch
- Form lines
- Crevasse

Survey, Photography, Photogrammetry and Compilation by the Special Services and Surveys Section, Water Survey of Canada, Water Management Service, Department of the Environment.

Rectangular Co-ordinate System chosen arbitrarily with Station 1 having co-ordinates X:-30,480.10 metres, Y:>30,480.10 metres, and Z:- 1, 524.00 metres (Assumed).

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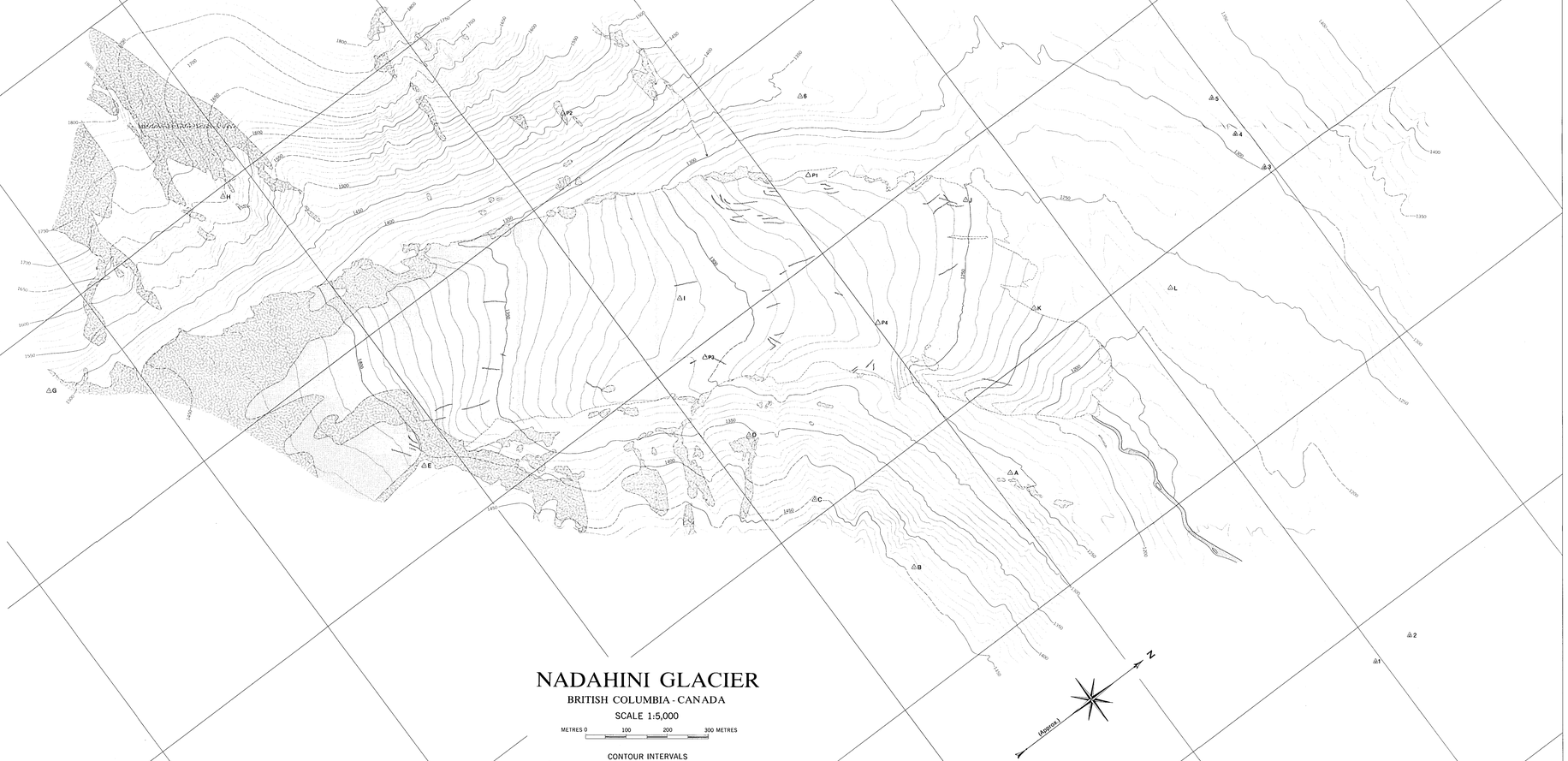

REFERENCE

- Horizontal control and photography station
- Horizontal control station
- Photogrammetric control
- Stake
- Prominent rock
- Ablation mound
- Contours
- Snow line
- Boundary of visible ice
- Snow Patch
- Form lines
- Crevasse

Survey, Photography, Photogrammetry and Compilation by the Special Services and Surveys Section, Water Survey of Canada, Water Management Service, Department of the Environment.

Rectangular Co-ordinate System chosen arbitrarily with Station 3 having co-ordinates X:- 30,480.10 metres, Y:- 30,480.10 metres, and Z:-1, 300.46 metres (Assumed).

NADAHINI GLACIER

BRITISH COLUMBIA - CANADA

SCALE 1:5,000

METRES 0 100 200 300 METRES

CONTOUR INTERVALS

5 metres interval below elevation 1400 metres
10 metres interval above elevation 1400 metres

Date of photography September 3, 1970

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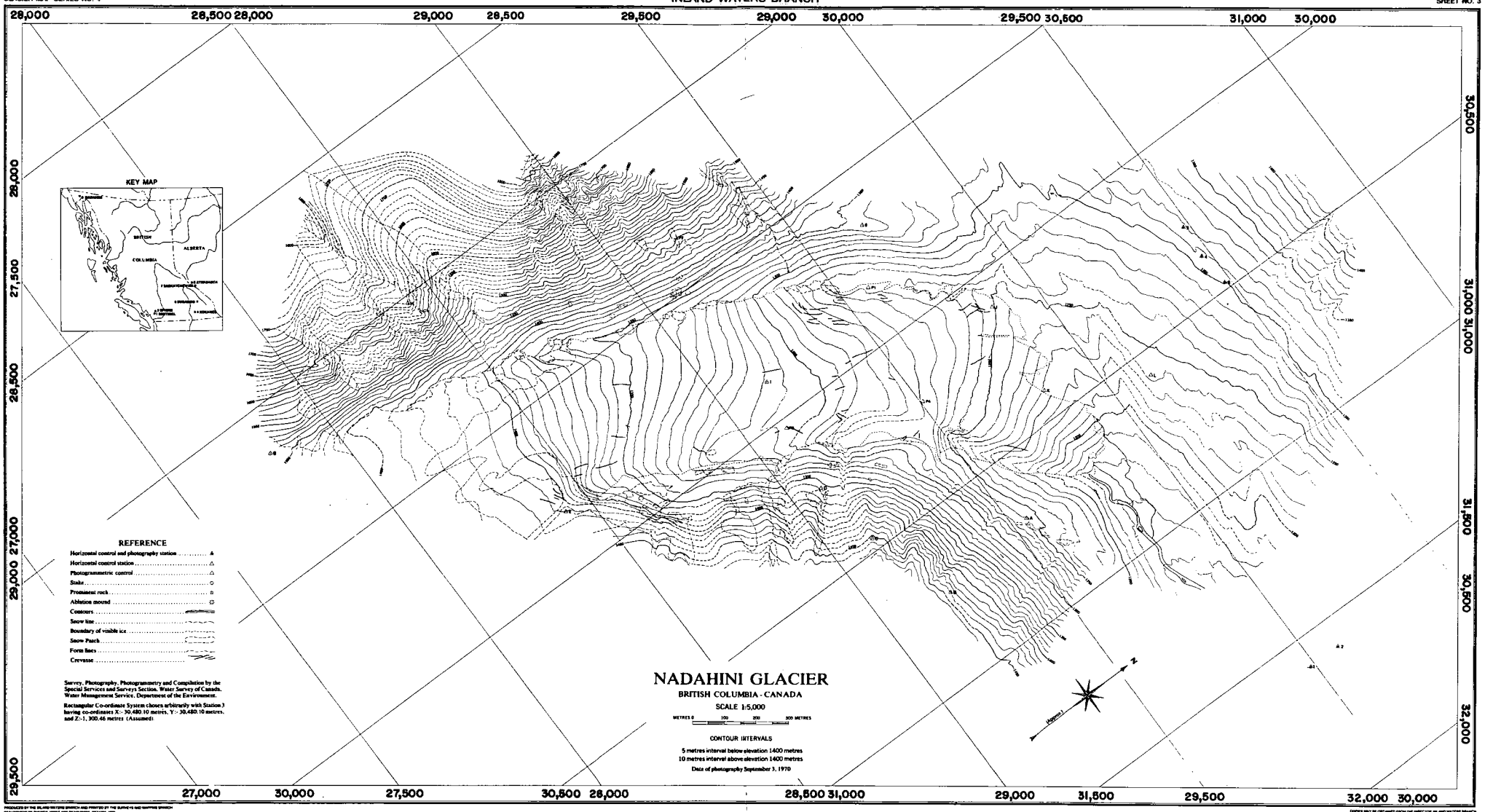
SHEET NO. 3



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