PEYTO GLACIER

ALBERTA

GEOMORPHOLOGY

AND

MASS BUDGET

OF

PEYTO GLACIER

ALBERTA

By

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A Thesis

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SCOPE AND CONTENTS:

As part of Canada's contribution to the International Hydrological Decade, the mass budget of Peyto Glacier, Alberta was determined for the budget year 1964-1965 from measurements of total accumulation and ablation. The mass budget is considered in relation to long-term climatic trends at Lake Louise. Techniques are described which permit detailed ablation rates to be related periodically and seasonally to weather conditions and topography of the glacier. Melt-river hydrology was provisionally established and is related to ablation and weather. The glacier and its features are described and glacial landforms are discussed to clarify ice recession in Peyto Valley. The trend and form of the valley is shown to be due to geological structure.

ACKNOWLEDGEMENTS

The author wishes to convey his appreciation to a number of individuals, without whose full cooperation the compilation of this thesis would have been rendered much more difficult, if not impossible.

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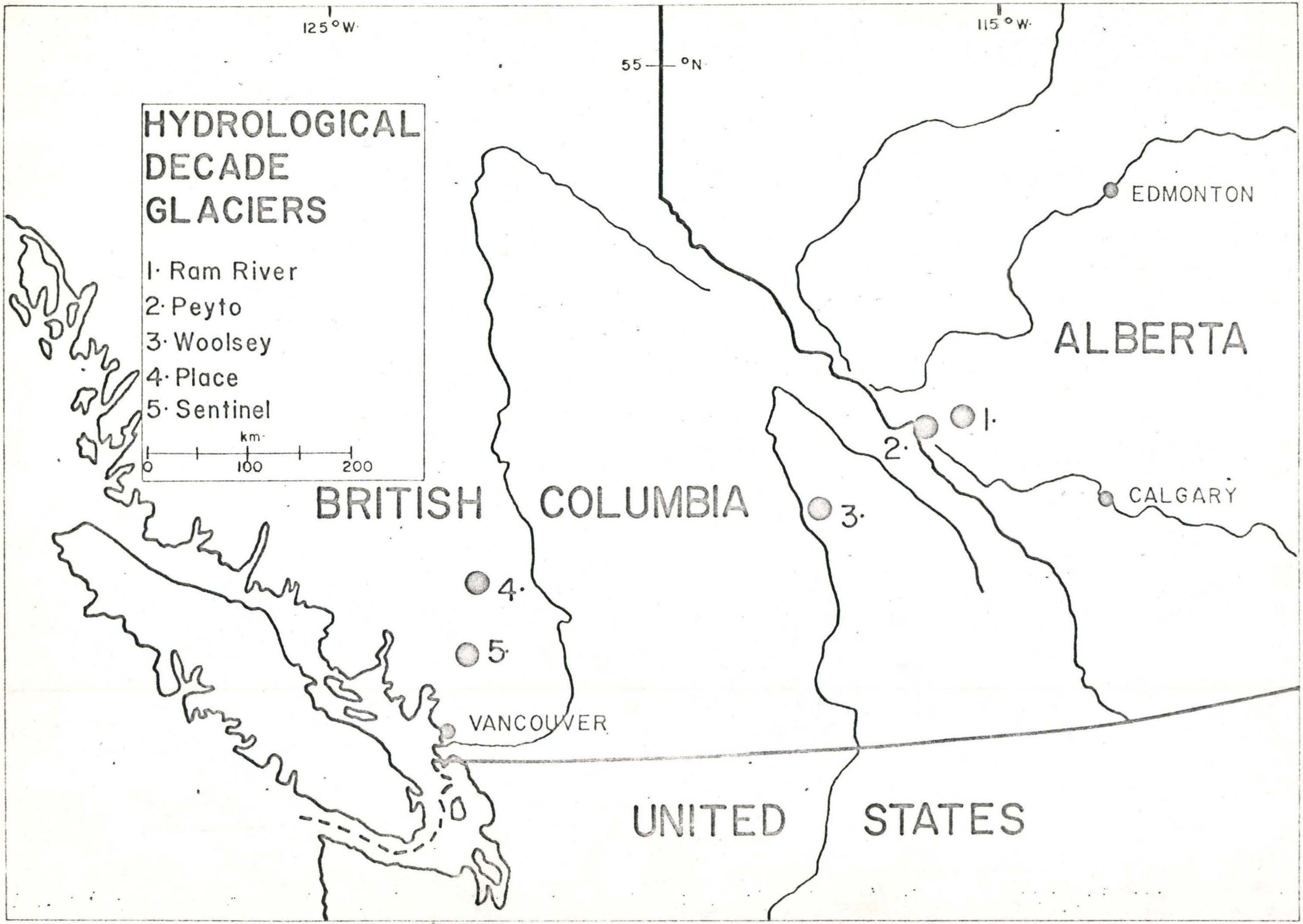
INTRODUCTION

GENERAL CONCEPT OF THE STUDY

A. Reasons for Glacier Research

Glaciers are perennial bodies of ice which overlie the land surface and exhibit signs of present or former motion.[(1.)] In Canada, glaciers cover almost 2% of the land area; not a large proportion but still representing 178,000 $km.^2$,[(2.)] an area three times as large as Nova Scotia. Seven percent of this glacierized area is found in the Western Cordillera of Alberta and British Columbia, while an additional 7% lies further north in the Yukon Territory and District of Mackenzie.

These ice-covered tracts are of increasing interest in Canadian resource-development, for glaciers are water reservoirs in the hydrologic cycle and, as such, form that part of the storage phase of the cycle about which least is known.[(3.)] As public debate on a Canadian water policy (which began on a national scale in 1965) grows more vociferous, and as water resources in the developed regions of Canada and the United States become over-extended, attention will inevitably focus on the glacial water resources of the Canadian Cordillera.


125°W
115°W
55°N
HYDROLOGICAL
DECADE
GLACIERS
1· Ram River
2· Peyto
3· Woolsey
4· Place
5· Sentinel
km
0
100
200
EDMONTON
ALBERTA
CALGARY
BRITISH COLUMBIA
VANCOUVER
UNITED STATES
1·
2·
3·
4·
5·

MAP 1.

Knowledge in detail of these glaciers; the mass gains and losses they undergo, the related climatic fluctuations, and the hydrology of their melt rivers, is a necessity for intelligent, comprehensive planning to utilize these limited but valuable water reservoirs. Inventories and frequency - duration - variability analyses of hydrological and climatological events must be undertaken before meaningful probability forecasts can be stated. Only then can the water requirements of irrigation, hydro-power, urban populations and recreation undergo efficient development.

B. Hydrological Decade Programme

The Glaciology Section of the Geographical Branch, Department of Mines and Technical Surveys (4.) had previously been involved in glaciology studies on and around the Barnes Ice Cap, Baffin Island, beginning with 1961 reconnaissance surveys. (5.) In 1964, the programme was extended to several outlet glaciers of the icecaps crowning the east coast mountains of Baffin Island. In 1965, detailed mass budget studies were initiated on Inugsuin Glacier in the same area.

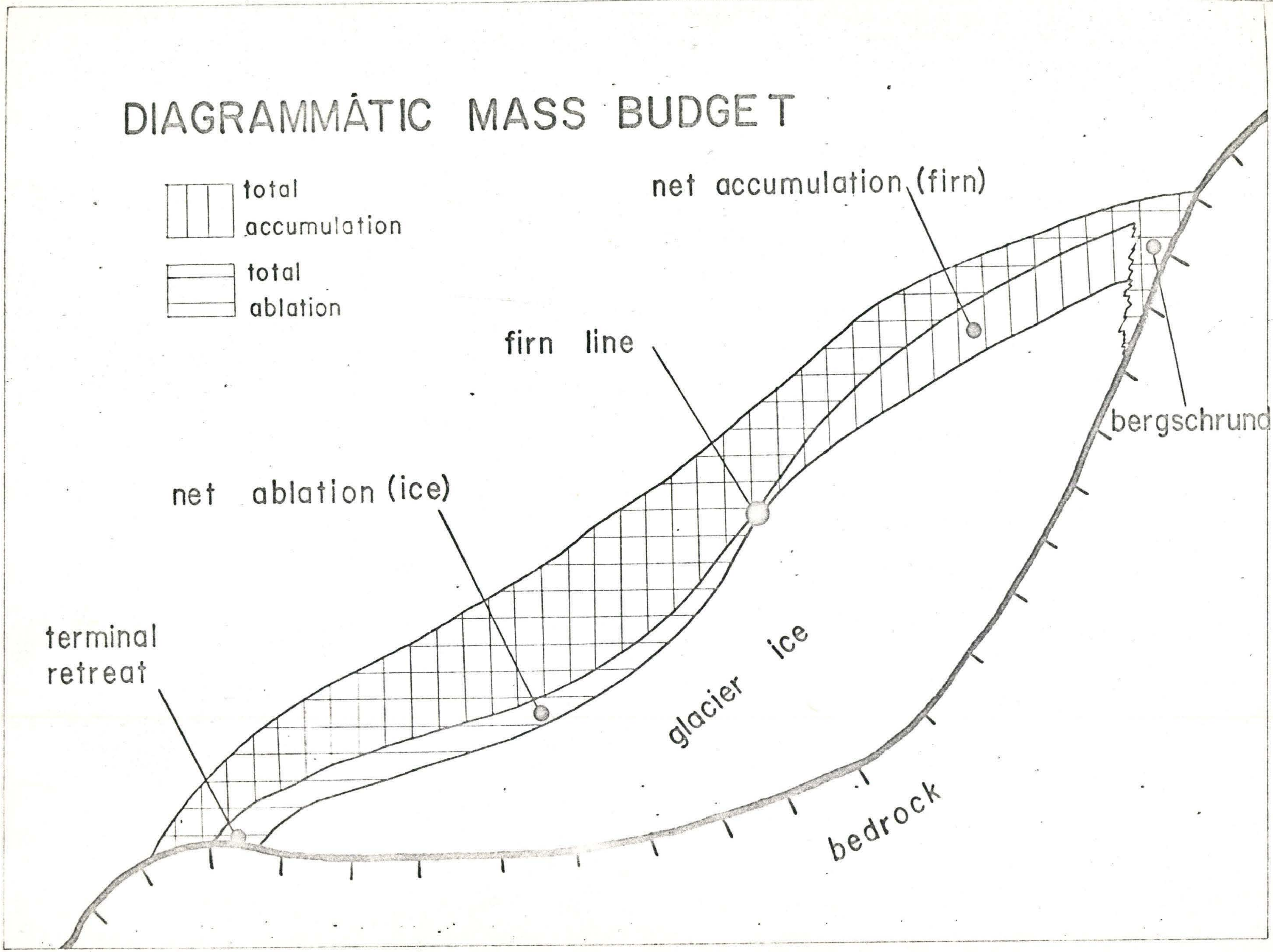
This latter research was undertaken as part of Canada's contribution to the International Hydrological Decade (6.) (1965-1975). To extend this work during the Decade, a full programme of glaciological research was instituted in 1965, and concentrated on the glaciers in the Western Cordillera.

For intensive study, several suitable glaciers were selected along an east-west profile across the Cordillera (see Map 1.) to include a variety of glacier regimens ranging from maritime to drier continental environments. Field programmes inaugurated on these glaciers are to continue for the full lenght of the Decade.

Place (Birkenhead) Glacier near Pemberton, British Columbia was thought representative of the maritime regimen in the eastern part of the Coast Range. Woolsey Glacier, north of Revelstoke, British Columbia was in the interior Columbia Mountain System. The drier Rocky Mountain regimen was typified by Peyto Glacier, northwest of Lake Louise, Alberta.

In 1966, two more glaciers are to be added for study throughout the Decade period. Ram River Glacier, east of Peyto Glacier, is in the driest section of the Canadian Rockies and Cordillera, while Sentinel Glacier in Garibaldi Provincial Park, British Columbia has a more maritime regimen than any of the other study areas.

A major portion of this Decade project comprises map compilation of the study glaciers at large scale (1:10,000) by surveying and air photography. Small scale inventory maps (1:1,000,000) of Cordilleran glaciers have been drawn to facilitate regional investigation of horizontal and vertical distribution of glaciers and associated geomorphic features. Periodic air photography will aid in the determination of firn line altitudes on a regional scale. Less pragmatic studies in ice physics and firnification are envisaged, both in the field and laboratory. Climatological research is an important



DIAGRAMMÂTIC MASS BUDGET
total accumulation
total ablation
net accumulation (firn)
firn line
bergschrund
net ablation (ice)
terminal retreat
glacier ice
bedrock

FIGURE 1.

part of the project to enable relationships between accumulation/ ablation and weather conditions to be found as well as quantitatively describing glacier regimens and their effects on mass budget. This latter work should permit accurate estimation of mass budget for less accessible glaciers utilizing statistics from local climatic stations. Glaciers are sensitive indicators of climatic fluctuations and the relationships developed will lead to clarification of speculations concerning glacier/climate variations, past and future. The ultimate aim is to contribute knowledge in all aspects of glaciology concerning Canadian glaciers.

It was as a graduate student, temporary field officer with this Geographical Branch programme that the author and an assistant were stationed at Peyto Glacier for approximately 11 weeks (June 18 - September 5, 1965) throughout the ablation period. The work completed during that field season provided the basic data for this dissertation.

C. Purpose of the Thesis

Essentially, the research will aim at establishing the mass budget (see Figure 1.) of Peyto Glacier but, as "glacier mass budget information provides the important link between glacier variations and climatic changes",[7.] the related climatology at Peyto Glacier will also be included. Utilizing measurements at a large number of points on the glacier at the end of the accumulation season in the late spring, the specific and total water gain can be calculated, and the conclusions are presented in this study. A similar technique will establish the specific and total water loss at the end of the ablation period, usually in the early autumn. The difference between these quantities is the mass budget, positive or negative, of the glacier for that particular budget year (from first permanent winter snow accumulation to the next annual first winter snowfall). This selfsame data will permit the net accumulation and the net ablation to be determined, and the net budget can also be calculated from their difference. This gives the annual mass change of the glacier and represents "the vital link between climatic environment and the dynamic adjustment of a glacier to that environment; neither accumulation nor ablation matter individually."(8.)

If measurements are made at shorter time intervals than biannually, the detailed rates and patterns of accumulation and ablation can be determined. Although weather conditions usually preclude periodic accumulation readings in winter, it is feasible to conduct detailed summer ablation surveys; and this limitation is not crucial for it is the ablation fluctuations which are of paramount significance for water resource planning. Consequently, a major part of this work will be concerned with these variations of the total ablation in time and space.

Because an "end product" of ablation is the glacial melt river, hydrological data was gathered from the Peyto River.

Glaciers have two characteristics (9.) which make them peculiarly suitable as water reservoirs. Melt river discharge usually peaks during July or early August while rivers draining glacier-free areas peak earlier in the spring. This lag effect tends to prolong the high discharge period of glacier-fed rivers into the warmer summer months when water demand is greater. In addition to this annual sequence, glaciers usually undergo their greatest ablation during warm, dry climatic cycles of several years duration, when water sources are most heavily taxed. Thus glacial melt waters supplement supplies at this peak demand period.

A discussion of the geological structure of the Peyto Glacier area is included to clarify the trend and form that the glacier and valley have adopted. However, this is not considered a major item of the dissertation.

A preliminary discussion of geomorphic features and their significance in determining advance/recession of the ice margins is presented to help establish the context of the present glacier regimen in the long-term climatic trends. Again this is only a provisional outline and did not comprise a major portion of the field work.

Because 1965 was the initial field season, the mass budget findings of this study are limited in their conclusiveness by the characteristics of incompleteness and lack of background information inherent in any study of a partial reconaissance nature. However, they do serve as a provisional foundation upon which future research may be based in the later years of the Decade programme.

FOOTNOTES - Introduction

1. Flint, 1957. p.11.

2. ibid. p.51.

3. Leopold, Wolman and Miller, 1964. p.50.

4. Since the conception of this project by the Geographical Branch, the Glaciology Section has become incorporated in the new Water Research Branch of the Department of Mines, Energy and Resources. This latter department replaces the Department of Mines and Technical Surveys.

5. Ives and Andrews, 1963. p.6.

6. For the following outline of the Hydrological Decade programme, the author is indebted to Dr. G. Østrem for access to an unpublished report of the Glaciology Section, dated January, 1966, setting out the proposed field studies.

7. Meier, 1962. p.252.

8. ibid. p.253.

9. Østrem, 1964. p.101, 109.

CHAPTER 1. - Peyto Glacier

A. Selection

Following the decision to implement a glaciological programme in the Western Cordillera region for the Hydrological Decade, criteria were evolved by the Geographical Branch to select the glaciers most suitable for research.[1.]

Prime consideration was given to the work-surface of the glacier. It was important to maximize the areas of low gradient, for motor-toboggans (which have a maximum slope-climbing ability of perhaps 10^{o}, depending on load and snow conditions) were to be utilized. As alpine glaciers often have steep slopes below the bergschrund, careful consideration was given to the upper reaches of the glacier. Crevassed portions also restrict the practical working area, although careful travel will allow some useful measurements to be conducted. Finally, complex glacier configurations involving nunatak areas or several flow outlets were to be avoided.

A reasonably small glacier area was considered more suitable for study to permit intensive measurements. In this respect, Peyto Glacier is somewhat larger than ideal (14 $km.^{2}$) especially when compared to the other glaciers selected (less than 5 $km.^{2}$), but other factors compensate for this deficiency.

A foremost consideration indirectly related to the glacier were the characteristics of the catchment basin. To simplify calculations, the glacier should represent as large a proportion as possible of the area drained by the melt river, and the divides of this basin should be distinct. Although several complications discussed later (see page 79.) enter into the first element, the divides of Peyto Glacier are well delimited except on the Wapta Icefield to the south-east.

For accurate hydrological measurements, a turbulent melt stream confined by bedrock is the ideal. Peyto River meets these criteria, but difficult access from the campsite to the river is a disadvantage (see page 81.).

Overall access to Peyto Glacier is perhaps its strongest point. It is within a two hour hike of the Banff-Jasper highway, and a five minute helicopter flight is practical as landing sites are available at both the highway and campsite.

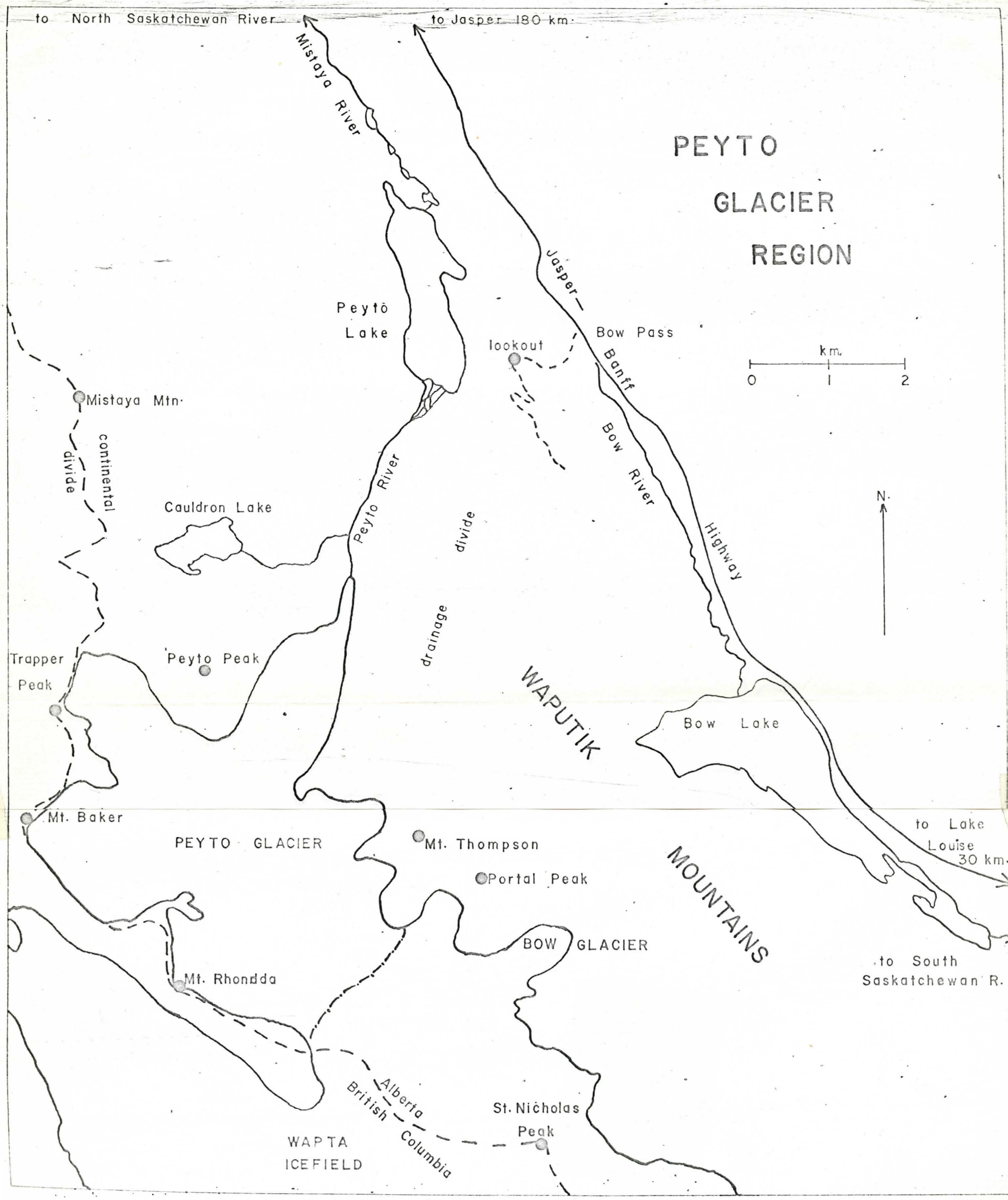
Also considered were factors affecting the suitability of a campsite. They included exposure, water supply, freedom from avalanches and rockfalls, drainage, space for camp expansion, and centrality to the work areas. The Peyto campsite is adequate and is discussed later (see page 25.).

Final thought was given to the safety of the field party. This aspect involved the melt river, avalanches and landslides, trails, and crevasses. Péyto was deemed sufficient except that a number of large crevasses necessitate care in travelling over parts of the surface.

With these criteria in mind, all available topographic maps were studied and approximately 50 glaciers appeared to warrant closer inspection. Interpretation of appropriate air photographs narrowed this choice to 30 glaciers. The available maps and air photos were not thought vital selection criteria, for mapping and photo surveys would be undertaken as part of the Decade project.[(2.)]

All available information on these glaciers was recorded on registration cards. Sketch maps of the glaciers and their accessibility were compiled while the geographic locations were plotted on a small scale regional map.

To finalize the choice, consultations were held at the Universities of Alberta (Calgary) and British Columbia and with National Park officials. Helicopter surveys, supplemented by traverses on foot, ski, and motor-toboggan were conducted to 17 glaciers in April, 1965.


to North Saskatchewan River
to Jasper 180 km
PEYTO
GLACIER
REGION
Mistaya River
Jasper
Bow Pass
Banff
Highway
Peyto Lake
lookout
km.
0
1
2
Mistaya Mtn.
continental
divide
Bow River
N.
Cauldron Lake
Peyto River
divide
drainage
Trapper Peak
Peyto Peak
WAPUTIK
Bow Lake
Mt. Baker
PEYTO GLACIER
Mt. Thompson
to Lake Louise 30 km.
Portal Peak
MOUNTAINS
BOW GLACIER
Mt. Rhondda
to South Saskatchewan R.
Alberta
British Columbia
St. Nicholas Peak
WAPTA ICEFIELD
MAP 2.

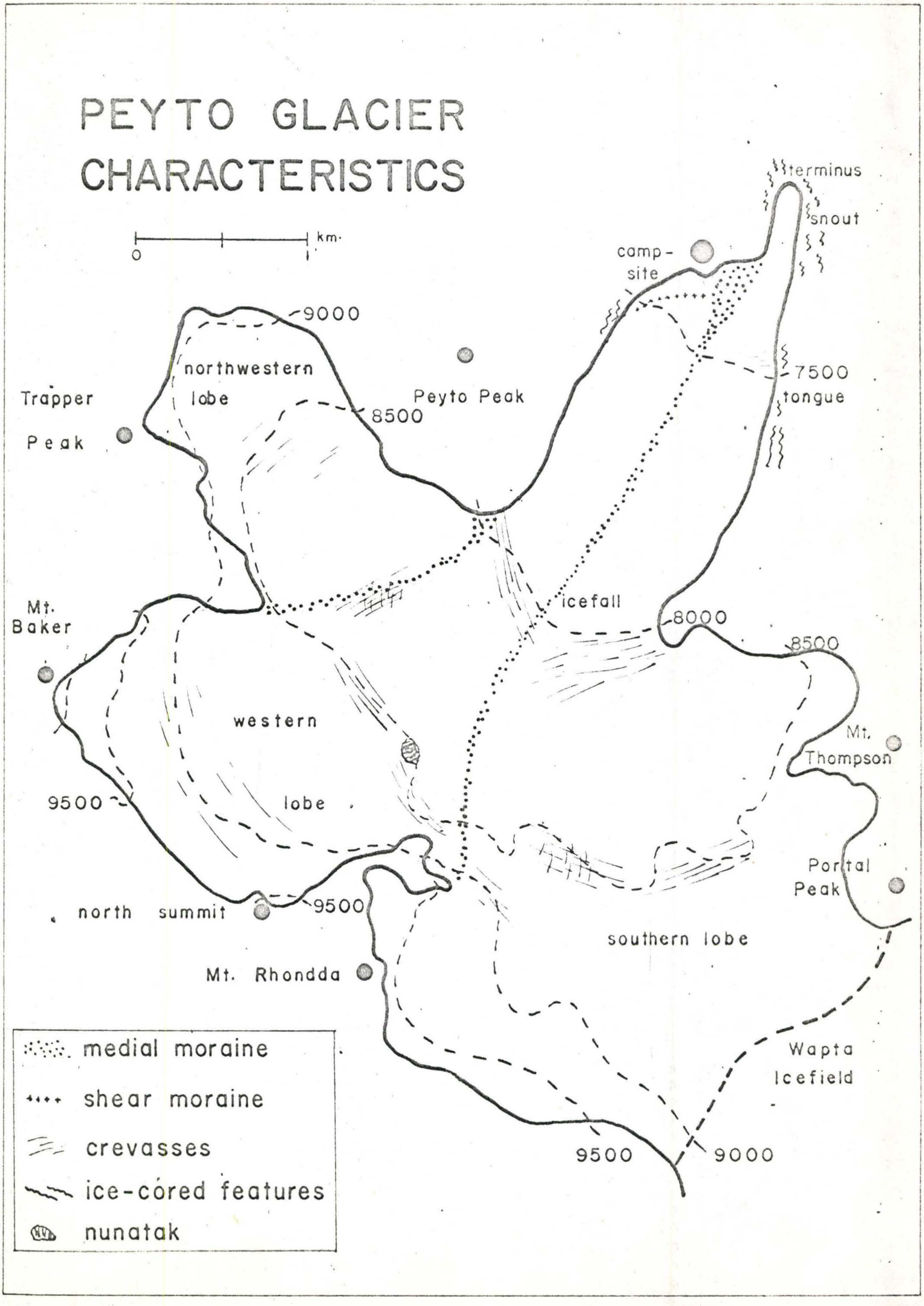
From this preliminary work, Peyto Glacier and the others included in the Decade programme were selected as most suitable.

B. Location and Situation

Peyto Glacier is located (see Map 2.) at 51° 40' N. latitude and 116° 34' W. longitude; approximately 37 km. north-west of Lake Louise, Alberta, in Banff National Park. The upper catchment area of the glacier (known as Wapta Icefield) lies on the eastern slope of the continental divide and, in fact, the western boundary of Peyto Glacier coincides with the peaks and ridges which form this divide. These peaks are part of the Waputik Mountains, a minor region of the extensive Rocky Mountain chain.

The glacier and Peyto River, its melt stream, are channelled north-eastward down a broad valley (henceforth called Peyto Valley) which opens into the head of the Mistaya River valley trending north-west, a tributary of the North Saskatchewan River. The Peyto River flows into Peyto Lake at the head of Mistaya Valley where the river of that name has its source. Immediately eastward over the ridge forming the east side of Peyto Valley lies the source of the Bow River and the head of its valley trending to the south-east. The Bow River is tributary to the South Saskatchewan River and hence this drainage divide separates the north and south basins of the Saskatchewan River at the upstream extremities

MAP 3·


PEYTO GLACIER
CHARACTERISTICS
0
km·
1
terminus
snout
camp-
site
9000
northwestern
lobe
Peyto Peak
7500
tongue
Trapper
Peak
8500
Mt.
Baker
icefall
8000
8500
western
Mt.
Thompson
9500
lobe
Portal
Peak
north summit
9500
southern lobe
Mt. Rhondda
medial moraine
shear moraine
crevasses
ice-cored features
nunatak
Wapta
Icefield
9500
9000

of its tributaries. The divide is low at this point (4.8 km. north-east of the tongue of Peyto Glacier), and is known as Bow Pass or Bow Summit, altitude 6787 ft. (3.) The pass is utilized by the main Banff-Jasper highway to traverse from one river basin to the other, and provides excellent access to Peyto Glacier and environs.

C. Glacier Characteristics

Peyto Glacier (see Map 3.) is a temperate alpine glacier with an area of 13.67 $km.^2$ which extends in elevation from approximately 6600 ft. to 10,000 ft. on Mt. Baker. It can be considered to be divided into two distinct sections, the upper and lower glacier, by a 100 m. high icefall at the 8000 ft. level. Above the icefall lies a large catchment basin (representing some 84% of the total glacier area) which is an extension of the Wapta Icefield. This basin has four distinct sections or lobes.

The north-west lobe lies in a cirque basin with the glacier margins delimited by ice-free rock. The east margin lies along the west slope of Peyto Peak (9700 ft.) and the east face of Trapper Peak (9800 ft.) borders the west. The glacier bergschrund contours the col between these two peaks about 9100 ft. elevation.

A second lobe lies to the south-west, reaching up the east side of the continental divide to the col at 9400 ft. between Mt. Baker (10,400 ft.) on the north and the north summit of Mt. Rhondda (9700 ft.) to the south. Snow fields are extensive in this tract.

The third portion is situated between Mt. Rhondda (10,025 ft.) on the southwest and Mt. Thompson (10,000 ft.) to the north-east. However, there is no definite boundary to the glacier along the col between Mts. Rhondda and Thompson as the ice surface extends over this col to the south-west and merges with the Wapta Icefield and the catchment area of Bow Glacier. This ice divide was arbitrarily defined for calculations across the flattest part of the icefield about 8750 ft. elevation, joining rock buttresses of Mts. Rhondda and Baker. This is the only indistinct divide of the Peyto Glacier catchment area, and intensive measurements of flow direction would be required to establish the precise divide; perhaps a project for future work in the Decade study. However, the error induced into the mass budget calculations by this subjective divide is negligible in comparison to the total glacier.

The fourth tract is a shallow basin just above the icefall from which the other three portions radiate. Lying approximately between the 8300 and 8400 ft. contours, it is part of the ablation area, some 40 m. below the firn line.

The lower glacier below the icefall (2.25 $km.^2$ or 16.5% of the total glacier area) is the outlet tongue extending 2.4 km. down Peyto Valley and generally 1.0 km.

wide. This tongue narrows rapidly below the 7500 ft. contour until, at 7100 ft., it lies in a section of the Peyto Valley constricted by rock walls where the glacier is only 0.15 km. wide. This snout consists of relatively thin ice and is receding rapidly up the narrow valley. The surface is steeply sloping at 15° and represents only 0.3% of the glacier area.

The surface gradient of the glacier is usually gentle to moderate with slope angles of $2\text{-}6^{\circ}$. However, the snout portion, slopes immediately below the bergschrund, and portions joining the upper lobes to the basin above the icefall are steeper. The latter areas likely overlie bedrock steps where icefalls would occur if the ice was thinner. This is evident from numerous transverse crevasses and one small nunatak area. Generally, only the portion above the 9000 ft. contour (approximately 2.33 $km.^2$ or 17%) is inaccessible, with small tracts between 8500-9000 ft. adding some 1-2% more. Crevassed areas increase this fraction slightly. Thus, for practical purposes, 80% of the glacier is practical work-surface.

The glacier has a number of features typical of alpine glaciers (see Map 3.). There are two medial moraines on the surface with superglacial angular rock fragments of cobble to boulder size. One moraine has its source on a corner of the rock buttress between Trapper Peak and Mt. Baker, and it extends to the north-west corner of the icefall where it peters out as lateral ablation drift at the bed-rock forming the icefall. A more imposing trail of similar debris originates on the flanks of Mt. Rhondda and extends down over the icefall to the 7300 ft. level of the tongue. Here, it fans out forming a wide band of superglacial ablation moraine along the west margin of the ice.

This section along the west margin of the glacier tongue is likely stagnating, for such scattering of debris is characteristic of ice in this stage due to surface lowering.(4.) A distinct line near this position between debris-laden ice and clean glacier ice marks the shear plane along the border of the active and stagnant portions of the margin.(5.) Beneath this super-glacial debris on the tongue are a number of ice caves which have likely been initiated by melt water running into small crevasses and cracks, and then enlarged by an influx of warm air into the original space. No signs of ice flowage around rock were noticed in these caves,(6.) but the depth reached was not likely sufficient for rapid flow even if the area was not stagnant.

Crevasses are a common occurence on the glacier, with the largest 3-5 m. wide being found at the lip of the icefall.

The same type occurs in a number of locations on the upper glacier above the steeper gradients.

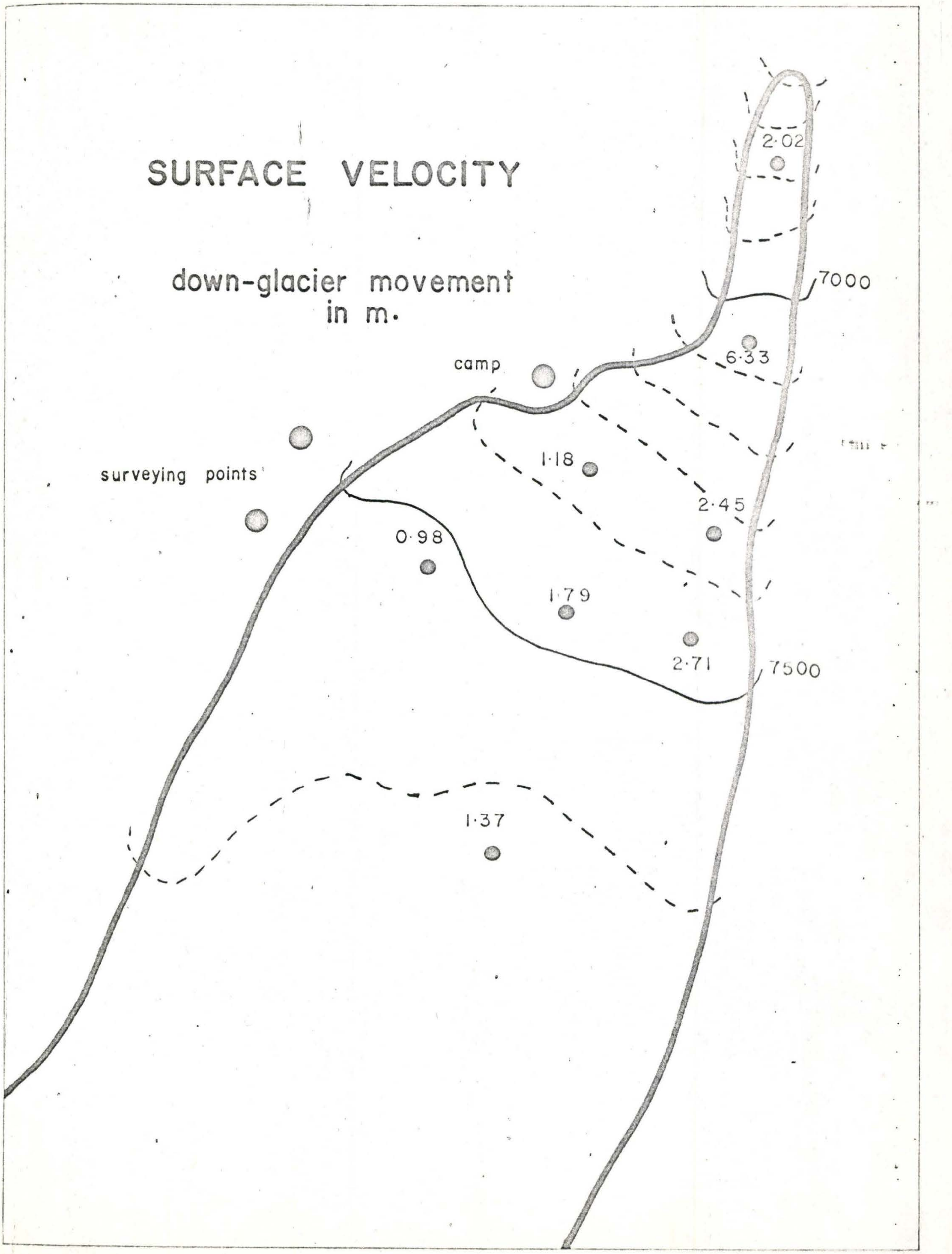
In the area of stagnant ice along the tongue margins are several small (1 m. wide) cracks which angle obliquely across and up the glacier. These tension features, caused by constriction of the ice along the narrowing bedrock valley sides, are the marginal type (8.) of crevasse.

Drainage streams on the surface of the glacier are noteworthy for the lack of any substantial channel development. The largest stream is perhaps only 1 m. wide and 30 cm. deep, although velocity and meanders appear normal. The lack of development of any major streams is probably due to the amount of sub-glacial and englacial drainage. Much of the melt water must percolate into the ice and many streams which have developed disappear into crevasses or moulins. Streams could be heard under the tongue and the main melt river emerges from a sub-glacial tunnel with no stream of consequence running off the terminus of the glacier.

D. Surface Velocity

A preliminary survey of 8 stakes imbedded in the ice on the snout of the glacier tongue was made to determine surface meovement in this area. Limitations of time precluded the drilling in of special velocity stakes aligned

MAP 4.


SURFACE VELOCITY
down-glacier movement in m.
camp
surveying points
2·02
7000
6·33
1·18
2·45
0·98
1·79
2·71
7500
1·37

at right angles to glacier flow, so measurements were made of regular ablation stakes already in place.

These stakes were surveyed with a theodolite from 2 fixed points 38.59 m. apart on August 8 and August 31. (see Map 4.). The points were located on the moraine terrace above the west margin of the glacier, a position which required the shooting of acute angles. However, as readings were taken to the nearest minute, variation at the longest sighting of approximately 300 m. was 0.087 m., a percent error of 0.03%. Thus the acute angles would not appear to be a source of large error.

A possible error in the measurements was induced by the large amount of ablation in this area. The surface lowering caused the stakes to melt out and redrilling was required. This necessitated placing the stake in a new location, thus involving movement of the stake not due to the flow of the glacier. Such an error was minimized by moving the stake as short a distance as possible (up to 0.5 m.) and always transversely to the glacier flow. But the total effect likely had a bearing upon the final results. However, the consistency of the values would suggest that the pattern and magnitude of the results are correct. Thus, the findings are presented as provisionally valid, setting the stage for future research.

The resultant values of movements obtained from the calculations are parallel to the general glacier orientation, although there may be some oblique movement of the stake relative to the flow direction. The velocity cross-profile is very assymetrical, with largest movements on the east side where down-valley flow is least obstructed. The low values on the west side (0.98 m. and 1.18 m.) are found in an area of probable stagnant ice (see page 20.). The relatively low value of 2.45 m. on the east side occurs where the glacier is somewhat obstructed by the encroaching bedrock of the valley side, evident from the marginal crevasses in that section. The highest value of 6.33 is possibly too great because of measurement error, but the value may be realistic as it is on the steepest portion of the tongue. The value at the terminus (2.02 m.) is also on this steep section, but thinning ice may cause decreased movement because of basal drag. Movements are generally consistent with slope and flow obstructions.

A similar velocity survey[(9.)] was previously conducted using plates imbedded in the ice. This survey was made when the tongue extended further down the valley and flow rates likely differed because of differing slope and obstruction characteristics. However, the data was summarized as follows:

period			movement (ft.)	annual rate (m.)
1945	-	1946	27	8.2
1946	-	1947	40	12.2
1947	-	1948	31	9.4
1948	-	1949	26	7.9
1949	-	1950	15	4.6
1950	-	1952	13.5	2.1
1952	-	1954	18.5	2.8
1954	-	1956	13.5	2.1
1956	-	1958	16.6	2.5
1958	-	1960	5.5	0.8

The 1965 figures represent a mean movement of approximately 3 m. in the 3 week survey period. This indicates an annual rate of advance of perhaps 10 - 12 m. Such a figure compares consistently in magnitude with the 1945-1960 values, especially considering the change in terminus location.

E. Camp Site

The camp site chosen at Peyto Glacier for the Decade glaciological programme is on a drift-covered knoll some 25 - 30 m. above the west side of the glacier tongue at 7248 ft. elevation (see Map 4.). The site is well-drained, with the glacier to the south-west and south-east of the knoll and a recent marginal drainage channel on the other side. Although the site is safe from avalanches or rock-falls from the face of Peyto Peak, it is somewhat exposed to wind coming down the valley on the glacier surface. However, this tends to keep it swept free of snow.

A wooden A-frame hut was erected (3 m. square floor area and 2 m. to the ridge-pole) and several others are planned for additional field members and as a garage for the motor-toboggan. A Stevenson screen to house the meteorological instruments was installed at the site (see page 53.).

The hut is reasonably well located for work on the glacier but access to the Peyto River for daily readings is too difficult to be practical (see page 81.). It is also necessary to keep the motor-toboggan above the icefall after the snow cover has melted off the lower glacier, as the surface is very hummocky. This entails a 40 min. walk to the vehicle.

FOOTNOTES - Chapter 1.

1. Østrem, 1965. (unpub.)
Østrem and Stanley, 1966.

The criteria and selection of glaciers for the Decade project were derived by S. Jonsson under the supervision of Østrem at the Geographical Branch, Ottawa.

2. Topographic maps (1:50,000 scale with 200 ft. contour interval) are available from the National Topographic Series. These are relatively accurate for work around the ice margins but, on the surface of the glacier, the contour interval is rather large for precision. Contour lines appear particularly inaccurate on the lower glacier tongue due to surface down-wasting since map surveys were completed. The relevant maps are listed as:

Hector Lake	82 N/9 W.
Blaeberry River	82 N/10E.

Air photo coverage is often marred by snow covering. Photos are useful for the surface of the glacier and surrounding areas, but margins and terminus positions at present were covered by ice when the photos were flown (see page 81.).

3. Although the metric system is used as a basis for measurement in this thesis, all elevations above sea level are given in feet because topographic maps employ this system.

4. Flint, 1957. p. 74.

5. ibid. p. 73.

6. Carol, 1947.

7. Flint, 1957, p. 15.

8. ibid.

9. McFarlane, 1960.

CHAPTER 2. - Literature

A. Peyto Glacier

Peyto Glacier is one of the better documented glaciers in the Rocky Mountains because of the relatively easy access via the Banff-Jasper highway. References exist in relative profusion from the late nineteenth century when a local guide, Bill Peyto, led several climbing and exploring parties into the area. However, most of these references make only brief mention of terminus positions of the glacier and certainly no estimates of mass budget were made.

The earliest scientific observor at Peyto Glacier was James Hector of the Palliser expedition, who traversed the Bow Pass in 1858. He makes no specific reference to the glacier but describes the pass area and nearby Bow Glacier.

The first photo and fixed marking of the terminus position of the glacier tongue was made by Wilcox in 1897 and appears to have been published by that writer in 1909. The photo locates the terminus well down the valley from the present position, reaching almost to the moraine arcs above the first riegel (see page 35.). The Peyto River at that time emerged from 2 tunnels at the front of the glacier (Wilcox, 1909) which are clearly evident in the photo.

The Alpine Club of Canada has rendered valuable service to glaciologists by occasionally publishing, in the Club's journal, summaries of terminal fluctuations of glaciers in the Western Cordillera. McCoubrey (1937) reports a retreat at Peyto Glacier of approximately 100 m. from 1933-1936 and publishes photos of the terminus in those two years. The terminus appears at that time to be at the conjunction of Peyto River and the creek draining Cauldron Lake. McFarlane (1946) summarizes work at Peyto Glacier undertaken by the Dominion Water and Power Bureau. No retreat measurements are given but discharge of the Peyto River from a cave on the east side of the glacier is estimated at a minimum value of 150 cfs (4.2 m^3/sec.). Reference is made to 1936, 1939 and 1942 terminus markings. In 1949, the Alpine Club conducted a field camp on the delta at Peyto Lake. Climbs in the immediate area of the glacier were made on the peaks of Thompson, Peyto, Portal, Trapper and Baker. References to the glacier by climbers such as Boeing (1949), Munday (1949) and Melville (1949) describe minor features of the glacier. Boeing mentions "giant blue seracs" which must refer to ice blocks breaking off the snout of Peyto Glacier. Field and Heusser (1954) summarize retreat from the terminal position in 1715 to 1953 as 3330 ft. (1015 m.) or 4.3 m. annually (see page 47.).

Meek (1948) details retreat from 1933 to 1947 in 2 and 3 year intervals with the range of annual retreat from 45 to 133 ft. (14 - 40 m.) (see page 47.). Such retreat, he claims, is related to slightly higher annual temperatures with longer periods of sunshine, supplemented by lower precipitation. Rate of surface flow is said to be 70 ft./yr. (21.3 m.).

Heusser (1956) has contributed the most extensive paper on Peyto Glacier. Dendochronological dating of trimlines suggests maximum ice advances to 1711 and 1863 (see page 44), correlating well with world-wide glacier fluctuations (see page 47).

McFarlane (1960) reports surveys of the glacier tongue from 1945-1960 undertaken by the Water Resources Branch. He recorded a retreat of 1135 ft. (346 m.) in this period or an annual rate of 76 ft. (23 m.) (see page 47.). Rate of surface flow decreased from 30 to 5 ft. (9 - 1.5 m.) annually in that period. Pictures of the snout in 1958 and 1960 indicate retreat up the gorge.

B. Europe

European writers were among the first to detail observations of glacier fluctuations, for the Alpine regions were inhabited, more accessible and less extensive than other glacierized regions of the earth. Scandinavian workers soon supplemented Alpine studies and there is no dearth of glaciological literature today on the glaciers of the Alps, Norway, Iceland and Greenland. A number of these papers were concerned with determination of the mass budget of certain glaciers in addition to establishing terminal fluctuations but, because of their remoteness to Peyto Glacier in distance and regimen, a discussion of the results was not considered imperative to this study. Ahlmann (1948) has best summarized work in these areas (with the exception of the Alps) and only a brief bibliographical listing of papers is included in this thesis.

The most valuable contribution of these European writers to the Peyto Glacier study was in setting out methodology useful on all glaciers. Numerous papers outlining techniques of determining accumulation/ablation and methods of graphical and tabular presentation have been refined over the years until, today, almost standardized procedures are used. These refinements, as used at Peyto Glacier, are outlined by Østrem (1963a, 1963b, 1964a, 1964b, 1966), and discussion of previous papers is unnecessary.

However, several papers concerning glacier regimen were useful in assessing results obtained at Peyto Glacier and are thus mentioned. Ahlmann (1940) evaluated the effects of temperature and precipitation on glaciers, pointing out the importance of temperature. Hoinkes (1955) established some working values for defining the contributions of varied ablation processes on the glacier (see page 108.). Hoinkes and Rudolph (1962) contributed valuable assessment of the climatic elements of regimen as they affect glacier mass budgets.

C. United States

Recent work from the United States was considered applicable to the Peyto Glacier area because American glaciers are much closer to the Peyto area in distance and regimen. The extensive tracts of glacierized areas and the numerous inaccessible glaciers in the Western Cordillera have delayed glaciological investigations until after 1945 in North America, and emphasis since then has been on more extensive surveys than in Europe, especially using air photography. Following a period of glacier recession from 1935-1950 (Meier and Post, 1962), American workers became interested in evidence of renewed glacier activity and these recent studies are relevant to Peyto Glacier.

Johnson (1949) first detected a thickening of ice on the Nisqually Glacier, Washington. This increased activity led to a number of papers defining terminus fluctuations in detail. Bengston (1956) detected an increase of the Coleman

Glacier on Mount Baker during the 1949-1955 period. Harrison set out fluctuations of the Nisqually Glacier on Mount Rainier from 1750 to 1955 and noted an advance since 1946. Hubley (1956) discussed increased glacier activity in the Washington Cascade and Olympic Mountains in the 1945-1954 period which he correlated with a cooler, wetter climatic trend beginning in 1943. Harrison (1956) summarized activity in the western United States, suggesting the recession of the past decades is ended or suspended.

However, in 1960, LaChappelle pointed out that the advance of the 1945-1955 period had ceased, a result concurred with by Meier and Post (1962), who postulate that the area of increased activity has moved north into southeastern Alaska. Mass budget studies were placed on a firmer foundation by Meier (1962) who defined terms for future studies. La Chappelle (1965) continued mass budget determinations in Washington but defined no distinct trends to 1963. However, air photographic techniques and graphical representation were further refined. Meier and Tangborn (1965) also continued mass budget studies and similarly, no definite trends were depicted. Mass budgets since 1961 have fluctuated about the equilibrium state.

CHAPTER 3. - Physical Geography

A. Geology and Structure

The Peyto Glacier area is scarcely mentioned in geological literature as most work has been concerned with the Bow Valley to the south-east and further north along the North Saskatchewan River.(1.) No detailed maps of the geology are available and, because of the complexity of lithology and structure in the Rocky Mountains, it is difficult to apply available information to unknown areas with any degree of accuracy. This discussion is derived from such regional information as is available and from observation around Peyto Glacier, supplemented by study of air photographs limited in usefulness by snow and ice cover.

The Rocky Mountains are an extensive tract of highly folded ranges with alternating ridges and valleys trending north-west/south-east, parallel to the axis of the folds. This ridge-and-valley topography is particularly evident in the Peyto region, manifested in the Bow and Mistaya Valleys with ridges some 1200 m. higher forming the valley sides.

Rocky Mountain lithology is usually complicated because of the thickness of exposed bedrock and consequently the large number of visible beds. However, in the Peyto area, sediments are essentially only of Cambrian age limestone-dolomite and shale with some quartzite.(2) Generally, the lower, tree-clad valley sides are Lower Cambrian with Middle and possibly Upper Cambrian forming the steep, upper valley sides and cliffs.(3.)

A number of major faults have been detected in the region of the southern Rockies but none are mapped in the Peyto area. Overthrusting of folds is a common occurence along these faults but, again, no evidence of such features is found near Peyto Glacier as the surrounding country is mapped as wholly Cambrian. However, likely minor faulting has ensued near Peyto Glacier and evidence of jointing is found.(5.)

The general structure of the Peyto area (see Figure 2.) can be established from the build of the Bow and Mistaya Valleys to the east. These were pre-glacial fluvial valleys which were eroded along the axis of an anticline and later deepened and U-shaped by glaciation.(6.) Peyto Glacier and Valley lie on the west flank of this anticline, so the local dip is to the south-west at a moderate angle of 20-30°. As well, a minor tilt of this dip slope is evident to the north-west about 10° so the actual dip is a rather complex component varying perhaps 50% within a short distance. This minor tilt is due, at least partially, to the slope imparted by the northward plunge of the anticline.

Peyto Valley is a major tributary of the Mistaya Valley, generally more than 1.5 km. wide, cutting through the local dip slope of the anticline flank at right angles to the strike. It does not hang above the Mistaya Valley, for its floor is accordant with that of the Mistaya Valley, although a series of steps in the Peyto Valley do have a hanging appearance. In long profile, the valley appears to be divided by these steps into four segments which are associated with structure (see Figure 2.).

The lowest segment consists of Peyto Lake (approximately 6050 ft. elevation) and a large delta at its head. The bedrock underlying this portion is Precambrian shale of the Hector formation.(7.) The lake basin has likely been glacially eroded into these shales, although the bedrock is masked by glacial drift and outwash gravels which cover the valley floor.

At the head of the delta (altitude 6100 ft.), separating the first and second segments, is a 40 m. high threshold or riegel [8.] of Lower Cambrian bedrock, possibly the Lake Louise formation, [9.] through which Peyto River has cut a narrow (30 m. wide) valley. This threshold is tree-covered with drift and some outwash gravels concealing the bedrock except in the stream-cut section. The rock is highly weathered, well-jointed limestone on the west side of the stream while on the east side shale is exposed. The dip of the shale is typically south-westward upstream and is also tilted to the north-west under the river. The water appears to be exploiting the contact of the shale and limestone and migrating down the tilt of the shale beds, so that the east bank is the slip-off slope and the west (limestone) bank is being undercut. This small stream valley could thus be termed homoclinal, although on a minor scale.

The second valley segment above this threshold comprises a widening of the valley to form a basin, within which the braided Peyto River meanders over outwash gravels of a valley train. This basin floor (of elevation 6200-6300 ft.) is separated from the third segment by another step beginning at the 6300 ft. level.

The lower portion of this second riegel has a homoclinal structure similar to the first threshold. The east side is possibly composed of Mt. Whyte [10.] shale dipping locally upstream and tilting diagonally under the river to the west. The formation is the lowest Middle Cambrian formation in the valley and forms the slip-off slope upon which the river migrates down-dip, undercutting more massive limestone on the west bank. Here, the bedrock is free of vegetation or drift covering and the shale bedding is seen to form a series of glacially plucked steps on the downstream lee side with smoothed stoss sides on the upstream dip slopes of the bedding. This structure is typical of argillite shales.[(11.)] Farther upstream, shale steps occur on both banks of the river. This shale section of the second riegel has a relief of perhaps 30 m. up to 6400 ft. elevation, over which the river flows in turbulent rapids.

The main portion of the step is composed of a massive dolomite-limestone ridge, likely of the Cathedral formation,[(12.)] through which the melt river has cut a very sharp gorge approximately 20 m. deep and 4 m. wide. Its resistance compared to the shale is noticeable, as the river falls over a 3-4 m. high knickpoint to enter the lower shale section of the threshold after it has left the limestone gorge.

Such a sharp cleft requires considerable erosion, especially considering that the glacier has only recently (post-1950)[(13.)] uncovered this portion of the bedrock. It is likely that the river was actively cutting this gorge in a sub-glacial tunnel even while the glacier overlay it, and perhaps erosion initiated when the glacier terminus was at a stage much further up the valley than at present or in the recent past. However, the characteristics of the cut suggest that the water has exploited a joint in the rock. Such a process is well known in the region (see footnote 5.).

At 6700 ft. elevation on the lip of the riegel, the stagnant glacier terminus (really an ice-cored ablation moraine) overhangs the upper end of the gorge and the river enters into the cut by falling some 4 m. from the mouth of a sub-glacial tunnel. This terminus lies in a section of the valley where it widens to form the third segment in the profile; a basin containing the lower glacier or outlet tongue of Peyto Glacier flowing from the catchment area of the Wapta Icefield. As this basin is ice-filled, nothing can be observed of the underlying bedrock floor, but it is likely part of the Stephen shale formation.(14.) Three hundred-meter high vertical cliffs on each side of the tongue indicate the powerful erosive forces of the ice cutting into the probable shale bedrock in this area.

The upper limit of this basin is formed by an icefall, the lip of which is approximately at 8000 ft. Marginal retreat at the corners of the icefall reveals a resistant

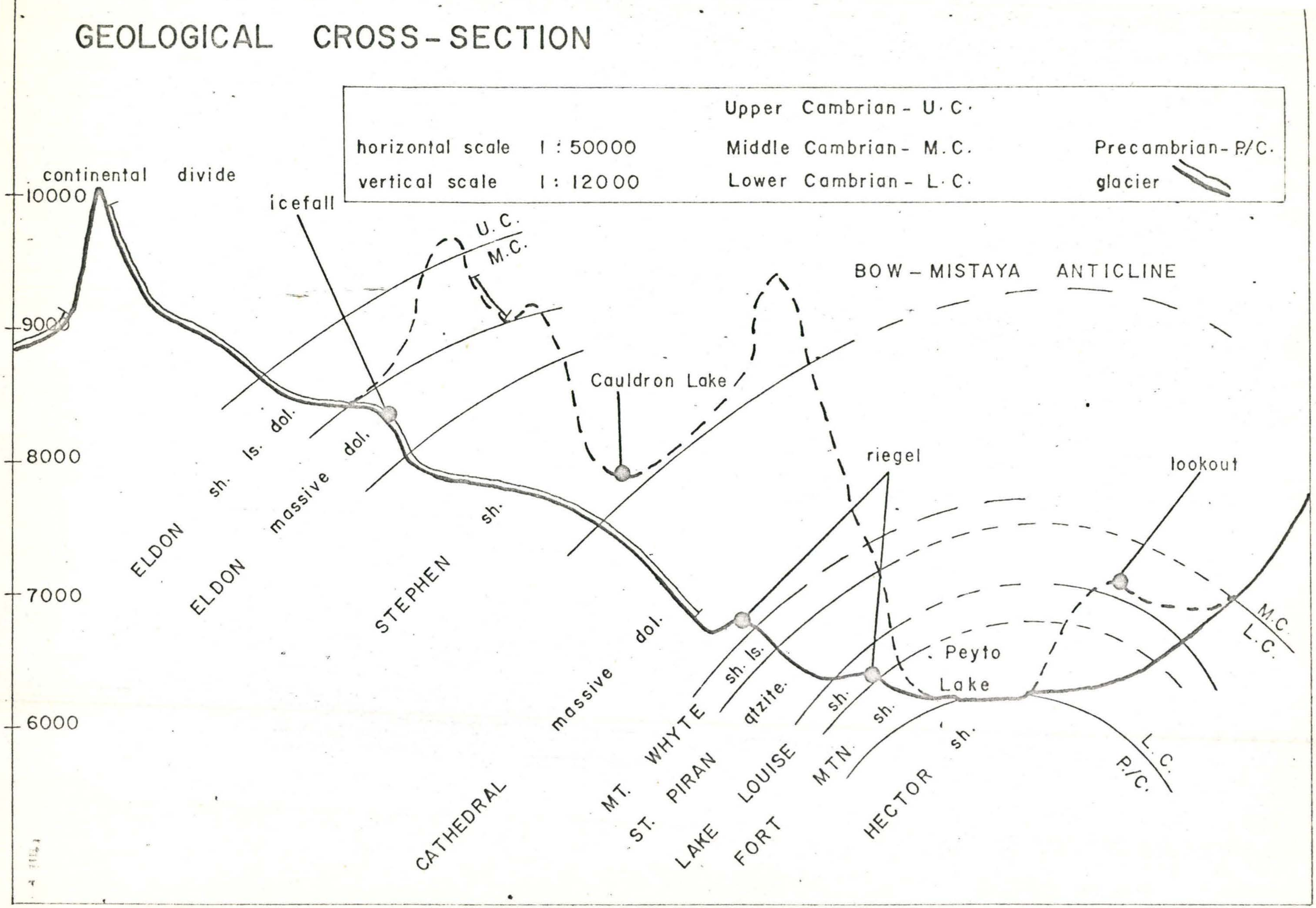

GEOLOGICAL CROSS-SECTION
horizontal scale 1 : 50000
vertical scale 1 : 12000
Upper Cambrian - U·C·
Middle Cambrian - M.C.
Lower Cambrian - L·C·
Precambrian - P/C·
glacier
continental divide
10000
9000
8000
7000
6000
icefall
U.C.
M.C.
BOW – MISTAYA ANTICLINE
Cauldron Lake
riegel
lookout
Peyto Lake
M.C.
L.C.
L.C.
P/C.
ELDON sh. ls. dol.
ELDON massive dol.
STEPHEN sh.
CATHEDRAL massive dol.
MT. WHYTE sh. ls.
ST. PIRAN qtzite.
LAKE LOUISE sh.
FORT MTN. sh.
HECTOR sh.

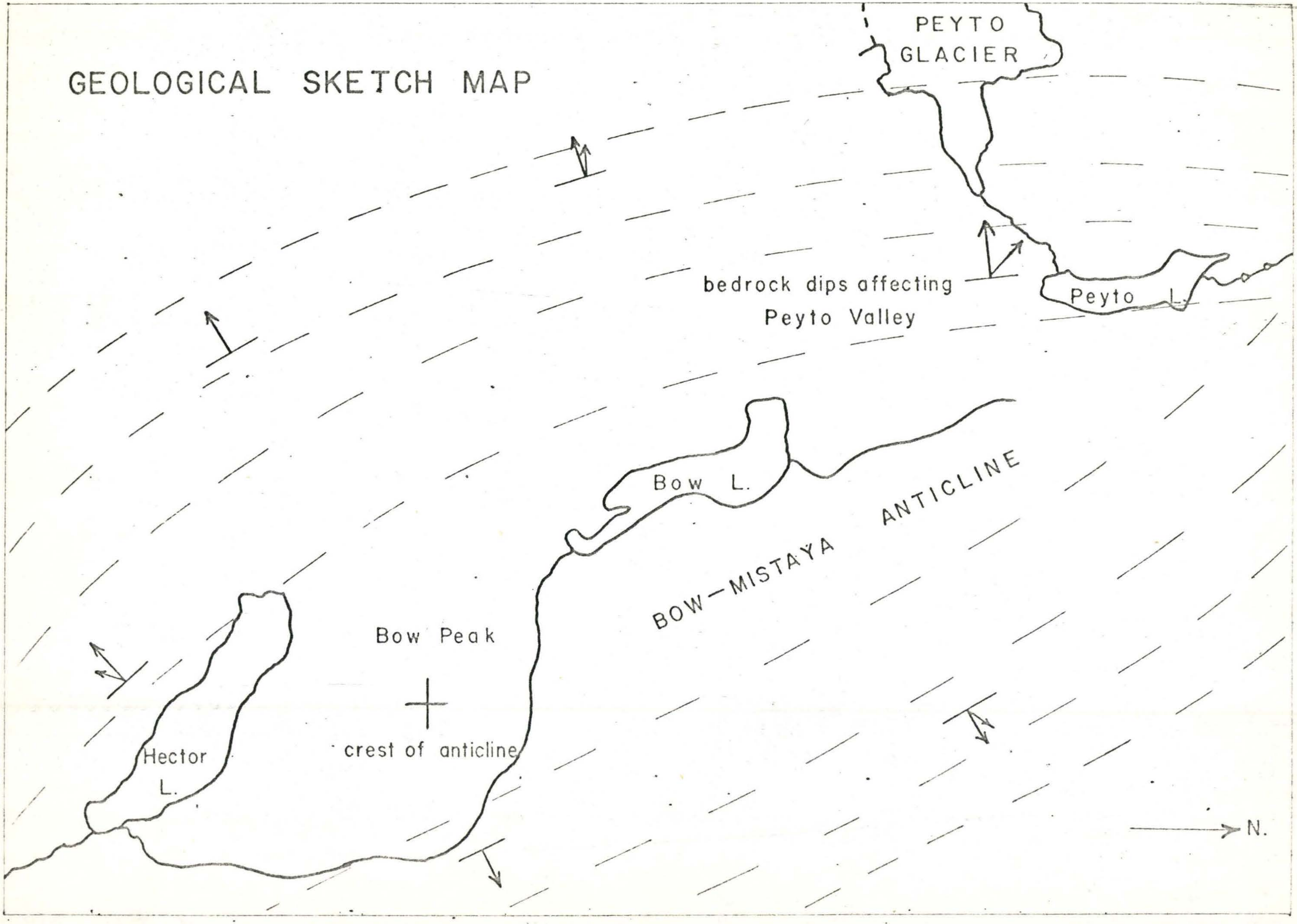
FIGURE 2.

limestone-dolomite step (likely formed by the Eldon formation) over which the ice "falls." At the margins it is almost 100 m. high, but the gradient of the ice-fall in the centre is much less, indicating erosion of the lip where the ice is thicker.

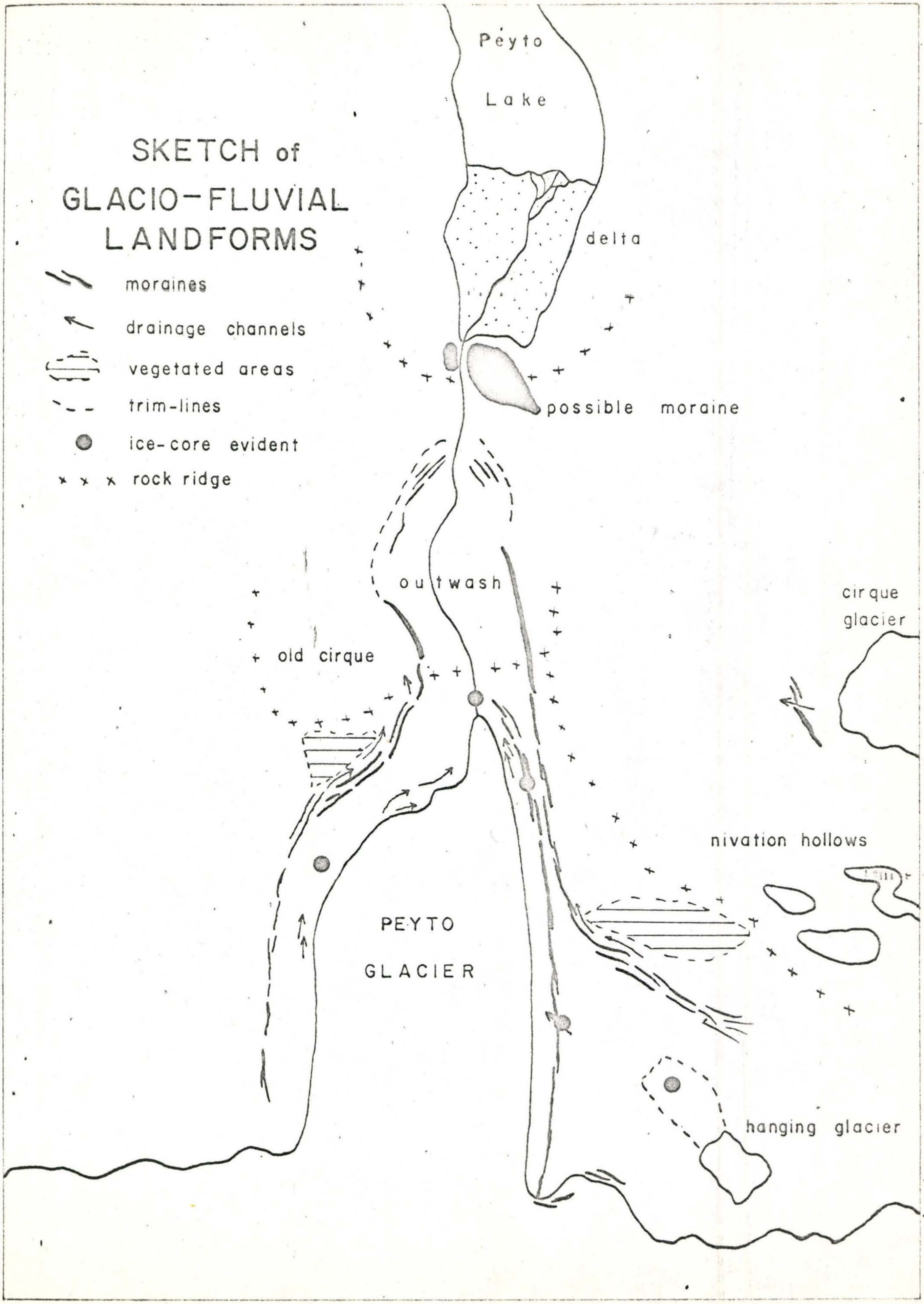
Little can be surmised about the bedrock in the upper basin, for the ice covering and difficult access prevents inspection. The peaks surrounding this fourth segment appear to be interbedded limestone and shales with perhaps some quartzite of the Middle Cambrian, possibly capped by Upper Cambrian formations.(16.) Bare rock exposures are rare but faces on Mt. Baker and Trapper Peak indicate complex folding with some beds almost vertical. The few exposures seen on the peaks suggest the basin and its extension, the Wapta Icefield, may be a synclinal valley, parallel to the Bow-Mistaya anticline but not as broad.

The size and configuration of Peyto Valley suggests that it is a major physical feature likely with some definite reason for its location and alignment. Fluvial erosion was probably initiated by drainage to the pre-glacial Mistaya River which cut into the anticline arch. This caused headward erosion on the back slope of the anticline flank, gradually forming the Peyto Valley. Similar headward erosion would have occured on the dip slope and capture of this westward draining river would have been possible.(17.) The total effect

FIGURE 3.


GEOLOGICAL SKETCH MAP
PEYTO GLACIER
bedrock dips affecting Peyto Valley
Peyto L.
Bow L.
BOW-MISTAYA ANTICLINE
Bow Peak
crest of anticline
Hector L.
N.

MAP 5.


SKETCH of
GLACIO-FLUVIAL
LANDFORMS
moraines
drainage channels
vegetated areas
trim-lines
ice-core evident
rock ridge
Peyto
Lake
delta
possible moraine
outwash
old cirque
cirque
glacier
nivation hollows
PEYTO
GLACIER
hanging glacier

would be the cutting of a valley across the flank of the anticline, transverse to the strike.

However, because the local dip slope to the south-west is complicated by a north-west tilt and the plunge of the anticline, the effective dip is a resulting component of these angles to the west (see page 35.). This indicates that the Peyto Valley cuts obliquely across the effective dip slope partially at right angles to the strike and partially parallel to it (see Figure 3.). The latter trend thus suggests that fluvial erosion has cut into less resistant beds on the anti-cline flank because of down-dip migration and so the valley can be designated partially homoclinal.

In addition, jointing and faulting may have partially guided the fluvial and/or glacial erosion along the trend of Peyto Valley. The alignment may also indicate structural control by the folds. A zig-zag alignment is common in areas of plunging anticlines and synclines,[(18.)] and the Bow-Mistaya anticline plunges northward and southward with the crest some-where near Bow Peak,[(19.)] south-east of Peyto Glacier. As mentioned, a syncline may underly the Wapta Icefields, again supporting this idea.

B. Glacial Geomorphology

Peyto Glacier has a number of marginal glacial-landform features (see Map 5.) which offer opportunity for correlation studies in advance and recession of the ice, although no detailed work has yet been attempted. The author proposes to discuss these features descriptively, with only tentative conclusions drawn to their importance in establishing the glacial history of the area.

It is thought that the Mistaya Valley contained a major valley glacier during the Pleistocene, with numerous tributary glaciers flowing into it from cirques and hanging valleys on both sides of the main valley.(20.) Peyto Glacier was one of these tributaries, and the terminus once extended to the north end of Peyto Lake, for the lake is dammed by a hummocky moraine in this position.(21.) This likely represents the terminal moraine of Peyto Glacier, for the configuration of the lake and moraine suggests that north of this position Peyto Glacier merged laterally into the flow of the main valley glacier.

It is possible that a major recessional moraine is located at the lowest rock threshold in the Peyto Valley. This riegel has a drift covering thick enough to support heavy forest growth, and the soil may be a moraine coincident with the rock barrier and deposited on and against it.

In the second segment of the valley profile, along the west side at elevation 6500 ft., there is a distinct trim-line in the forest cover, but scrub vegetation is now beginning to colonize this barren drift area. A similar, though less definite, trim-line is evident on the east side. Below this trim-line, on both sides of the valley and again less distinct on the east side, are several parallel arcuate ridges which are lateral/end moraines representing short still-stands of the receding glacier terminus. These ridges have been breached and eroded by the melt river in the centre of the valley over the width of the braided valley floor.

Dendochronological dating of these trim-lines (22.) suggests the eastern one represents an eighteenth century ice maximum with a subsequent nineteenth century advance to within 50 ft. (15 m.) of the earlier one. Recession of the earliest maximum began in 1711 with the later recession commencing in 1863. On the west side of Peyto Valley, only evidence of the later maximum was found, suggesting the earlier maximum was over-ridden. Recession from this position began in 1861. Dating of the arcuate moraines within the trim-lines gave dates of recession commencing in 1880, 1888, 1895 and 1908.

Aligning with these trim-lines and moraines are two major lateral moraines which are plastered on the bedrock sides of the valley. They almost correspond in height, gradient and configuration; the west one extending up from 6200 ft. to 6620 ft. elevation. The upper ends of these lateral moraines grade into less imposing lateral moraine and drift deposits which can be traced almost continuously along the east and west margins of the present glacier tongue, where they formed at a higher ice level than present. On the east side, this moraine system is less pronounced, as it is plastered on bedrock cliffs; but on the west side it reaches a high point of almost 7700 ft., some 120 m. above the present ice surface in that area. It then merges into a major, lateral, terrace-like moraine flanked by minor distinct moraines and marginal channels.

These lateral deposits delimit the greatest marginal extent the tongue of Peyto Glacier achieved during the recent maximums of the eighteenth and nineteenth centuries (see page 44.), for adjacent to these former ice-covered areas are tracts made conspicuous by the amount and type of vegetation in comparison to the barren drift.[(23.)] No evidence of glaciation in the form of other landform features was evident above this moraine border. However, a large cirque on the west side of Peyto Valley, opening into the second segment and floored at 6700-7000 ft., was considered evidence of a much older and more severe period of glaciation, possibly the main Wisconsin.

Peyto Glacier is notable for ice-cored moraine features. In front of the glacier terminus, above the melt river gorge, is an area of stagnant ice with an ablation drift cover some 1-4 m. in thickness. The river flows under this debris with small melt streams disappearing into the unconsolidated drift. Steep slopes on both valley sides above the terminus also appear to have extensive ice cores. Particularly interesting are lateral terrace features or moraines above the glacier tongue which have at least partical ice cores. On the east side is a remarkably sharp-ridged moraine which likely was formed during the nineteenth century ice maximum. Beyond this lies a distinct vegetation trim-line of the eighteenth century advance.(24.)

All these features make it evident that the glacier margins and terminus are in retreat. Peyto Glacier has been known and observed since about 1880, but useful references before that date are unknown. However, a recent recession period such as these features indicate would correlate well with the general, world-wide recession during 1860-1945.[25.]

The recession of Peyto Glacier has been documented by assorted writers[26.] and is summarized as follows from the terminal position in 1715 A.D.:

period			recession (ft.)	annual rate (m.)
terminal	-	1897	995	1.7
1897	-	1933	750	6.4
1933	-	1936	237	24
1936	-	1939	351	36
1939	-	1942	399	41
1942	-	1945	231	14
1945	-	1946	140	43
1946	-	1947	70	21
1947	-	1948	110	34
1948	-	1949	75	23
1949	-	1950	70	21
1950	-	1952	180	21
1952	-	1954	35	27
1954	-	1956	65	5.3
1956	-	1958	255	9.9
1958	-	1960	235	39

Much of this recent large retreat is due to the terminus melting up the narrow gorge section where the ice is thin and tends to break off in stagnant blocks,[27.] but it would still seem to be indicative of the rapid recession Peyto Glacier has recently undergone.

Above the tongue of Peyto Glacier were several other glaciated areas. To the east was a small cirque glacier with its melt stream flowing from a hanging valley into the

Peyto River. This glacier exhibited signs of recent recession in the form of an end moraine with a vegetation trim-line below it. The glacier was on the shady side of the ridge topping the east side of Peyto Valley above 8500 ft. elevation.

A small hanging glacier with icefall was evident on the shady side of Mt. Thompson, near the cirque glacier, above 8500 ft. Its melt stream has cut a gully transversely into an ice-cored lateral moraine before joining a marginal stream beside the Peyto Glacier tongue. It, too, has retreated recently, for below its terminus is an ice-cored ablation drift area.

Between these two glaciers are several nivation hollows with firn deposits indicative of incipient glaciation. Signs of advance or retreat of these snow patches were not noticed. However, an interesting mass balance study could be attempted here.

FOOTNOTES - CHAPTER 3.

1. see Bibliography

2. Belyea, 1964. p. 5-6.

3. ibid. p. 38-39.

4. Clark, 1949.

5. Evidence of faulting has been found in two locations in Peyto Valley. A minor stream (draining the hanging Cauldron Lake above the west side of Peyto Valley into the Peyto River) has cut a gorge and plunge-pool some 30 ft. down through limestone. Although, the erosion may be along a joint, highly brecciated rock in the gorge is indicative of a fault. Further up Peyto Valley, the oblique displacement of beds on the east face of Peyto Peak indicates a normal fault line.

   Examples of jointing are more numerous. The same creek draining the hanging lake falls over a cirque headwall from joints and caves in the rock well below the top of the cliff. The same stream has cut a narrow gorge, indicative of a joint, obliquely through massive limestone to join the Peyto River. Several other waterfalls have cut into lips of cliffs along probable joint lines. Reference to similar situations are recorded (Belyea, 1964.).

6. Belyea, 1964. p. 38.

7. ibid. p. 39

8. ibid. p. 38

9. Stockwell, 1957. p. 325.

10. ibid.

11. Belyea, 1964. p. 18.

12. Stockwell, 1957. p. 325.

13. McFarlane, 1960.

14. Stockwell, 1957. p. 325.

15. ibid.

16. Belyea, 1964. p. 39.

17. Such capture is plausible when it is considered that the Mistaya River was of greater size in the past. At that time, the river included the headwaters of the present Bow River above Lake Louise but since then the Bow River has captured this section by its own headward erosion (Belyea, 1964. p. 17.).

18. Thornbury, 1954. p. 225.

19. Belyea, 1964. p. 37-39.

20. ibid. p. 14.

21. ibid. p. 15.

22. Heusser, 1956. p. 278.

23. The vegetation on the non-glaciated areas is of the alpine tundra type, consisting of moss, flowers and stunted pines and junipers. Rocks were well weathered limestone with a lichen covering. The newly-emerged drift was composed of coarse angular fragments of limestone from pebble to boulder size and was almost totally devoid of any plant growth. Separating the two areas were deep, snow filled gullies, probably marginal channels. A similar situation existed on the east side of the tongue, although this area was not closely examined, and there is evidence of two separate trim-lines. The estimate of 100-200 years since glaciation is based upon the time required for such vegetation to colonize and become maturely established.

24. ibid.

25. Flint, 1957. p. 24.

26. Field and Heusser, 1954; Meek, 1948; McFarlane, 1960.

27. McFarlane, 1960.

CHAPTER 4. - Weather and Climate

A. Methods and Equipment

The meteorological data garnered during the 1965 field season at Peyto Glacier was employed in two basic approaches to the problem of depicting the climatic characteristics affecting the mass budget. Firstly, the meteorological summaries were compared with mean statistics from the nearest, suitable, regular meteorological station at Lake Louise to utilize that station as representative of the Peyto Glacier regimen for a more extensive time period than the field season. Long-term records from Lake Louise were analyzed to place the 1965 field season within the context of climatic trends in that region of the Rocky Mountains and hence to establish the field season's typicality with reference to past seasons. Thus, the mass budget conclusions can be considered in their proper perspective, linking glacier variation and weather conditions typical or non-typical of the established climatic trends.

Secondly, analysis of the glacier meteorological data was attempted to facilitate correlation in later discussion with melt river discharge and surface lowering.

This is to clarify the relationships between fluctuating glacier ablation and weather conditions.

Air temperature was considered the best indicator of overall glacier regimen during the ablation season,(1.) and continuous-profile temperature recordings were taken. The recorder was corrected for time and temperature errors, usually 4 times daily at the observation hours of 0800, 1200, 1800 and 2200 local time. The profile was then utilized to construct a daily mean temperature value from 24 hourly readings and to obtain daily maximum and minimum temperature figures. The same recorder provided continuous-profile relative humidity data, and values at the 4 daily reading times were used to interpolate a mean daily relative humidity figure for 1500 hours when ablation was likely greatest in the diurnal cycle. Thermohydrograph was housed in a standard Stevenson screen at the campsite approximately 70 m. from the western margin of the glacier tongue at 7272 ft. elevation , some 15 m. above the glacier at this location.

At each daily observation time, cloud cover was estimated in tenths of sky area to provide a daily mean percentage value. This index was considered indicative of short-wave solar radiation reaching the glacier and was supplemented by qualitative estimates of visibility.

Winds were estimated in speed and direction at the screen site at each observation time, but the prevalence of south winds (93% of occurences) renders the data almost meaningless on a regional scale. However, the significance of this local wind is discussed later (see page 57.).

Rainfall measurements were obtained from 9 gauges placed at various altitudes (6440 ft. to 8490 ft.) in the valley and on the glacier surface (see Map 6.). This data provides a volume calculation of the total liquid precipitation, falling in the drainage area of the melt river. It is subtracted from river discharge values as it is not part of the ablation runoff.[2.]

At the glacier, the metric system was adopted and all readings were taken in these units except wind speed (m.p.h.). This wind data was later converted to km./hr. for standardization. The statistics from Lake Louise meteorological station were also converted to metrics for comparison with Peyto Glacier figures.

B. Weather at Peyto Glacier

Although the primary reason for taking meteorological data at the glacier was to correlate with ablation, several generalities regarding observed weather conditions can be made.

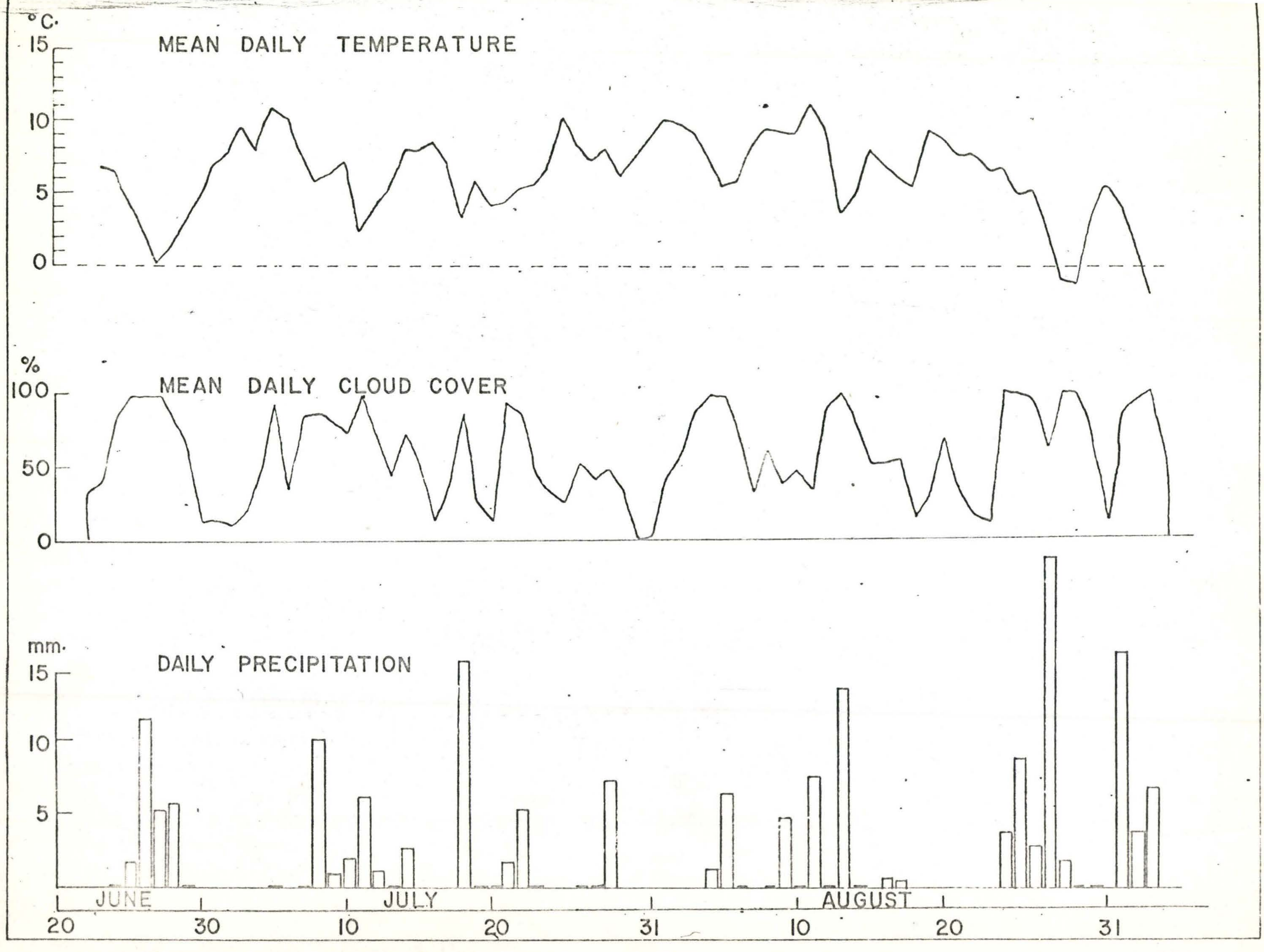
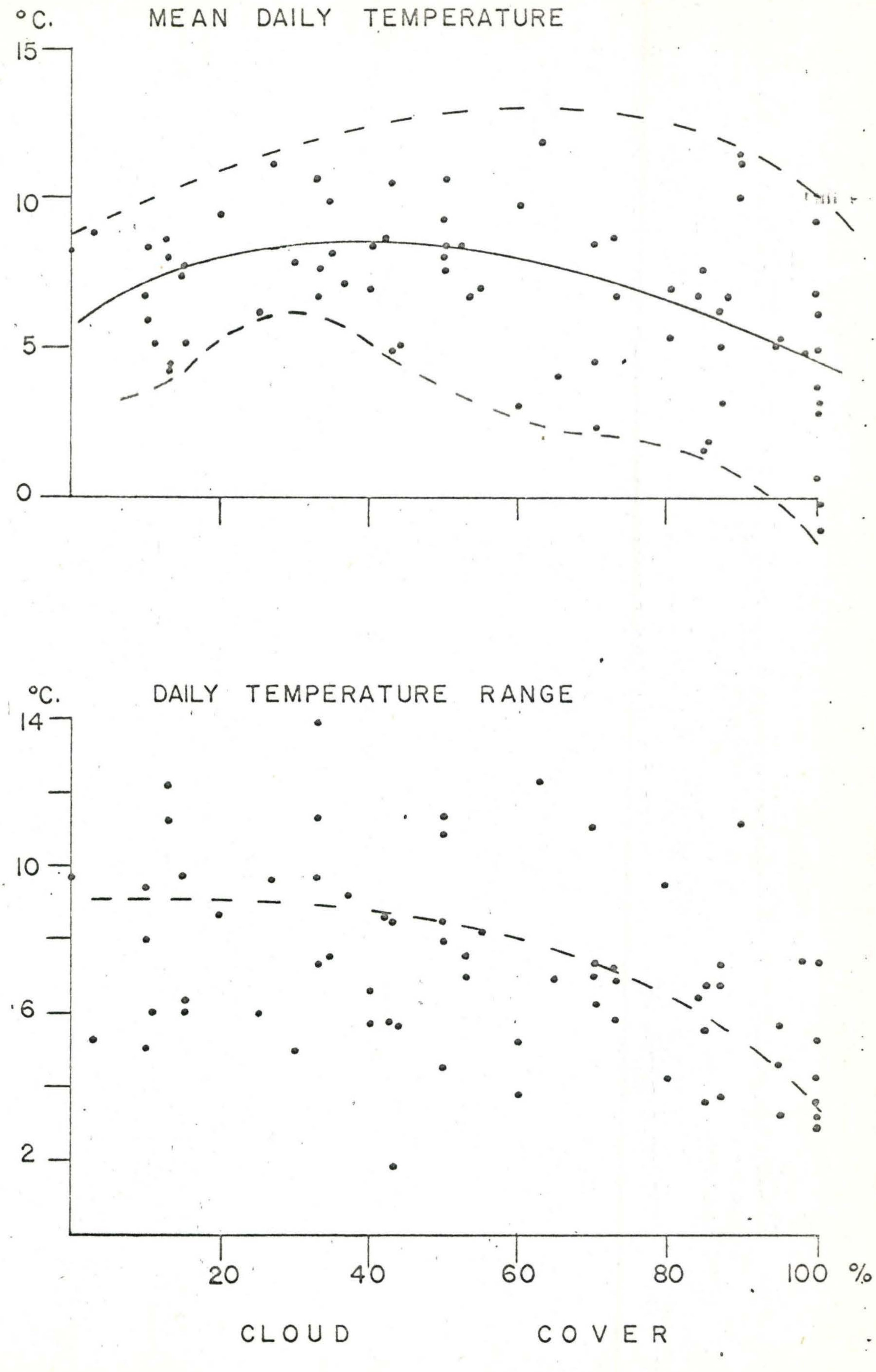

°C.
MEAN DAILY TEMPERATURE
15
10
5
0
%
MEAN DAILY CLOUD COVER
100
50
0
mm.
DAILY PRECIPITATION
15
10
5
JUNE
JULY
AUGUST
20
30
10
20
31
10
20
31

FIGURE 4.

FIGURE 5.


°C.
MEAN DAILY TEMPERATURE
15
10
5
0
°C.
DAILY TEMPERATURE RANGE
14
10
6
2
20
40
60
80
100 %
CLOUD COVER

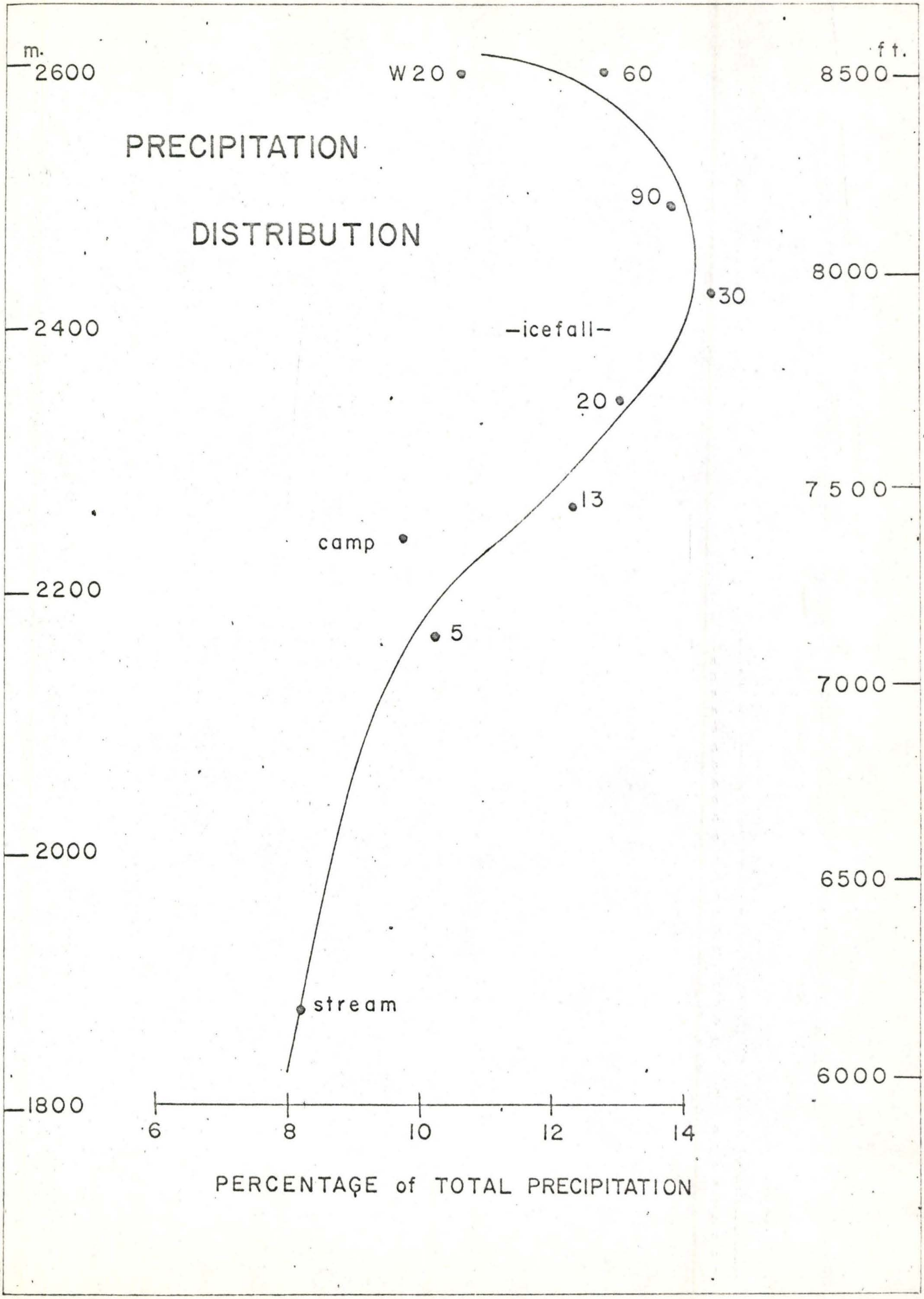
Mean daily temperature did not correlate well with cloud cover, (see Figure 4.) although there was some tendency for low cloud and high temperature to relate. This is partially due to night radiation under clear skies leading to a low minimum temperature which depressed mean daily figures. However, the mean daily range also bore only an approximate relationship to cloud cover (see Figure 5.) as well, and from the weather records, it appears that the air mass characteristics govern mean daily temperature to a large extent. The highest mean daily figures were achieved with cloud cover 30-40% (see Figure 5.), again emphasizing that night radiation must be decreased to raise the daily mean temperature value.

Winds were usually steady and moderate (13-16 km./hr.) in speed but gusts associated with thunderstorm activity reach 80 km./hr. or more. Calms were rare, and 93% of wind recordings were from the south flowing down the glacier tongue into Peyto Valley. Because such winds usually peaked in velocity during early afternoon, they were likely caused by a convectional effect due to insolation heating of the ice-free lower valleys. Thus they were similar to katabatic winds but occured in the daytime due to convection.(3.)

TABLE 1.

Rain Gauge Altitude ft.	Location	Period 1 ppt. cm.	Period 1 % total	Period 2 ppt. cm.	Period 2 % total	Period 3 ppt. cm.	Period 3 % total	Period 4 ppt. cm.	Period 4 % total	Period 5 ppt. cm.	Period 5 % total	Period 6 ppt. cm.	Period 6 % total	Mean %
6153	valley	-	-	17.2	8.3	19.8	6.4	3.4	15.1	23.0	7.5	5.0	3.4	8.1
7091	5	25.8	14.2	18.3	8.8	26.7	8.6	1.5	6.7	27.1	8.9	21.5	14.5	10.2
7270	camp	28.0	15.3	20.7	10.0	25.5	8.2	0.7	3.1	31.9	10.5	17.1	11.6	9.7
7280	13	28.0	15.3	19.0	9.1	36.3	11.7	2.1	9.3	40.2	13.2	23.0	15.5	12.3
7635	20	19.6	10.7	25.0	12.0	41.8	13.4	3.8	16.9	34.7	11.4	20.2	13.7	13.0
7938	30	20.0	11.0	26.8	12.9	40.0	12.9	4.5	20.0	37.0	12.1	26.0	17.6	14.4
8157	90	24.0	13.2	28.4	13.7	37.0	11.9	2.0	8.9	36.0	11.8	35.0	23.6	13.8
8480	W20	21.0	11.5	24.5	11.8	42.0	13.5	1.0	4.4	36.0	11.8	-	-	10.6
8483	60	16.0	8.8	28.0	13.5	42.0	13.5	3.5	15.6	39.0	12.8	-	-	12.8
		182.4		207.9		311.1		22.5		304.9		147.8		

FIGURE 6.


m.
2600
2400
2200
2000
1800
ft.
8500
8000
7500
7000
6500
6000
PRECIPITATION
DISTRIBUTION
W20
60
90
30
-icefall-
20
13
camp
5
stream
6
8
10
12
14
PERCENTAGE of TOTAL PRECIPITATION

On 5 separate days the wind reversed itself 180^{o}, coming from the north or north-east up Peyto Valley. On these occasions, associated weather included snow flurries or light drizzle, light winds, and poor visibility due to low ceilings at or below camp level. Temperatures were usually depressed at these times. Such conditions, however, were short-lived and were probably caused by passage of a front. Study of synoptic weather charts for the days in question could clarify the issue, but such a study goes beyond the limits of this paper.

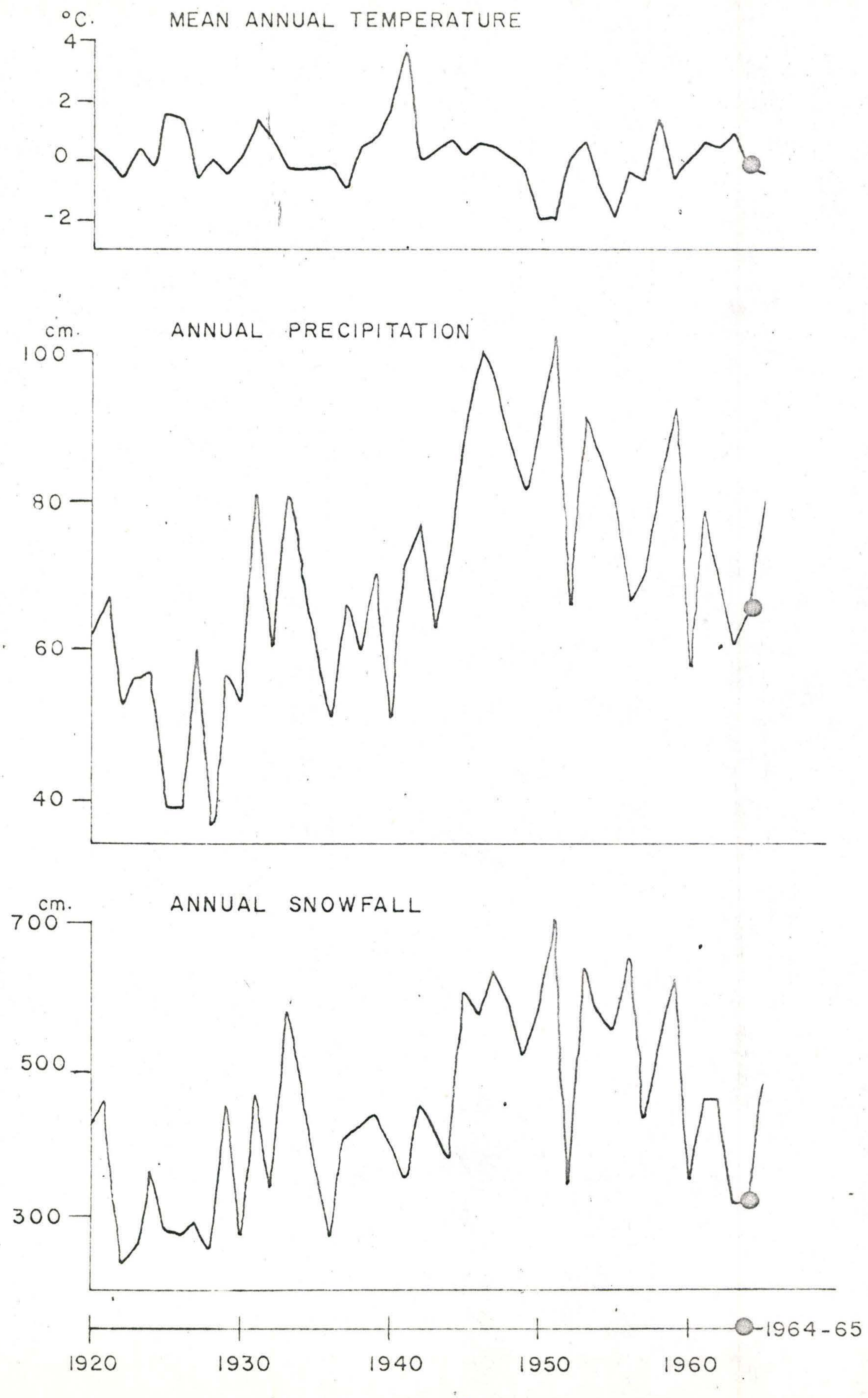
Periods of precipitation showed good correlation with cloudy periods (see Figure 4.) as might be expected. Precipitation totals for 10-day periods were measured at each rain gauge, permitting construction of a curve for precipitation/altitude for each period. These 6 curves were integrated into a single, generalized curve of precipitation distribution with altitude for the whole drainage basin by using percentage figures (see Table 1.). For each period, the precipitation measured at a gauge was calculated as a percentage of the total precipitation recorded at the 9 gauges. These percentage values for each gauge for 6 periods were averaged to determine the mean percentage of total precipitation occuring at each individual gauge. Thus the precipitation/altitude curve (see Figure 6.)

was derived for elevations below 8500 ft. which allowed precipitation estimates to be made for any elevation or at any gauge when only one gauge was read.

The curves for each of the 6 periods had a shape similar to the generalized curve although, as the percentage values in Table 1. indicate, variations existed. These variations were due to complications induced by snowfall or freezing on the upper levels, tilting of gauges from differential ablation (although large wooden bases on the gauges minimized this), and minor variations of precipitation patterns due to weather conditions.

The curve (see figure 6.) indicates a linear increase of precipitation with increasing altitude to about 8000 ft., just above the icefall. Precipitation then decreases, indicating a possible rain shadow at higher levels. Because the curve cannot be extrapolated accurately above 8500 ft., it is impossible to say whether this rain shadow is in the lee of the continental divide or if it is a minor facet of the precipitation pattern, occuring on the steep slopes leading into the basin above the icefall. Further gauges at high elevations are needed to clarify this question. However, consideration of the location of gauges 60 and W20 (which are at similar elevations of 8485 ft.) points out that the decrease is

FIGURE 7.



°C.
MEAN ANNUAL TEMPERATURE
4
2
0
-2
cm.
ANNUAL PRECIPITATION
100
80
60
40
cm.
ANNUAL SNOWFALL
700
500
300
1964-65
1920
1930
1940
1950
1960

is greater near the divide than it is approaching the Wapta Icefields (see Map 6.). This would support the idea of a major rain shadow in the lee of the divide.

The number of gauges was insufficient to develop a distribution map of precipitation within the drainage basin and additional gauges at varied locations and altitudes are needed in future, especially in the upper snowfield.

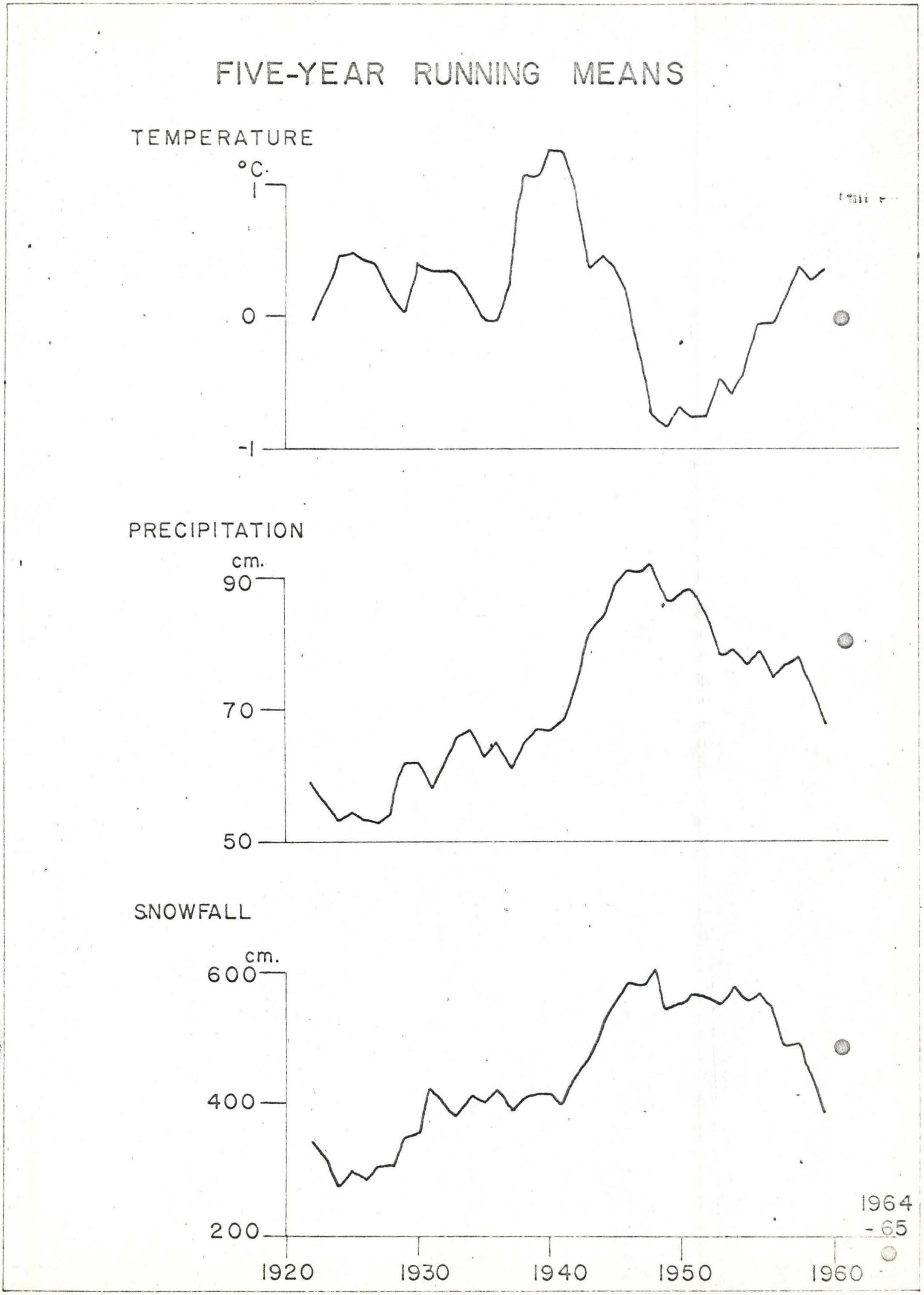
C. Annual and Season Trends

1. Introduction

Annual climatic records from Lake Louise are consistent since 1920, but a change in station location in 1932 gives truly continuous data only from 1933. The 1920-1932 temperature statistics were utilized by correcting them for the change in station elevation. As there was little or no apparent, appreciable fluctuation in precipitation for which the station change could be held responsible (see Figure 7.), the precipitation figures were used unaltered.

To detect long-term fluctuations, the averages of the budget year of 1964-1965 (September 30, 1964 to August 31, 1965) were compared to the values derived from the last decade 1955-1964 and from the periods 1920-1932 and 1933-1954. Also, the 1920-1954 periods were combined to obtain long-term means of certain variables.

FIGURE 8.


FIVE-YEAR RUNNING MEANS
TEMPERATURE
°C.
1
0
-1
PRECIPITATION
cm.
90
70
50
SNOWFALL
cm.
600
400
200
1964
- 65
1920
1930
1940
1950
1960

Statistics from Lake Louise station (see Figure 7.) were smoothed by calculating 5-year running means (see Figure 8.) from 1920 to 1964. This technique also helped to eliminate any variation caused by the change in station location.

In addition to mean annual data, calculations were made involving mean monthly figures in order to depict the seasonal characteristics of the Lake Louise climate. From the mean monthly temperatures (see Table 2.), it was felt the seasons in the region were best represented as follows:

autumn	-	September, October
winter	-	November, December, January, February, March
spring	-	April, May
summer	-	June, July, August

Although these arbitary limits are not the commonly accepted ones of 3-month seasons, it is more accurate to include all those months with well below 0° C. as winter and those months of approximately 10° C. as summer. Also, although some days in May and September would see some ablation at Peyto Glacier, the ablation season can be considered to effectively occupy the 3 summer months only.

2. Temperature

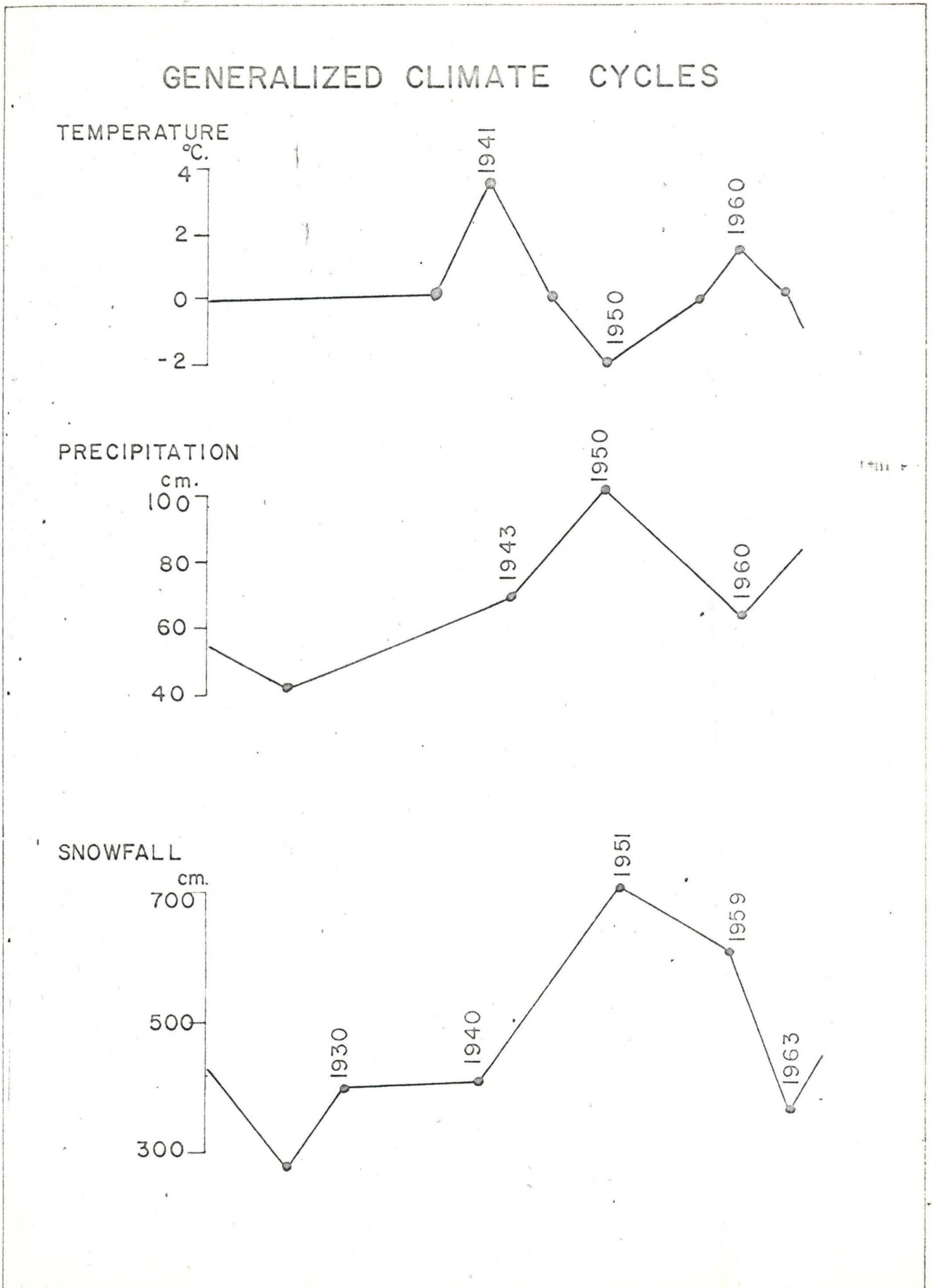
(a.) Annual:

Study of the mean annual and running mean temperature profiles (see Figures 7,8.) reveals one outstanding

TABLE 2.

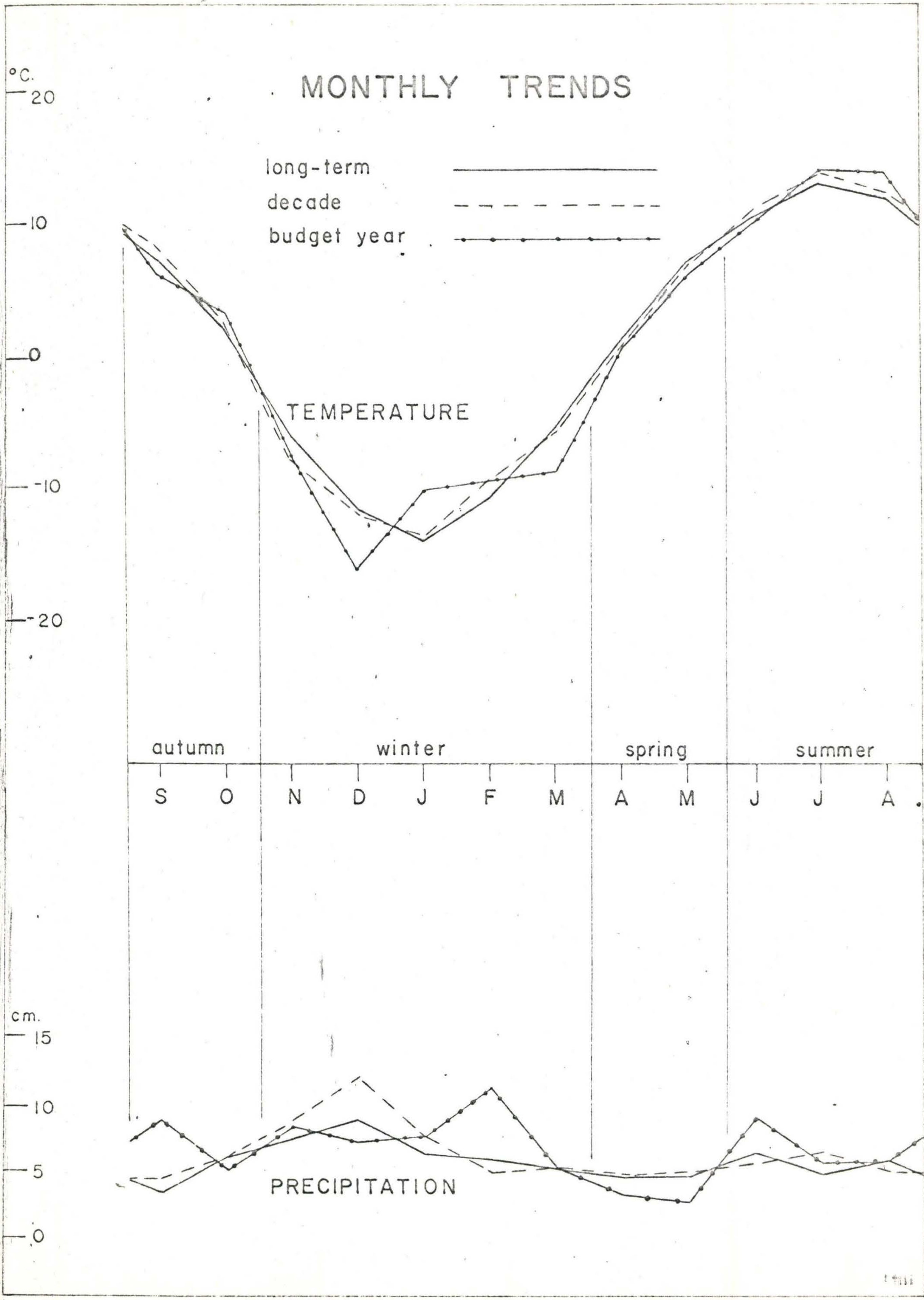
	Temp. °C. long term	Temp. °C. 10 yrs.	Temp. °C. 1964 -65	ppt. cm. long term	ppt. cm. 10 yrs.	ppt. cm. 1964 -65	Snowfall long term cm.	Snowfall long term % ppt.	Snowfall 10 yrs. cm.	Snowfall 10 yrs. % ppt.	Snowfall 1964-65 cm.	Snowfall 1964-65 % ppt.	Max. Temp °C. 10 yrs.	Max. Temp °C. 1964 -65	Min. Temp °C. 10 yrs.	Min. Temp °C. 1964 -65	No. days with freezing temp. 10 yrs.	No. days with freezing temp. 1964 -65
utumn - Sept.	6.8	7.8	5.8	3.5	4.7	9.0	5	14	5	11	0	0	14.4	12.2	-0.1	-0.7	17	18
Oct.	1.7	1.9	3.0	6.1	6.1	5.2	32	52	37	61	36	69	8.0	14.4	-4.2	-4.5	27	29
Avg.	4.2	4.8	4.4	4.8	5.4	7.1	18	38	21	39	18	25	11.2	13.3	-2.2	-2.6	44	47
inter - Nov.	- 6.6	- 8.1	- 7.7	7.5	8.8	8.4	72	96	90	100	84	100	-2.1	-2.1	-14.2	-12.6	30	30
Dec.	-12.0	-12.2	-16.6	8.8	12.1	7.0	85	97	121	100	65	93	-6.7	-7.2	-17.6	-13.8	31	31
Jan.	-14.5	-14.1	-10.6	6.1	7.6	7.6	72	100	75	99	76	100	-7.6	-5.0	-20.8	-16.3	31	31
Feb.	-11.1	- 9.9	-10.0	5.8	4.8	11.2	61	100	45	94	112	100	-2.5	-3.1	-17.2	-16.9	28	28
Mar.	- 5.9	- 6.2	- 9.2	5.0	5.1	5.1	49	96	50	98	51	100	1.1	1.7	-13.7	-20.1	31	31
Avg.	-10.0	-10.1	-10.8	6.6	7.7	7.9	68	100	76	99	78	98	-3.6	-3.1	-16.7	-16.0	151	151
pring - Apr.	0.5	0.0	0.0	4.3	5.4	3.0	39	91	42	78	30	100	6.7	9.7	- 6.4	- 7.0	29	29
May	6.2	6.1	5.3	4.4	4.5	2.4	14	32	18	40	13	54	13.9	12.2	- 1.7	- 1.7	23	20
Avg.	3.4	3.0	2.6	4.4	5.0	2.7	26	59	25	50	22	82	10.3	11.0	- 4.0	- 3.8	52	49
ummer - June	9.7	10.2	9.2	6.1	5.3	8.9	3	4.9	0	0	0	0	17.8	16.9	2.4	1.5	8	10
July	12.2	12.8	13.1	4.5	6.1	5.4	0	0	0	0	0	0	21.7	22.0	3.9	4.2	3	0
Aug.	11.0	11.4	12.8	5.4	4.7	5.7	0.5	1.0	0	0	0	0	19.8	20.4	3.0	5.2	7	2
Avg.	11.0	11.5	11.7	5.3	5.4	6.7	1.2	2.3	0	0	0	0	19.8	19.8	3.1	3.6	18	12
ean Annual	-0.17 -0.2	-0.02 10.0	-0.41 -0.4	67.5	75.2	78.9	432	64	483	63	467	59	6.2	7.7	-7.2	-6.9	265	259

FIGURE 9.


GENERALIZED CLIMATE CYCLES
TEMPERATURE
°C.
4
2
0
-2
1941
1950
1960
PRECIPITATION
cm.
100
80
60
40
1943
1950
1960
SNOWFALL
cm.
700
500
300
1930
1940
1951
1959
1963

characteristic. This is the depression of temperatures from 1947 to 1957 with a recorded-period minimum in 1950. This period was initiated in 1941 when temperatures began to decrease from the high temperature period of 1937 to 1946 and has been documented by other workers.(4.) It is significant that the depression coincides with a period of increased glacier activity in the north-western United States (see page 31.) and, as the temperature decrease from 1941 to 1950 was approximately 2 ^{o}C., the increased glacier activity probably occured at Peyto Glacier as well.(5.) However, since that period of depression, temperatures have risen steadily throughout the past decade, at least until 1963, and are now slightly above the overall mean. Thus they correspond to general levels achieved before 1937. Post-1963 temperatures levelled off and, in 1964 and the budget year, there was a decrease. Whether this change represents the beginning of a trend is indefinite; possibly it is only a short-term fluctuation. However, there is some tendency for a cycle of 10 years duration(6.) from low to high points on the profiles (see Figure 9.). If this is the case, the statistics for the last 2 years may represent significant values indicating a reversal of the cycle, and temperatures in the next few years may decrease.

FIGURE 10.


MONTHLY TRENDS
°C.
20
10
0
-10
-20
long-term
decade
budget year
TEMPERATURE
autumn
winter
spring
summer
S
O
N
D
J
F
M
A
M
J
J
A
cm.
15
10
5
0
PRECIPITATION

Treated statistically with no reference to profiles, the fluctuations appear as follows:

period			mean annual temperature
1920	- 1964	(overall)	0.16°C.
1920	- 1932		0.30°C.
1933	- 1954		0.14°C.
1955	- 1964	(decade)	0.06°C.
1964	- 1965	(budget year)	-0.40°C.

In this case, the 1933-1954 period appears close to the overall average because the high period of 1937-1946 cancels the low figures of 1947-1957. A slight general decrease is evident after 1932 (perhaps due to the station change), but only in the budget year is a really significant variation found; 0.46°C. below the decade mean. This emphasizes the cool mean annual figure of the budget year.

(b.) Seasonal:

Autumn and summer temperatures (see Figure 10, Table 2.) during the last decade have been noticeably (0.5 - 0.6°C.) higher than in the long-term period, while spring temperatures have fallen slightly. This suggests a shift of the budget year later in the calendar year with a possible increase in the length of the ablation season. It may also be possible to say climate is exhibiting more continental characteristics.

In the 1964-1965 budget year, however, temperatures decreased (0.4 - 0.7°C.) in autumn, winter and spring; materially lengthening the accumulation period. Above - decade temperatures in August may have slightly offset this (and indicated more continental characteristics) but generally the budget year was one of depressed temperatures except for July and August.

Study of maximum and minimum temperatures (see Table 2.) indicate a general tendency for both to rise in the budget year in comparison to the past decade. However, the mean annual maximum has risen 12.4% and the minimum only 10.4%. This increases the daily temperature range and may indicate a decrease in cloud cover during the budget year. Such a change could correspond to the increasingly continental temperature characteristics mentioned above.

3. Precipitation

(a) Annual:

Precipitation profiles, especially the running mean data (see Figure 8.) indicate a tendency for increasing precipitation to correspond with decreasing temperature but the relationship does not hold as well before 1940, possibly due to the change in station location and less accurate instruments. The outstanding feature of the profile is the mirror-image effect of high precipitation during the low temperature period in 1943-1959. As with temperature, a reversal of trend may have occured in 1963 and the last 2 years show a substantial increase of precipitation raising the budget year value above the long-term average. Annual means outlining these trends are as follows:

period	mean annual precipitation	
1920 - 1964	71 cm.	(overall)
1920 - 1932	58	
1933 - 1954	78	
1955 - 1964	73	(decade)
1964 - 1965	80	(budget year)

(b.) Seasonal:

The last decade has seen increasing precipitation in all seasons (see Table 2., Figure 10.) with the major increase during the winter. The budget year continued this trend except for a noticeable decrease during the spring. This decrease seems associated with the unusual depression of spring temperatures, particularly during May in the budget year.

4. Snowfall

(a.) Annual:

Running means for snowfall (see Figure 8.) closely parallel the curve for precipitation, with one notable exception. Although precipitation fell steadily from 1951 to 1963, snowfall maintained a relatively high value until 1959 when it quickly fell to levels corresponding to 1963 precipitation trends. This fact is evident in the table of mean annual snowfall:

period	mean annual snowfall (cm.)	snowfall (% of total precipitation)
1920 - 1964 (overall)	442	62
1920 - 1932	335	58
1933 - 1954	495	63
1955 - 1964 (decade)	476	65
1964 - 1965 (budget year)	484	60

In comparison with the table of mean precipitation (see page 70), the percentage in 1955-1964 is highest of any period, although the precipitation in that period was less than that of two other periods. No reason is suggested for this anomaly.

Figure 8. reveals that a substantial increase in snowfall occured in comparison to the last several years, corresponding to the suggested reversal in trend of temperature and precipitation.

Percentage values of seasonal snowfall compared to annual totals are as follows:

	long-term	decade	budget year
autumn	8.5	8.7	7.7
winter	78.5	78.8	83.2
spring	12.3	12.4	10.8
summer	0.7	0	0

They indicate that decade and long-term distribution has not varied beyond a slight decrease in summer amounts.

However, winter snowfall in the budget year increased at the expense of autumn and especially spring percentages, most of it occuring in February.

(b). Seasonal:

Percentage figures for the seasonal distribution of snowfall compared to the seasonal rainfall distribution are found in Table 2. The values vary little from the long-term to decade but the budget year saw a substantial autumn decrease of snowfall as a percentage of precipitation. Most of this apparent decrease was due, however, to excessive rainfall in September. The deficiency was largely made up in the spring, and annual figures indicate only slightly less precipitation occured as snowfall in the budget year.

5. Summary

The 1964-1965 budget year saw a substantial reversal of climate in comparison to the last decade. Annual temperature decreased 0.4°C. while precipitation and snowfall both increased, a change favouring a positive glacier mass budget. Also favourable to a healthy mass budget were low temperatures in autumn, winter and spring; thus extending the accumulation season. However, higher July and August temperatures partially offset this effect. Thus, a more severe winter and a warmer summer indicate a trend toward a more continental climate but, whether this reversal is a short term fluctuation or the initiation of a new cycle, is not apparent.

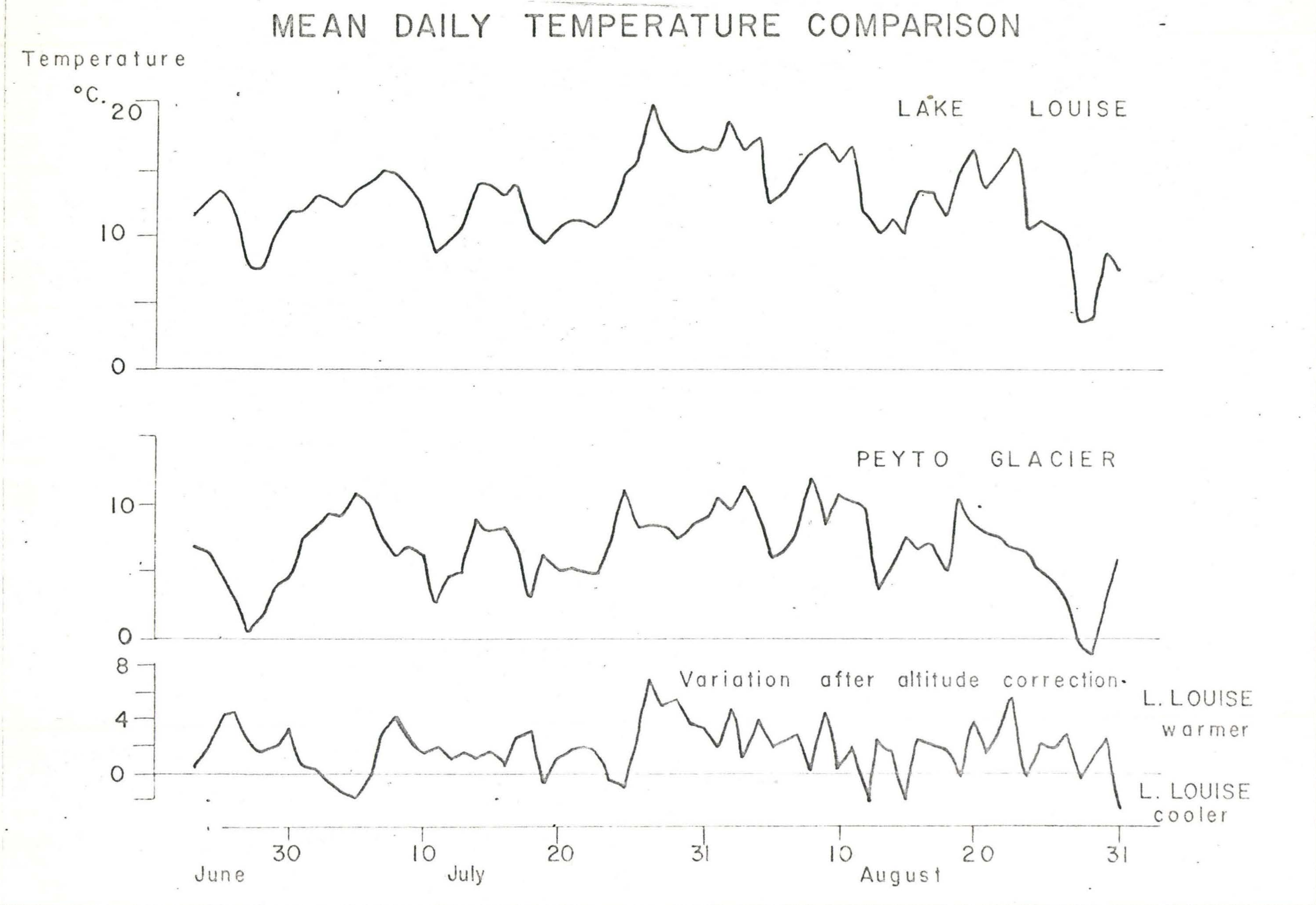

MEAN DAILY TEMPERATURE COMPARISON
Temperature
°C.
20
10
0
LAKE LOUISE
10
0
PEYTO GLACIER
8
4
0
Variation after altitude correction
L. LOUISE warmer
L. LOUISE cooler
30
10
20
31
10
20
31
June
July
August

FIGURE 11.

D. Comparison of Peyto Glacier and Lake Louise.

Because Lake Louise climatic statistics were studied to interpret long-term climatic trends, at Peyto Glacier, it was felt worthwhile to investigate the comparability of certain climatic variables recorded during the summer of 1965 at the two locations.

Both stations are located on the leeward side of the Waputik Range. These mountains form the west side of the Upper Bow Valley and are continuous along the upper Mistaya Valley near Peyto Glacier. Although the altitude difference between stations can be compensated for in temperature data, Lake Louise is below timberline in the forested valley floor, a site which probably decreases range and mean annual temperatures about 2°F. (1.1°C.). In summer, this cooling effect may be as much as 5°F. (2.8°C.) but, as the meteorological screen is near a house in the townsite of Lake Louise, the possible heat island effect, and especially the forest clearings, likely offset this depression of temperature. Adding to this heat island is increasing urbanization in the town site.

Plots of daily mean temperatures (8.) from the two stations (see Figure 11.) indicate similar patterns but maximum and, to a lesser extent, minimum points on the curve are often 1-2 days later at Lake Louise. Possibly air mass movements associated with these temperature fluctuations progress from the Peyto Glacier area down the Bow Valley to Lake Louise with a 1-2 day lag.

Correlations of precipitation recorded at the two stations coincide well in regard to time as wet periods of several days duration usually occur at both locations simultaneously. However, as would be expected, amounts differ; generally Lake Louise received more precipitation but trace amounts were more prevalent at Peyto Glacier because the methods of recording differed.

In comparing the temperature variations from the two stations, correction for the 687 m. difference in altitude was made at the normal lapse rate of 0.6 °C. per 100 m. This gave a correction of 4.1 °C. However, it was found that usually the difference between the stations was greater than altitude difference alone would warrant. Because it is unlikely that the Lake Louise station had some influence making it unaccountably warm (see above discussion) and thus altering the normal altitude variation, it was felt that the Peyto Glacier readings are usually cooler than elevation considerations justify because of prevailing winds off the cool glacier surface. This cool factor was normally distributed about a mean of 1.9 °C.

In studying those 14 occasions out of 70 days when Peyto Glacier was warmer than Lake Louise (after correction for altitude), it was found that 10 occurences had the following characteristics at the glacier:

1. rising temperature with mean 8.5 $^{\circ}$C.
2. rising or steady winds; generally 13-16 km./hr., gusting to 24 km./hr.
3. fair weather with moderate cloud cover of 30-40%
4. falling humidity and fairly low mean relative humidity of 58%

Several of these characteristics (rising temperature, gusty winds, falling humidity) are typical of föhn (chinook) effects (9.) that could account for the unusually warm conditions at the glacier meteorological site. Balmy gusts have been encountered on the Victoria Glacier (10.) near Lake Louise, and the author can recall a similar wind on the tongue of Peyto Glacier one afternoon. Further analysis of this problem would require the study of data from regional synoptic charts and other meteorological stations; a project beyond the scope of this discussion. However, it may be fruitful future research, as a chinook would probably have an important effect on the ablation of the glacier.

Although long-term analysis of the glacier regimen was completed in this chapter and preliminary generalities concerning weather conditions at Peyto Glacier were set out, the major correlation of ablation with weather is reserved for discussion in Chapter 7. concerning ablation.

Footnotes - Chapter 4.

1. Ahlmann, 1940. p. 188.
   Flint, 1957. p. 27.

2. Østrem, 1964 (a).

3. Hannell and Stewart, 1952.

4. Heusser, 1956. p. 287.
   Powell, 1965.
   Hubley, 1956.

5. Heusser (1956) suggests a lag of 1 decade or more before any activity at the terminus of Peyto Glacier will occur in response to climatic fluctuations. This lag is quite reasonable and if there is a 10-year cycle in present climatic fluctuations, then the terminus would not indicate any signs of activity in response to climate changes.

6. see footnote 5.

7. Critchfield, 1960. p. 327.

8. Mean daily temperatures at Lake Louise are derived by summing the daily maximum and minimum and dividing by 2. This is not as accurate as averaging 24 hourly readings (the regular Peyto Glacier technique--see page 53.) but was used in this section for more accurate comparison of the 2 stations.

9. Critchfield, 1960. p. 136.

10. Sherzer, 1907. p. 13.

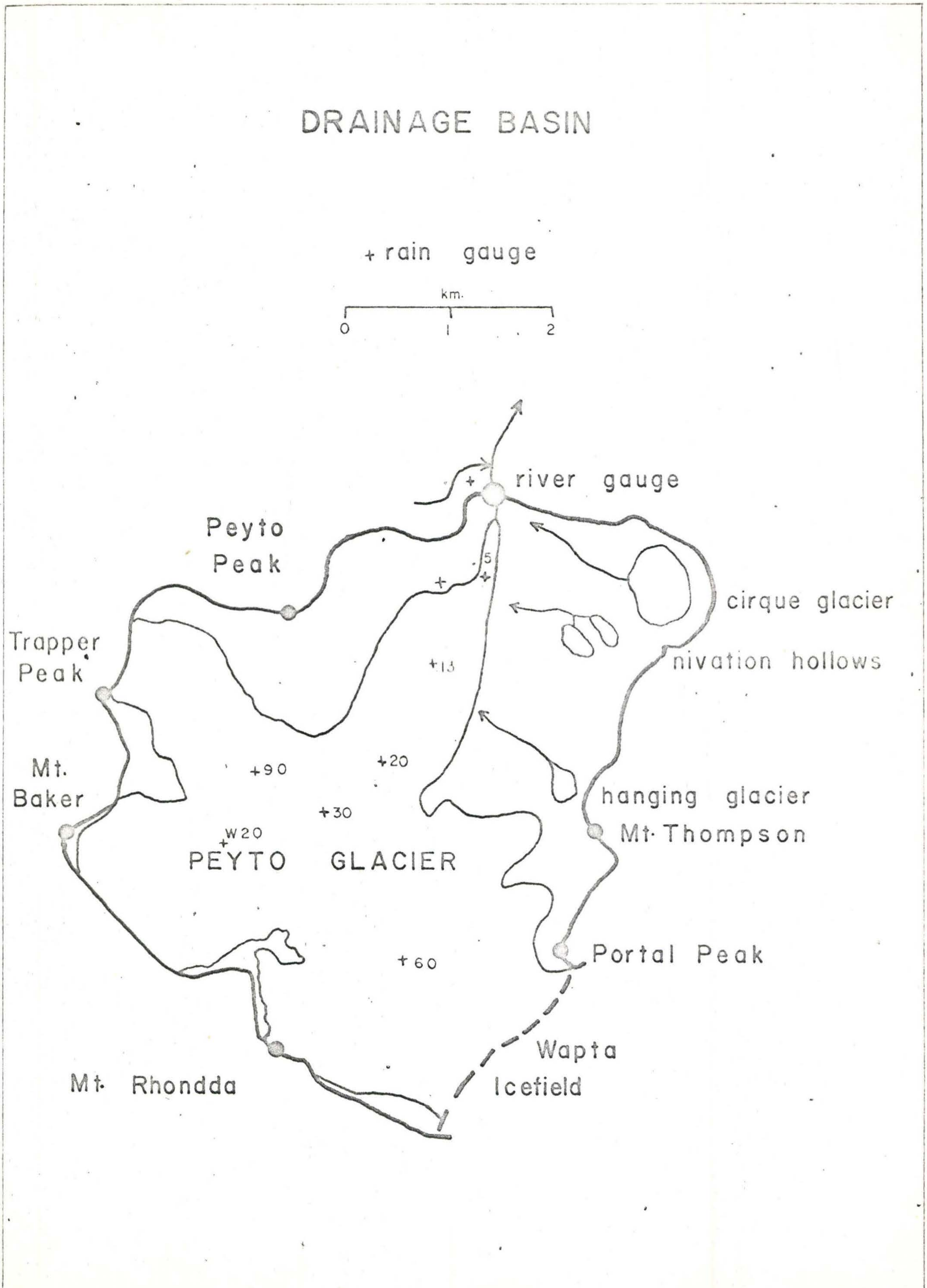
CHAPTER 5.-Meltriver Hydrology

A. Introduction

Stream discharge measurements on Peyto River were undertaken with two purposes in mind. Such data would clarify the frequency, duration and range of discharge fluctuations and thus provisionally depict the "personality" of the river. This aspect of the total hydrology of a river is necessary prerequisite for estimating potential water resources, especially on a short-term basis. In addition, discharge figures are necessary to distinguish between that flow due to precipitation and that originating from the ablating glacier. Hydrological data also outlines discharge behavior under varied weather conditions; information valuable in predicting discharge in melt rivers, not only at a specific glacier, but at similar glaciers with known regimens and weather conditions.

Measurements of water levels were taken in order to establish river stage and thus discharge. To maintain a constant stage-discharge relationship, a stable channel section is required; a criterion usually calling for a river confined by bedrock. Peyto River

MAP 6.


DRAINAGE BASIN
+ rain gauge
km.
0
1
2
river gauge
Peyto Peak
5
cirque glacier
Trapper Peak
+13
nivation hollows
Mt. Baker
+90
+20
+30
hanging glacier
W20
Mt. Thompson
PEYTO GLACIER
+60
Portal Peak
Wapta Icefield
Mt. Rhondda

has a suitable location in the lower shale portion of the second valley riegel, some 300 m. from the mouth of the gorge underlying the glacier terminus (see page 37. - 38.).

The gauge itself was a 1.5 m.-long wooden shaft marked in 5 cm. segments which was mounted on a broad wooden base and placed in a pool on the west side of the stream. The base was weighted with rocks and the shaft was steadied with wires attached to the bedrock. Water levels could be read quite easily and estimated to 1 cm. accuracy.

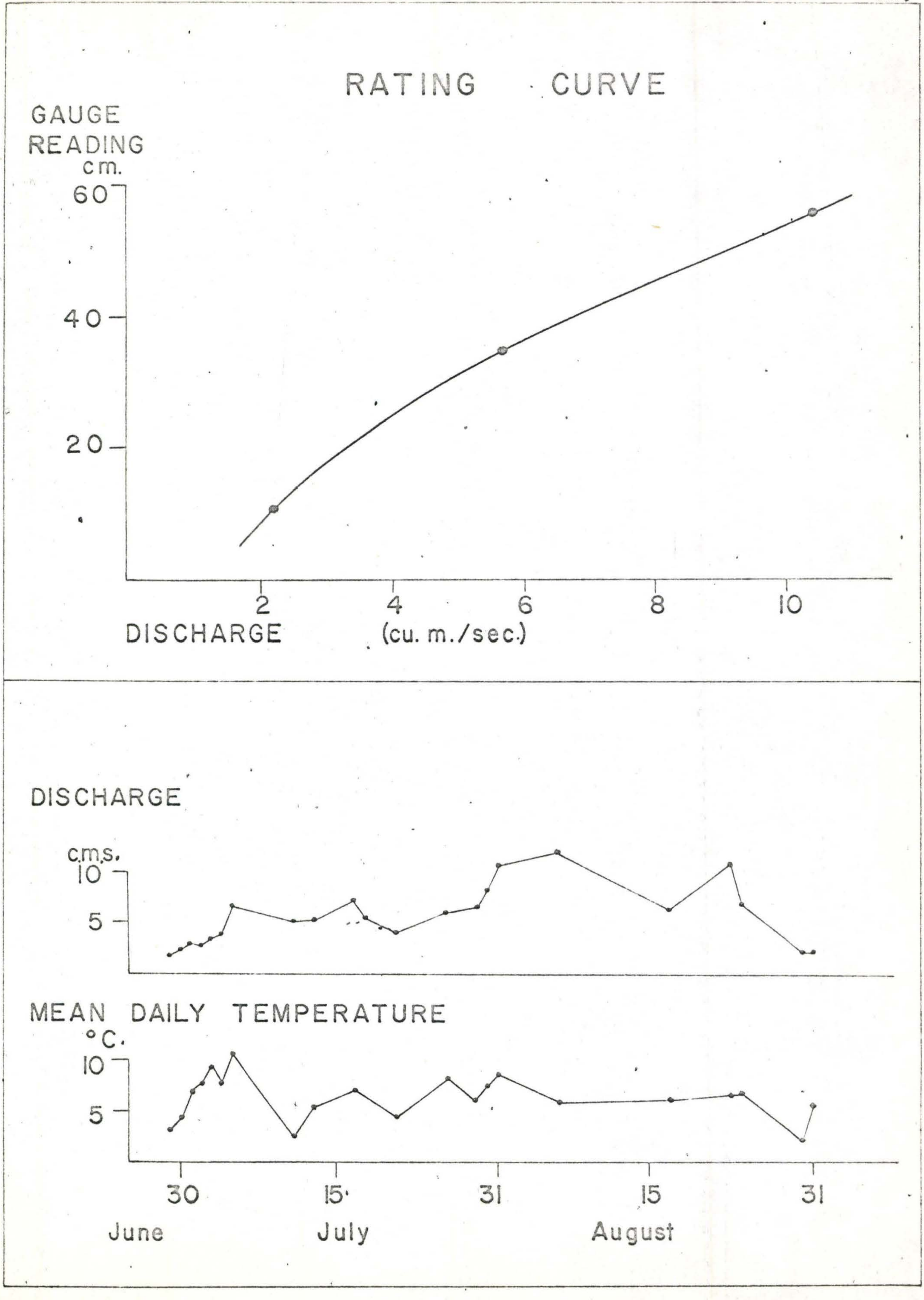
For gauging purposes, the effective drainage basin of Peyto River (see Map 6.) lies upstream from the measuring point, and any catchment area tributary to Peyto River downstream from the gauge can be effectively disregarded. This location therefore eliminates the complications induced by the major tributary of Peyto River; a stream draining Cauldron Lake to the west.

Peyto Glacier covers approximately 60% of the total area of this gauged drainage basin. Several nunatak areas along the continental divide, adjacent to the upper glacier, contribute a sizeable fraction of the non-glaciated tracts; but the major portion consists of substantial slopes flanking both sides of the glacier tongue. Most of this non-glacierized area contributes snow meltwater, then unconcentrated overland and rill flow to the Peyto River. Three minor streams draining from the hanging and cirque glaciers and nivation hollows on the east side of Peyto Valley also are tributary to the melt water drainage. These appear to be small fractions of the total river discharge at the guage, but, if the discharge of these tributaries could be established in future, more accurate calculations of discharge originating with ablation of Peyto Glacier would be possible.

B. Problems

The initial hydrological programme called for daily readings of the stream gauge at the diurnal high and low stage, likely about 0600 and 1600 hrs. Several consecutive hourly readings in the early morning and late afternoon would soon establish these diurnal high/low discharge times. However, preliminary air photo interpretation [1.] did not reveal the topography around the present glacier terminus and melt river because of more extensive ice cover when the photos were exposed. Thus, the field party found that a trip from the camp to the stream gauge required traversing the ablation moraine and a rock face to avoid the gorge. This required so much time that daily readings were impractical and an afternoon reading at varying times was made

FIGURE 12.


RATING CURVE
GAUGE READING cm.
60
40
20
2
4
6
8
10
DISCHARGE (cu. m./sec.)
DISCHARGE
c.m.s.
10
5
MEAN DAILY TEMPERATURE
°C.
10
5
30
15
31
15
31
June
July
August

every few days. Thus the readings of discharge throughout the season are irregular. A further difficulty was encountered when the first two stream gauges were washed away by the rising river after the ablation season initiated. Each newly installed gauge was placed in a location which appeared more suitable under the rising water conditions but, from field knowledge of the stream and gauge locations, it was possible to relate readings on the different gauges. Thus the previous readings were not useless but were integrated into the total number of readings.

C. Methods

In order to convert the gauge readings into discharge values, actual discharge measurements were conducted at periods of low, medium and high water levels using a salt-dilution method.(2.) This gave a provisional rating curve (see Figure 12.) of stage/discharge for the majority of river levels which are encountered.

To establish the diurnal cycle of discharge, 26 successive readings were taken over a period of 28 hours under clear, sunny, warm conditions. As well, 22 successive readings in as many hours during cloudy weather with steady precipitation were made. A short period of 5 consecutive hourly readings was recorded during an afternoon of varied sunny/cloudy weather. These values were plotted to show the diurnal cycle of discharge and were used to calculate the percentage of peak discharge achieved for each hour. The latter curves permitted the irregular daily discharge reading times to be corrected to the maximum discharge value for that day, no matter what time the reading was taken.

D. Results

The values of maximum daily discharge at the peak period were related to a number of climatic variables (daily mean temperature, daily mean cloud cover, maximum daily temperature, precipitation, daily temperature range, etc.) in an attempt to derive a variable from which daily discharge values could be accurately estimated for the days during the field season when readings were not obtained. However, because of the scarcity of daily discharge readings, no such variable was determined. Discharge must be a result of a number of weather variables and such complexity may well preclude the existence of any simple relationship. But, during the only period for which successive daily discharge figures are available (June 29-July 5), the curve of the values parallels that of daily mean temperature (see Figure 12.). This suggests that some correlation does exist and future research is needed to clarify the situation.

FIGURE 13.

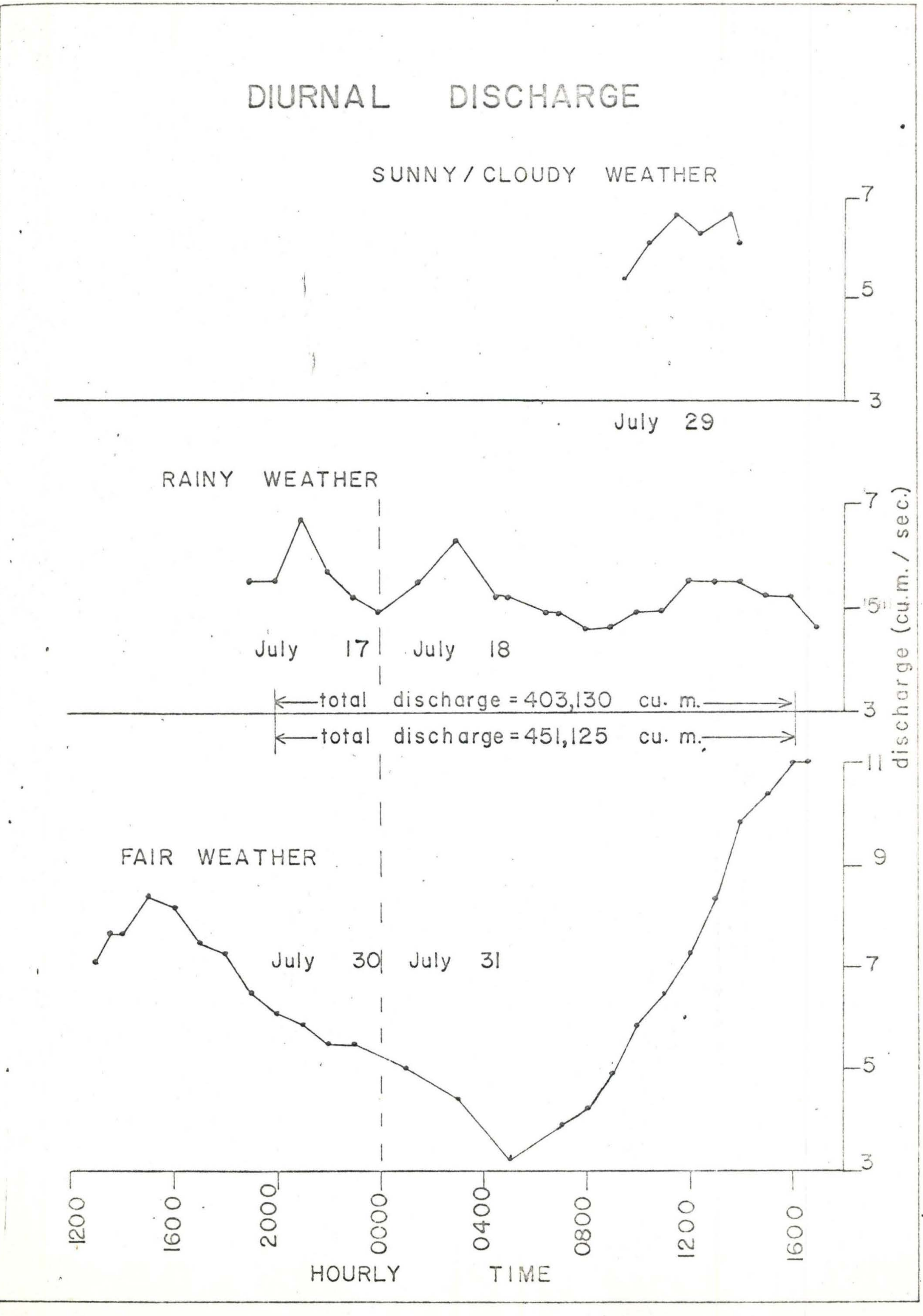
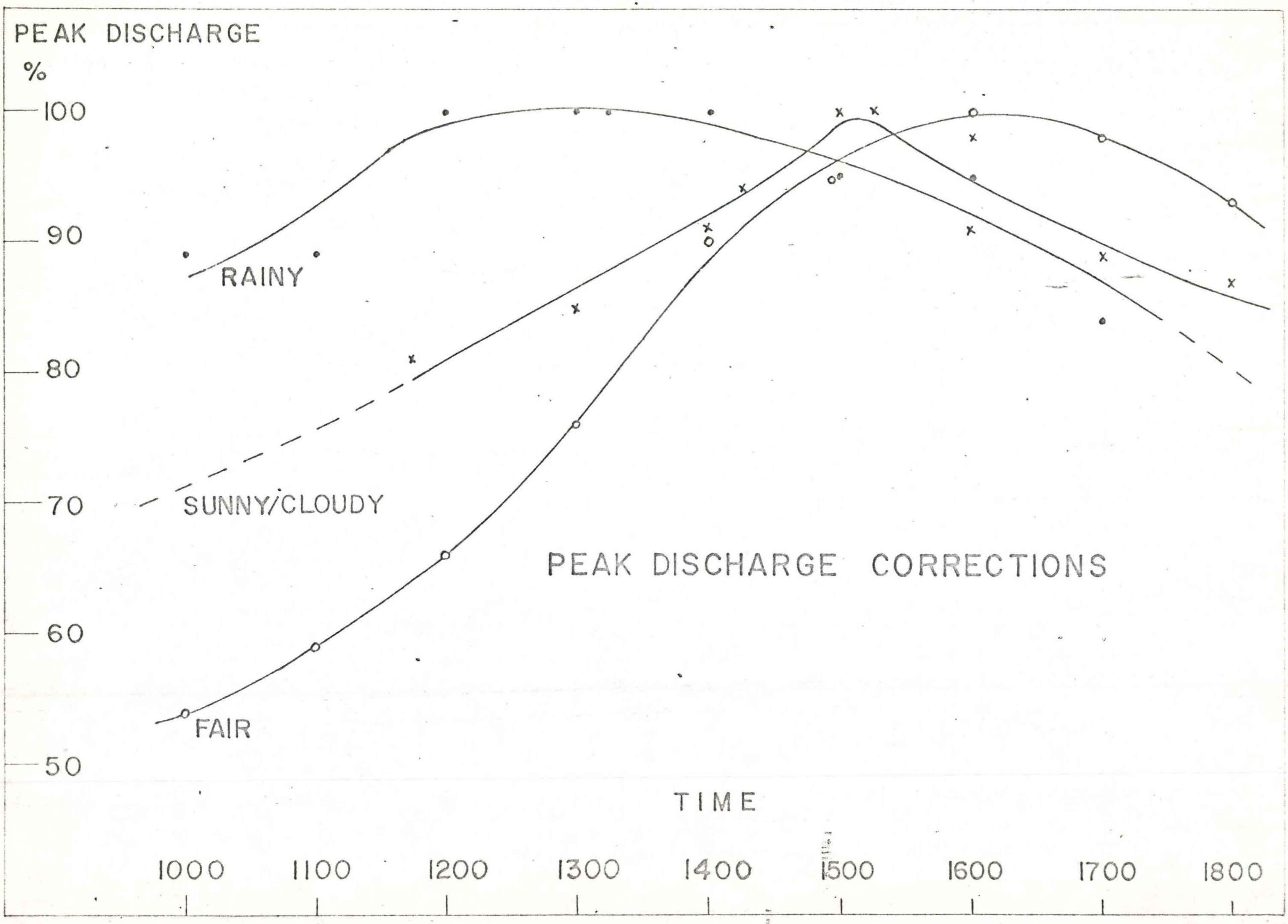

DIURNAL DISCHARGE
SUNNY / CLOUDY WEATHER
July 29
RAINY WEATHER
July 17
July 18
total discharge = 403,130 cu. m.
total discharge = 451,125 cu. m.
FAIR WEATHER
July 30
July 31
discharge (cu.m. / sec.)
7
5
3
7
5
3
11
9
7
5
3
1200
1600
2000
0000
0400
0800
1200
1600
HOURLY TIME

FIGURE 14.


PEAK DISCHARGE
%
100
90
80
70
60
50
RAINY
SUNNY/CLOUDY
FAIR
PEAK DISCHARGE CORRECTIONS
TIME
1000
1100
1200
1300
1400
1500
1600
1700
1800

The diurnal curves of discharge are more meaningful (see Figure 13.). The plot from values taken in a period of steady precipitation indicate only a slight tendency to follow a normal diurnal cycle, and peaks at 2100 hrs. and 0300 hrs. were due to heavy precipitation. The increased discharge at 1100 hrs. was associated with clearing weather and decreasing rainfall; it marks the initiation of a more regular diurnal cycle. Generally, the precipitation would appear to have a greater influence on discharge than diurnal changes in insolation and temperature. In contrast, the curve of discharge during a period of clear, warm weather displays a very strong diurnal effect with a range of discharge from 3.2 - 11.0 $m.^3$/sec; a variation of 244%.

Similar to the results of these curves are the variations of percentage of peak discharge with time for the afternoon (see Figure 14.). As expected, the curve for wet weather is flattest while the cloudy/sunny curve is transitional to the sharp curve for clear weather. There is a tendency for discharge to build up quickly before the peak but to taper off more slowly. This latter effect may be due to a build-up of water in the crevasse system of the glacier, although the hourly readings are not accurate enough to really delimit such a wave of discharge.[3] It is also noticeable that the peak discharge time occurs successively later in the afternoon as weather clears; a result of altered insolation values.

Volume calculations were made of the total discharge from 2000 hrs. to 1600 hrs. the following day for the wet period and clear period. Although peaks achieved in the clear period were 69% higher, the steadier river discharge during the wet weather almost made up the difference (451,000 $m.^3$ to 403,000 $m.^3$ or 12% difference). This emphasizes the importance of factors other than temperature in influencing the discharge values of the melt river.

The curve for precipitation/altitude (see page 59.) was utilized to estimate total volume of rainfall which fell on the drainage basin during the wet weather period when regular hourly discharge values were available. A rain gauge was located at the stream gauging station as the key gauge. In addition, the rain gauges on the lower glacier were checked on July 19, immediately after the precipitation period to verify the readings at the stream. Planimeter measurements of elevation intervals were multiplied by the expected rainfall for each interval to derive the total volume of precipitation during this period.

Precipitation at the stream began to decrease in the morning and ended by 1100 hrs. and it was presumed that a similar situation existed throughout the drainage basin, although there may have been a time lag. It was felt that the major portion of the precipitation occuring before 1100 hrs. would have thus reached the stream gauge by 1600 hrs., July 18; evén from distant parts of the basin. However, consideration of the minimum temperature at the camp on the night of July 17/18 indicates that, above 8600 ft., temperatures dropped below freezing. This would cause precipitation in the form of snow and retard the runoff. Thus, only that amount of the total precipitation below 8600 ft. was considered to have reached the gauge by the end of the period under consideration, and this was the quantity involved in volume calculations.

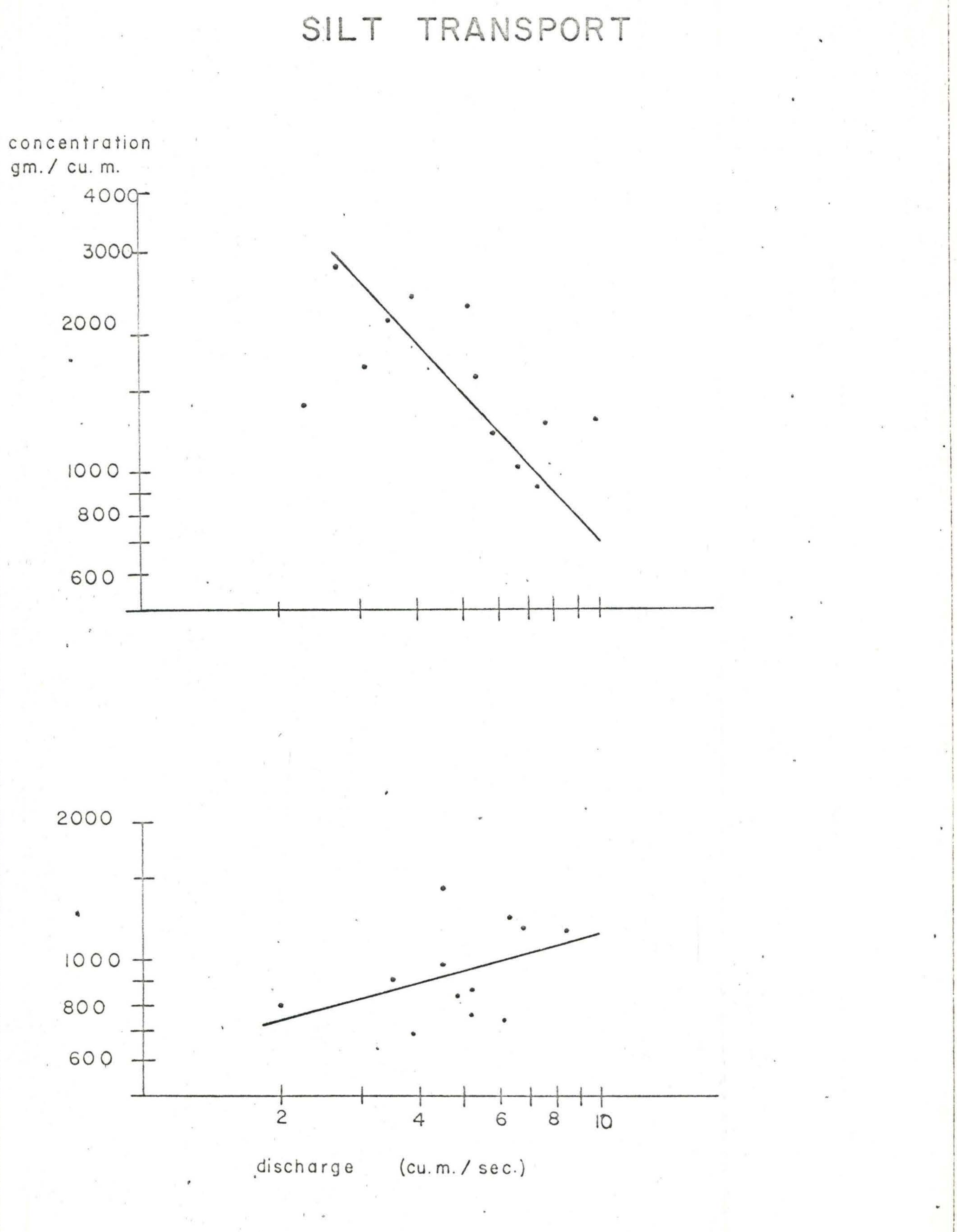
This volume of 155,000 $m.^3$ represents 38% of the total discharge during the period with the remainder being due to the glacier ablation. However, it is possible some runoff from above 8600 ft. reached the gauge in the morning and precipitation may have accounted for up to 50% of discharge. These calculations, although crude because much of the data is only provisional, point out the means by which volume calculations of precipitation can be made for fixed periods throughout the ablation season to distinguish between that fraction of total discharge due to meltwater and that caused by precipitation. However, a larger number of rain gauges are required, especially on the flanks of the glacier to integrate the non-glaciated areas, before consistently accurate calculations can be made. By utilizing mean percentage precipitation curves for altitude intervals (see page 59.) it will not always be necessary in future to utilize all these proposed gauges. Once precipitation patterns are determined, only a limited number of "check" gauges in strategic locations will be necessary to make accurate calculations. It is a matter of learning the "total personality" of the drainage basin by experience, and future studies should aim at depicting this aspect.

E. Sediment Load

Preliminary attempts to estimate the loads of silt transported by the Peyto River at the gauging station were carried out. Due to the turbulence of the river at this point, mixing was likely complete throughout the stream cross-section and a sample was thought to represent almost any point in the stream with the exception of the bed.

A sample of 0.471. size was obtained by plunging a bottle as far out and down in the stream as was practical by hand. This sample was filtered in the field

FIGURE 15.


SILT TRANSPORT
concentration
gm. / cu. m.
4000
3000
2000
1000
800
600
2000
1000
800
600
2
4
6
8
10
discharge (cu. m. / sec.)

and the filter papers were returned to Ottawa. Analysis in the Geographical Branch laboratory (4.) consisted of weighing and burning of the papers to determine the amount of non-combustible ash per volume of water. This provided a value of sediment concentration of gm./m.^{3} (p.p.m.).

The values obtained correspond well in magnitude with those taken from a similar melt river, (5.) being only slightly lower. However, plots of concentration/discharge (see Figure 15.) do not appear to follow the normal linear curve obtained on log-log paper (with concentration increasing at a faster rate than increasing discharge). (6.) Although a scatter of points is normal, (7.) the points from Peyto Glacier are exceptionally scattered and no curve is really a close fit. However, there is a tendency for two curves to be apparent. Under fair weather conditions, the concentration appears to decline with increasing discharge; but, in rainy weather, concentration increases, though at a slower rate, with discharge. It is suggested that during clear weather, the discharge is mainly due to ablating ice which has a relatively constant amount of sediment contained in it. Increasing discharge dilutes this constant amount of debris, lowering concentration. But, in rainy weather, sediment transport from the non-glaciated areas is increased by overland and rill flow and the total sediment in the river is increased, causing an increase in concentration.

It is evident that many more samples are necessary to clarify this aspect of the hydrology and experiments in sampling techniques must aim at more consistent and representative samples. However, the velocity of the river is sufficient to make this a great problem in future studies.

Footnotes - Chapter 5.

1. This was carried out by S. Jonsson of the Geographical Branch.

2. Østrem, 1964 (b.).

3. Fahnestock, 1963. p. 12.

4. The analytical work was conducted by T. Bellar-Spruyt of the Geographical Branch.

5. Fahnestock, 1963. p. 32.

6. Leopold and Maddock, 1953. pp. 20-21.

7. ibid, p. 20.

CHAPTER 6. - Accumulation

A. Introduction

"Accumulation" embraces all those processes by which ice is added to a glacier.[1] The term includes the following phenomena:[2]

1. direct precipitation of snow and ice (in the form of hail).

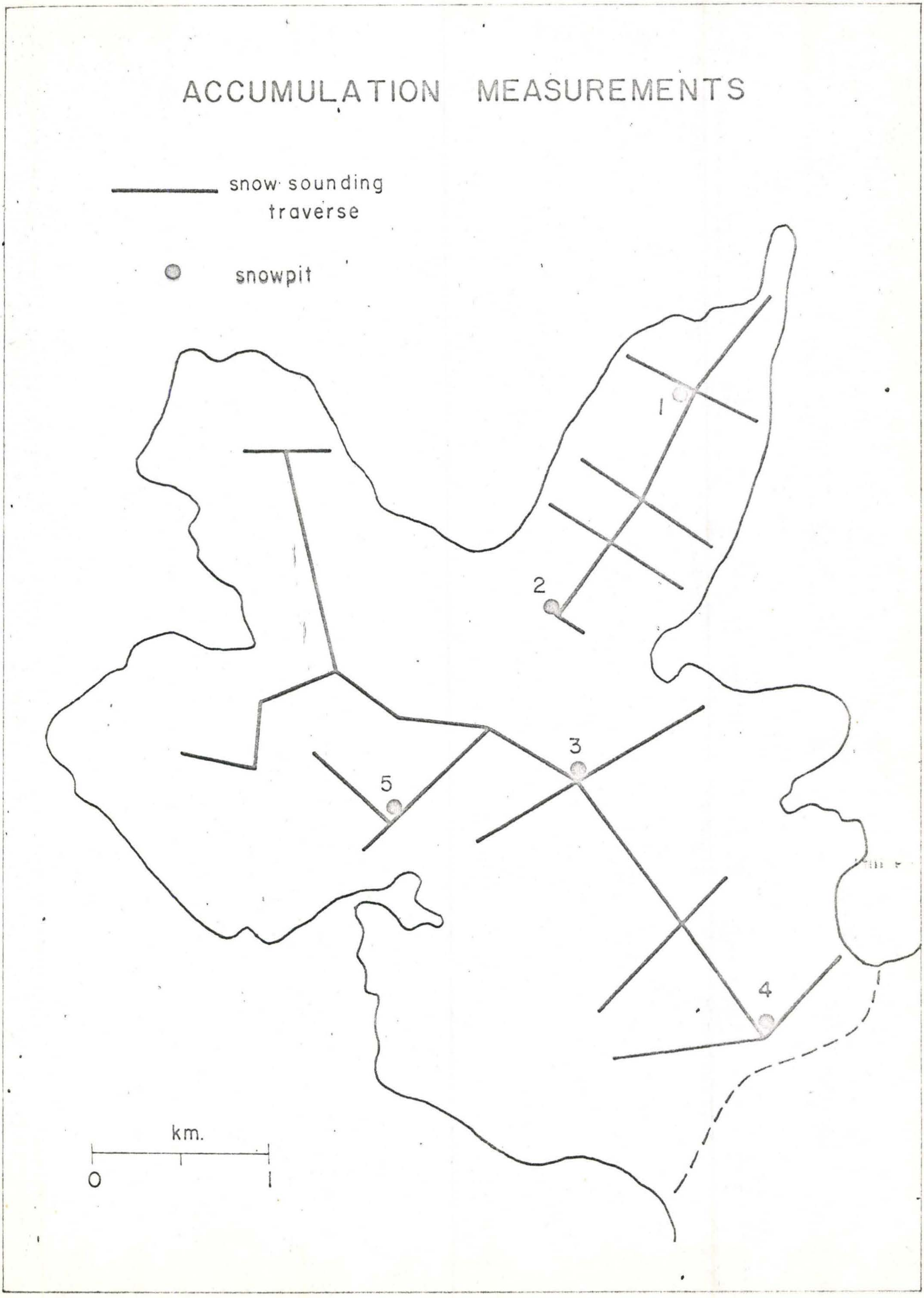
2. freezing of liquid precipitation from rain and sleet (freezing rain).

3. condensation of ice (in the form of hoar frost or rime) from vapour by sublimation.

4. transport of snow or ice to the glacier by avalanching from surrounding heights and wind transport of snow.

Beyond stating that snowfall accumulation is, quantitatively the more important process (perhaps 95% of total accumulation), no subjective judgments are made concerning the effectiveness of the other phenomena. During the field season, no sleet or hail was recorded at the glacier, nor was hoar-frost found on any ablation stakes (a sommon occurence on some glaciers). Snow contributed by avalanches was found around Mt. Rhondda and to a lesser extent Mt. Baker, but the amounts did not appear to be a large portion of total accumulation. Thus, measurements

MAP 7.


ACCUMULATION MEASUREMENTS
snow sounding traverse
snowpit
1
2
3
4
5
km.
0
1

of accumulation were concerned only with determining the amount of snowfall.

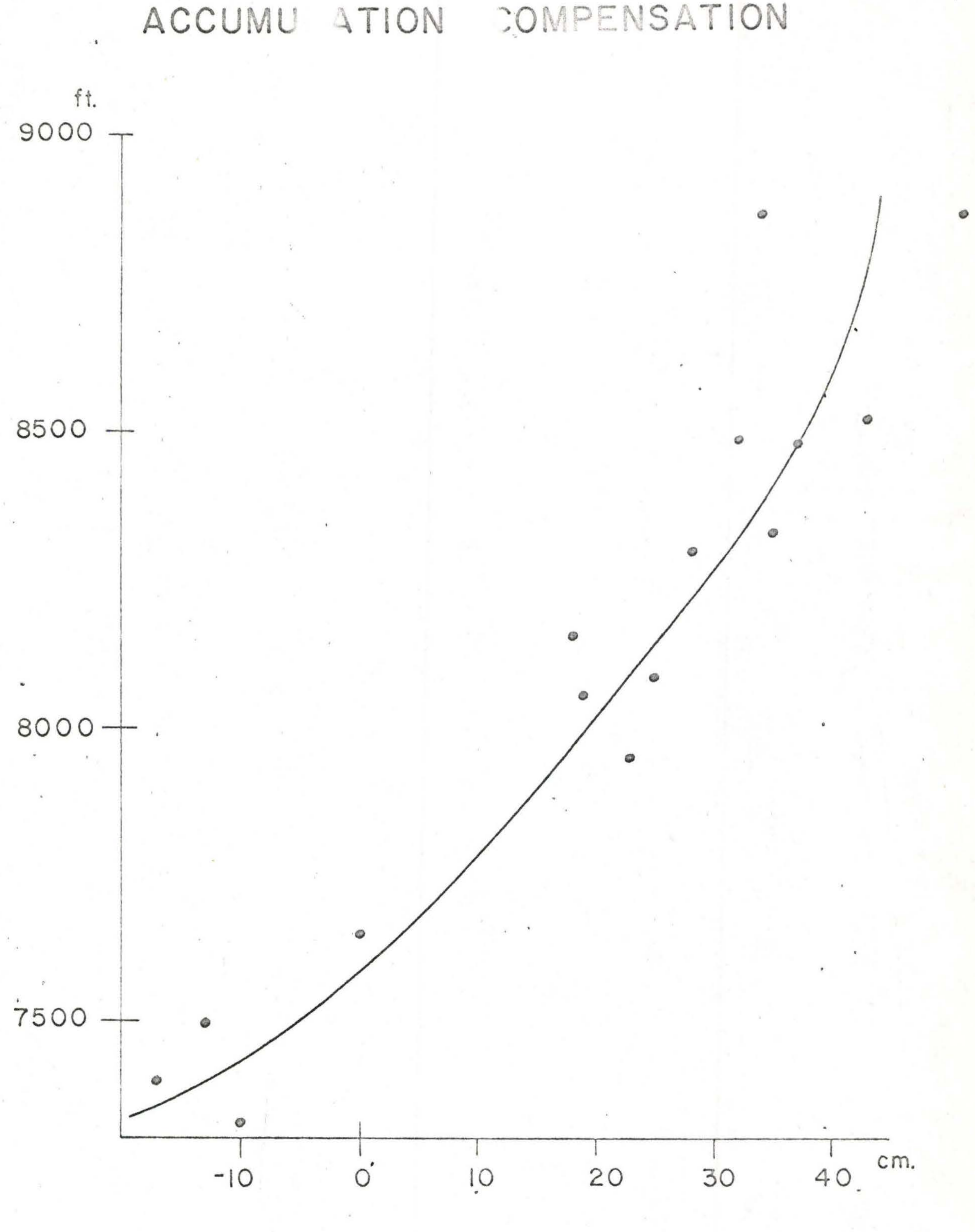
B. Techniques

Snowfall depths vary greatly within short distances, chiefly because of erratic wind action,[3.] but also due to slope, topography, and the irregularities of the underlying ice or firn surface. Thus, accurate snowfall determinations must be based upon a large number of snowdepth soundings spread evenly over the glacier surface.

To distribute the soundings randomly, traverses were made over various parts of the glacier forming a network (see Map 7.). At every 50 m. along the traverses a sounding was made and, on Peyto Glacier, almost 300 such soundings were made along 15 traverses.

The accumulation soundings are conducted at the theoretical time between the end of accumulation and the initiation of ablation sometime in the spring. However, these conditions usually overlap, at least with altitude, and the actual point in time is impossible to detect. For this reason, 150 soundings were made on Peyto Glacier at a likely time near the end of the accumulation period in early April, 1965 by a Geographical Branch field party.[4.]

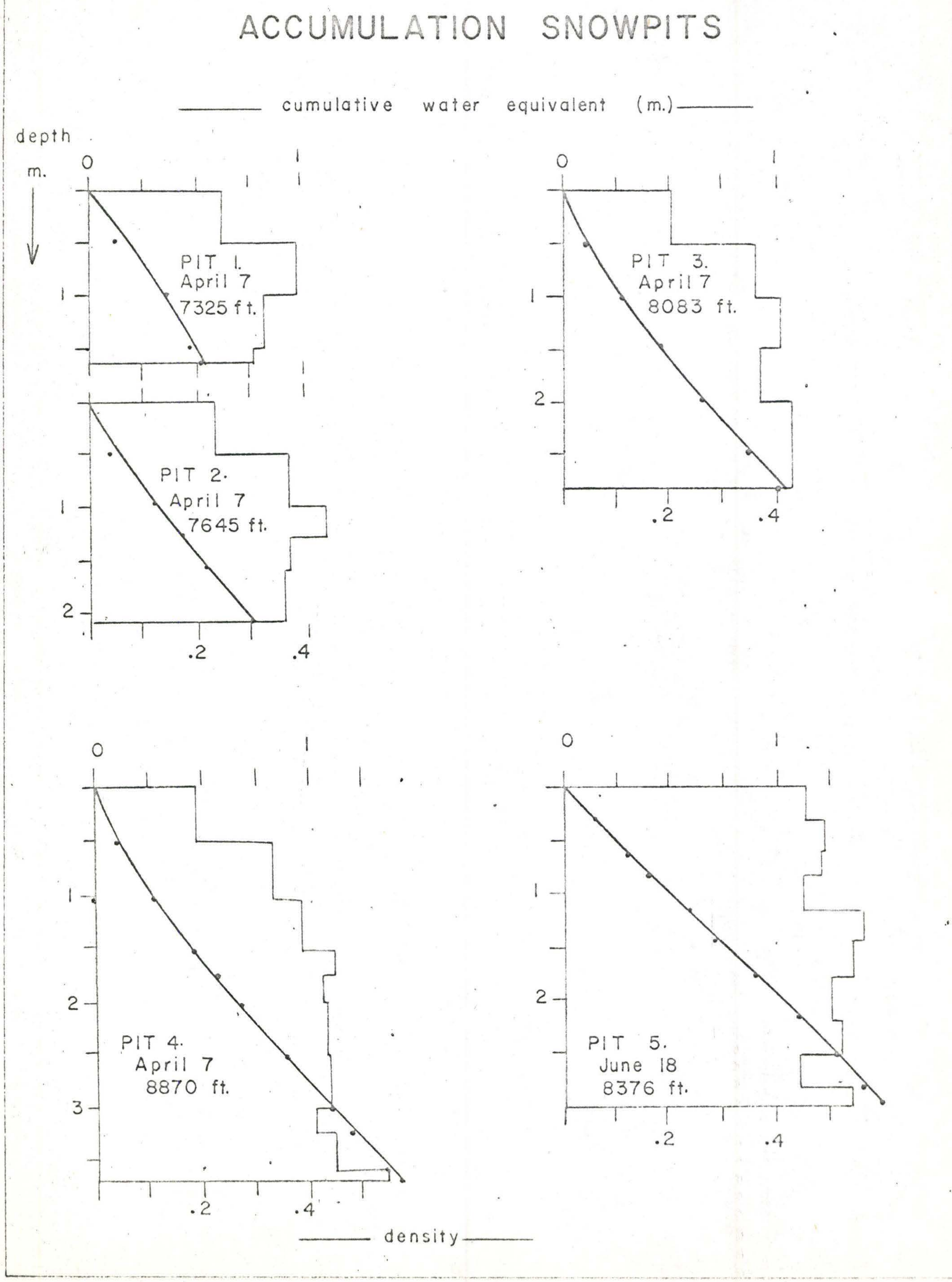
FIGURE 16.


ACCUMULATION COMPENSATION
ft.
9000
8500
8000
7500
-10
0
10
20
30
40
cm.
additional snowfall

The remaining 130 soundings were completed by the author in mid June to cover areas missed in April, and to check on the suitability of the April measurements. In order to utilize the June soundings as accurate measurements of final accumulation, fibre plates were placed on the snow surface in April at marked locations. In June, new snowfall on these plates was measured, allowing a compensating curve for additional snowfall after April to be constructed (see Figure 16.). Additional quantities of snow were added to the totals of April according to the curve, to determine final snowdepths at the absolute end of the accumulation season.

Soundings were made with a pointed steel rod constructed of 4 inter-locking 1 m. extension lengths marked in cm. The ice surface of the lower parts of the glacier under the snowcover was easily located, but some care was required to detect the summer surface (the division between the winter's fresh snow and last year's "old snow") in the firn area. Providing the last summer has not been unusually cold, the upper surface of the old snow has a crust easily felt by experienced sounders, and no difficulty was experienced at Peyto Glacier in this regard.

Because snow density varies with altitude and location, it is necessary to reduce these snowdepth measurements to a common non-variable; the water

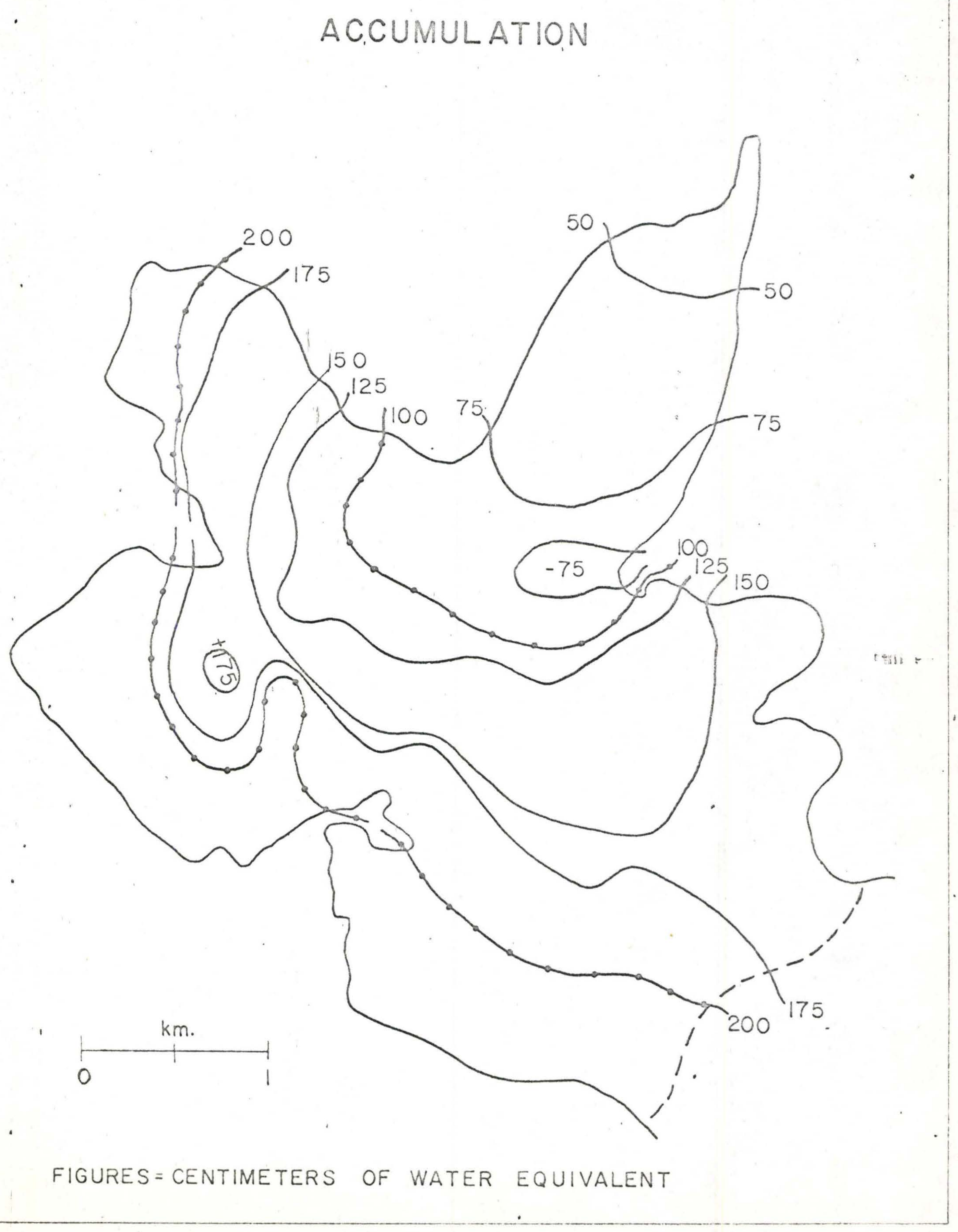

ACCUMULATION SNOWPITS
cumulative water equivalent (m.)
depth m.
0
1
2
3
.2
.4
PIT 1. April 7 7325 ft.
PIT 2. April 7 7645 ft.
PIT 3. April 7 8083 ft.
PIT 4. April 7 8870 ft.
PIT 5. June 18 8376 ft.
density

equivalent. This allows meaningful comparisons of accumulation to be made from point to point on the glacier and from one glacier to another.

To obtain density data, a cylindrical snow sampler is pressed vertically into the snow at the bottom of a pit dug successively deeper. This permits a continuous sample to be taken to include minor density variations at depth caused by weather conditions during and after deposition. The normal sample obtained (approximately 30-50 cm. long) is extracted from the sampler and weighed on a spring balance to within ·1% of the normal sample weight of 400-700 gms.

These values of weight and length of sample permit density/snowdepth graphs (see Figure 17.) to be constructed for each pit. But, to facilitate use of these density figures in converting snowdepths to water equivalent depths, cumulative density/depth curves are constructed for a vertical section with area 1 cm.^{2}. This allows direct water equivalents to be plotted from the curve for any snowdepth.

Four snowpits were dug in early April, at different elevations,[5.] to determine how density varied with altitude at Peyto Glacier. This showed variation was slight and, in June, one pit was considered sufficient to represent density conditions at the absolute end of the accumulation period.


ACCUMULATION
200
175
150
125
100
75
50
50
75
-75
100
125
150
175
175
200
km.
0
1
FIGURES = CENTIMETERS OF WATER EQUIVALENT

The sounded snowdepths were plotted on a map as water equivalents to derive a distribution map. Isolines of equal accumulation were interpolated to show patterns of accumulation (see Map 8.). These values permitted volume calculations of water accumulation to be made and both specific and total accumulation with altitude was then available.

C. Results

The curve constructed to determine additional snowfall from April to June (see Figure 16.) indicates a regular increase of snowfall with altitude except in the upper portion where snowfall tends to decrease. This is a similar pattern to the curve for summer precipitation, although the break in the curve is higher and less severe. The lower portion of the curve is complicated by small amounts of ablation which may have occurred at low altitudes below 7600 ft.

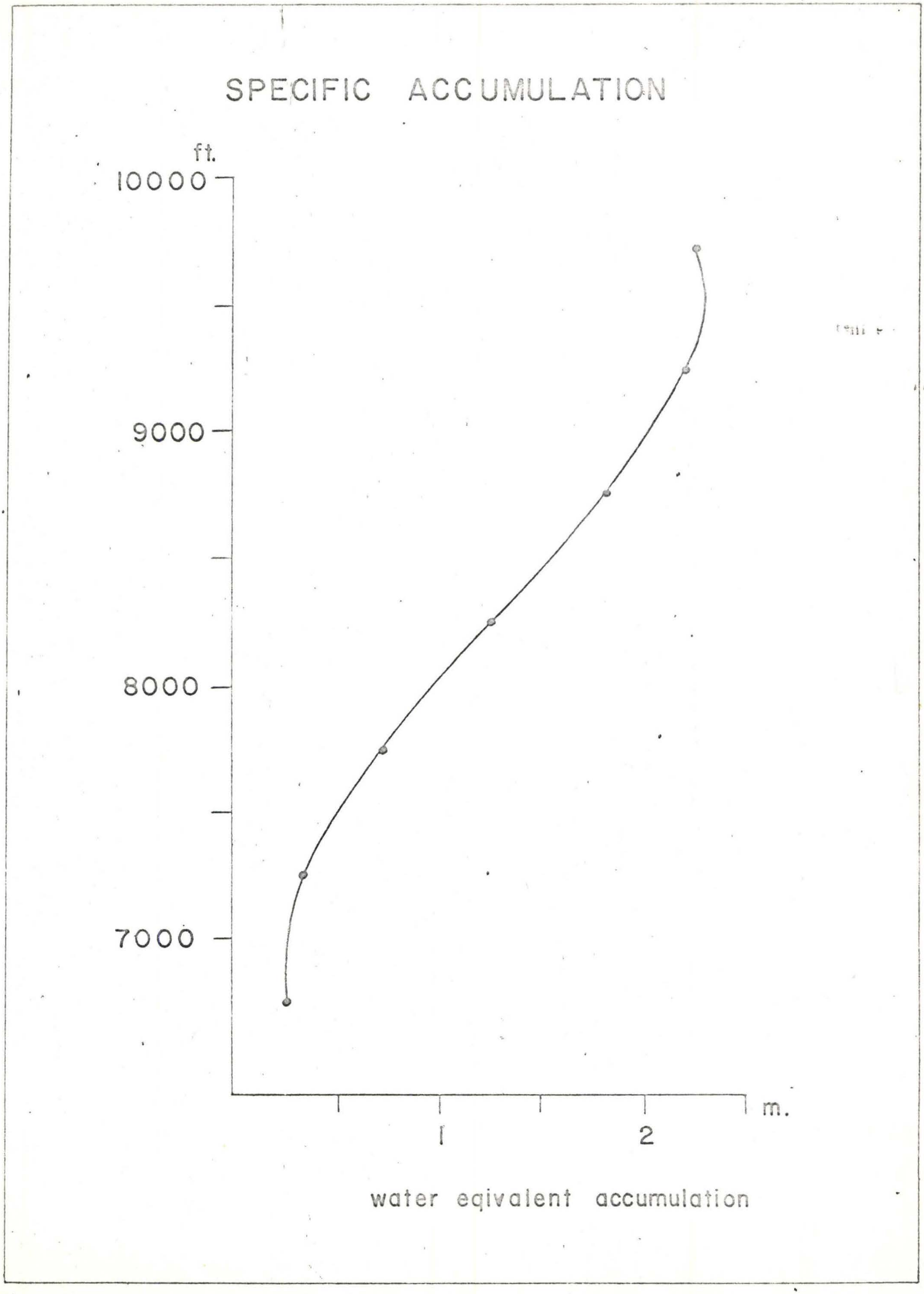
Study of the 4 snowpit density graphs indicates a maximum variation with altitude of 6 cm. of water at 1 m. depth. This is not really significant as snowdepth measurements can easily err an equivalent of 50% or more of this value. The remaining maximum variation of 3 cm. representing the actual density change with altitude is lost in the mapping generalities inherent in interpolating isolines. The density variation with altitude is due chiefly to the compaction of snow by its own weight and is really a function of snowdepth, not altitude. Thus apparent altitude changes occur because snow tends to be deeper at higher altitudes.

The density graph for June shows a significant change in density because of the change in season. Meltwater from ablating snow at the surface has percolated into the snowpack but was not lost from the glacier as it was trapped in the lower layers of the snow. This is the main reason for the density increase. Temperature readings in the side of the snowpit confirmed that, below approximately 1 m., percolating meltwater would re-freeze.

It is interesting to point out that the previous summer surface is evident from density graphs. The highest snowpit in April was dug slightly into the firn, as shown by the sudden density change from 0.45 to 0.55 in the bottom 12 cm. This change is visually evident in the pit by the dark colour of the old snow crust.

The map of accumulation (see Map. 8.) indicates the usual increase with altitude, but the isolines do not closely follow the contour lines. The glacier tongue has 2 abnormalities. A patch in the area of 50-75 cm.

FIGURE 18.


SPECIFIC ACCUMULATION
ft.
10000
9000
8000
7000
1
2
m.
water eqivalent accumulation

has less than 50 cm. where wind scour on the crest of the tongue removes snow. At the icefall, the tract of less than 75 cm. occurs below the vertical face of the icefall, likely because of a sheltered effect.

On the upper glacier, abnormalities also occur. The deep area of greater than 175 cm. in the western lobe is in a basin into which snow has blown. The deep (over 200 cm.) area east of this lies on the lee slope of the ridge forming a side of the basin.

The fact that altitude largely governs accumulation is evident from a curve of specific accumulation with altitude (see Figure 18.). From 7,400 to 9,200 ft. there is a regular linear increase. However, the upper end of the curve shows the "rain shadow" detected in the summer precipitation curve and the April - June snowfall curve, but at these high inaccessible elevations, measurements may be too sparse for much validity to be put on this finding. The section below 7,200 ft. has a relatively constant value of accumulation with increasing altitude on the steeply sloping terminus of the glacier tongue where no snowdepths were sounded before ablation began.

The table of accumulation (see Table 3.) emphasizes the importance of the contribution of the middle and upper portions of the glacier to the total water volume;

TABLE 3.

PEYTO GLACIER

Accumulation 1964-65

ELEVATION INTERVAL (ft.)	Under 50 cm. km.^{2}	Under 50 cm. 10^6 m.^{3}	51-100 cm. km.^{2}	51-100 cm. 10^6 m.^{3}	101-150 cm. km.^{2}	101-150 cm. 10^6 m.^{3}	151-200 cm. km.^{2}	151-200 cm. 10^6 m.^{3}	Over 200 cm. km.^{2}	Over 200 cm. 10^6 m.^{3}	TOTAL AREA km.^{2}	TOTAL ACC. 10^6 m.^{3}	SPECIFIC ACC. m.
- 7000	0.04	0.010	-	-	-	-	-	-	-	-	0.04	0.010	0.25
7000 - 7500	0.32	0.080	0.06	0.045	-	-	-	-	-	-	0.38	0.125	0.33
7500 - 8000	0.06	0.015	1.77	1.328	-	-	-	-	-	-	1.83	1.343	0.73
8000 - 8500	-	-	0.83	0.623	2.55	3.188	0.85	1.488	-	-	4.23	5.299	1.25
8500 - 9000	-	-	-	-	0.27	0.338	3.63	6.353	0.96	2.160	4.86	8.851	1.82
9000 - 9500	-	-	-	-	-	-	0.12	0.210	1.65	3.713	1.77	3.923	2.22
9500 -	-	-	-	-	-	-	-	-	0.56	1.260	0.56	1.260	2.25
7000 - 9500+	0.42	0.105	2.66	1.996	2.82	3.526	4.60	8.051	3.17	7.133	13.67	20.811	1.52

not only because of deepr snowdepths, but because of the greatly increased areas. As in many natural phenomena, it is the moderate values (in this case, snowfall and altitude) which are by far most important because of their frequency of occurence (manifested in the form of large areas). The total accumulation represented 20.811 million cm^3. , a volume corresponding to a specific accumulation on the glacier of 1.52 m.

FOOTNOTES - Chapter 6.

1. Meier, 1962. p. 253
2. Critchfield, 1960. pp. 92 - 94
3. Østrem, 1964. p. 102.
4. The party was headed by Dr. G. Østrem, aided by S. Jonsson.
5. see footnote 4.
6. Planimeter measurements and calculations were made by R. Sherwood of the Geographical Branch.

CHAPTER 7. - Ablation

A. Introduction

"Ablation" embraces all those processes by which ice is lost from a glacier. These processes are the means by which solar heat energy is applied to the glacier and involves direct solar radiation or indirect conduction, condensation and convection. (1.) These processes are active in the following phenomena: (2.)

1. direct radiation; which is altered by the albedo of the encountered surface generally as follows: (3.)

fresh snow	75 - 85%
dense cloud	60 - 90%
old snow	40 - 70%
clear firn	50 - 65%
clean glacier	30 - 46%
dirty firn snow	20 - 50%
dirty glacier ice	20 - 30%

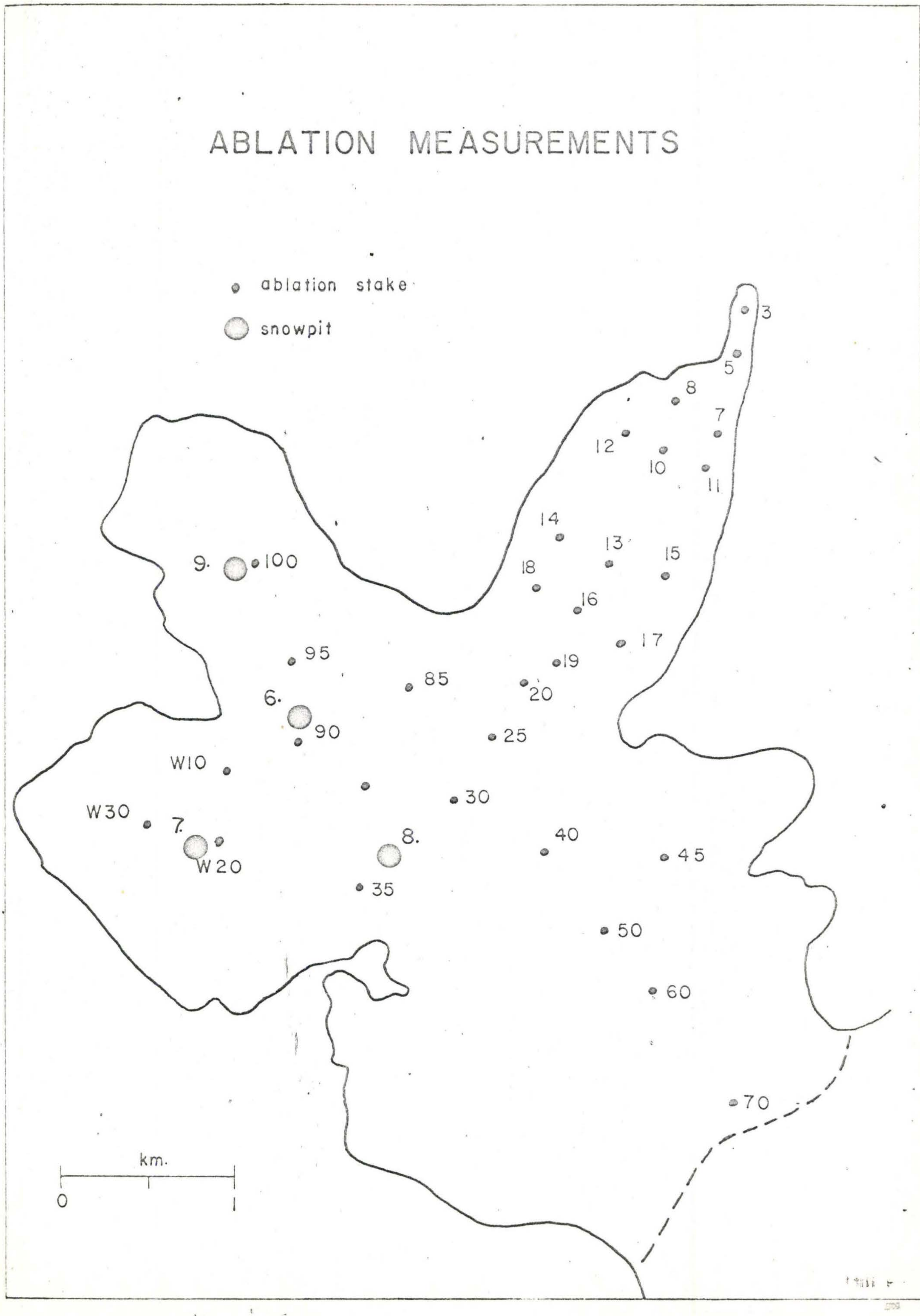
2. conduction of heat from warm air and rain.
3. condensation of water vapour in contact with the cold ice surface, releasing latent heat.
4. convection due to air turbulence; in which condensation can continue even from dry (51% relative humidity), warm (above 10°C.) air.
5. evaporation and sublimation; which occurs if the above 2 limits are reduced.

6. deflation of snow and ice by wind action.
7. calving into water bodies.

The effectiveness of these factors (4.) varies with the seasons, weather conditions, and the glacier regimen. Among ablation processes, direct radiation is the least efficient in converting ice to water because the rate of heat exchange is slower. But direct radiation is quantitatively important, especially at high elevations in continental climates, where this process may account for approximately 82% of total ablation in high open basins of Alpine glaciers. This situation would apply to Peyto Glacier above the 8500 ft. level. However, in lower enclosed basins, as on the tongue of Peyto Glacier, direct radiation is responsible for perhaps 60% of ablation. This reduction is chiefly due to shorter periods of direct sunshine because of encroaching mountain peaks and greater air turbulence. Cloud cover obviously affects radiation values and usually reduces that reaching the glacier by 67-75% on overcast days. (5.) Conduction from warm air may account for 15-30% of ablation, while latent heat of condensation causes 5-15% of total ablation. Evaporation is likely negligible, usually less than 1% on temperate glaciers except for a short time in the spring.[6.] Evidence of deflating snow was not encountered at Peyto Glacier. and calving is impossible. However in the narrow valley at the glacier terminus, large blocks of ice break off and stagnate; a process similar to calving into standing water bodies.

Although past glacier studies were usually concerned with terminal retreat, the amount of ablation occuring in this area is almost negligible compared to that ice removed by thinning of the glacier by surface downwasting.[7.] It is generally felt that ablation is more critical to the mass budget of a glacier than accumulation, and hence temperature[8.] is the most reliable overall ablation indicator in the absence of hard-to-derive radiation measurements. This fact can be best seen by considering the direction from which each process works.[9.] Accumulation preceeds from high to low elevations and increasing precipitation normally affects successively smaller areas while a small increase in temperature affects successively larger areas. Augmenting this temperature factor is the change in albedo values throughout the ablation season.[10.] As the snowcover melts, the snowline[11.] retreats up the glacier to higher elevations, thus exposing successively larger areas with a lower albedo value (70% for snow to 30% for ice).

MAP 9.


ABLATION MEASUREMENTS
ablation stake
snowpit
3
5
8
7
12
10
11
14
13
15
9.
100
18
16
17
95
19
85
20
6.
90
25
W10
30
W30
7.
8.
40
45
W20
35
50
60
70
km.
0
1

This increases the effectiveness of solar radiation as the ablation season proceeds.

B. Techniques

Ablation data was derived from readings of surface lowering made with reference to stakes imbedded in the glacier. When the Geographical Branch field party visited Peyto Glacier in April for accumulation snow soundings (see page 95.), 15 key stakes were positioned on the glacier. Later, in June, this stake net was extended by the author until a total of 31 stakes were in place (see Map 9.).

The stakes are 4 m. long aluminum alloy tubes which are marked in 1 m. segments. They are drilled into the ice with a brace-and-bit type drill and, as long as 1-1.5 m. remains fixed into the ice, the stakes are solid and give reliable readings. Surface down wasting requires redrilling of stakes periodically as the ablation season progresses to maintain this critical depth. In the firn area, stakes are pushed into the snow to rest on the last year's summer surface or, preferably, are placed on a fibre plate at the bottom of a snowpit. This is to prevent sinking of the stake when percolating meltwater disrupts the underlying snow later in the ablation period. Measurements are made from the top of the stake to the snow and/or ice surface. Differences in readings represent ablation.

Because ablation usually varies directly with altitude, fewer measuring locations are required in comparison to accumulation snow-soundings. Each stake can represent a relatively large area, providing the represented tract has consistent altitude and topographic characteristics. Thus stakes were purposely placed to represent a certain area which visually appeared to have these characteristics.

For comparative purposes (see page 98.), all readings were converted to water equivalent values. When stakes were located in ice, conversion entailed a simple multiplication by a factor of 0.9, the approximate ice density. However, for snow-covered areas, snowpits were utilized (see page 98.) to derive density data for conversion purposes.

Of particular importance to the study is the form used to record ablation data (see Figure 19.). This not only records the actual readings but a cumulative check is made in the field of ablation at each stake as well as recording snowdepths and detecting superimposed ice which may occur below the snow cover.

Calculations of total ablation at each stake

GLACIER

Elevation m.

ft.

Al
Steel
Wire
Bamboo

Total length of stake m.
Sheet

(w. q.= water equivalent)

Mon.	Date	Time diff.	Top to Snow	Top to Ice	Snow density	Snowdepth					Difference							Cumulative w. q.		Net w. q.		Notes
						Sounded		Computed			Super-imp. ice		Snow		Ice			ACC.	ABL.			
			cm.	cm.		cm. snow	cm. w.q.	cm. snow	cm. w.q.		cm. ice	cm. w. q.	cm. snow	cm. w. q.	cm. ice	cm. w. q.		cm.	cm.	cm.		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
		2-2					6·7				9-7	K·12	4-4	6·14	5-5	K·16		15+15	17+17	19-20		

FIGURE 19.

were plotted on maps and isolines of equal ablation were interpolated. Planimeter measurements of elevation intervals with given ablation were made to permit volume calculations of water to be determined (a similar technique to that used for accumulation calculations).

Because the field party was continuously stationed at the glacier throughout the field season, it was possible to utilize relatively short-term periods of approximately 10 days duration as the basis for a time interval between ablation measurements, but, because of poor weather conditions which restricted field work, intervals varied from 8-12 days. The periods were set out as:

Period	Date	Duration
1.	June 25 - - July 4	10 days
2.	July 5 - - July 13	9 days
3.	July 14 - - July 23	10 days
4.	July 24 - - August 3	11 days
5.	August 4 - - August 15	12 days
6.	August 16 - - August 26	11 days
7.	August 27 - - September 3	8 days

The date of initiation was determined by practical working conditions. It was the first date upon which the thermograph recorder, the rain gauges, and most of the stakes were in position. It would seem that a small amount of ablation had occured by this date on the glacier snout, but this amount was negligible compared to the total ablation on the whole glacier, and no attempt was made to compensate for this factor.

The final date followed several days of depressed temperatures during which up to 30 cm. of snow fell on the upper glacier. This was considered the termination of the ablation season, although a small amount of ablation may have occured from the lower glacier on occasional days in September. Any such additional ablation would be evident in measurements made for the following budget year 1965-1966, and it is not an important aspect of this study.

The ablation data so derived was considered in a synthetic approach to discussing ablation. Specific ablation values at individual stakes were considered; then ablation data was investigated periodically. Finally, the patterns of total ablation at the end of the ablation season were analyzed. This format of an intensive, progressing to an extensive, picture of ablation was used to discuss the changing ablation processes as they evolved throughout the ablation period.

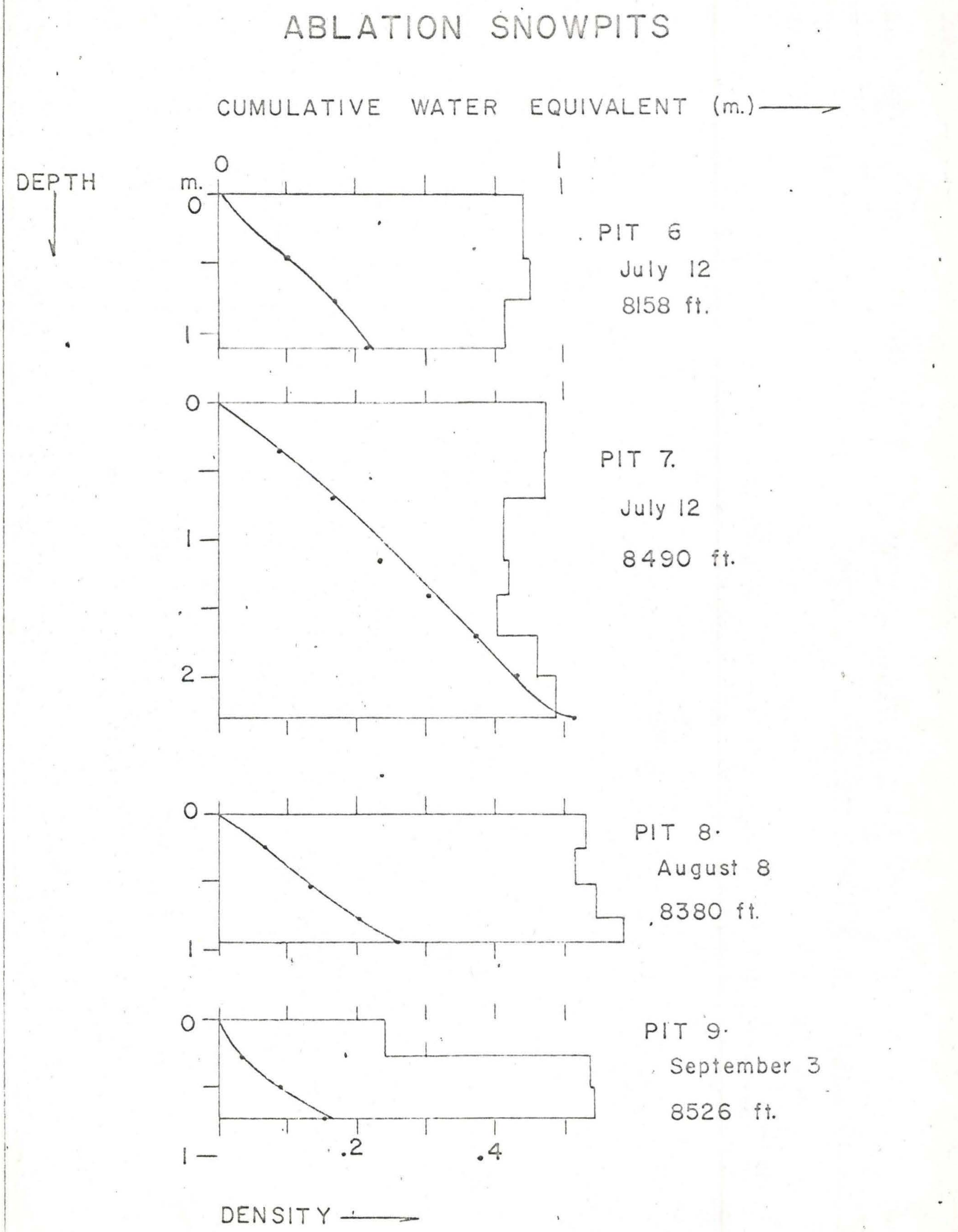
C. Results

1. Specific (Stake) Ablation

Calculation of ablation at a specific point on the glacier (as represented by an ablation stake) must consider the changing water-equivalent values of the snowpack throughout the ablation season (see page 111.). For this reason, 3 pits were dug on 3 separate dates during the ablation period. These, together with a pit dug at the beginning of the melt season (see Figure 17.) on June 18, provided a constant check on the changing snow conditions. Densities do not differ greatly from point to point on the glacier once the melt begins, so one pit was considered sufficient to cover the continually-decreasing snow-covered portions of the glacier.

As in the accumulation determination (see page 98.), derivation graphs of the snowpit data were plotted (see Figure 20.) for absolute density and the cumulative water equivalent at any depth. The data for pit 6. and 7. was obtained on the same day at 8158 ft. and 8480 ft. respectively. Although, at 100 cm., the water equivalent difference is very slight, higher densities are reached in pit 7. because of greater snow depth and thus compaction. The sharp increase in density at the previous summer surface is also evident in this pit. Pit 8. reveals a density increase because it was dug later in the season when snow compaction and percolating meltwater have caused greater water equivalent values at depth. The summer surface is evident in this pit as well. The pit dug on September 3, at the end of the ablation period, shows

FIGURE 20.


ABLATION SNOWPITS
CUMULATIVE WATER EQUIVALENT (m.)
DEPTH
m.
0
1
0
1
2
PIT 6
July 12
8158 ft.
PIT 7.
July 12
8490 ft.
PIT 8.
August 8
8380 ft.
PIT 9.
September 3
8526 ft.
.2
.4
DENSITY

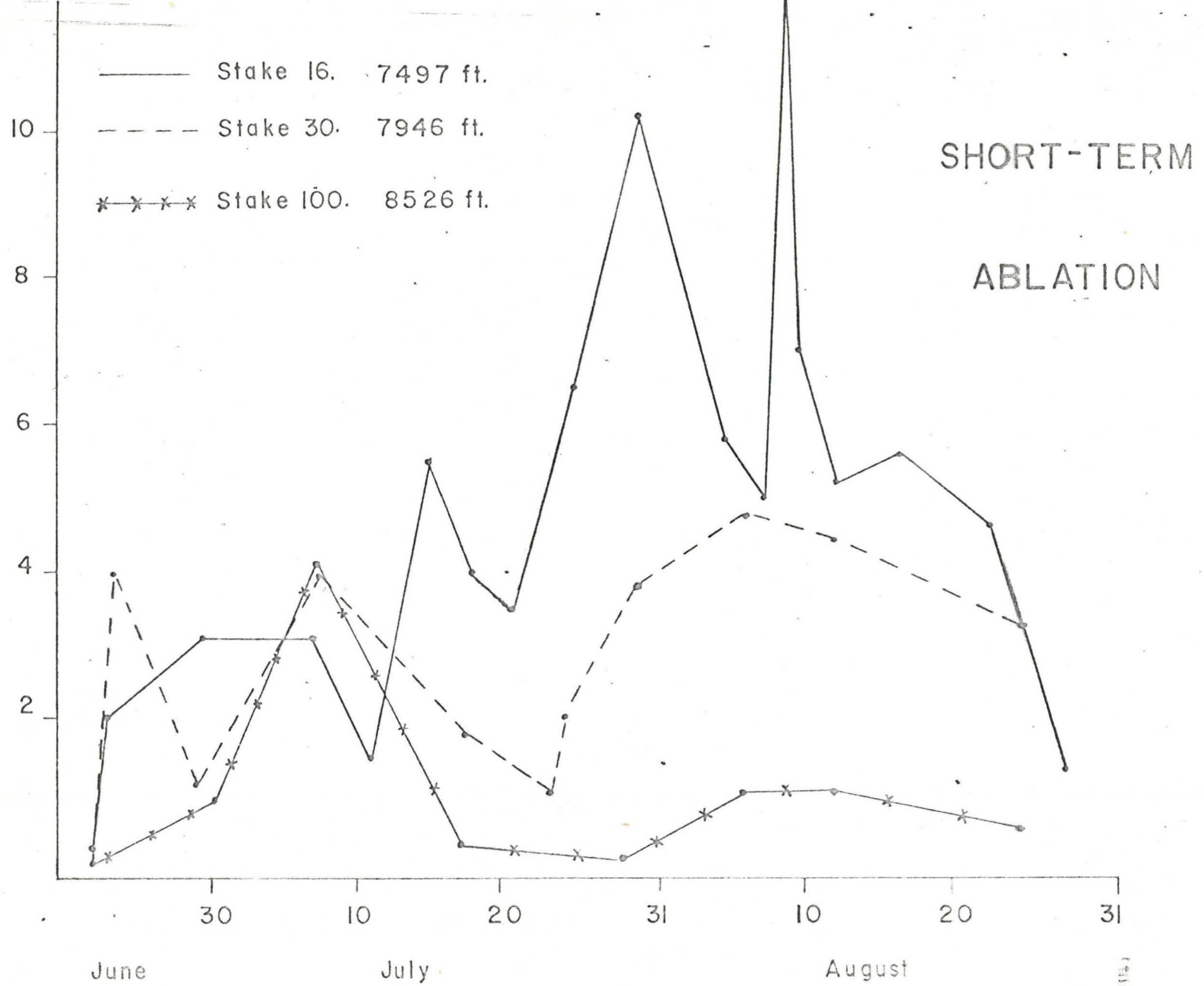

Stake 16. 7497 ft.
Stake 30. 7946 ft.
Stake 100. 8526 ft.
SHORT-TERM
ABLATION
10
8
6
4
2
30
10
20
31
10
20
31
June
July
August

FIGURE 21.

little density change from that on August 8. However, a 27 cm. deep layer of new snow is evident in this pit with a low density of 0.243.

The ablation measurements taken at various intervals of time (1-12 days, depending upon stake location and weather conditions) permitted a mean daily ablation rate to be determined for each interval by dividing ablation during that interval by the number of days in the interval. This could be done for each stake and a graph of 3 such calculations is given (see Figure 21.). It is evident that the shorter the interval between measurements, the greater the irregularities of the curves because minor fluctuations of ablation are detected. This is the reason that stake 16. displays irregularities more than the other stakes for it was on the lower glacier and was measured more frequently (1-4 days). In fact, ablation graphs of stakes with short time intervals on the lower glacier are too confused to be utilized, although they pinpoint detailed variations. Despite the many minor fluctuations, it is apparent that the 3 curves are essentially different in form and this suggests that ablation rates over the 7 periods differ for 3 different portions of the glacier; the lower glacier, the upper glacier, and the upper firn area. Therefore, a method of averaging ablation values in the 3 tracts was employed.

FIGURE 22.

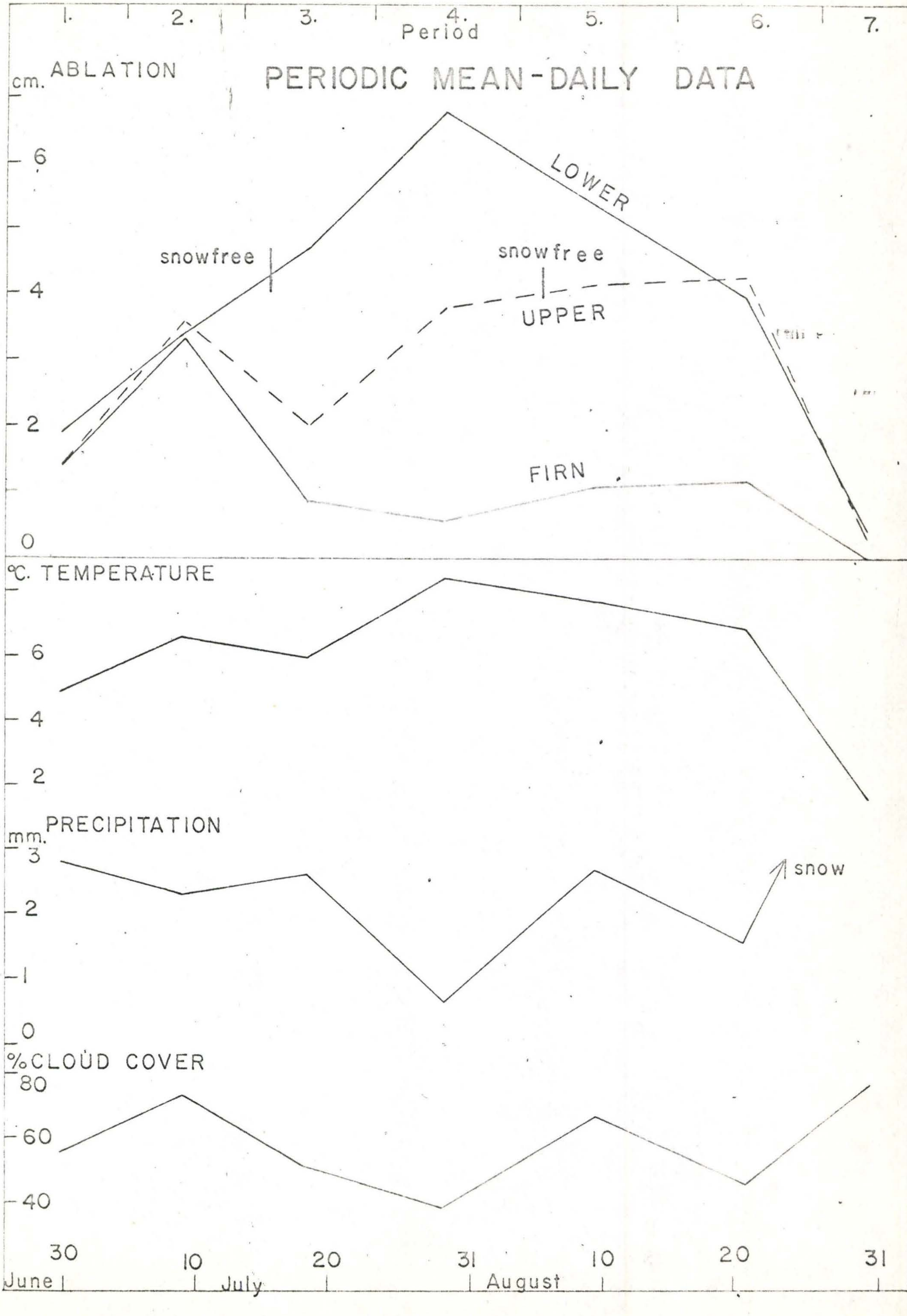
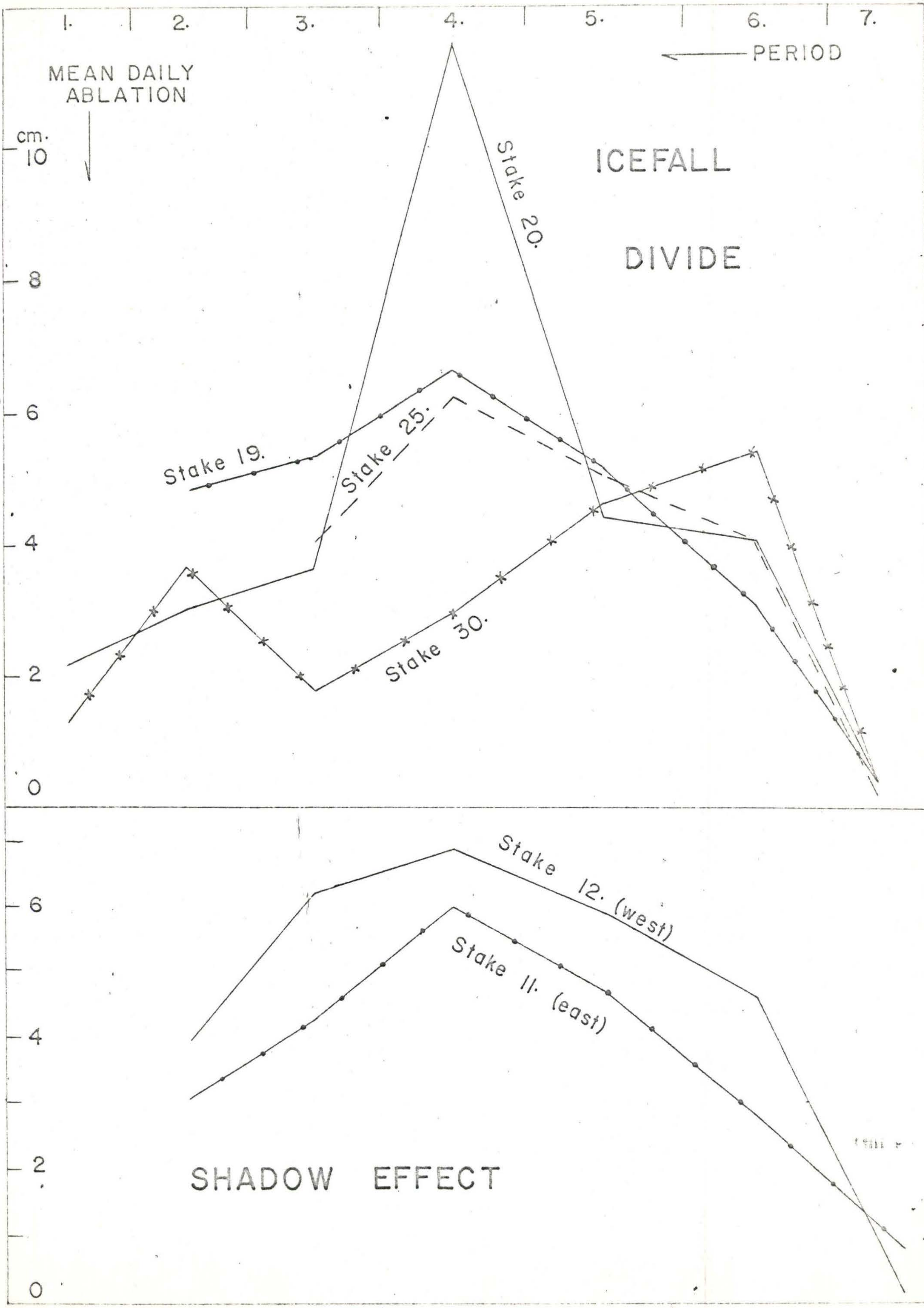

1. 2. 3. 4. 5. 6. 7.
Period
PERIODIC MEAN-DAILY DATA
cm. ABLATION
6
4
2
0
LOWER
snowfree
snowfree
UPPER
FIRN
°C. TEMPERATURE
6
4
2
mm. PRECIPITATION
3
2
1
0
snow
% CLOUD COVER
80
60
40
30
10
20
31
10
20
31
June
July
August

FIGURE 23.



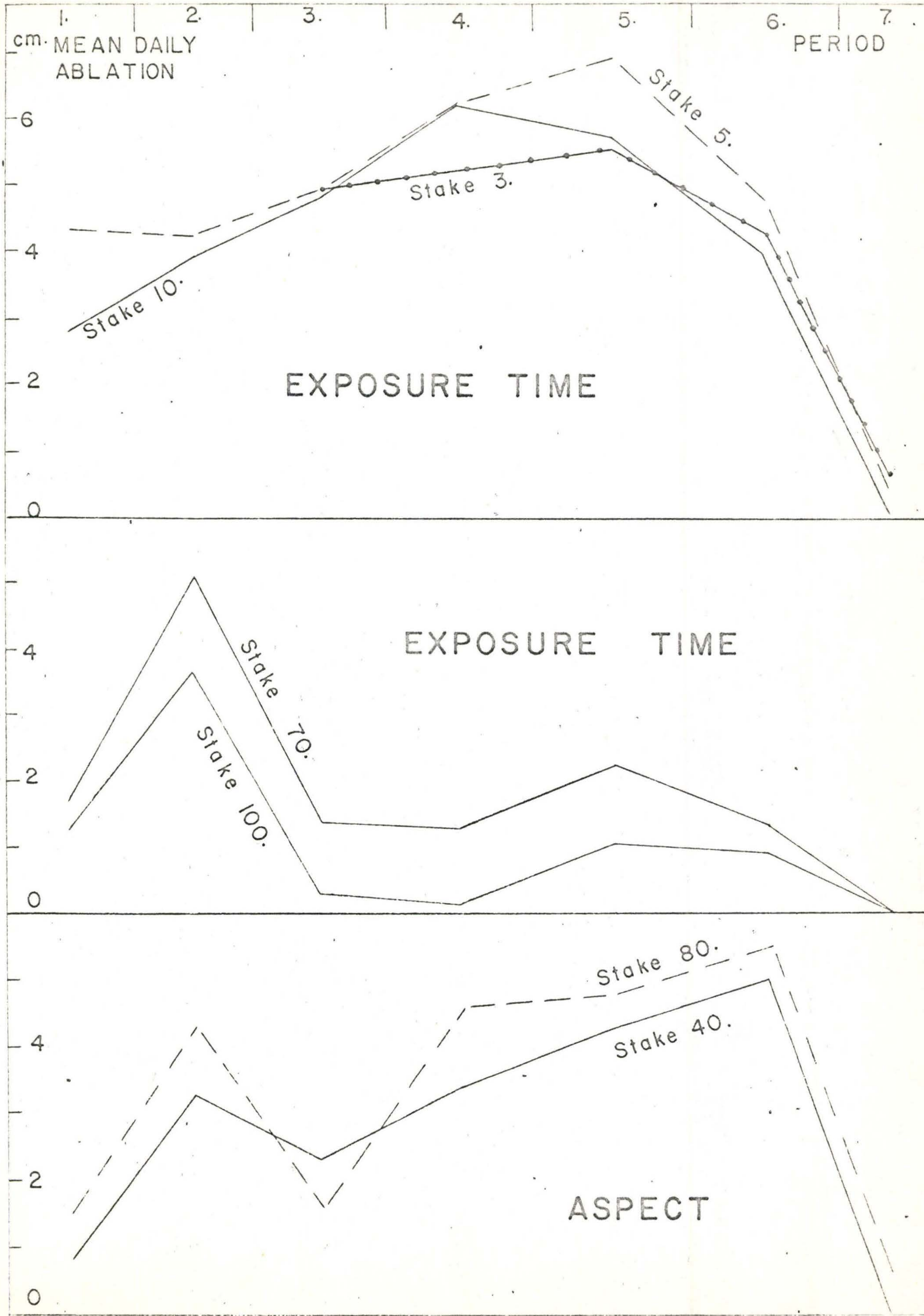
1.
2.
3.
4.
5.
6.
7.
PERIOD
MEAN DAILY ABLATION
cm.
10
8
6
4
2
0
ICEFALL
DIVIDE
Stake 20.
Stake 19.
Stake 25.
Stake 30.
6
4
2
0
Stake 12. (west)
Stake 11. (east)
SHADOW EFFECT

The mean daily ablation values for all stakes in each of these 3 areas were summed to obtain a mean value to construct generalized ablation curves representing the 3 tracts (see Figure 29.). These curves were representative of the 3 distinct glacier portions, and the stakes which occured in one of these tracts had individual ablation curves which closely conformed to the generalized curve. However, slight variations of individual stake curves did exist, and these provided interesting detailed insight into ablation.

Curves for 4 stakes in the icefall area (see Figure 23.) point out the importance of this feature as the divide between the upper and lower glacier. Stake 19., 20., 25., are all below the lip of the icefall and have a curve similar to that generalized for the lower glacier. Stake 30. above the lip, is definitely of the upper glacier type. Stake 20. reveals the highest peak of any stake in any period (11.7 cm./day) and is likely due to meltstream channelling near the stake.

The effect of the shadows from peaks along the east side of the tongue is evident in curves of stake 11. and 12. Here, the western stake has a consistent ablation rate of 1-2 cm. per day higher. Again these stakes are typical of the curve for the lower glacier.

FIGURE 24.

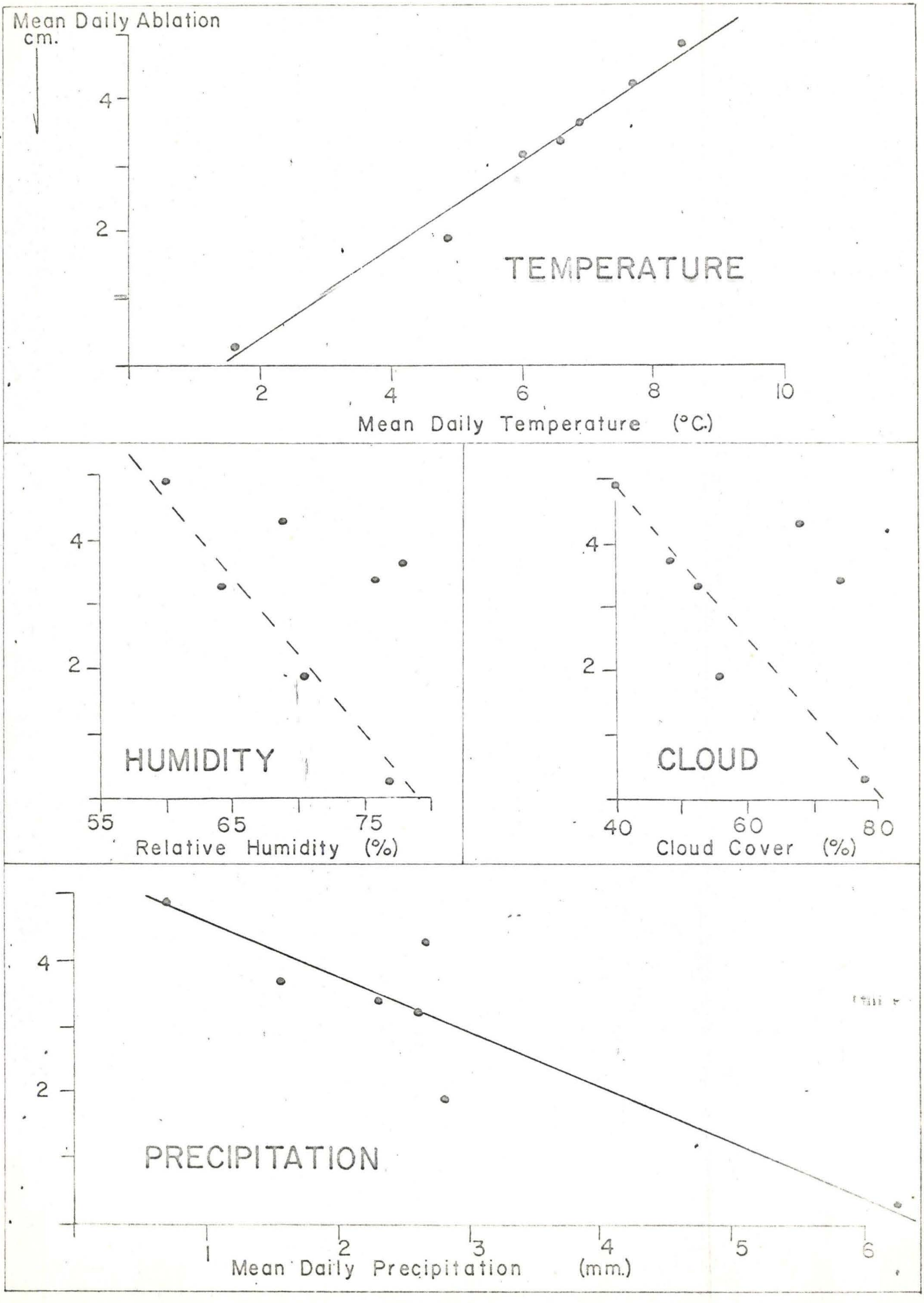

1.
2.
3.
4.
5.
6.
7.
cm. MEAN DAILY ABLATION
PERIOD
6
4
2
0
Stake 5.
Stake 3.
Stake 10.
EXPOSURE TIME
4
2
0
Stake 70.
Stake 100.
EXPOSURE TIME
Stake 80.
Stake 40.
4
2
0
ASPECT

Exposure time to the sun's rays are shown by 3 stakes on the snout (see Figure 24.). The lowest stake has less ablation due to the narrow valley walls and this effect has been referred to in previous discussion. The curve for stake 5. reveals the high ablation rate in period 1., as the snow cover was removed from that area by that time.

Two curves from stakes in the firn area (see Figure 24.) reveal the importance of exposure. Stake 100. is sheltered from afternoon sun by rock walls surrounding the north-west lobe, while stake 70. is likely not shaded at any time. Thus, although the latter is more than 100 m. higher, it has consistently higher ablation. Both curves closely conform to the generalized curve for the firn area.

The effect of aspect can be shown by curves for stakes 40. and 80. (see Figure 24.). The latter generally has greater ablation because it is on a south-facing slope while stake 40. lies on a slight north-facing slope. Relief difference of 8 m. is not likely sufficient to account for the ablation difference. Again, both curves demonstrate a pattern similar to the generalized curve for their area, the upper glacier; although no

FIGURE 25.


Mean Daily Ablation cm.
TEMPERATURE
Mean Daily Temperature (°C.)
HUMIDITY
Relative Humidity (%)
CLOUD
Cloud Cover (%)
PRECIPITATION
Mean Daily Precipitation (mm.)

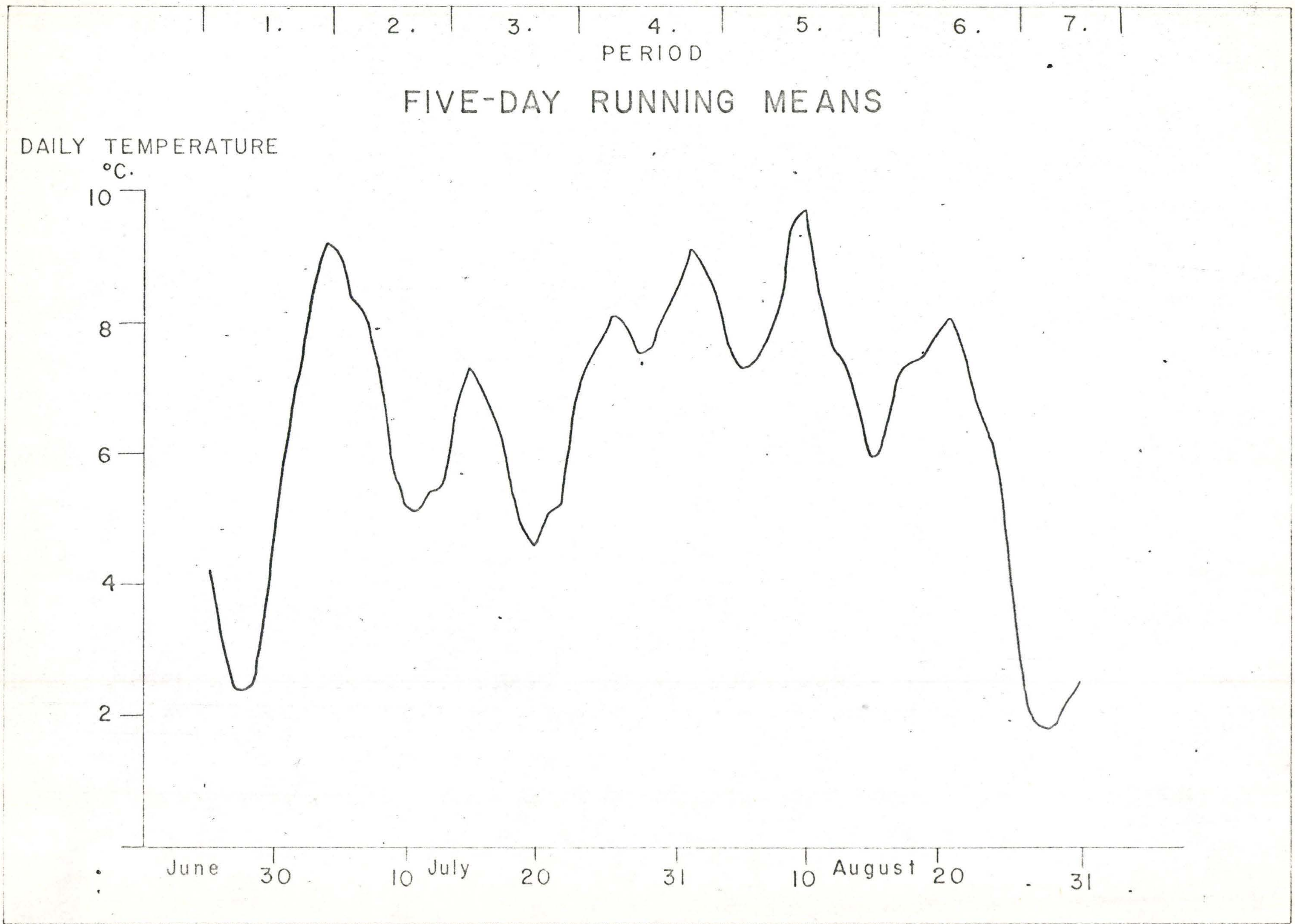

1.
2.
3.
4.
5.
6.
7.
PERIOD
FIVE-DAY RUNNING MEANS
DAILY TEMPERATURE
°C.
10
8
6
4
2
June
30
10
July
20
31
10
August
20
31

FIGURE 26.

reason can be seen in period 3 for depression of the stake 80. curve below that of stake 40.

Thus, the individual stakes reveal minor differences in ablation rate which can be accounted for by topography, daily exposure time, and aspect. These factors were also investigated periodically.

2. Periodic Ablation

For each of the seven periods, a daily mean value was determined for the following factors:

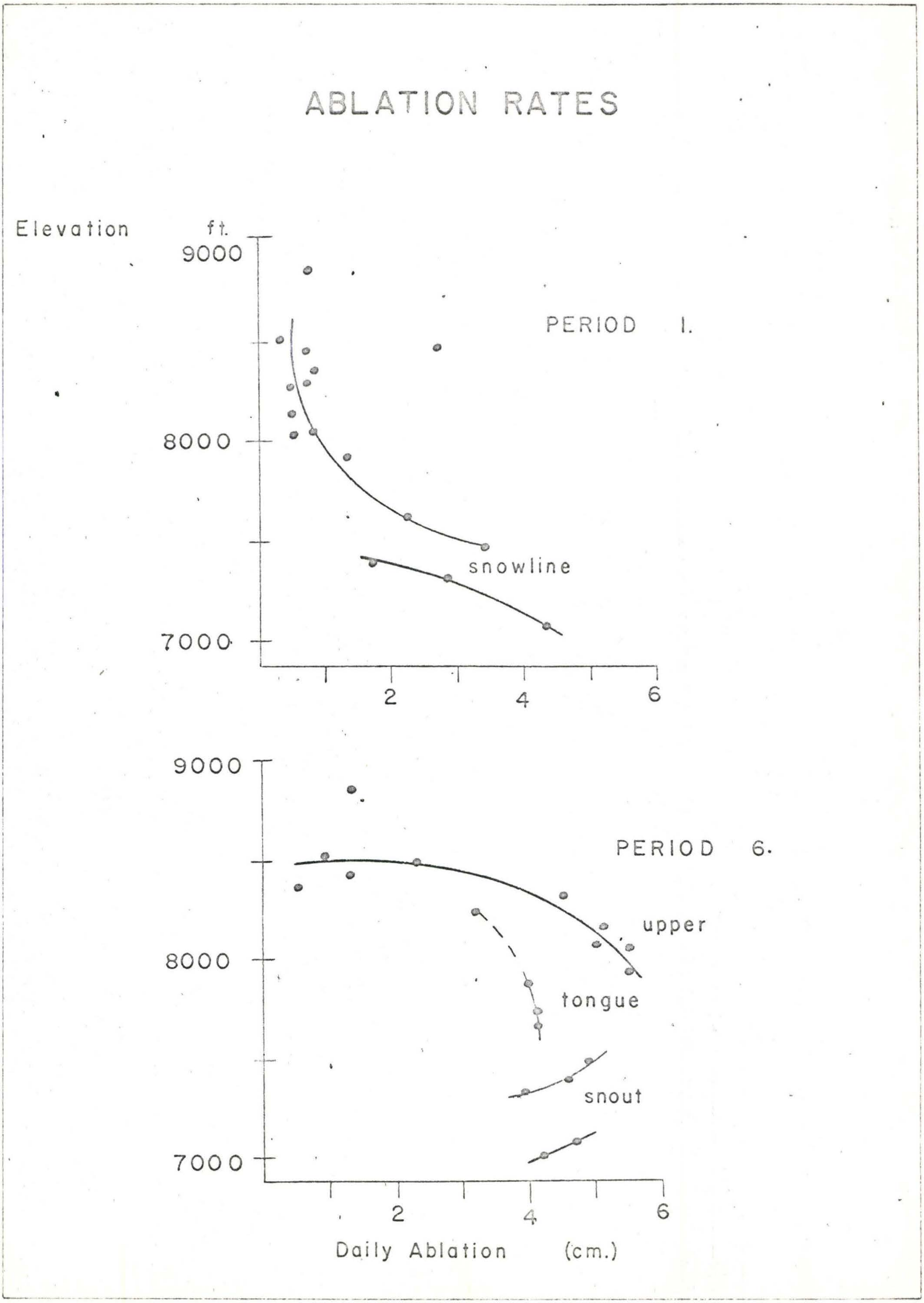
period	1.	2.	3.	4.	5.	6.	7.
Ablation (cm.)	1.9	3.4	3.2	4.9	4.3	3.7	0.3
Temperature (C°.)	4.9	6.6	6.0	8.4	7.7	6.9	1.6
Relative Humidity (%)	70.	76.	64.	60.	69.	78.	77.
Cloud Cover (%)	56.	74.	52.	40.	68.	48.	78.
Precipitation (mm.)	2.8	2.3	2.6	0.7	2.7	1.6	6.3

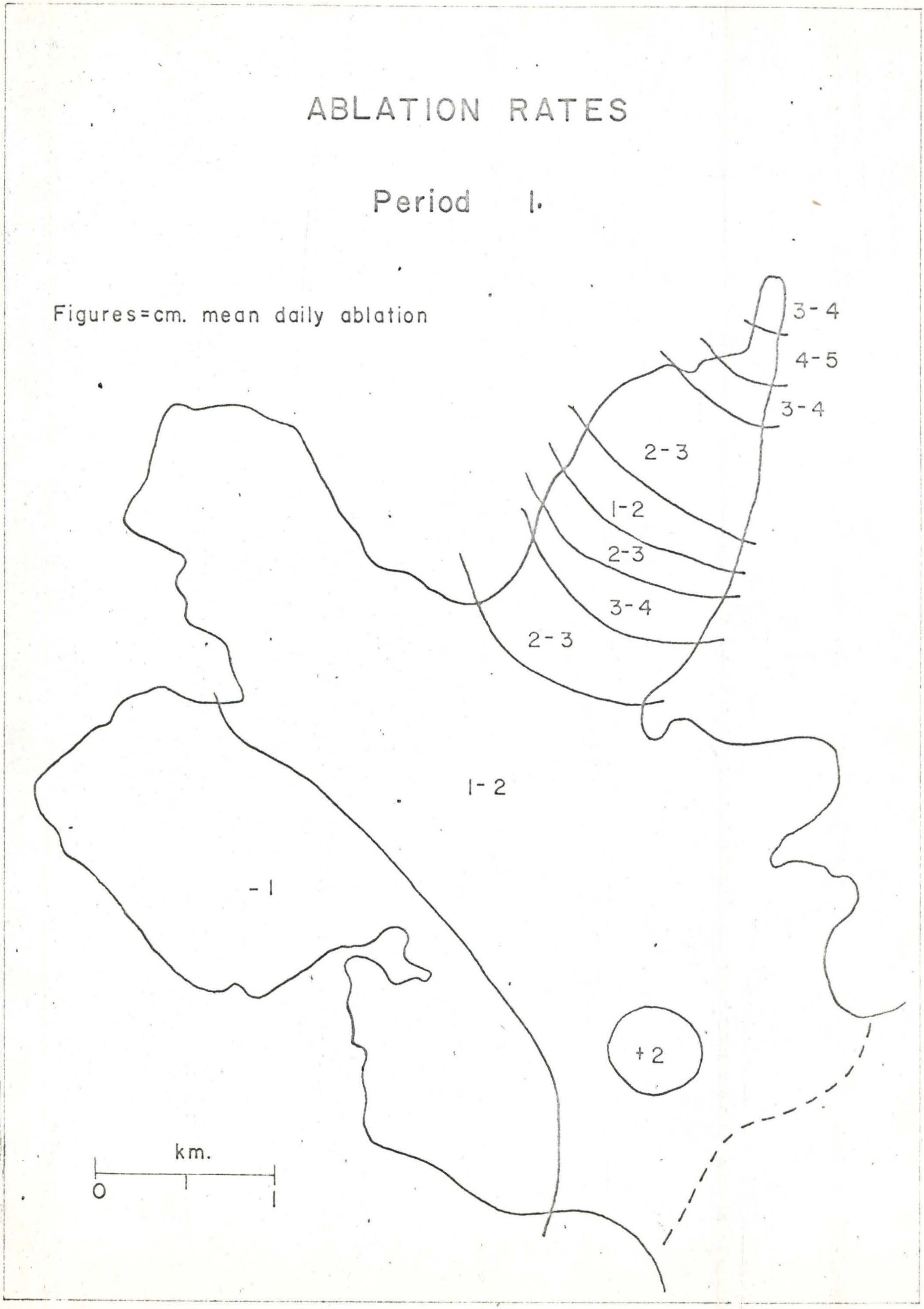
The weather variables were plotted against ablation rate (see Figure 25.) to determine possible relationships of weather and ablation rate. Temperature was the only close relationship as the scatter of points on the other graphs are too wide to be significant. Precipitation, however, did display some tendency for an inverse relationship but this may be due to precipitation and cloud cover being in harmony (see page 60.) and for cloud to inversely affect ablation.

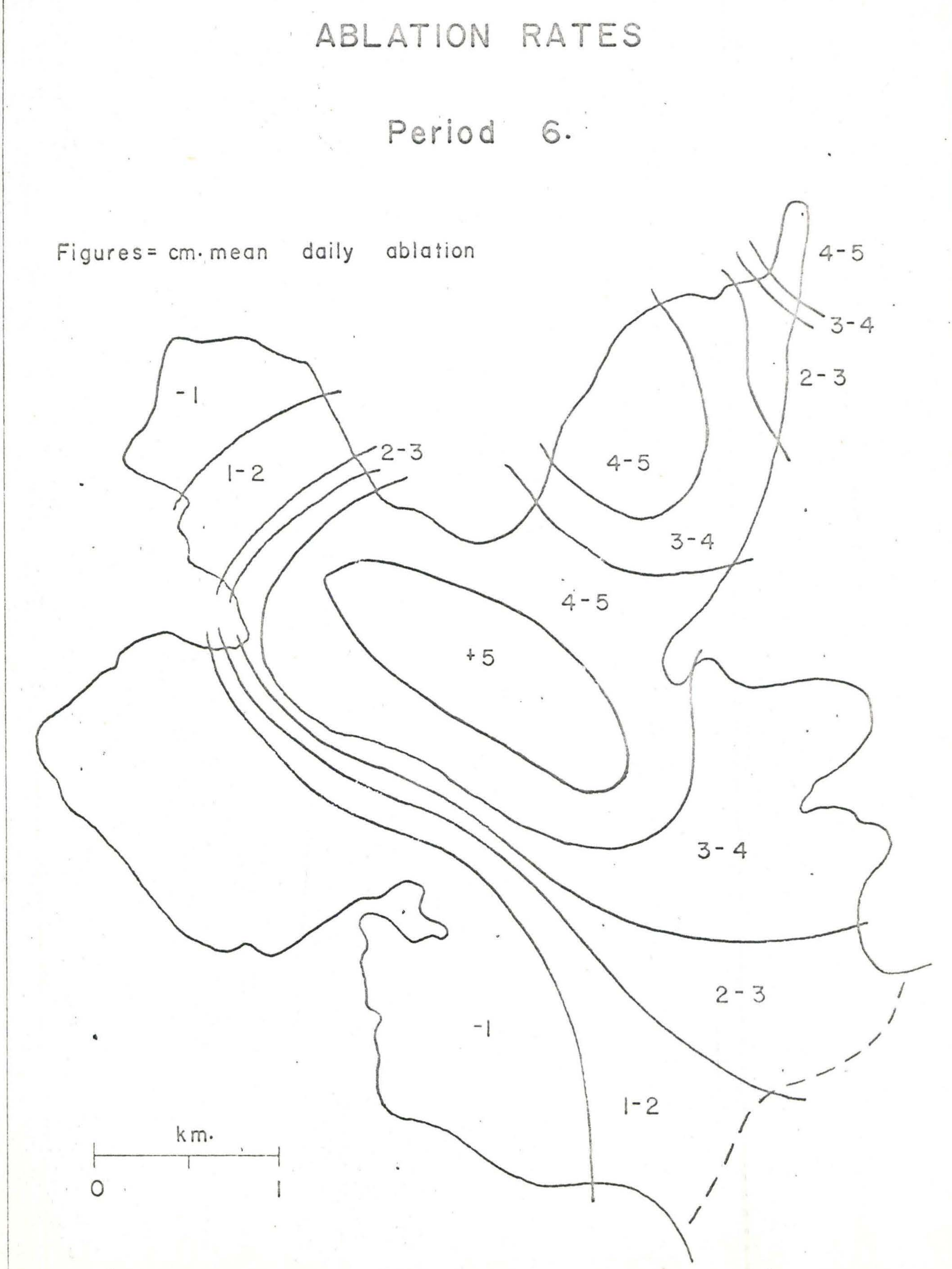
The maxium (up to 14 cm./day on the lower glacier) short-term period of ablation occured on August 8-10 (see Figure 21.). This period coincided with high daily mean temperatures (see Figure 26.) and, in fact, the highest maximum of the season (18.3°C.) was recorded on August 8. This period also saw convective afternoon thundershowers with a particularly heavy downpour on August 9. It seems plausible that the high ablation rate was due to a combination of high temperature and precipitation. However, occurences of other relatively heavy precipitation did not appear to relate to high ablation rates. Precipitation doesn't appear to have a great effect on ablation according to river discharge data for July 17-18, a period of steady rain (see page 83.). Total discharge was less in that period than during a time of strong sunshine with high temperatures, while precipitation was considered to have contributed 38-50% of the total discharge. If ablation was increased by precipitation, likely total discharge would be higher and the percentage contributed by precipitation a smaller fraction.

To further investigate these complications, curves of daily ablation with elevation were plotted

FIGURE 27.


ABLATION RATES
Elevation ft.
9000
8000
7000
PERIOD 1.
snowline
2
4
6
9000
8000
7000
PERIOD 6.
upper
tongue
snout
2
4
6
Daily Ablation (cm.)


ABLATION RATES
Period 1.
Figures=cm. mean daily ablation
3-4
4-5
3-4
2-3
1-2
2-3
3-4
2-3
1-2
-1
+2
km.
0
1


ABLATION RATES
Period 6.
Figures= cm. mean daily ablation
4-5
3-4
2-3
-1
1-2
2-3
4-5
3-4
4-5
+5
3-4
2-3
-1
1-2
km.
0
1

for periods 1. and 6. at the beginning and end of the ablation season (see Figure 27.). Period 1. indicates a smooth curve, but with a break where the snowline migration had reached by that date. Above 8200 ft. ablation was constant at 0.5 cm./day, likely due to radiation which is important this time of the year acting on a constant snow albedo (see page 109.).

However, the curve in period 6. indicates several breaks and changing angles of slope representing different portions of the glacier. These minor changes in the ablation rate are likely due to variations in topography, aspect and albedo.

Maps of the rates of ablation for the two periods under consideration are more revealing (see Maps 10., 11.). In period 1., there is evidence of the distinct changes with elevation on the tongue where isolines are close together. However, there is little change on the upper glacier as seasonal changes in the snowpack have not occured yet. In period 6., the pattern has substantially changed. An area on the lower glacier on the west side has a high ablation rate because it is reached by morning sun. There may also be some re-radiation from the bare rock face of Peyto Peak, particularly

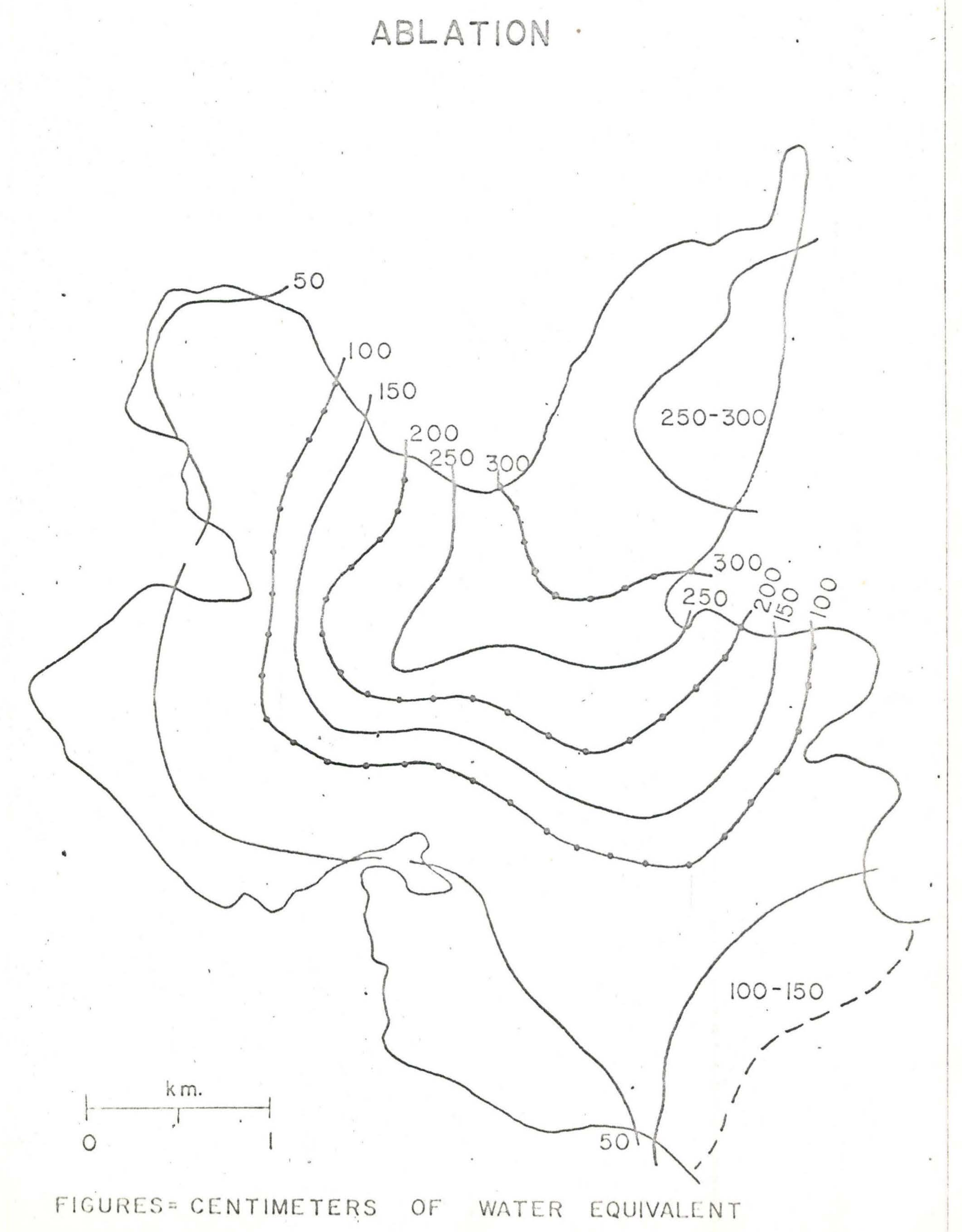
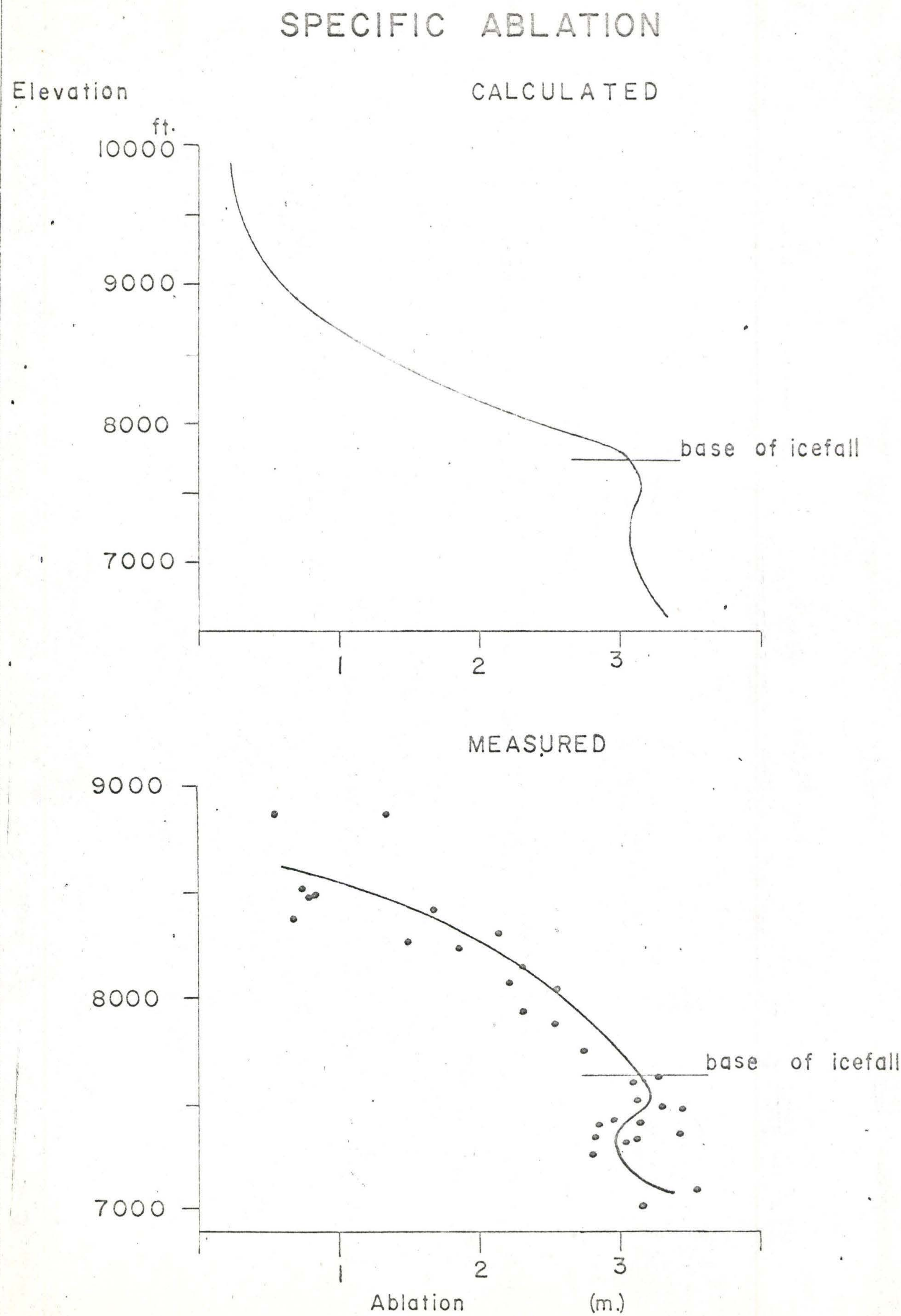

ABLATION
50
100
150
200
250
300
250-300
300
250
200
150
100
100-150
50
km.
0
1
FIGURES = CENTIMETERS OF WATER EQUIVALENT

FIGURE 28.


SPECIFIC ABLATION
Elevation
ft.
CALCULATED
10000
9000
8000
7000
base of icefall
1
2
3
MEASURED
9000
8000
7000
base of icefall
1
2
3
Ablation
(m.)

in the early evening. On the upper glacier, an area of maximum ablation occurs in the basin above the icefall. This area has the highest rate on the whole glacier because the moderate altitude cooling is more than offset by the increased time of daily exposure to the sun. These variations with altitude aspect and topography are further evident in total ablation patterns at the end of the ablation period when the results of the variations show the cumulative seasonal effects.

3. Total Ablation

The map of total ablation at the end of the season (see Map 12.) shows the tendency for ablation to vary indirectly with elevation (the isolines generally parallel the contours) but several abnormalities to this generalization are evident. A tract of relatively low ablation occurs on the east side of the tongue, caused by the shadow effect of mountain peaks. The area of high total ablation on the Wapta Icefield divide is due to the openess of the area with no overshadowing peaks. The flat expanse allows maximum daily length of insolation time to take place in this area. A similar open expanse is found in the western lobe and the ablation intervals extend above the 8,500 ft. contour for this reason. For similar, but opposite reasons, the lowest ablation interval (under 50 cm.) extends below this contour in the north-west lobe because of shading from surrounding peaks. Thus, although altitude has an important effect on ablation, slope, exposure-time and aspect are again shown to complicate the relationship.

The curve of specific total ablation (see Figure 28.) emphasizes the importance of the icefall as a divide between the upper and lower glaciers. Above the icefall, ablation decreases with altitude until, above 9500 ft., the ablation achieves a relatively constant value of approximately 25 cm. The lower portion of the snout exhibits a similar slope to the curve as the extreme upper glacier, possibly because of similarities in gradient. Naturally ablation is much greater in magnitude on the snout because of the lower elevation. Just above the snout, on the break in slope leading to the tongue portion, the ablation increases with increasing altitude for a short distance. This is due to the decreasing slope angle (which increases the effective striking angle of insolation) and particularly to the widening of the valley which permits insolation to reach the snout for a longer daily time.

TOPOGRAPHIC/ABLATION PROFILES

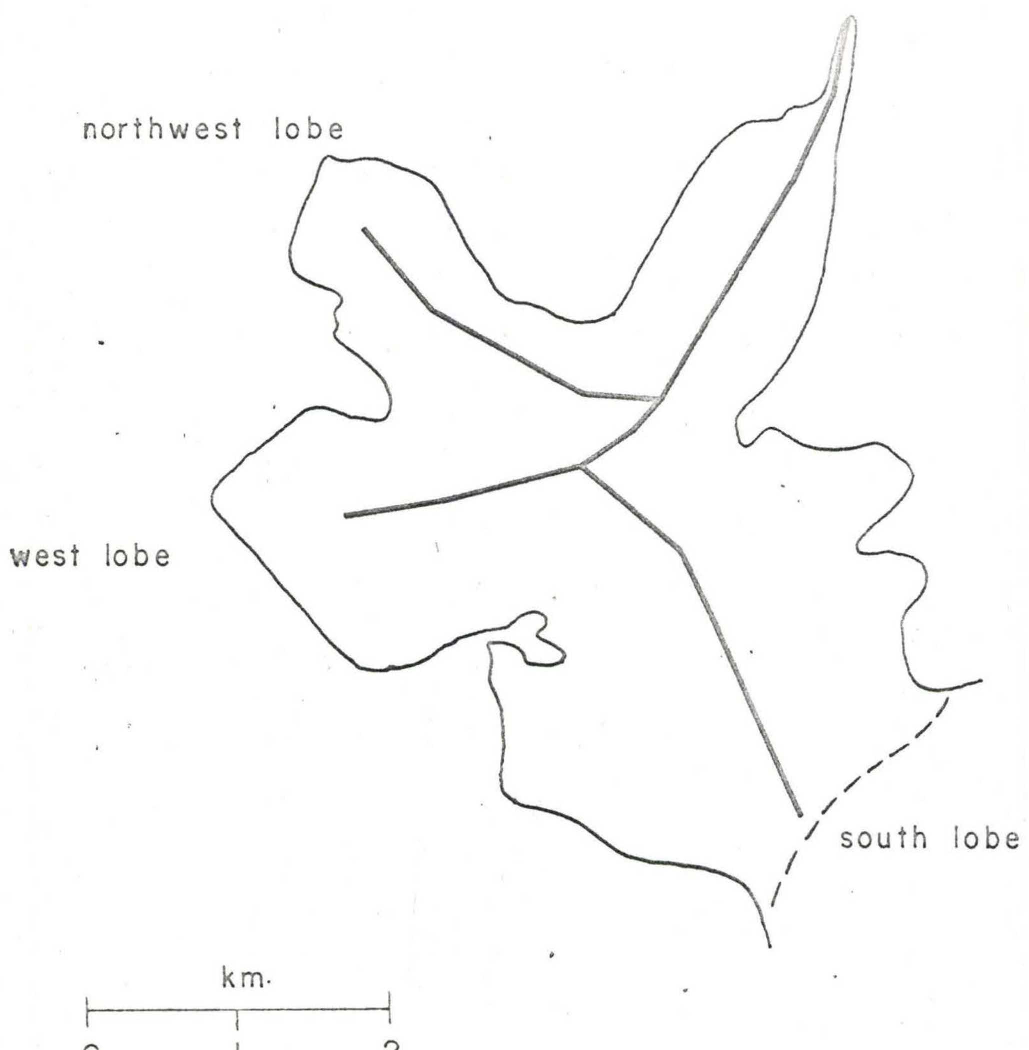
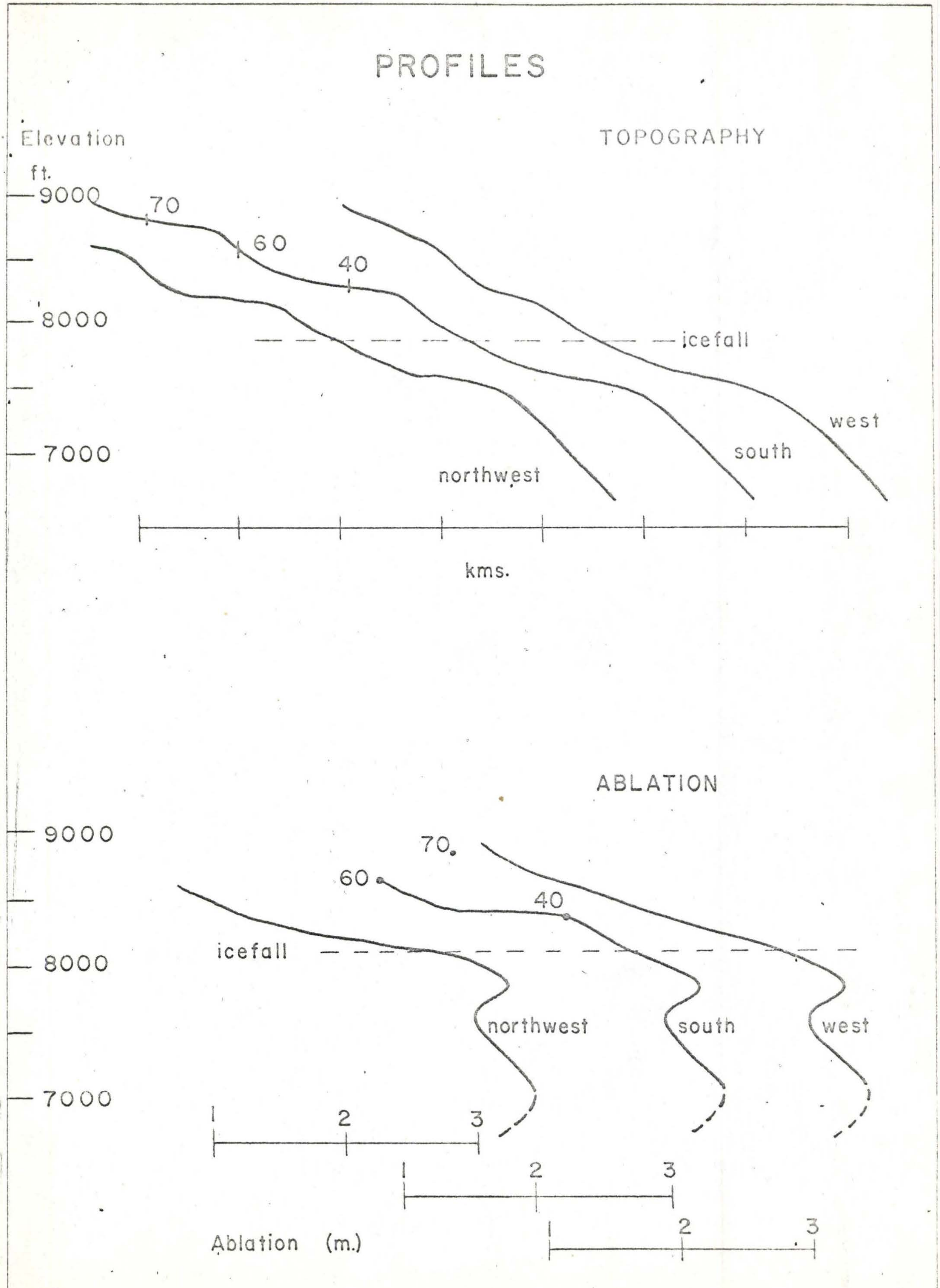


FIGURE 29.


PROFILES
TOPOGRAPHY
Elevation
ft.
9000
8000
7000
70
60
40
icefall
northwest
south
west
kms.
ABLATION
9000
8000
7000
70
60
40
icefall
northwest
south
west
1
2
3
Ablation (m.)

A curve obtained by plotting the total ablation at the end of the season for each stake (see Figure 28.) reveals two significant points. Although the slope of the lower part of the curve is similar to the specific ablation curve, the upper portion decreases with altitude at an increasing rate. This may be considered the more accurate representation, for the ablation values are not obtained from volume and area measurements but are actual readings. Also evident is the wide scattering of points, indicative of the discussed complications induced by aspect, gradient and surrounding topography, which disrupts the regular altitude/ablation relationship.

To further investigate these complications, topographic profiles (see Map 13.) were constructed using 1:50,000 topographic sheets from the terminus to the highest ablation stake in each of the 3 lobes of the firn area. Ablation was then plotted for each stake at its location on the profiles (see Figure 29.) to compare total ablation curves for different tracts of the glacier.

The lower tongue exhibits the S-shaped curve depicted in previous discussion, although it is emphasized more as only those few stakes in the centre of the tongue were on the profiles, and thus scattering of points (which leads to averaging and smoothing of the curve) was not encountered.

Only the curve representing the southern lobe appears to vary to any extent with topography. The relationship appears to be inverse, in that a large change in altitude gives a relatively small change in ablation and vice-versa. This suggests that altitude is not a major factor, at least in relatively short distance. A flat expanse (little elevation change) finds a large amount of ablation because that tract is not shadowed by nearby slopes, and exposure time is longer. Stakes 70. and 40. support this thesis. However, as stake 60. suggests, an area lying at the foot of a rise can be affected by shadowing which retards ablation.

It is significant that stake 60. and the southern lobe profile are the ones to display the ablation retardation effects of topography. Their northern aspect faces away from incoming radiation and thus topographic variations are more critical than on profiles with southern aspects. Thus, aspect and exposure-time rather than gradient are the more important topographic criteria.

TABLE 4.

PEYTO GLACIER.

ABLATION 1965

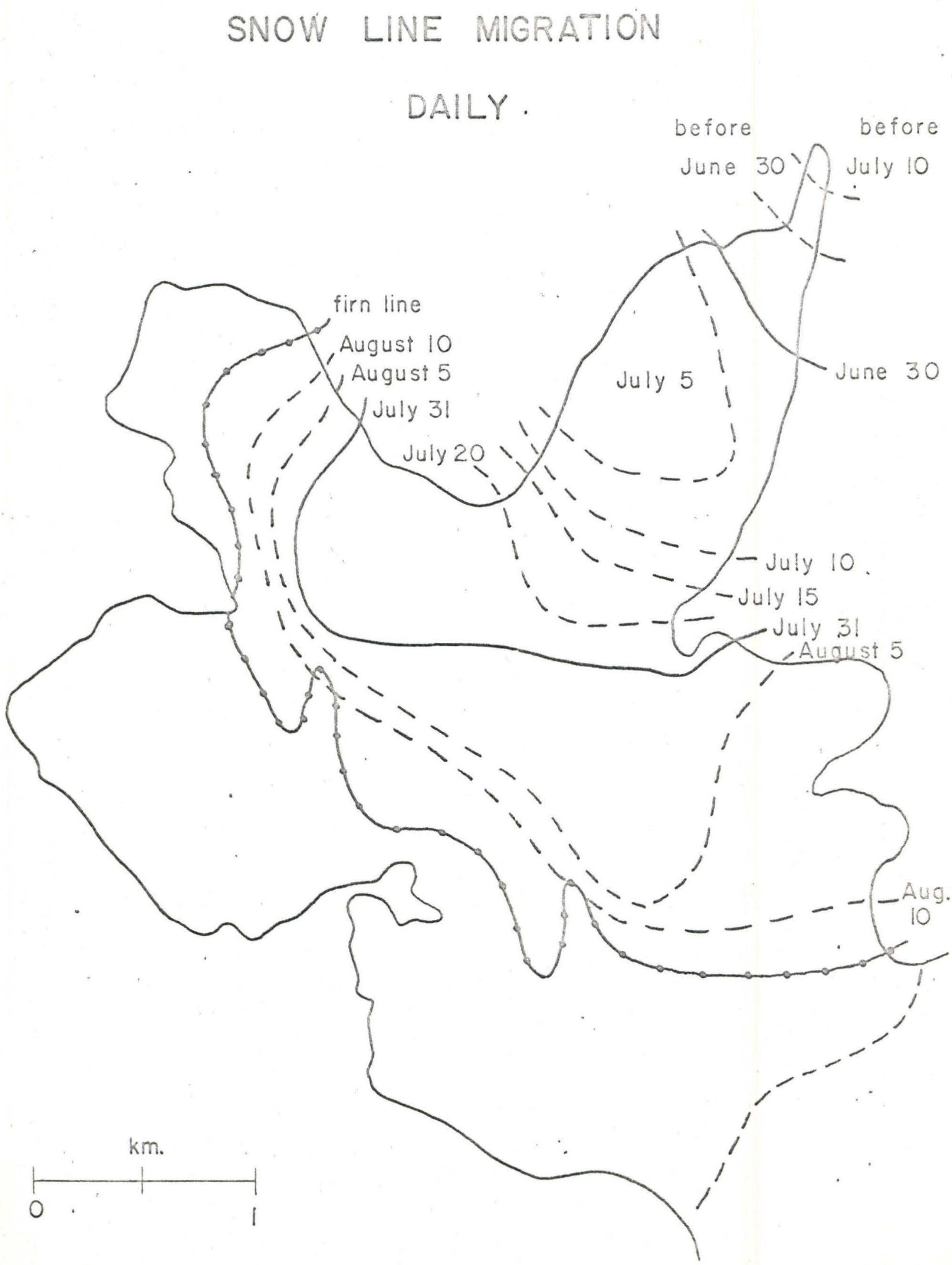
ELEVATION INTERVAL (ft.)	Under 50 cm. km^2	$10^6 m^3$	51-100 cm km^2	$10^6 m^3$	101-150 cm km^2	$10^6 m^3$	151-200 cm km^2	$10^6 m^3$	201-250 cm km^2	$10^6 m^3$	251-300 cm km^2	$10^6 m^3$	Over 300 cm km^2	$10^6 m^3$	Total Area km^2	Total Abl. $10^6 m^3$	Specific Abl. (m.)
-7000	-	-	-	-	-	-	-	-	-	-	-	-	0.04	0.130	0.04	0.130	3.25
7000-7500	-	-	-	-	-	-	-	-	-	-	0.14	0.385	0.24	0.780	0.38	1.165	3.07
7500-8000	-	-	-	-	-	-	-	-	-	-	0.67	1.843	1.16	3.770	1.83	5.613	3.07
8000-8500	-	-	0.61	0.458	0.84	1.050	1.07	1.873	1.04	2.340	0.67	1.843	-	-	4.23	7.564	1.79
8500-9000	0.05	0.013	3.48	2.610	1.16	1.450	1.15	0.201	0.02	0.045	-	-	-	-	4.86	4.319	0.89
9000-9500	1.40	0.350	0.31	0.233	0.06	0.075	-	-	-	-	-	-	-	-	1.77	0.658	0.37
9500+	0.56	0.140	-	-	-	-	-	-	-	-	-	-	-	-	0.56	0.140	0.25
7000-9500+	2.01	0.503	4.40	3.301	2.06	2.575	1.22	2.074	1.06	2.385	1.48	4.071	1.44	4.680	13.67	19.589	1.43

The calculations of ablation volumes (see Table 4.) emphasize (as did the accumulation volumes) the importance of area in the total volume figures. However, it would appear that area is less critical for ablation, as the two largest volumes are not associated with the two largest areas (as was the case with accumulation). This is evident in the table, as the area of the tongue (below 8,000 ft.) accounts for only 16.5% of the area but 35% of the total ablation. Specific ablation values also emphasize this difference. Total ablation was 19.589 million m^3., a volume equal to a specific ablation of 1.43 m. over the whole glacier.

The conclusions reached after a discussion of the specific, periodic, and total ablation suggests that different ablation processes may be at work at different areas of the glacier at various times throughout the ablation season and an attempt is now made to depict these differences in a discussion of the evolution of ablation.

4. Ablation Processes

Only in the early part of the ablation season (period 1-2) are the amounts and rates of ablation in the 3 glacier areas similar (see Figure 22.) This is


SNOW LINE MIGRATION
DAILY.
before June 30
before July 10
firn line
August 10
August 5
July 31
July 20
July 5
June 30
July 10.
July 15
July 31
August 5
Aug. 10
km.
0
1

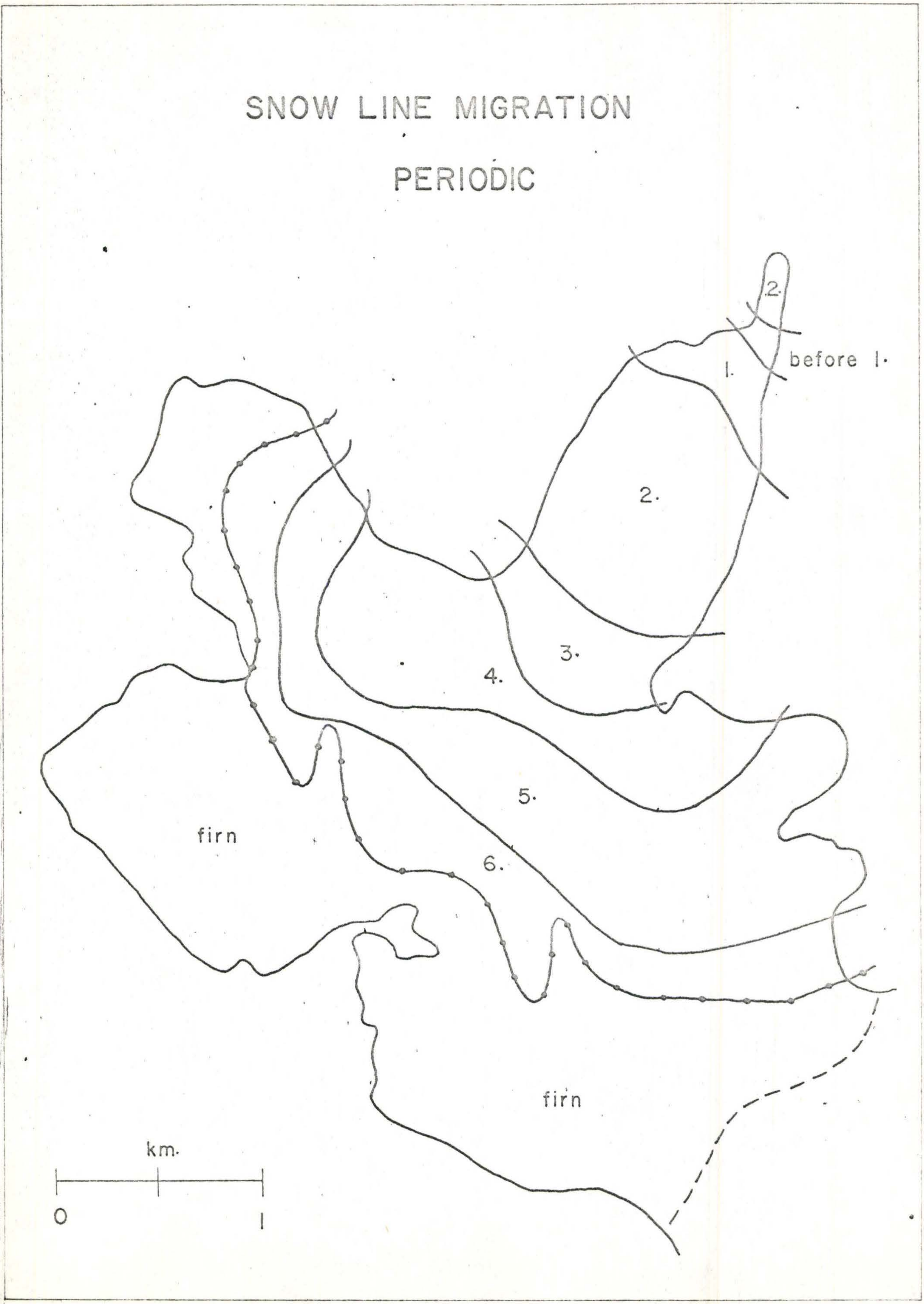
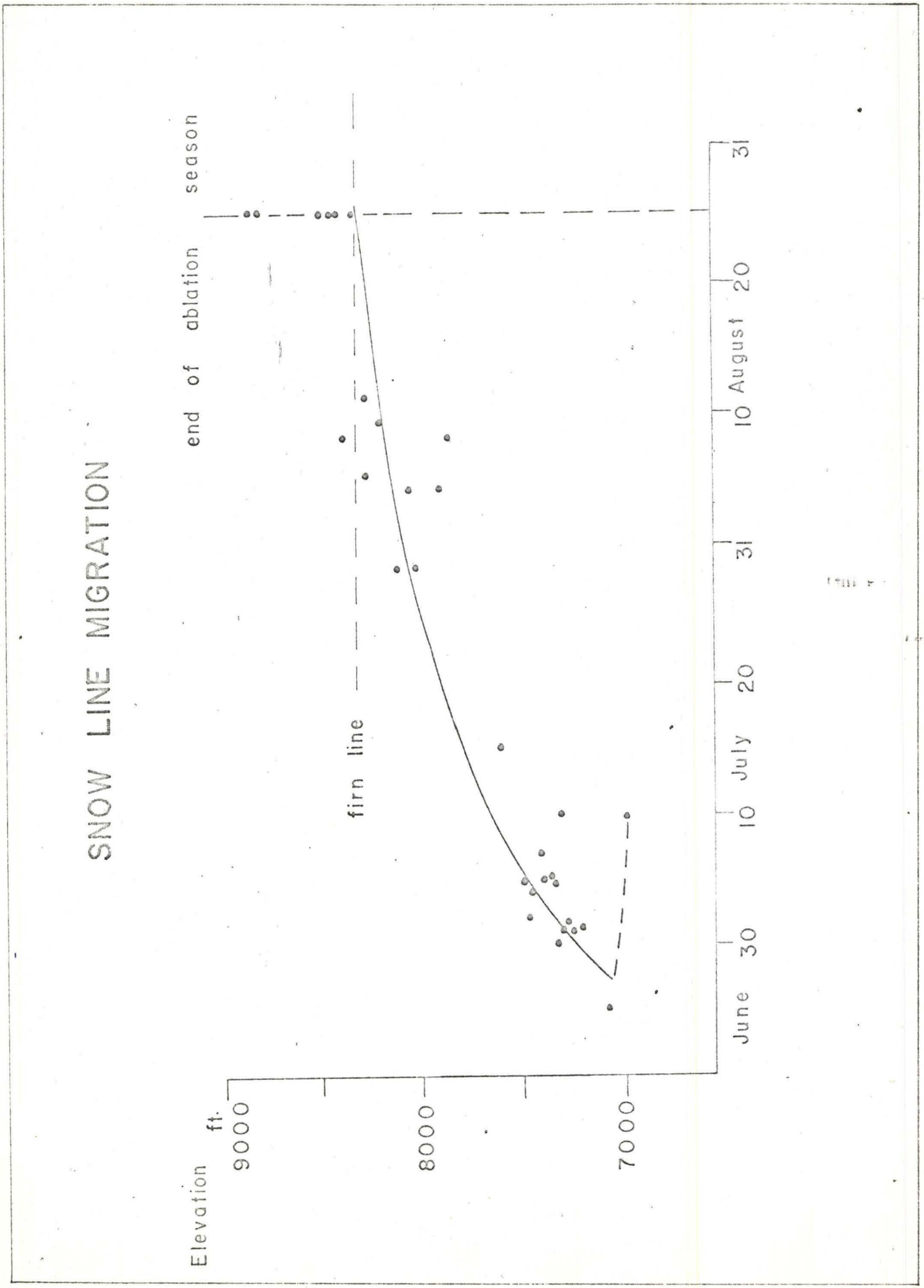

SNOW LINE MIGRATION
PERIODIC
2.
before 1.
1.
2.
3.
4.
5.
6.
firn
firn
km.
0
1

FIGURE 30.


SNOW LINE MIGRATION
Elevation ft.
9000
8000
7000
June
30
10
July
20
31
10
August
20
31
firn line
end of ablation season

likely due to all parts of the glàcier being snow covered and thus they respond equally to insolation. This response suggests the importance of albedo and temporary snowline; and the ablation forms permitted receding snowline positions to be considered.

Plotting the dates at which the snowline reached a particular ablation stake (determined from the ablation stake forms) allowed 5-day isochrones to be interpolated (see Map 14.). Similar data allowed compilation of a map showing the retreat of the snow-line by periods (see Map 15.), and a curve of snowline retreat with altitude in relation to the time of season (see Figure 30.).

The ablation curves indicate an initial upsurge of ablation rate in the early season. This is a response to the high temperatures from June 28 - July 8 (see Figure 25.), during which the "ripened" snowpack[12.] suddenly began to melt. It is significant that, on the afternoon of July 3, a substantial melt stream was initiated on the lower glacier in a matter of several hours; evidence of the sudden surge of ablation in this period. It is also significant that superimposed ice was calculated on the stake forms only on June 22-24. After that date, no such deposit was found which significantly altered the ablation calculations. This is evidence of the change in temperature accompanying the change in the snowpack. Once the melt initiated, temperature in the snow cover and glacier ice was at a minimum of 0°C., except for temporary night temperatures below freezing.

Following this initial melt period, the ablation curves for the upper glacier and firn areas declined, likely in response to declining temperatures (see Figure 22.). However, the curve for the lower glacier continued to rise because the retreating snowline exposed more area with low albedo (see page 109.) and insolation on this darker area was sufficient to offset the potential decline of ablation caused by falling temperature. By July 15, the lower glacier was clear of snow, thus establishing a relatively constant albedo for the remainder of the season. Hereafter, ablation rate was likely more a function of convection and conduction. It followed a seasonal peak of temperature and high sun in period 4. and then declined steadily.

The curve of the upper glacier declined in response to falling temperatures to the third period but, at that time, the retreating snowline reached the lower portions of the area (July 20); then the decreasing albedo effect previously noted on the lower glacier became significant. Ablation rose sharply to period 4. in response to the increasing temperatures and insolation acting on increasingly larger areas of bare ice with low albedo. Although the high sun period was achieved in period 4., ablation continued to rise as the snowline retreated. This portion of the glacier is also least affected by shadowing of peaks, and a declining sun did not greatly decrease the length of time of diurnal exposure to the sun. Thus, the peak ablation was achieved in period 6., followed by a sudden decrease to almost zero following the onset of cool temperatures and the end of the ablation period (as marked by snowfall) after August 24.

The curve of the firn area shows the effect of the changing snowpack throughout the season. Peak ablation occured in period 2. due to the initial melt of the ripened snowpack (see page 143.). Thereafter, a fairly constant albedo of 40-70% (that of old snow) was maintained, and response to temperature (conduction and convection) was similar to that on the lower glacier.

The slight increase in mid August (peaking at a high in period 6.) is a function of the relatively constant high temperatures prevailing at this time. Again, the minor peak is delayed to period 6. because the firn area was open and little changes in the diurnal sun period occured despite the declining angle of the sun. Generally, the firn area displays what may be considered the "normal" curve, with deviations from it being due to the changing albedo effect caused by the retreating snowline.

Although the curve of migration of the snowline with time (see Figure 30.) indicates a fairly regular progression through the season, some irregularities are obvious. The curve on the snout of the glacier indicates that removal of snowcover was delayed at the lowest levels. This pattern is indicated in Figure 28. of total ablation, and is due to the encroaching valley sides limiting daily exposure time. The scatter of points also indicates effects not solely due to the changing albedo.

The map of firn line migration (see Map 14.) indicates patterns relating to topography. The basin above the icefall was clear on the south-facing side approximately 5 days before the north-facing slope, revealing the importance of aspect. However, this also parallels the contour lines and could be considered as a direct altitudinal effect.

Thus, the ablation appears to depend a great deal upon the altered albedo as the snowline retreats. This function is modified by topography (exposure time) and aspect of localized areas on the glacier.

FOOTNOTES - Chapter 7.

1. Flint, 1957. p. 25.
2. Flint, 1957. p. 25-27; Meier, 1962; Hoinkes, 1955.
3. Geiger, 1961. p. 15.
4. Hoinkes, 1955. p. 498.
5. ibid. p. 500.
6. Flint, 1957. p. 27.
7. ibid. p. 32.
8. ibid. p. 27; Ahlmann, 1940. p. 188.
9. Ahlmann, 1940. pp. 189-203.
10. Hoinkes, 1955. p. 500.
11. United States Army, Corps of Engineers, 1956. p. 437.

TABLE 5.

PEYTO GLACIER, 1964-65

ELEVATION (ft.)	INTERVAL (m.)	AREA % Total	AREA km^2	ACCUMULATION TOTAL $10^6 m^3$	ACCUMULATION SPECIFIC m.	ABLATION TOTAL $10^6 m^3$	ABLATION SPECIFIC m.	NET BUDGET TOTAL $10^6 m^3$	NET BUDGET SPECIFIC m.
6500-7000	1980-2130	0.3	0.04	0.010	0.25	0.130	3.25	-0.120	-3.00
7000-7500	2130-2285	2.8	0.38	0.125	0.33	1.165	3.07	-1.040	-2.74
7500-8000	2285-2435	13.4	1.83	1.343	0.73	5.613	3.07	-4.270	-2.34
8000-8500	2435-2590	30.9	4.23	5.299	1.25	7.564	1.79	-2.265	-0.54
8500-9000	2590-2740	35.6	4.86	8.851	1.82	4.319	0.89	+4.532	+0.93
9000-9500	2740-2895	12.9	1.77	3.923	2.22	0.658	0.37	+3.265	+1.85
9500-10,000	2895-3045	4.1	0.56	1.260	2.25	0.140	0.25	+1.120	+2.00
6500-10,000	1980-3045	100.0	13.67	20.811	1.52	19.589	1.43	+1.222	+0.09

CHAPTER 8. - Conclusions

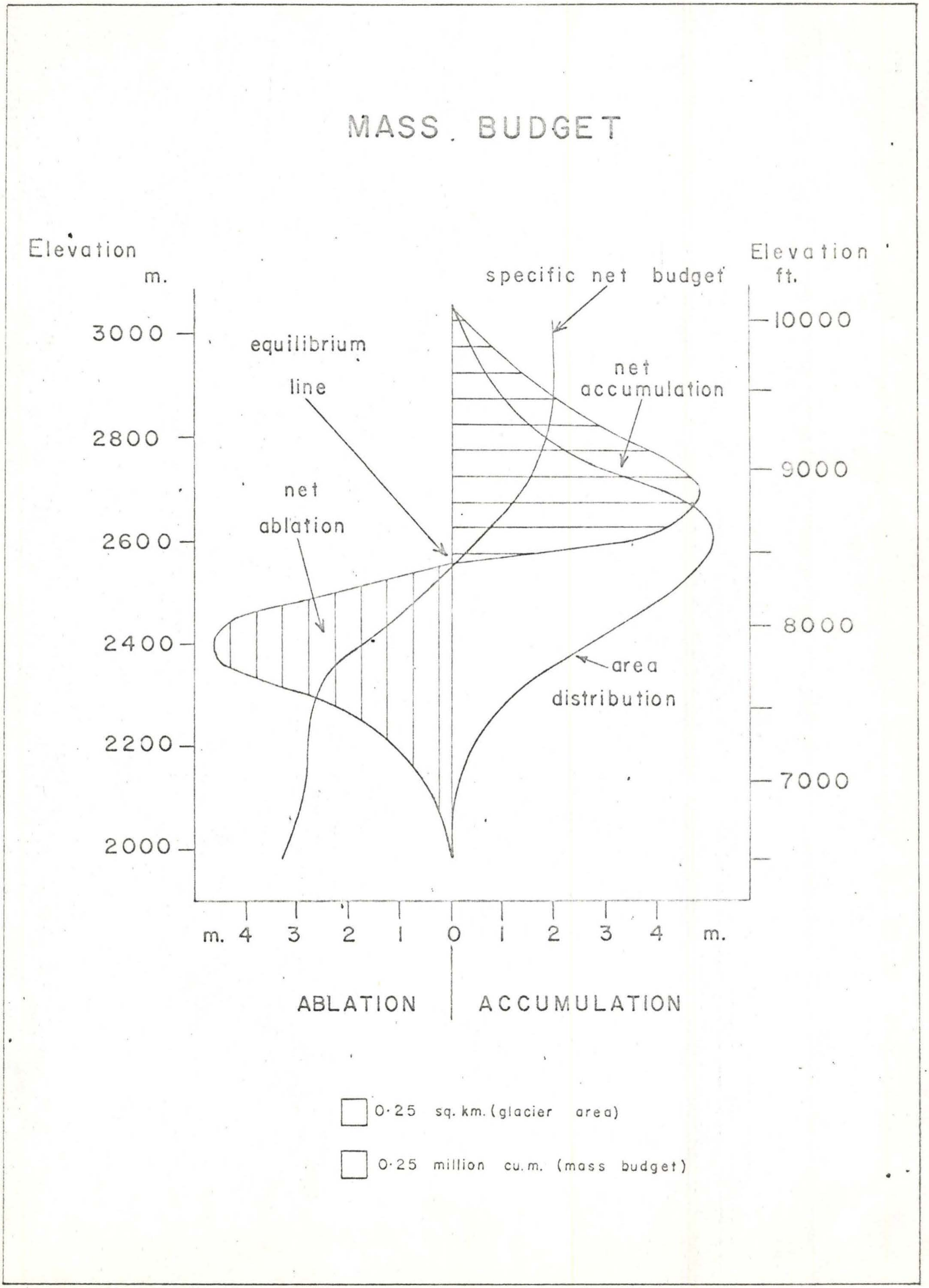
A. Mass Budget

The primary aim of the Hydrological Decade project, and a major part of this dissertation, is the determination of the mass budget. The budget is computed from the differences between accumulation and ablation totals (see Introduction), and the calculations are set out in Table 5. for visual comparison.

Total figures from the table indicate that, in the budget year 1964-1965, Peyto Glacier had a total accumulation of 20.811 million m^3. and a total ablation of 19.589 million m^3. Hence, the mass budget was slightly positive, with a gain of 1.222 m^3. of water equivalent.

This mass budget value may also be computed from net accumulation and ablation (see page 7.) totals. Considering only the accumulation area (8500 - 10,000 ft.), the accumulation was 14.034 million $m.^3$ and ablation was 5.117 million m^3.; leaving a net accumulation of 8.917 million m^3. In the ablation area, accumulation was 6.777 million m^3. and ablation was 14.472 million m^3., giving a

FIGURE 31.


MASS BUDGET
Elevation m.
Elevation ft.
3000
2800
2600
2400
2200
2000
10000
9000
8000
7000
specific net budget
equilibrium line
net accumulation
net ablation
area distribution
m. 4 3 2 1 0 1 2 3 4 m.
ABLATION
ACCUMULATION
0·25 sq. km. (glacier area)
0·25 million cu. m. (mass budget)

net ablation value of 7.695 million m^3. The difference between net accumulation and ablation again gives the positive budget figure of 1.222 million m^3.

These results are portrayed graphically in Figure 31. The almost equal areas of the net accumulation and net ablation portions emphasize that the budget was only slightly positive in the budget year and the mass budget can be considered to be in a state of near-equilibrium.

Discussion of the budget year climate in relation to past trends (see Chapter 4.) showed that the year was characterized by a lower annual temperature, increased precipitation and snowfall, and an extended accumulation season. Such conditions are condusive to a positive mass budget and, despite warmer summer temperatures, the budget figure must be considered unusually healthy for glaciers in this region.

Mass budget results from glaciers in the United States[1.] indicate that the period 1961 - 1963 was typified by small fluctuations about the equilibrium state, and the positive 1964 - 1965 Peyto Glacier budget can be considered one of these fluctuations. This period since 1960 of near-equilibrium budgets follows a decade of generally positive mass budgets in the United States,[2.]

and climatic data from the Peyto Glacier area suggests that similar healthy budget values would have been obtained for Peyto Glacier during that period. Whether the trend to more healthy budgets has temporarily stabilized around the equilibrium point in 1961 - 1964, or whether a reversal of trend of the last decade to negative budgets is imminent, cannot be determined.

Further proof of the unusually healthy budget is found in calculations of the accumulation area ratio[3.] (A.A.R. - the area of accumulation compared to total glacier area). In 1964 - 1965, the A.A.R. was 0.53; higher, and thus healthier, than the expected A.A.R. of 0.3[4.] for glaciers in this region.

The mass budget results (see Table 5.) permit derivation of the specific net budget and this parameter is graphically presented in Figure 31. The specific net budget for 1964 - 1965 was 0.09 m. over the whole glacier and the equilibrium line altitude (E.L.A.) occured at 8400 ft. approximately (2550 m.).

These results from Peyto Glacier are best considered with the mass budget results from the other glaciers included in the Decade programme[5.] as follows:

Glacier	Net Budget (10^6 m.^{3})	Specific Net Budget (m.)	E.L.A.	
Peyto	+ 1.2	+ 0.09	8360 ft.	2550 m.
Woolsey	- 1.9	- 0.60	7420	2260
Place	- 2.6	- 0.65	7110	2170

A progressive change from maritime to more continental regimens relates to a progressive change from negative to positive mass budgets, with successively increasing elevations of the E.L.A. Thus the Peyto Glacier findings are consistent with other glaciers in 1964-1965 budget year. It remains to analyze regimen changes in time and space for the other glaciers and to correlate these findings with mass budget values obtained in future years of the Hydrological Decade. This will clarify the mass budget determination as a link between glacier and climatic fluctuations (see page 6.).

B. Distinct Glacier Areas

Consideration of specific net budget values for Peyto Glacier (see Table 5.) and the shape of the specific net budget curve (see Figure 31.) reveals the importance of the portion below the icefall as the primary ablation area. This serves to point out a second major conclusion of this dissertation;--the importance of the icefall as a divide between two distinct portions of the glacier (termed the upper glacier and the lower glacier). The icefall, and/or the basin just above it, appear to be a critical area in which precipitation distribution and accumulation/ablation patterns vary. Several times during the field season, cloud levels appeared to have a base at the lip of the icefall; suggesting attendant changes in weather variables between the upper and lower glaciers. Future research should aim at pinpointing these differences, utilizing numerous ablation stakes, wind recorders, rain gauges, thermographs and radiation recorders; until the differing patterns above and below the icefall are established. It would appear that the primary reason for these variations is topographic, which is partially a function of structure. At this critical level, the glacier and valley become much more constricted by mountain peaks than on the open expanse of the upper glacier; with inherent differences of exposure to sun and weather elements.

These differences in exposure and topography are manifest in the changes of ablation rates which are evident throughout the ablation season. It has been shown (see Chapter 7.) that ablation is largely a function of changing albedo values incurred in migration of the snowline. But superimposed on this relationship are complications induced by the topography (exposure time) and aspect of the glacier surface. Thus, future investigations should attempt to further clarify these topographic complications, with emphasis upon the icefall divide.

The topographic nature of Peyto Glacier, which includes a wide range of glacier elements, makes it an ideal field area; despite its size which is slightly larger than is desirable for detailed investigations. It incorporates three basic glacier types in one. There is a narrow valley glacier, the outlet tongue; there is a large accumulation basin with a cirque character particularly in the north-west lobe; and an icecap area to the south on the Wapta Icefields. The integration of these three distinct glacier types into one mass budget evaluation provides the knowledge by which more extensive regional glacier studies can be undertaken throughout the Western Cordillera of Canada.

Footnotes - Chapter 8

1. LaChappelle, 1965.
   Meier and Tangborn, 1965.

2. Meier and Post, 1962. p. 73.

3. Meier and Post, 1962. p. 70.

4. ibid, p. 71.

5. Østrem, 1965 (a).

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