CANADIAN THESES ON MICROFICHE

THÈSES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL 339 (r. 86/09)

Canada

FLUVIOGLACIAL SEDIMENT AND HYDROCHEMICAL DYNAMICS, PEYTO GLACIER, ALBERTA

by

Gilles G. Binda

Thesis presented to the School of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Arts in Geography.

UNIVERSITY OF OTTAWA

UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION

CHAPTER 2 - LITERATURE REVIEW

CHAPTER 3 - METHODOLOGY AND TECHNIQUES

CHAPTER 4 - CLIMATOLOGY, MASS BALANCE, HYDROLOGY: RESULTS AND INTERPRETATION

CHAPTER 5 - GLACIER HYDROCHEMICAL AND SUSPENDED-SEDIMENT REGIMES: RESULTS AND INTERPRETATION

CHAPTER 6 - CONCLUSIONS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I wish to thank all the persons, who at one stage or another, helped in the completion of this thesis. I am especially grateful to my supervisor and mentor, Dr. Peter G. Johnson, Department of Geography, University of Ottawa, for his constant guidance and support throughout this study. I will always treasure his friendship. I would also like to acknowledge the advice, the helpful comments and friendship given by Dr. Wayne H. Pollard and Richard J. Kodybka, Department of Geography, University of Ottawa, during the preparation of this thesis.

Other persons are sincerely thanked for their professional advice during the writing of the various sections of this thesis. Included are; Dr. Gordon J. Young, Chief, Secretariat and Liaison, Environment Canada, for his expert advice in glaciology and hydrology, John M. Power and John Anderson, National Hydrology Research Institute, Environment Canada for their helpful comments in hydrology, C. Simon Ommanney, National Hydrology Research Institute, Environment Canada for his advice in glaciology and to Dr. David N. Collins, Department of Geography, University of Manchester, for his expertise in glacier hydrochemistry.

The National Hydrology Research Institute, Environment Canada, is gratefully acknowledged for generously providing logistics at the Peyto Glacier research base camp, scientific equipment and unpublished mass balance, meteorological and hydrological data.

I would like to thank Yvan Carrier, Murray Fitch, Richard Fabbro, Mike Bourns for their much needed and appreciated field assistance. Paul and Nicole Binda are gratefully acknowledged for their laboratory assistance and data processing.

Financial support for this research was provided by Natural Sciences and Engineering Research Council operating grant A7486 awarded to Dr. P.G. Johnson and from Department of Supply and Services contract 09SU.KL299-1-4159 to Dr. P.G. Johnson.

I would like to thank my parents for their constant encouragement and financial help throughout the years. My in-laws are also thanked for their encouragement.

Finally, I want to especially thank my wife, Monique, for her never ending encouragement, understanding and love.

CHAPTER 1

INTRODUCTION

The study of glacier hydrology has in recent years evolved as a key component of glacier research (e.g., Elliston, 1973; Stenborg, 1969; Young, 1983). In particular, the analysis of suspended-sediment load and hydrochemistry of glacier discharge has proven to be a useful indicator of glacial erosional processes (Collins, 1979a). Previous studies (e.g., Collins and Young, 1979a; Østrem, 1975a; Zeman and Slaymaker, 1975) have focused mainly on discharge characteristics over periods of short duration, while only a few studies have considered the entire ablation season. It is evident that more research is required in this area. Studies of this nature will contribute to a better understanding of the significance of seasonal glacial discharge regimes and their application to glacial geomorphology by relating the various components (e.g., suspended-sediment load and hydrochemical load) to stream discharge over the entire melt period.

This dissertation focuses on two aspects of importance to the understanding of erosional processes active in glacierised regions of the Canadian Rocky Mountain ranges. Glacier hydrochemistry is adressed first followed by a discussion on suspended-sediment characteristics.

Great amounts of solutes are transported by glacial meltwater streams (Statham, 1977). Solute concentrations in glacier runoff are directly related to weathering processes active in an alpine environment and at the base of a glacier. Thus, insight into chemical weathering processes can be obtained through the detailed study of glacial meltwaters hydrochemistry.

Sediment movement is central to the discipline of geomorphology (Statham, 1977). Suspended-sediment concentrations in glacial streams reflect the glacier's erosional capability. An investigation of the temporal variations in suspended-sediment concentration is important to gain a better understanding of processes which led to the formation of fluvioglacial landforms.

1.1 Objectives and hypotheses

1.1.1 Objectives

The aim of this study is to investigate the suspended-sediment and the hydrochemical dynamics of the discharge of Peyto Glacier, Banff National Park, Alberta. The objectives are threefold:

i) To measure the temporal variations in suspended-sediment concentrations from the glacier system. The investigation of seasonal, diurnal and short-term (15 minutes) variations in sediment concentration may lead to a better understanding of storage and release mechanisms within the glacier system.

ii) To investigate the temporal variations in selected hydrochemical parameters of meltwaters. The internal routing of meltwater may be inferred from the diurnal and seasonal changes in concentration and load of the four major cations (Calcium (Ca^{++}), Magnesium (Mg^{++}), Sodium (Na^{+}), Potassium (K^{+}).

iii) To investigate the temporal variations in the attached cationic load of the suspended-sediment. The cation attachment could be used to determine the storage time and the internal routing of the sediment.

1.1.2 Hypotheses

Three hypotheses were formulated following a literature review and reconnaissance field work. These are:

1) The temporal variations in suspended-sediment concentration and total suspended-sediment load are regular and related to either discharge or meteorological conditions as found for non-glacier-fed streams.

2) Temporal variations in meltwater hydrochemistry reflect increasingly greater contact with the geological strata higher in the basin.

3) The attached cationic load is not a function of the routing and the contact time of the sediment through the basin.

1.2 Field area

1.2.1 Location

The study area is the Peyto Creek basin (116° 33'W, 51° 40'N) (Figure 1). It is situated approximately 37 km northwest of Lake Louise, in the Waputik Mountain Range, within the limits of Banff National Park (Stanley, 1970). The basin, on the east side of the continental divide of the Canadian Rocky Mountains, covers an area of 23.0 km^2 (Collins and Young, 1981) and contains Peyto Glacier, an easterly facing extension of the Wapta Icefields (Figure 2).

The glacier covers 13.9 km^2, about 61% of the total basin area. It has an elevation range of 2090 m to 3172 m a.s.l. (Collins and Young, 1981). At the 2400 m level, a 100 m high icefall divides the glacier into two major sections; the snout with 15% of the total area and the icefield zone with 85% (Young, 1981).

Peyto Creek (Figure 3) is the only discharge stream draining the basin (average annual volume of $45 \times 10^6 m^3$) (Loijens, 1974). This runoff consists of meltwaters originating from Peyto Glacier, glacierets,

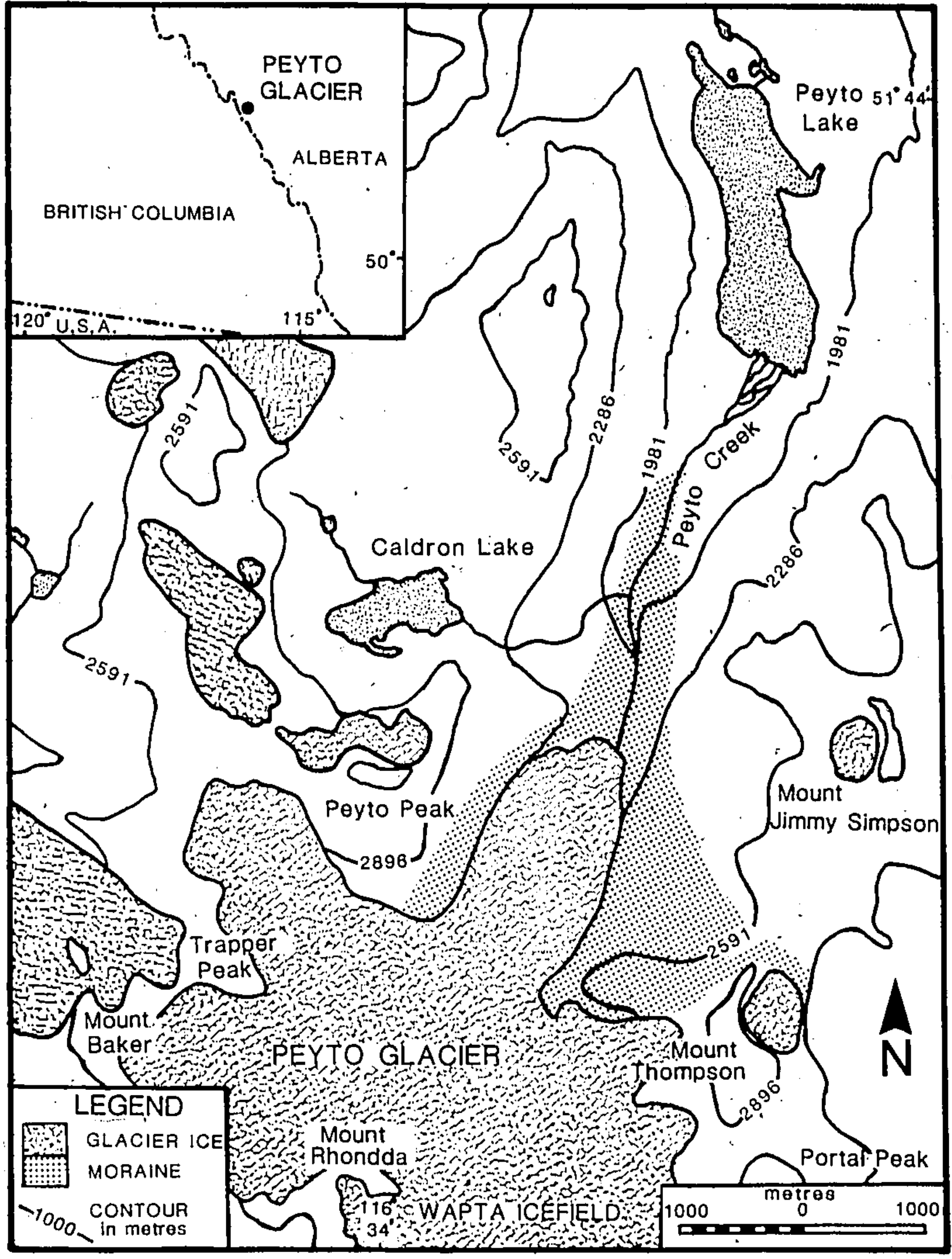

Figure 1 Location map of Peyto Creek basin, Alberta.
Source: N.T.S. map 82N/10, 1980.

COLOURED PICTURES
Images en couleur

Figure 2 Peyto Glacier and surrounding area. The location of the N.H.R.I. base camp is indicated by an arrow. Photograph: July, 1980.

Figure 3 Northeast section of Peyto Creek basin, Alberta. Photograph: July 1981.

Figure 4 N.H.R.I. research base camp, Peyto Glacier, Alberta. Photograph: June, 1981.

COLOURED PICTURES
Images en couleur

ice-cored moraines, perennial snow patches and from Caldron Lake drainage. Peyto Creek drains the meltwaters from the basin into Peyto Lake, which in turn flows into the Mistaya River, a tributary to the North Saskatchewan River.

Two major factors contributed to the choice of this site. First, there exists a record of mass balance and climatic data beginning from 1965 when the area was chosen as a representative basin for Canada's participation in the International Hydrological Decade (Østrem, 1966; Østrem and Stanley, 1966). Summary of the mass balance from 1965 to 1980 is provided by Ommanney (1984) and by Young (1981). In addition, Peyto Creek has been gauged continuously since 1966. Secondly, the basin is easily accessible. The National Hydrology Research Institute (N.H.R.I.) research base camp (Figure 4), which has been maintained since 1965, is located approximately 8 km from the Banff-Jasper Highway, thus facilitating the transport of supplies and equipment.

1.2.2 Climate

The climate of the area is considered typical of the Rocky Mountain region where disruption of air masses results in great variability in temperature, precipitation and relative humidity (Sedgwick, 1966; Sedgwick and Henoch, 1975).

The nearest Environment Canada meteorological station is located in Lake Louise, Alberta. The average temperature, precipitation and snowfall over the last thirty years (1951-1980) are listed in Table 1 (Environment Canada, 1982a, 1982b). Snow cover data (1971-1981) for Bow Summit, located approximately 8 km from Peyto Glacier at an elevation of 2030 m a.s.l., reveal an average annual snowfall of 365 mm of water equivalent ranging from 226 mm in 1977 to 553 mm in 1972 (Environment Canada, 1981).

A meteorological station was located at the N.H.R.I. research base camp to provide more site-specific data. The station is situated on a lateral moraine at 2225 m a.s.l., west of the glacier snout. Temperature (daily mean, maximum and minimum), relative humidity, wind run and direction, precipitation, atmospheric pressure and incoming solar radiation are measured on a daily basis throughout the ablation season.

1.2.3 Vegetation

The Peyto Glacier valley has three distinct vegetation communities. In the Peyto Lake area, a mature forest association dominated by the Engelman spruce (*Picea Engelmannii* Parry) is present. The valley floor and the well drained areas of the basin form a second zone. The vegetation consists of different species of willow (*Salix arctica* Pall., *Salix Barratiana* Hook., *Salix glauca* L., *Salix nivalis* Hook., and *Salix vestita* Pursh var. *erecta* Anderss.) and various wildflowers such as Indian Paintbrush (*Castilleja miniata* Doug.), Fireweed (*Epilobium latifolium* L.) and avens (*Dryas Hookeriana* Juz. and *Dryas Drummondii*

MONTH	MEAN TEMPERATURE (0°C)	MEAN PRECIPITATION (mm)	MEAN SNOWFALL (mm)
Jan.	-15.2	78.6	78.2
Feb.	-10.0	52.5	51.5
Mar.	- 6.7	43.3	41.5
Apr.	- 0.3	41.0	33.7
May	5.7	46.9	12.7
Jun.	9.6	57.5	0.2
Jul.	12.2	53.8	0.1
Aug.	11.4	51.0	0.0
Sept.	7.1	46.5	4.8
Oct.	1.5	46.9	30.6
Nov.	- 7.7	68.0	66.8
Dec.	-12.9	97.9	97.8
Year	- 0.4	683.9	417.9

Table 1 - SUMMARY OF SELECTED METEOROLOGICAL DATA FOR LAKE LOUISE, ALBERTA (1951-1980). SOURCE: ENVIRONMENT CANADA (1982a, 1982b).

Richards). The third zone, an alpine tundra community, consists of wildflowers such as Purple Saxifrage (*Saxifraga oppositifolia* L.), mosses such as Moss Campion (*Silene acaulis* L.) and different grass species in the well drained and sunny areas.

1.2.4 Geology

The geological structure of the Peyto Creek basin is typical of the highly folded ranges of the Rocky Mountains (Sedgwick, 1966). Evidence of folding is apparent in the exposed rock wall of Trapper Peak (Figure 5) where the rock strata are almost vertical. The basin is situated on the western flank of the Bow-Mistaya anticline. It is composed of Lower, Middle and Upper Cambrian sedimentary rock consisting of interbedded permeable limestones, dolomites, shales and sanstones (Figure 6) (Cook, 1975; Sedgwick, 1966; Sedgwick and Henoch, 1975).

The basin is divided into four distinct physiographic areas (Sedgwick, 1966). The first, including the Peyto Lake and outwash plain areas is underlain by Precambrian shale (Hector Formation). The second area consists of the principal stream valley and is separated from the first area by a riegel of Lower Cambrian rock (Lake Louise Formation). This area is characterised by Peyto Creek meandering through glacially deposited unconsolidated material overlying Lower Cambrian quartzites (St Piran Formation) and interbedded shales and limestones

COLOURED PICTURES
Images en couleur

Figure 5 Evidence of folding, Trapper Peak, Alberta. Note the nearly vertical rock strata. Photograph: August, 1981.

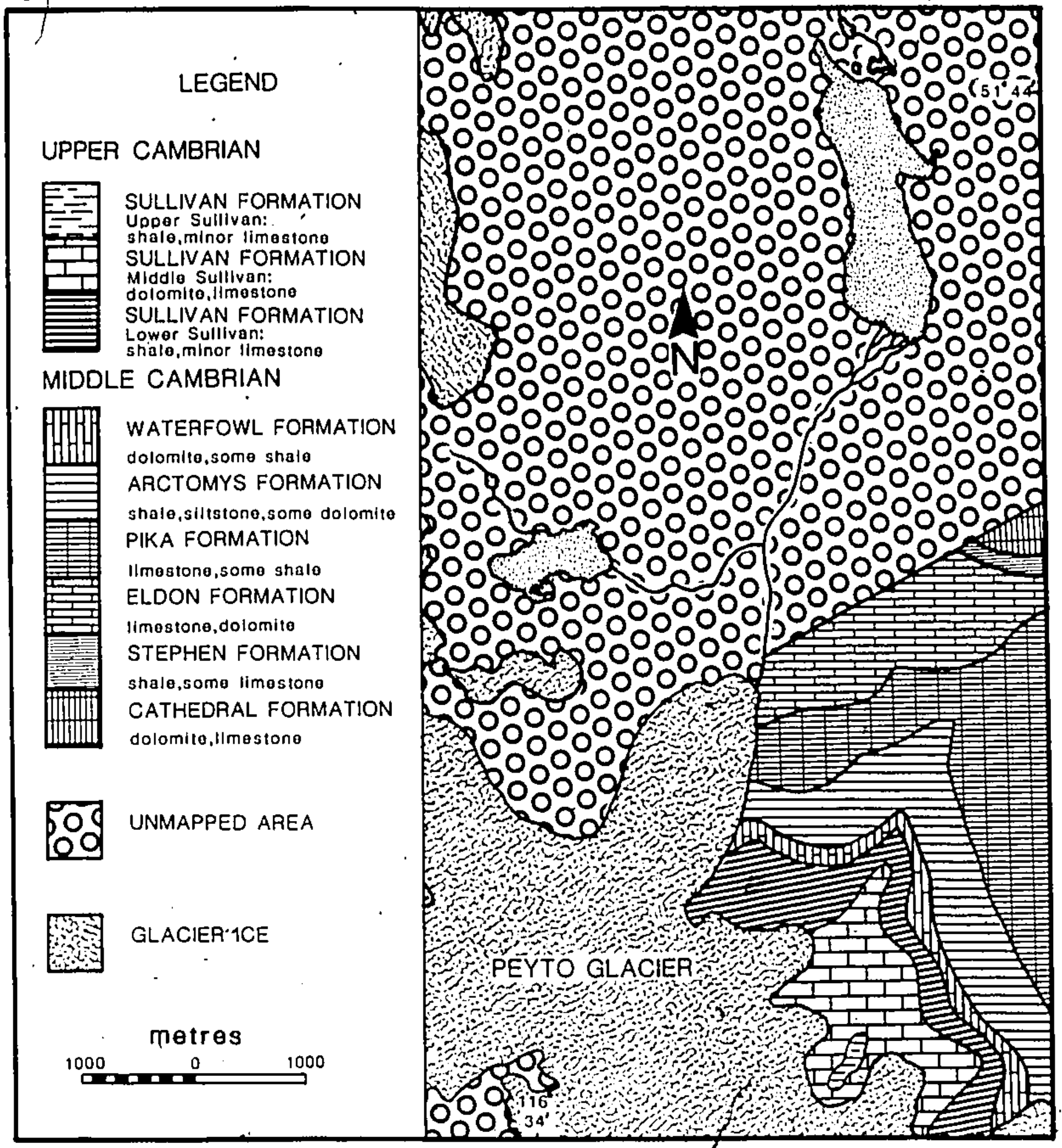

Figure 6 Geological map of the study area. Source: Cook, 1975.

(Mt Whyte Formation).

The third part of the basin, the glacier snout area, is separated from the second by a Lower Cambrian shale (Mt Whyte Formation) riegel. It consists of massive dolomites and limestones of the Cathedral, Stephen, Eldon, Pika, Arctomys and Waterfowl formations (Middle Cambrian) (Cook, 1975). The fourth area is above the 2400 m elevation where a 100 m high icefall separates the glacier snout from the icefield. This area is perenially snow and ice covered and the geology is assumed from the surrounding peaks. Cook (1975) identifies this area of the basin as Sullivan Formation (Upper Cambrian shales and limestones).

1.2.5 Glacial geomorphology

Many glacial landforms are present in the Peyto Glacier valley. Moraine sequences reflect glacial advances, recessions and the probable extent of the ice flow.

A hummocky moraine located at the north end of Peyto Lake probably represents the terminal position of Peyto Glacier during the Pleistocene (Sedgwick, 1966). A major recessional moraine coincides with the riegel separating the outwash plain area from the major stream valley (Sedgwick, 1966). In the main valley, numerous smaller moraines reflect the quick retreat of the glacier.

Lateral moraines, reaching an elevation of approximately 2350 m, have been deposited on both sides of the valley indicating the previous extent of the glacier.

On the east side, glacial debris has been plastered against the rock wall while the western lateral moraine is terraced or step-like (Sedgwick, 1966).

Peyto Glacier basin is characterised by the presence of numerous ice-cored moraines (Johnson, 1971; Østrem, 1959, 1962, 1964a; Østrem and Arnold, 1970; Souchez, 1971). These features are composed of stagnant glacier ice covered by 1 to 4 m of drift (Figure 7) and reflect rapid glacier retreat. They are present on both sides of the glacier and at the terminus where rapid melting of the glacier tongue deposited a large section of ice in the valley.

The shale outcrops also bear evidence of past glacier movement. The stoss side of these outcrops have been smoothed and striated while the lee side has been glacially plucked forming steps, which according to Belyea (1964) is typical of argillitic shales.

COLOURED PICTURES
Images en couleur

Figure 7. Ice-cored moraine located on west side of Peyto Glacier. Evidence of instability and recent slumping appears in centre of photograph. Photograph: July, 1981.

CHAPTER 2

LITERATURE REVIEW

2.1 Peyto Glacier

Peyto Glacier is well documented in the alpine literature. Historically, two periods of investigation on Peyto Glacier can be distinguished (1933 to 1960 and 1964 to present). The first photograph of the glacier terminus was published by Wilcox (1909). At that time, Peyto Creek flowed from two portals at the glacier terminus, which was positioned much further down valley than at present.

Summaries of fluctuations in terminus positions have been published by the Alpine Club of Canada. Research by McCoubrey (1938) indicates that Peyto Glacier retreated 100 m during the period 1933-1936. Results of the Dominion Water and Power Bureau's surveys at Peyto Glacier are summarized by Ommanney (1972), with specific details presented in McFarlane (1945, 1946, 1947), McFarlane and May (1948), McFarlane, Blair and Ozga (1949), May, Blair and Harry (1950) and Carter (1954). Averaged annual retreats of: 14 to 40 m (1933-1947) (Meek, 1948), 23 m (1945-1960) (McFarlane, 1960) and 4.3 m (1715-1953) (Field and Heusser, 1954) have been recorded. These variations are largely attributed to valley morphology and to averaging over different time periods. Rapid recessions tend to occur in the narrow areas of the basin where the ice is thin and breaks away (McFarlane, 1960).

More intensive research was initiated in 1964 when Peyto Glacier was selected as a representative basin for the International Hydrological Decade program, marking the beginning of the most recent period of investigation. These studies initially focused on mass balance and climatology but have since expanded to include hydrology and hydrochemistry. Mass balance research at Peyto Glacier was initiated by Gunnar Østrem (Østrem, 1966; Østrem and Stanley, 1966), followed by Sedgwick (1966) and by Young (1974, 1981). Relationships between mass balance and terrain characteristics (Young, 1970, 1975, 1976) and meteorological parameters (Föhn, 1973; Young, 1977a) have been reported. Young (1981) calculated an annual mass loss of 0.21 m of water equivalent for the period 1965-1978.

Climatological research is a necessary component of glacier research and at Peyto Glacier has included global radiation distribution (Goodison, 1970, 1972a), energy exchanges (Munro, 1975; Munro and Davies, 1977; Munro and Young, 1982), temperature distribution (Foessel, 1974) and katabatic wind characteristics (Stenning, 1980; Stenning, Banfield and Young, 1981).

The importance of meltwater runoff in water resource management and for agricultural use in the Canadian Prairies has prompted many studies in the basin. These consist mainly of hydrological (Collins, 1982; Young, 1977b, 1980, 1983) and hydrochemical (Collins and Young, 1979a, 1979b, 1981) studies. Dye tracing by Collins (1982) showed that the average flow-through velocity in Peyto Glacier ranged from 0.13 $m\cdot s^{-1}$ to 0.35 $m\cdot s^{-1}$ with delay times that varied from 5 hours at low flow to less than 2 hours at high flow. Collins and Young (1979b) separated the total stream discharge into it's components (groundwater flow, subglacially routed meltwaters and dilute meltwaters) using hydrochemical techniques. A comparison of the hydrology and hydrochemistry between a nival and a glacial catchment was conducted by Collins and Young (1981). They showed that during the snowmelt period both basins exhibit similar responses but during the summer when the snow cover is depleted, the regimes differ due to the substantial amount of meltwaters released by the glacier. Young (1983) demonstrated that the response time of the Peyto basin to ice and firn melt is directly related to the progression of the transient snowline up the glacier.

A number of hydrologists have used data from Peyto Glacier to develop glacier discharge simulation or prediction models. Derikx (1973) tested a conceptual model which simulated the glacier's discharge as a groundwater system. A statistical model (Goodison, 1972b) predicted glacier runoff from meteorological data. Peyto Glacier discharge was simulated by Gottlieb (1980), who applied the Nielsen and Hansen (1973) conceptual lumped-parameter model (NAM-model) to mass balance, runoff and meteorological data. Results showed good correlations between the measured and the simulated hydrograph at low and medium flows but underestimated the major peak flows. Mass balance, meteorological and hydrological data from Peyto Glacier (1968 and 1969) were employed by Derikx and Loijens (1971) to simulate glacier runoff with a mathematical model. Power and Young (1979a, 1979b) used a modified version of the UBC-model (Quick and Pipes, 1977) to simulate melt production and runoff from glaciated areas as well as non-glaciated areas. This model reproduced historical flow records with considerable accuracy by modifying the glacier melt component.

2.2 Glacier hydrology and hydrochemistry

2.2.1 Glacier hydrology

In view of the established use of glacial rivers for hydroelectric power generation (e.g., Scandinavia and Europe) and agricultural use, the potential effects of increased or decreased glacier melt are critical.

Glaciers are natural regulators of streamflow (Krimmel and Tangborn, 1974). For example, during years of high winter precipitation, the snowpack delays the ablation of the glacier ice due to the high albedo of snow. Thus, most of the runoff originates from snowmelt of non-glacier areas. However, during years of low winter precipitation glacier ice becomes exposed to solar radiation earlier compensating for the reduction of streamflow from non-glacier areas (Krimmel and Tangborn, 1974; Young, 1983).

In the spring, the first snowmelt does not initially contribute to runoff as it is used to warm the snowpack and refreezes within the snow (Male and Gray, 1981; Stenborg, 1970; Wendler *et al.*, 1973). When the snowpack becomes isothermal at 0°C and the liquid-water holding capacity has been satisfied, meltwater will move downward through the snow to the snow-ice interface (Male and Gray, 1981). Some water is retained within the snowpack by capillary attraction or by ice layers (Stenborg, 1970). These ice layers occasionally merge to form a continuous mass of ice called superimposed ice which acts as an impermeable boundary (Patterson, 1981). Slush flows occur when sufficient amounts of water accumulate at the snow-ice interface and instigate lateral flow (Male, 1980). The major effect of the snowpack on runoff is to delay the time of peak discharge of the stream (Male and Gray, 1981).

In the ablation zone, at the beginning of the melt season, surface flow constitutes the greatest part of the runoff but as the melt season progresses water begins to flow into previously blocked moulins and crevasses to reach the internal drainage system. Meltwaters can also reach this system by percolation through a network of passages located along intergranular boundaries in the ice (Nye and Frank, 1973). In the accumulation zone, the drainage veins are frequently blocked by the settling of the firn. The runoff is therefore delayed because the meltwaters that percolate through the snow and firn accumulate to form a saturated layer (firn aquifer) (Golubev, 1973; Stenborg, 1970). Thus, only lateral movement is possible until the entrances to the internal drainage system become clear (Stenborg, 1970).

Water in a glacier drains through three distinct systems of passages or conduits. The supraglacial system, can be compared to a river system in a karst area (Shreve, 1972). The englacial system, is a dendritic system of passages penetrating the glacier from the bed to the surface (Shreve, 1972). The subglacial system, is composed of channels penetrating the bedrock (Nye-channels or N-channels) (Nye, 1973) and channels incised into the basal ice (Röthlisberger-channels or R-channels) (Röthlisberger, 1972) and by thin basal films (Vivian, 1970; Weertman, 1964, 1966). Adduction galleries designed to capture subglacial torrents for hydroelectricity in the Alps have shown that subglacial channels are very unstable (Vivian, 1977; Vivian and Zumstein, 1973).

In winter, the internal conduits tend to close due to ice overburden pressure and to glacier movement stress trapping water in cavities and channels (Lang *et al.*, 1977; Tangborn *et al.*, 1975). However, during warmer summer months the englacial and subglacial conduits become larger as the production of meltwater increases. The deformability of the ice allows the passages to expand and contract in response to changes in water pressure. Conduit walls melt due to heat generated by viscous dissipation carried by meltwaters above 0°C. The larger passages gradually increase in size at the expense of smaller ones because more heat is generated by the greater volumes of water (Shreve, 1972).

The warmer meltwaters entering englacial and subglacial systems also help to enlarge reservoir exits enabling higher discharge and decreasing the residency time through the glacier (Elliston, 1973; Lang, 1973). Thus, supraglacial meltwaters enter the englacial and subglacial systems through moulins and crevasses in order to reach the glacier portal in a relatively short time span (Elliston, 1973; Stenborg, 1970). Dye and salt tracing methods used to determine the delay time within alpine glaciers confirmed that in the ablation zone meltwaters drain within a few hours and that in the accumulation zone the lag time is greater (Behrens *et al.*, 1975; Collins, 1982; Krimmel *et al.*, 1973; Stenborg, 1969).

A major characteristic of glacier-fed streams is their diurnal rhythm in discharge (Elliston, 1973; Lang, 1973). Golubev (1973) stated that discharge is composed of a background flow, originating from water previously stored within the glacier, and diurnal variations reflecting the changing rates of ablation. Water in a glacier is stored in crevasses, englacial pockets, subglacial cavities, basal moraine, pools in the ice surface, firn and surface snow (Collins, 1982; Golubev, 1973). These reservoirs accumulate meltwaters up to a threshold level then drain. Only a portion of the total daily meltwater production attains the portal on the same day, the remainder is delayed (Martinec, 1970). At the beginning of the ablation season, inflow exceeds the glacier outflow as the meltwaters fill these reservoirs. However, as the inflow decreases through the summer, the stored waters are evacuated and the outflow exceeds the inflow (Golubev, 1973). Behrens *et al.* (1975) state that no reservoir was present beneath the Hintereisferner in the Austrian Alps while Collins (1980) describes the presence of a pool of water trapped behind a riegel in the bedrock under Peyto Glacier, Alberta.

2.2.2 Glacier hydrochemistry

The separation of glacier discharge into it's contributing components is essential to understand the physical processes involved in a glacier's hydrological regime. The nature and behaviour of these different runoff components are of importance to short and long-term prediction of discharge from glaciers (Collins, 1980).

The natural environmental isotopic content of glacial meltwaters has been used by many researchers to separate the total discharge into it's component parts (e.g., Ambach *et al.*, 1976, 1982; Behrens *et al.*, 1971; Moser and Stichler, 1975; Oerter *et al.*, 1980; Prantl and Loijens, 1977). This analysis is based on the hypothesis that meltwaters contain different concentrations of tritium, deuterium and oxygen-18 depending on their origin (Behrens *et al.*, 1971).

Tritium (^3H) is a radioactive isotope that originates from cosmic radiation. In glaciological research, the application of tritium content measurements is based on the steep rise of tritium content in precipitation since 1952 when thermonuclear weapon testing began. Snow that has been deposited since 1952 has a higher tritium content than older glacier ice which contains no tritium (Behrens *et al.*, 1971). Tritium levels also vary seasonally and daily. Winter precipitation is characterised by low tritium levels, therefore, in the spring, meltwaters contain very little tritium because they are mostly derived from snowmelt from the past winter's accumulation (Ambach *et al.*, 1982). In the summer, runoff is derived from the ablation of tritium free glacier ice. However, the tritium level increases in periods that are unfavorable to ice melt because the runoff is composed of snowmelt waters enriched by summer rain and subglacial spring water (Ambach *et al.*, 1982). In autumn, after the main ablation season, tritium levels increase due to the input from subglacial springs (Behrens *et al.*, 1971). Dincer *et al.* (1970) separated meltwaters originating from baseflow from those of snowmelt using tritium content.

Deuterium (^2H) concentration has also been used to separate the different flow components because the content of the heavy isotope decreases with rising altitude and decreasing condensation temperature (Moser and Stichler, 1975). During the metamorphism of snow, enrichment in heavy isotopes is caused by fractionation processes during phase transition (melting, evaporation, freezing and sublimation) (Moser and Stichler, 1975). Winter precipitation contains less deuterium than summer rain and snow. Spring melt, produced mostly from seasonal snowcover also has a low deuterium content. During the summer the deuterium content increases due to the contribution of glacier icemelt and summer precipitation. The changing proportions of snowmelt and icemelt each day produce a diurnal fluctuation in deuterium concentration (Collins, 1980).

The measurement of solute concentration has also been used in glaciology to separate runoff into its component parts (Collins, 1977, 1979b, 1979c, 1981; Collins and Young, 1979a, 1979b, 1981; Oerter *et al.*, 1980; Rainwater and Guy, 1961; Zeman and Slaymaker, 1975).

The properties of meltwaters in glacierised catchments vary diurnally and seasonally depending on contributions from different sources and different routes in the basin (Collins and Young, 1981).

Rain, snowmelt and icemelt retain their original chemical properties if they flow supraglacially or in englacial tunnels (Church, 1974; Collins, 1977) but become chemically enriched if they are routed subglacially (Collins, 1979b). The bed of the glacier (bedrock, subglacial morainic deposits and sediment-laden ice) is a rich source of solutes (Collins, 1981). Meltwater flowing slowly at the ice-sediment-bedrock contact becomes enriched by travelling through the ion-rich morainic materials (Collins, 1979b, 1979c; Nakamura, 1971). Other sources of solutes include suspended-sediment in transit, morainic deposits alongside the glacier, subglacial springs (Collins, 1977; Reynolds and Johnson, 1972; Stenborg, 1969), aeolian particles and atmospheric salts (Zeman and Slaymaker, 1975) and from the biological cycle of micro-organisms (Kol, 1942).

As dilute meltwaters come into contact with ion-rich sediment, partial dissolution (Reynolds and Johnson, 1972; Slatt, 1972) and desorption occur and the desorbed ions are liberated into solution (Lorrain and Souchez, 1972). This desorption follows the law of mass action and is influenced by the size and the concentration of the sediment and the amount of adsorbed ions on their surface (gouy layer) (Kennedy, 1965). The gouy layer is a film surrounding the sediment particle where cations are in excess of anions (Lemmens and Roger, 1978). Glacier abrasion and crushing create new surfaces and minute particles which offer greater mineral surface area for ion exchange (Lorrain and Souchez, 1972). Lemmens and Roger (1978) have noted that initially a rapid reaction occurs but that subsequent change is very slow. Significant amounts of soluble materials can be acquired by snowmelt within a metre of the edge of the snowpack (Feth, Robertson and Polzer, 1964; Zeman and Slaymaker, 1975).

Glacial meltwaters transport great amounts of ions out of the basin, in solution and adsorbed on sediment surfaces. Eyles *et al.* (1982) estimated a cationic denudation rate of 947 milliequivalent m^{-2} $year^{-1}$, for the

Berendon Glacier basin, which is much higher than the continental average of 390 milliequivalent m^{-2} $year^{-1}$. Calcite and silicate deposits at the base of recently retreated glaciers reflect the importance of ion transport and deposition in glacial streams (Ford *et al.*, 1970; Hallet, 1975, 1976).

Glacial meltwater streams characteristically have an inverse solute-discharge relationship (Behrens *et al.*, 1971; Bryan, 1972; Church, 1974; Collins, 1977; Rainwater and Guy, 1961). The solute concentration peak occurs during the night when most of the runoff is furnished by subglacially routed water. The source of "pure" meltwater (icemelt and snowmelt routed englacially and supraglacially) that usually dilutes the solute-rich water (baseflow) is cut off by colder temperatures that curtail melt (Collins, 1979c, 1981; Collins and Young, 1981; Rainwater and Guy, 1961). Collins (1980) estimated that 60% of Peyto Glacier runoff occurring during the night was baseflow. During the winter, high electrical conductivity levels reflect high solute concentrations which can be attributed to subglacial springs (Stenborg, 1965). Enhanced solutional activity in winter has been noted by Vivian and Zumstein (1973) in the French Alps.

Rainwater and Guy (1961) used solute concentrations to differentiate groundwater flow from precipitation and glacial melt. Oerter *et al.* (1980) separated groundwater from ice-free areas from glacier icemelt and Collins (1979b, 1979c, 1981) identified meltwater source areas within the glacier.

2.3 Glacier suspended-sediment discharge

Suspended-sediment loads of glacial meltwater streams are usually much higher than those of non-glacier-fed streams (Church and Ryder, 1972; Østrem, 1975a). Suspended-sediments are also transported for longer periods of time in glacial streams in comparison to warmer waters because sedimentation rates decrease with decreasing water temperature (Colby and Scott, 1965; Guy, 1970; Straub, 1955; Straub *et al.*, 1958; Vivian, 1970). The study of suspended-sediment has mainly focused on establishing stream discharge versus suspended-sediment concentration relationships (i.e., Borland, 1961; Østrem, 1975a, 1975b; Roaas, 1973). Suspended-sediment data have also been used as a basis for calculating denudation rates (Arnborg *et al.*, 1967; McPherson, 1971; Mills, 1979) and are taken into consideration in the design of structures for hydroelectric power generation (Østrem, 1975a, 1975b).

Suspended-sediment concentrations in glacier-fed streams are highly variable seasonally and diurnally (Collins, 1979a; Gurnell, 1983; Østrem, 1975a). Silt concentrations are usually higher at the beginning of the ablation season than at the end. In addition, peaks occur with the very high discharges of the mid-season (Mathews, 1964; Østrem *et al.*, 1967; Smith *et al.*, 1982). This is due to changes in sediment availability throughout the melt season, created by a "washing out" or "flushing out" of material at the beginning of the season and at each successive higher discharge (Bogen, 1980; Flemming and Poodle, 1969; Gurnell, 1983; Østrem, 1975a).

Glacier-fed streams are characterised by water temperature and suspended-sediment concentration peaks that precede the daily discharge peak by a few hours (Arnborg *et al.*, 1967; Fahnestock, 1963; Mathews, 1964; Østrem, 1975a; Østrem *et al.*, 1967; Rainwater and Guy, 1961). Hysteresis prevents the formulation of a simple relationship between water discharge and suspended-sediment concentration because greater concentrations are present on the rising limb of the hydrograph than for the same discharge on the falling limb (Bogen, 1980; Church and Gilbert, 1975; Collins, 1979a; Statham, 1977). Roaas (1973) states that suspended-sediment concentrations tend to correlate better with discharges during the falling stage. Greater shear stress at the glacier bed, caused by higher flow velocities and greater water surface slope during rising stage, lead to greater sediment entrainment (Skibinski, 1967). Arnborg *et al.* (1967) stated that the first sediment transported by the rising stage was material deposited during the last falling stage.

Glacier-fed streams also experience irregular fluctuations of suspended-sediment concentration (Collins, 1979a; Gurnell, 1983; Østrem *et al.*, 1967). These large magnitude variations or "sediment clouds" reflect the instability of the subglacial zone (Gurnell, 1983) where approximately 66% of the stream's sediment originates (Mills, 1979). The re-routing of the subglacial drainage channels causes the basal streams to migrate into new supplies of sediment. In addition, slumping from unstable morainic deposits will produce sudden increases in transported sediment followed by a rapid exhaustion (Collins, 1979a; Gurnell, 1983).

Thus, discharge magnitude does not directly control the suspended-sediment transport regime. It is a combination of factors such as the rate of increase in discharge, the length of time the water will flow over an area to be eroded and the size of the area (Liestøl, 1967).

2.4 Discussion

In view of the literature, it is apparent that the main thrust of glacial research has been moving away from the qualitative approach of past years. Current studies focus on the quantitative understanding of glacier processes through the use of mass balance measurements, hydrochemical and hydrometeorological parameters.

However, there seems to be a general lack of attention to suspended-sediment dynamics from glaciers. This is the main point addressed by this thesis. The research is by no means singular in approach because it includes a combined suspended-sediment, hydrochemical, meteorological and mass balance study which should lead to a better understanding of glacier dynamics.

Thus, research of this nature should address some of the voids existing in the literature and thus contribute to a better comprehension of glacial processes and glacial geomorphology.

CHAPTER 3

METHODOLOGY AND TECHNIQUES

3.1 Data collection

The hydrochemical and suspended-sediment sampling site is located at a bedrock outcrop, 30 m from the glacier portal, immediately upstream from the gorge section of the basin (Figure 8). This location was chosen to reduce secondary hydrochemical and sediment inputs from snowmelt and icemelt runoff from lateral ice-cored moraines down valley. Previous hydrochemical studies at Peyto Glacier (Collins, 1980; Collins and Young, 1979a, 1979b, 1981) were undertaken at the established gauging site located 1.5 km downstream from the glacier terminus and were subject to these inputs. The accessibility of the site also permitted the easy transport of instruments and samples.

Water and suspended-sediment samples were collected daily during the period May 23 to September 8, 1981, at approximately mid-stage, to assess the seasonal variations of the meltwaters. Samples were obtained by hand-dipping a litre bottle into the stream at a 45° angle upstream (Hjulström, 1939; Østrem, 1975a). It is assumed that Peyto Creek's highly turbulent nature resulted in uniform mixing and samples will be representative of the whole stream (Østrem, 1975a).

Hourly water and suspended-sediment sampling was undertaken for 48 hours every 10 to 14 days to assess the

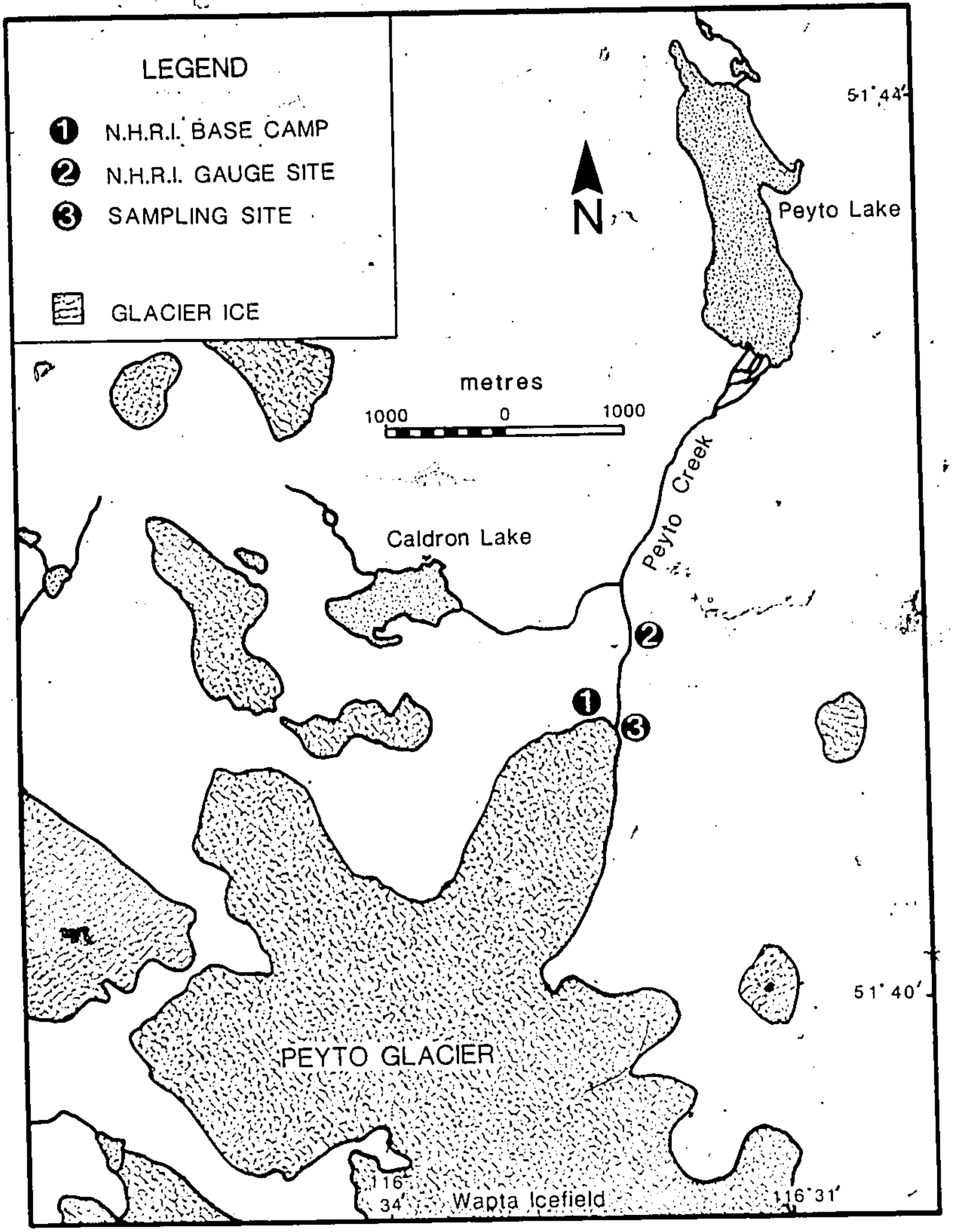

Figure 8 Location map of sampling and stream gauging sites.

diurnal variations occurring in the stream. The samples were taken using a Cygnus Automatic Liquid Sampler (model 24-1M) (Figure 9). The intake nozzle of the instrument was positioned in the channel at approximately six-tenths the stream's depth to minimize bedload contamination. A fifteen minute sampling interval was also carried out for 12 to 18 hours every 10 to 14 days, using the automatic sampler, to detect short-term variations in suspended-sediment concentration.

The samples were immediately gravity filtered in the field to prevent further adsorption on the suspended-sediment particles (Lorrain and Souchez, 1972). The daily and hourly samples were filtered using Whatman GF/C very fine glass microfibre papers because of their high particle retention and fast filtering speed properties. The filter papers were dried and stored in labelled plastic bags. A 500 ml sample of the filtrate was stored in a polyethylene bottle which had been prewashed with 1:1 nitric acid and rinsed with distilled, deionised water. The 15 minute samples were filtered through slower Whatman 42 ashless filter paper due to the number required and cost limitations. All filter papers were weighed in the laboratory at the end of the season.

Water temperature and electrical conductivity measurements were taken in the stream at the time of collection of the daily water and suspended-sediment samples. Electrical conductivity is a useful indicator of the total

COLOURED PICTURES
Images en couleur

Figure 9 Cygnus automatic liquid sampler located at the sampling site, 30 m from Peyto Glacier terminus. Photograph: June, 1981.

solute content in glacial meltwaters (Collins, 1977). It permits an indirect view of subglacial chemical activity as the meltwaters emerging at the glacier portal reflect the mixing of water originating from different areas and thus different chemical composition. It is quite useful in glacial streams because it can be determined using portable equipment. A Yellow Springs Instruments Model 33 Salinity, Conductivity and Temperature Meter was used. For the hourly samples water temperature and conductivity were measured at the base camp.

Hydrological inputs to the main melt stream were monitored on a regular basis to assess their contribution to Peyto Creek's total hydrochemical and sedimentological regime. Water samples were collected from supraglacial streams and from small tributary streams alongside the glacier for hydrochemical analysis. In addition, rain and ice samples were obtained from different areas of the glacier for analysis.

Stream discharge was measured at the established N.H.R.I. gauging site. Insufficient mixing length and great variations in stream configuration between low and high flows (Figures 10 & 11) prevented discharge measurements at the sampling site. These data were used to explore relationships between stream discharge and hydrochemical parameters and suspended-sediment concentrations. At low flow, discharge was measured manually using traditional current meter methods (Church and Kellerhals,

Figure 10 Peyto Glacier terminus with Peyto Creek at low flow. Note the well defined stream configuration. Photograph: July, 1981.

Figure 11 Peyto Glacier terminus with Peyto Creek at high flow. Note the inundated proglacial zone. Photograph: August, 1981.

COLOURED PICTURES
Images en couleur

1970). At higher discharge the relative salt dilution method was employed (Day, 1977; Church and Kellerhals, 1970; Østrem, 1964b). This method consists of injecting a known volume of brine into the stream and observing its passage at a point downstream by monitoring electrical conductivity changes with time. At high flow, fluorometric procedures were employed (Church and Kellerhals, 1970; Warner, 1968; Wilson, 1968). Initially, the constant rate dye injection method was attempted (Figure 12). It is performed by adding a fluorescent dye, Rhodamine WT, of known solution strength at a constant rate to the stream water. The dye becomes uniformly mixed across the stream at a certain location downstream, creating a constant rate of dye flowing at that point. The concentration of dye present in the water at this point depends on the stream discharge, the injection rate and the concentration of the injected dye. The collected sample's concentration was then compared to a calibration curve using a Turner, model 110, "Filter Fluorometer" (Figure 13). Problems developed when suspended-sediment from the streamwater used to dilute the dye blocked the output nozzle preventing a constant injection. Therefore the slug-injection method was also used to measure high discharges. It consists of introducing a known amount of dye into the stream and collecting a sufficient number of samples downstream in order to define the time-concentration curve of the passing solution wave. A major difficulty with this method is knowing when to stop sampling since the dye

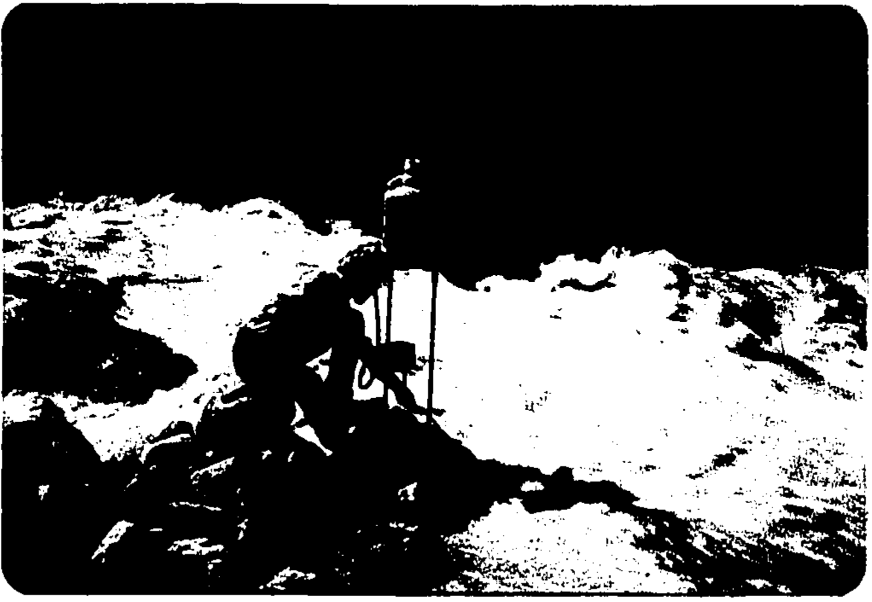

Figure 12 Constant rate dye injection method of measuring stream discharge, Peyto Creek, Alberta. Photograph: July, 1981.

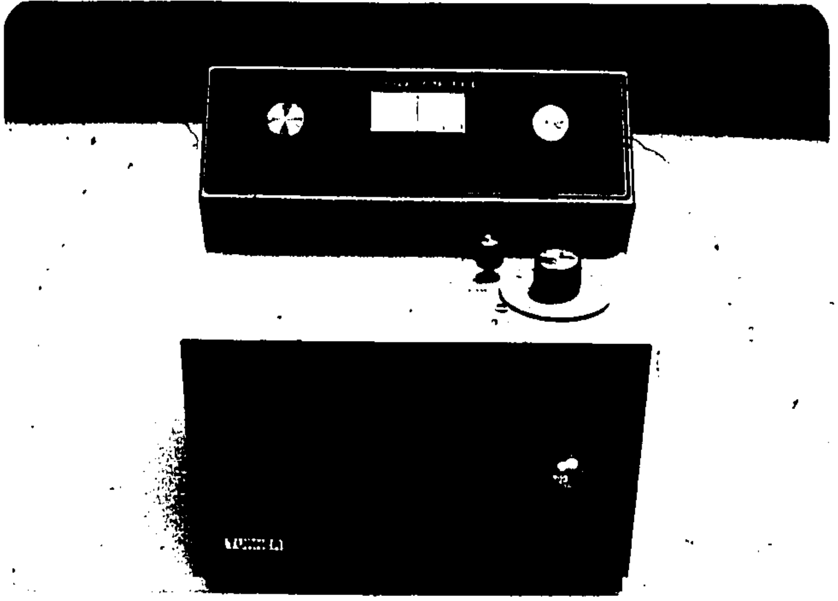

Figure 13 Turner Filter Fluorometer, model 110, used to measure dye concentrations at base camp. Photograph: September, 1981.

concentration becomes invisible at the tail-end of the dye wave (Figure 14).

The stage-discharge curve for Peyto Creek was constructed from the discharge measurements and the corresponding stage, recorded by a Stevens A-71 recorder located 1.5 km from the glacier terminus at 1960 m a.s.l. operated by N.H.R.I. (former Water Survey of Canada station 05DA008) (Figure 15). High discharges were interpolated from a stage-discharge curve established from many years of data collection (Figure 16) because changing stream bed configuration, standing waves at the gauge site and the silting up of the stilling well led to inaccurate measurements. A computer program, provided by N.H.R.I., was used to transform the recorded water levels into the hourly discharges required to render the data compatible with the hourly suspended-sediment and water samples collected.

Meteorological data for Peyto Glacier were collected to examine their influence on suspended-sediment output rates and on variations in the hydrochemistry of the meltwaters. Air temperature and relative humidity were measured with a Lambrecht thermohygrograph, precipitation with a standard rain gauge and a Fisher-Porter automatic precipitation recorder, wind run and direction with a Lambrecht anemometer and incoming shortwave radiation with a cumulative solarimeter (Figures 17 to 20).

Figure 14 Slug injection method of measuring stream discharge, Peyto Creek, Alberta. Photograph: July, 1980.

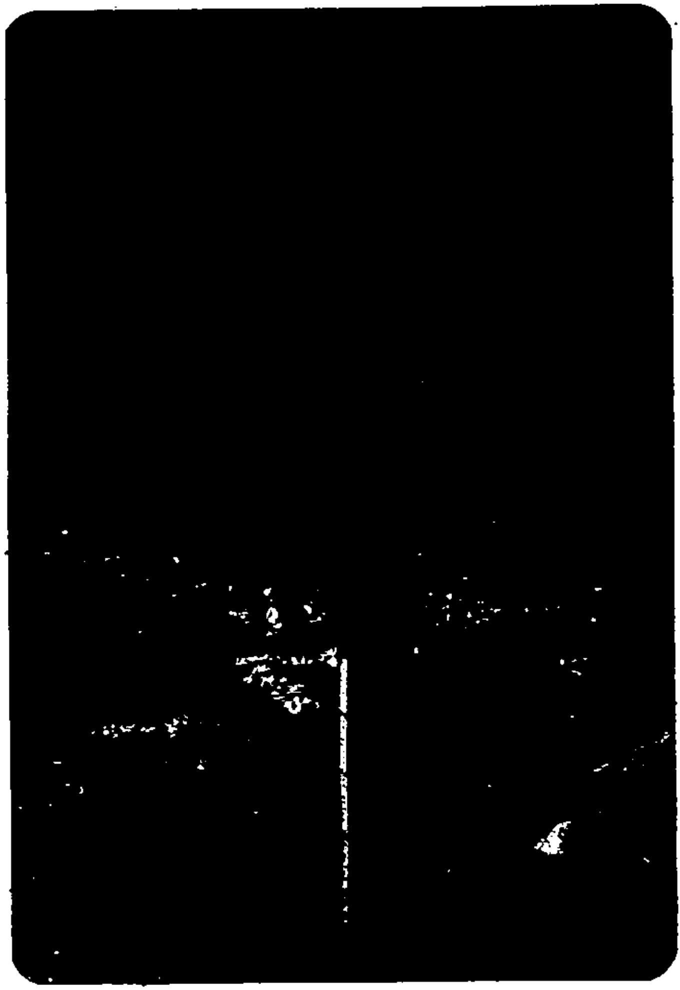

Figure 15 N.H.R.I. stream gauge site, Peyto Creek, Alberta. Photograph: July, 1981.

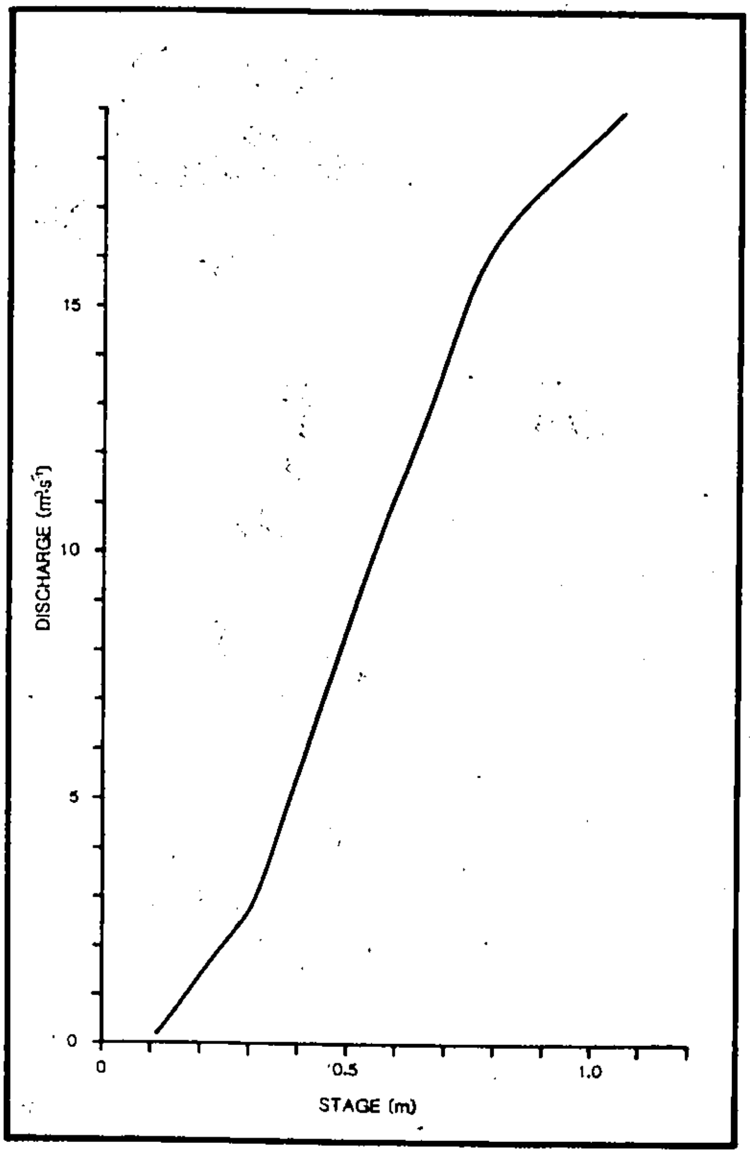

Figure 16 Peyto Creek stage/discharge curve. Source: unpublished data, N.H.R.I.

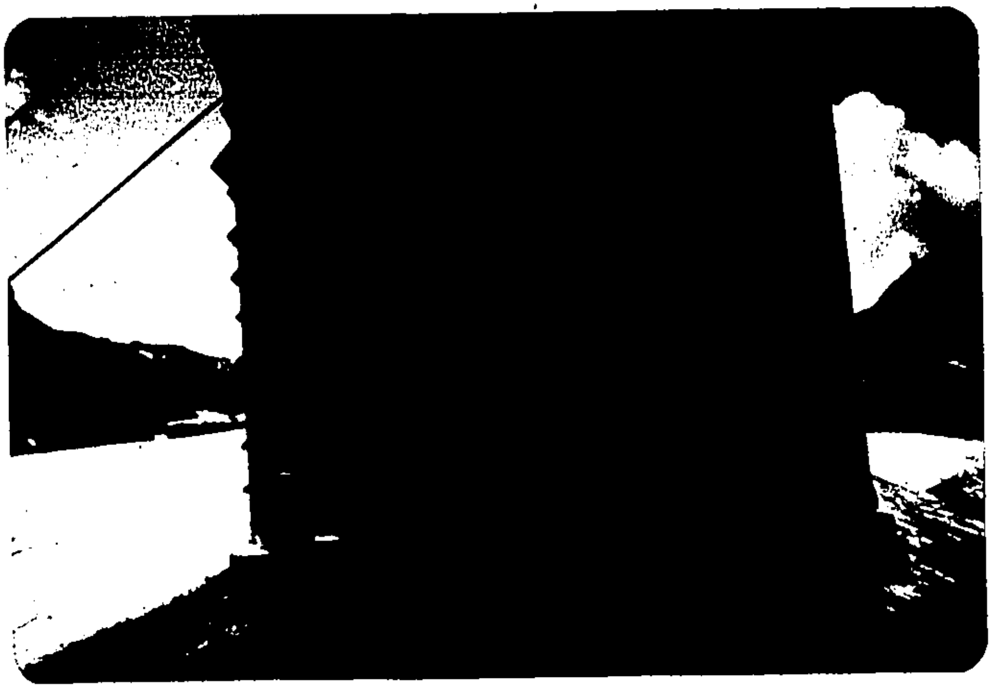

Figure 17 Stevenson screen with Lambrecht thermohygrograph and thermometers. Photograph: July, 1982.

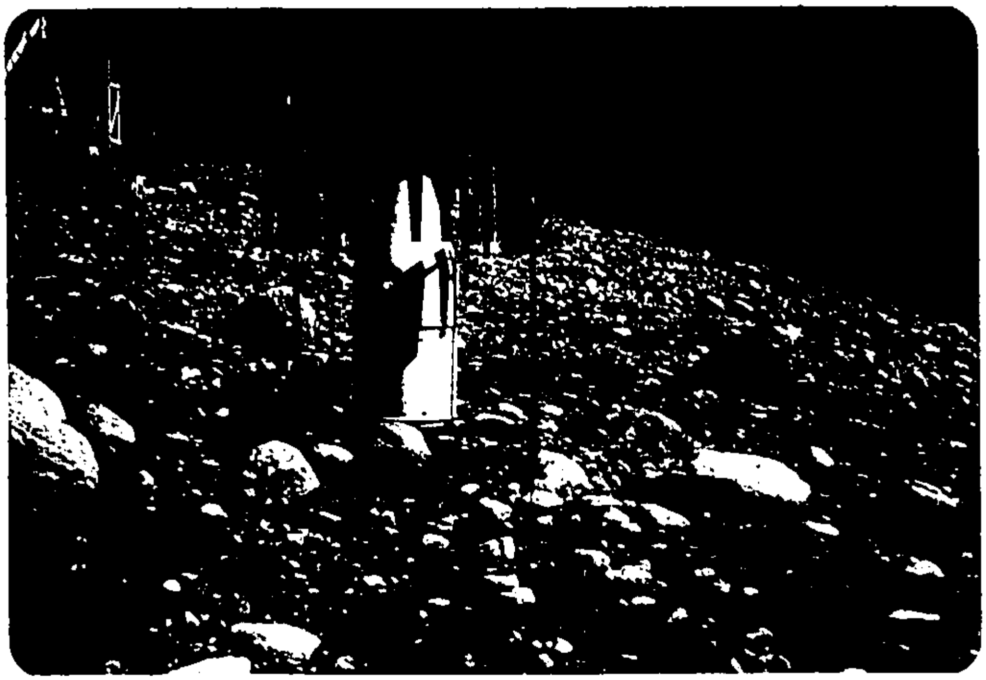

Figure 18 Fisher-Porter automatic precipitation recorder. Photograph: August, 1981.

COLOURED PICTURES
Images en couleur

Figure 19 Lambrecht anemometer. Photograph: August, 1981.

Figure 20 Meteorological instruments: a) standard rain gauge, b) cumulative solarimeter, c) sunshine recorder and d) actinograph. Photograph: August, 1981.

3.2 Laboratory analysis

Water samples were analysed for major ion concentration using atomic absorption spectrophotometry. The amount of absorbed radiation is proportional to the concentration of the test element in the solution (Angino and Billings, 1967; Van Loon, 1980). An Instrumentation Laboratory model 1L357 Atomic Absorption Spectrophotometer, with an accuracy of 0.001 ppm, was utilised to perform the analysis (Figure 21).

The samples were analysed for their Calcium (Ca^{++}), Magnesium (Mg^{++}), Sodium (Na^{+}) and Potassium (K^{+}) concentrations. These four major cations were chosen because they are among the most abundant elements present in glacial meltwaters (Church, 1974; Freeze and Cherry, 1979) and for comparison with values obtained in other hydrochemical studies (e.g., Rainwater and Guy, 1961; Eyles *et al.*, 1982; Reynolds and Johnson, 1972; Slatt, 1972; Zeman and Slaymaker, 1975).

The variability of ion adsorption with respect to suspended-sediment particles was determined to detect the effects of routing within the glacier. Sediment samples were rinsed three times with 10 ml of ammonium acetate solution (1N) as a cation exchanger (Lorrain and Souchez, 1972). The 30 ml residual solution was analysed by atomic absorption spectrophotometry.

COLOURED PICTURES
Images en couleur

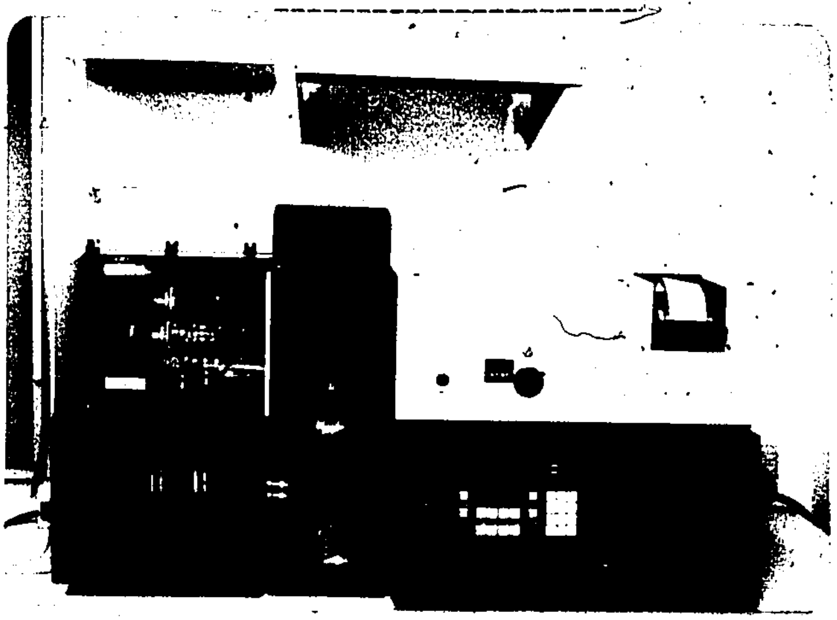

Figure 21 Instrumentation Laboratory atomic absorption spectrophotometer used for hydrochemical analysis. Photograph: September, 1982.

CHAPTER 4

CLIMATOLOGY, MASS BALANCE, HYDROLOGY: RESULTS AND INTERPRETATION

4.1 Climatology

Large variations in runoff from nival and glacial basins occur from year to year as well as over longer time-spans. The amount of runoff is directly dependent on snowmelt and icemelt which is dependent on winter snowfall and summer solar energy and precipitation inputs. These variations produce considerable problems in the management of water resources for irrigation, hydroelectricity and municipal supply. Thus, the investigation of the trends and inter-relationships of meteorological parameters throughout the years is of utmost importance.

The temperature regime at the N.H.R.I. base camp during the study period, May 19 to September 09, 1981 (Figure 22) is divided into four major components roughly corresponding to the divisions of the hydrological regime which are identified later. From May 19 to June 24, the relatively cold temperature, in comparison to the remainder of the ablation season, is shown by a low total of 73.7 degree-days (daily mean of 1.9 degree-days). The mean daily temperature was 2.0°C while the minimum daily dipped below 0°C on twenty-two days.

The second component, June 25 to July 07, shows the temperature variability typical of mountain environments. A total of 73.5 degree-days (daily mean of

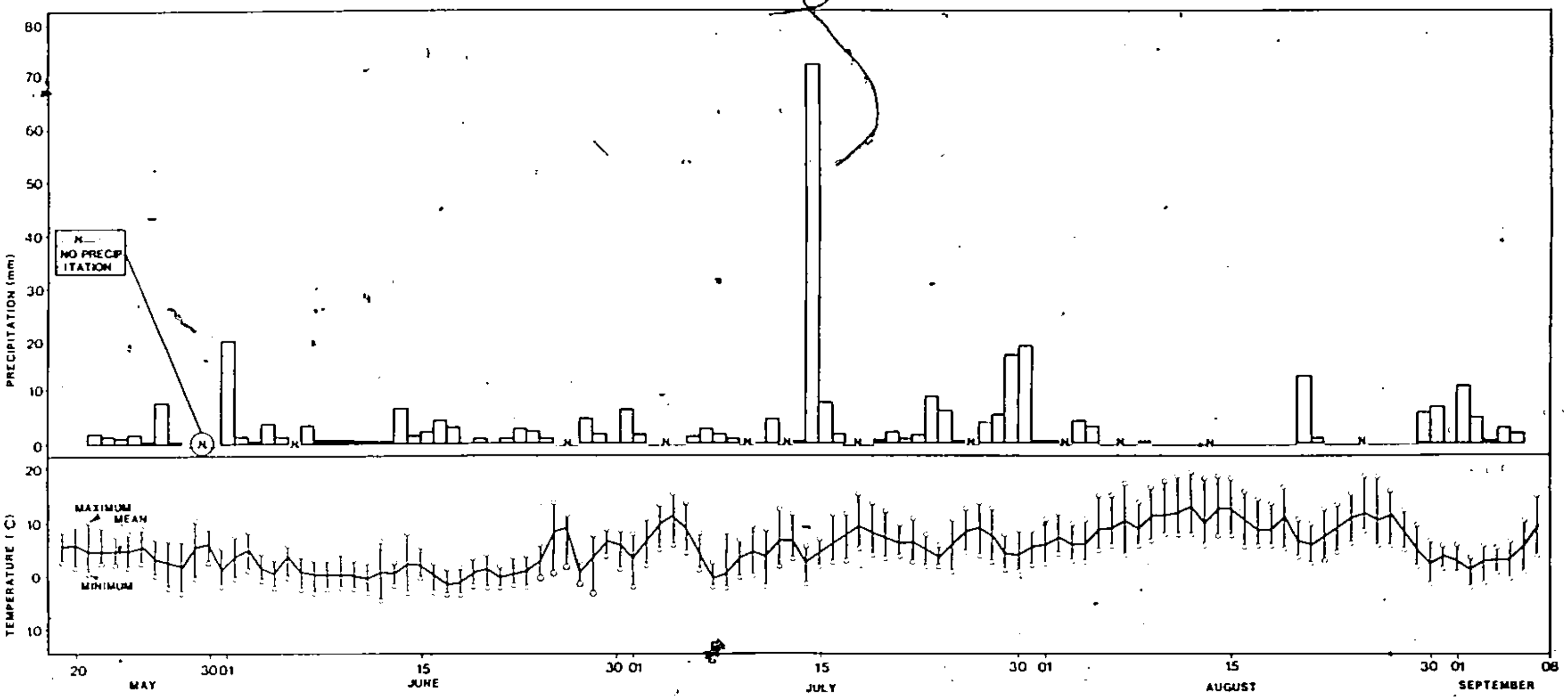

Figure 22 Temperature and precipitation regimes, N.H.R.I. research base camp, Peyto Glacier, Alberta, 1981. Source: unpublished data, N.H.R.I.

5.7 degree-days) were received at the glacier during this time period. The mean daily temperature was 5.9°C, ranging from 0.4°C on June 27 to 11.2°C on July 04.

The third component, July 08 to August 28 is characterised by an increasing trend in mean daily temperature to a maximum of 13.0°C, during which the basin received a total of 392.2 degree-days (daily mean of 7.5 degree-days). A season high of 18.9°C occurred on August 12.

The fourth component, August 29 to September 07, was characterised by a return to colder temperatures, reflected by a low total of 37.2 degree-days (daily mean of 3.7 degree-days). The mean daily temperature was 3.7°C and the minimum daily temperature dipped below 0°C three times demonstrating a return toward winter conditions.

The passage of high and low pressure systems had a direct influence on the glacier melt regime throughout the summer ablation period. During periods of high pressure, cloud cover was diminished and the glacier received greater amounts of incoming shortwave radiation and experienced low relative humidity (e.g., July 12, 14,760 coulombs, 42% relative humidity) (Figure 23). However, the reverse occurred during periods of low pressure, as increased cloud cover blocked out incoming solar radiation (e.g., July 14, 5,160 coulombs, 92% relative humidity).

A total of 295.1 mm of precipitation (rain and snow water equivalent) occurred during the study period. It was unevenly distributed throughout the summer (Figure 22).

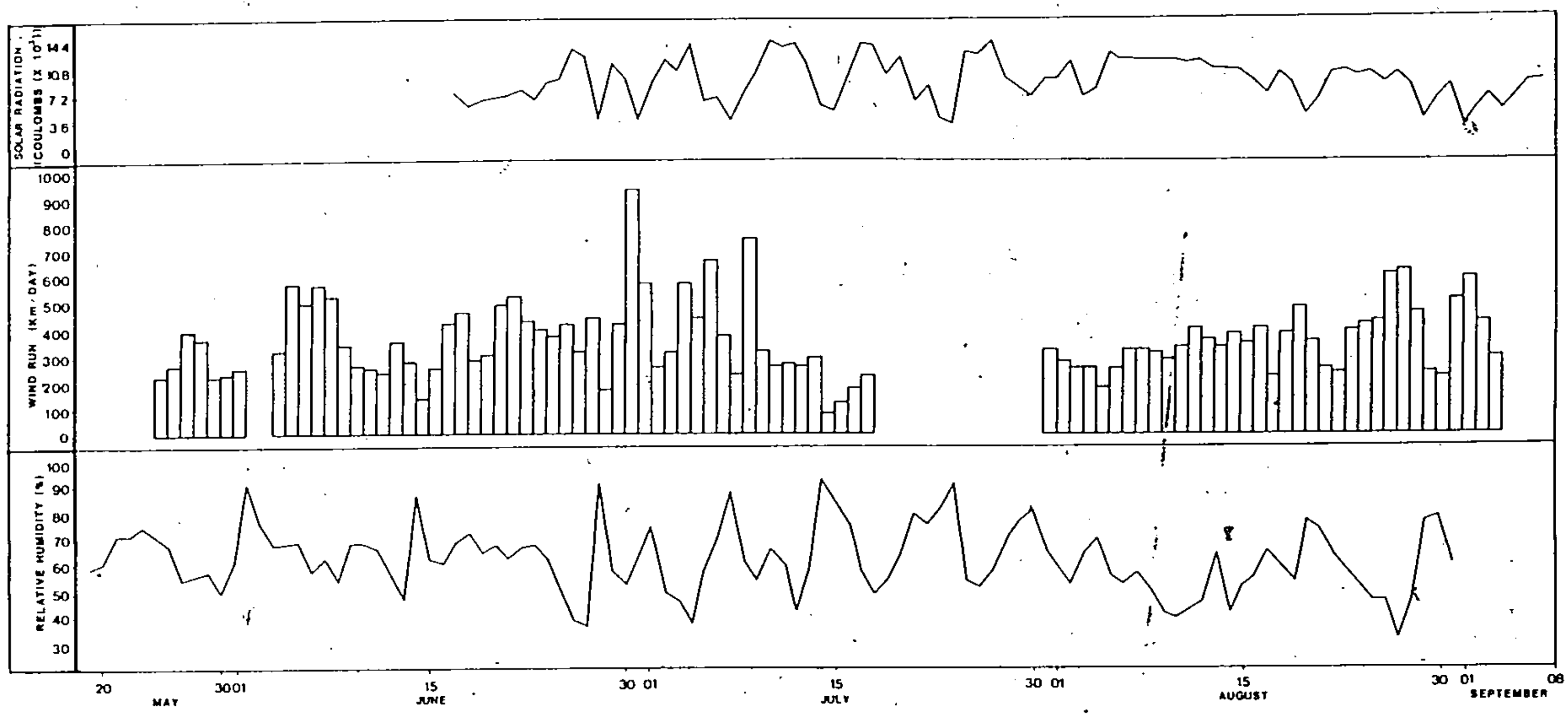

Figure 23 Solar radiation, wind run and relative humidity regimes, N.H.R.I. research base camp, Peyto Glacier, Alberta, 1981. Note that breaks in wind run record were due to instrument malfunction. Source: unpublished data, N.H.R.I.

Six major storm events accounted for 51% of the total precipitation (May 31, July 14, 29, 30, August 20, September 01). A snowfall on July 14 accounted for 24% of the season's total precipitation. With regard to the four sub-divisions of the temperature regime, previously described, the precipitation during the corresponding periods was 70.1 mm, 15.3 mm, 171.4 mm and 33.7 mm respectively.

Analysis of the meteorological data collected during the study period indicated a seasonal range in temperature. Precipitation inputs of the basin were relatively low compared to Coast Range glacier basins which are subject to greater maritime climatic influence.

4.2 Mass balance

The net balance of Peyto Glacier for 1981 (Figure 24a) shows that the glacier had a negative budget year. A specific loss in mass of 1.12 m of water equivalent was calculated. The spatial distribution of the mass balance is illustrated in Figure 24b. A historical presentation of Peyto Glacier mass balance, 1966 to 1981 (Figure 25), reveals that 1980/81 and 1969/70 were the most highly negative budget years and that a negative trend has developed since 1977 resulting in great glacier mass loss (Ommanney, 1984; Young, 1981).

The net winter balance of 1.18 m of water

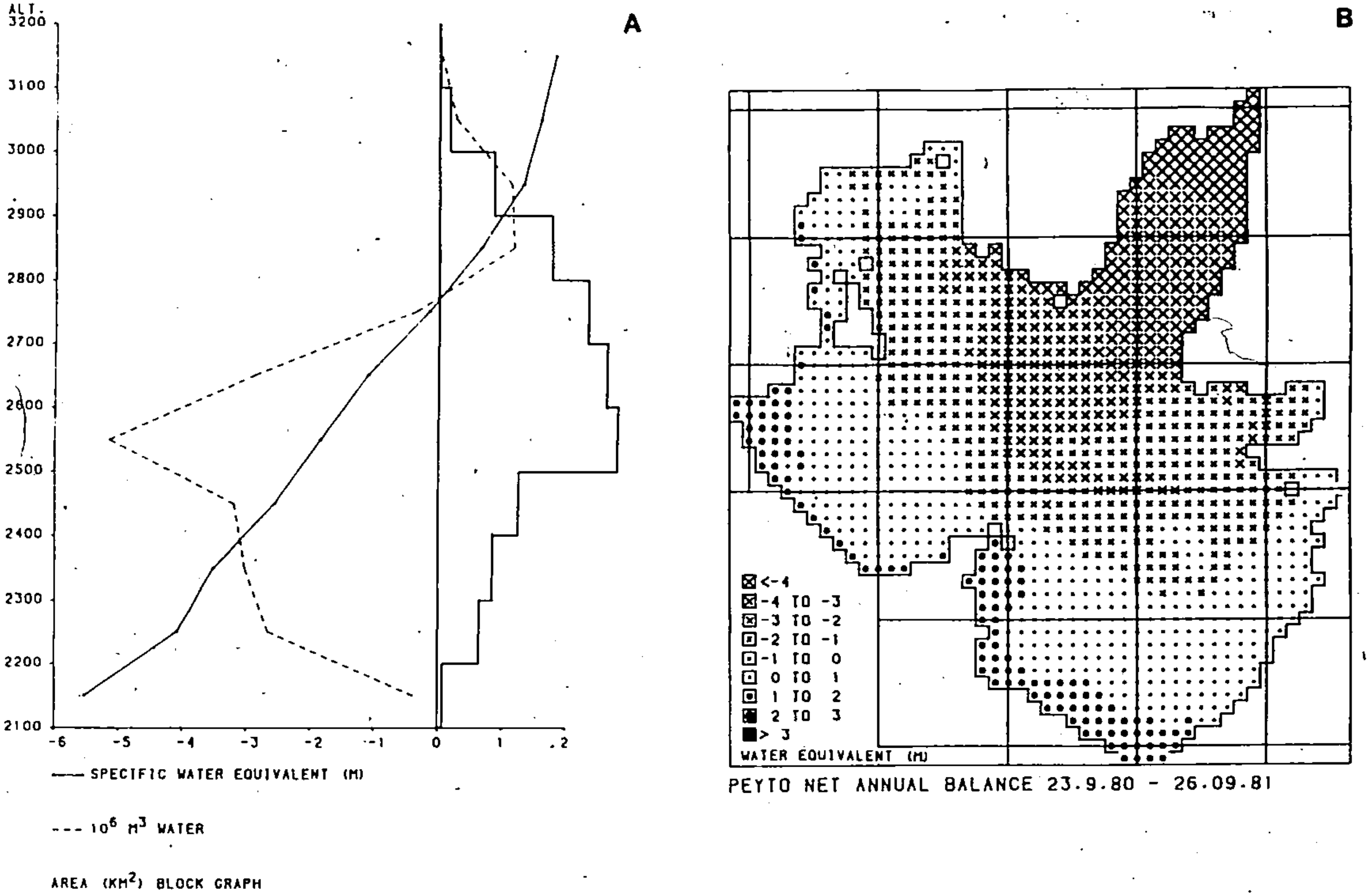

Figure 24 Peyto Glacier net annual balance for 1981. a) mass balance curve, and b) spatial distribution. Source: unpublished data, N.H.R.I.

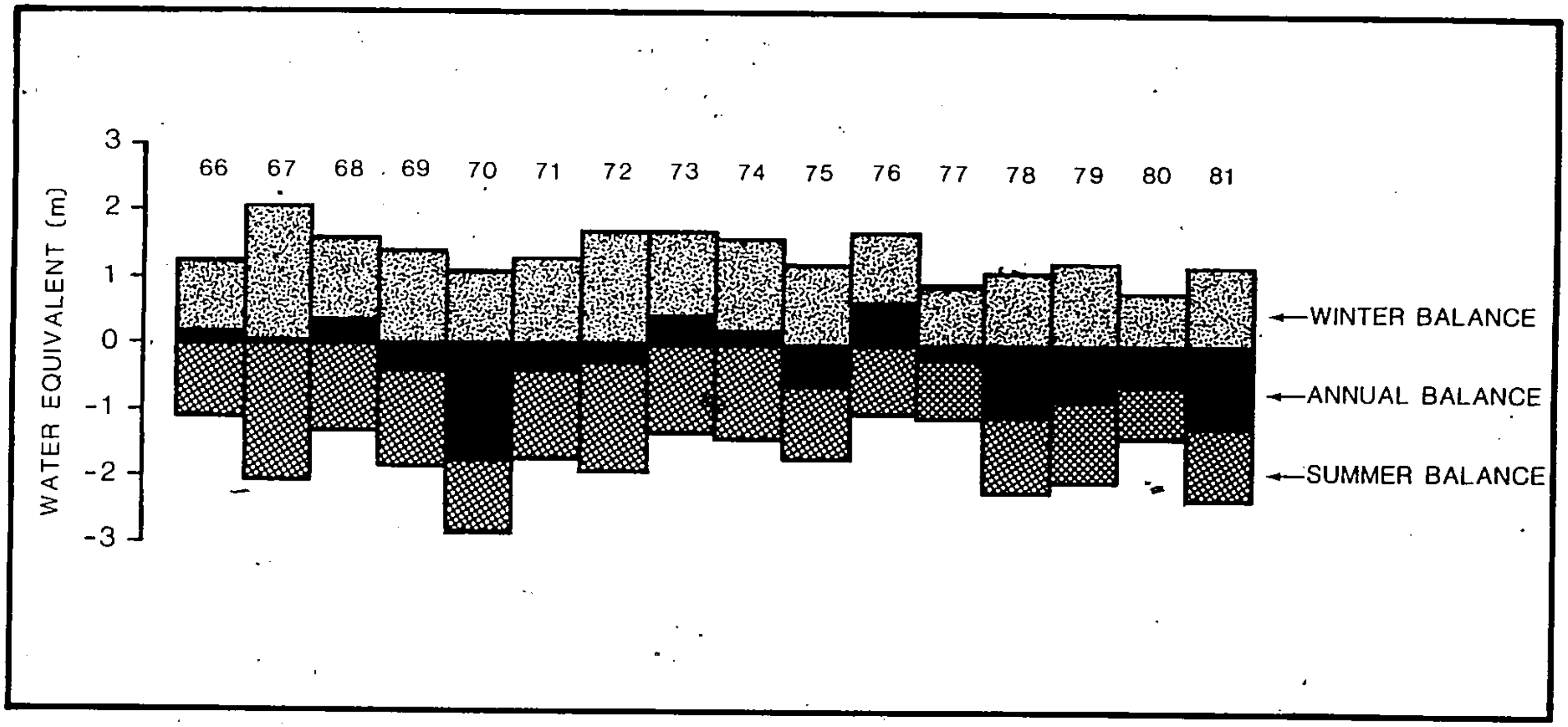

Figure 25 Presentation of Peyto Glacier mass balance (1966-1981). Source: Ommanney, 1984; Young, 1981.

equivalent for 1981 (Figure 26) was much lower than the 13-year mean of 1.43 m presented by Young (1981). In comparison to years of high winter snowfall, this low winter precipitation and normal spring melt conditions led to an early exposure of the glacier ice. The low albedo glacier ice was therefore exposed for a longer period of time, which increased glacier ablation and subsequently glacier runoff.

4.3 Glacier hydrology

Peyto Glacier's hydrological regime (Figure 27) can also be divided into four distinct components. During the early melt season, from May 19 to June 29, Peyto Creek's daily discharges remained low (0.26 to 0.84 x $10^6 m^3 \cdot d^{-1}$) with a peak instantaneous discharge of 10.2 $m^3 \cdot s^{-1}$ occurring on May 26. During this period, the stream's discharge is composed mainly of baseflow and snowmelt inputs from non-glacierised areas. It is assumed that early season snowmelt on the glacier surface did not contribute to runoff as meltwater warmed the snowpack and refroze within it. The snowpack delayed potential runoff. Lateral movement, such as slushflows, occurred during the latter part of June as the snowpack became saturated and isothermal at 0°C. These meltwaters cannot reach the englacial conduits and subglacial channels because surface openings (i.e., crevasses and moulins) are still blocked. Thus during

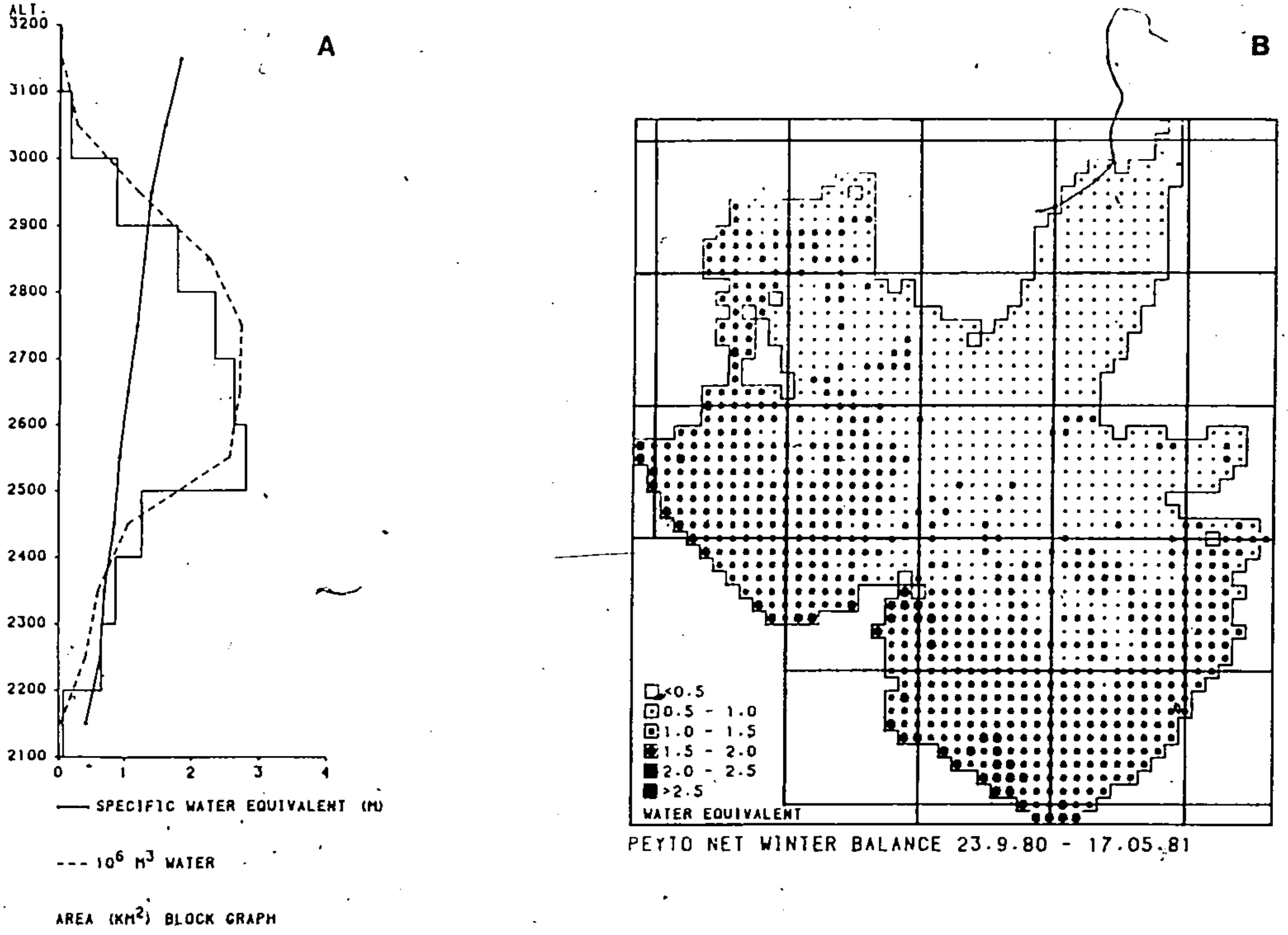

Figure 26 Peyto Glacier net winter balance for 1981. a) winter balance curve, and b) spatial distribution. Source: unpublished data, N.H.R.I.

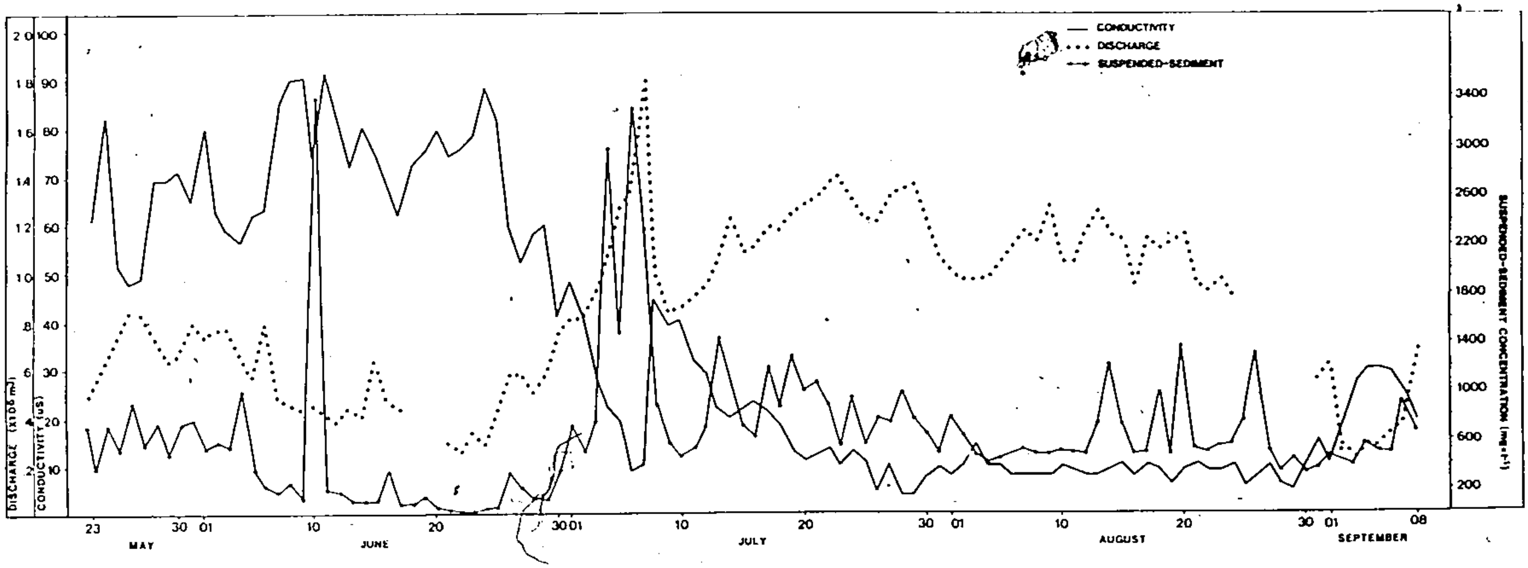

Figure 27 Peyto Glacier discharge, electrical conductivity and suspended-sediment concentration regimes for the 1981 ablation season (May 23 to September 08). Note that the breaks in discharge curve were the result of instrument malfunction.

this component of the seasonal hydrograph, glacier surface flow is an important input to Peyto Creek discharge. This is apparent in the daily hydrograph, as releases from the snowpack resulted in diurnal fluctuations of low amplitude.

The second component, the freshet, occurred from June 30 to July 09. The daily discharge suddenly increased to the season's peak daily value of 1.77 x $10^6 m^3 \cdot d^{-1}$ on July 07. The peak instantaneous discharge for this period ($16.7\ m^3 \cdot s^{-1}$) occurred on July 05. It is hypothesized that this rapid increase was due to the sudden release of water stored in englacial cavities and/or subglacial pockets by the opening of previously blocked conduits. The hydrostatic pressure of the stored water increased with the addition of meltwater which led to increased frictional melt of the internal conduit walls. This permitted the rapid evacuation of the trapped water.

From July 10 to August 28, the daily hydrograph rose steadily in July and gradually fell in August. Peaks occurred in response to precipitation events (i.e., July 14; July 23; July 29; August 20) and to periods of sustained ablation (particularly August 05 to August 28). The daily discharge averaged 1.12 x $10^6 m^3 \cdot d^{-1}$ during this period, ranging from 0.86 to 1.40 x $10^6 m^3 \cdot d^{-1}$. The peak instantaneous discharges, which occurred progressively earlier during the day, attained a season high of $17.6\ m^3 \cdot s^{-1}$. During this period, as more low albedo glacier ice became exposed, increased melt (glacier ice and firn) led to a greater amplitude in the diurnal hydrograph. The progressive growth of the englacial and subglacial channels during the summer led to the increase in discharge. Thus, an increasing volume of meltwater is added to runoff with decreasing delay times.

A return to baseflow occurred between August 29 and September 08. Low temperatures effectively limit glacier ablation, reducing daily discharge to below 0.7 x $10^6 m^3 \cdot d^{-1}$ (0.22 - 0.68). In addition, a number of englacial and subglacial channels probably closed when ice overburden and ice movement stress became greater than the hydrostatic pressure due to decreased meltwater volumes travelling through these conduits.

4.4 Seasonal glaciological and hydrological conditions

The purpose of this section is to correlate the different hydrological events with the various glaciological conditions at Peyto Glacier during the 1981 ablation season. The progression of glaciological and hydrological events are depicted in a series of photographs and corresponding portions of the hydrograph (Figures 28 to 37).

On May 26 (Figure 28), the glacier is completely snow covered with minor evidence of melt in the form of slush patches near the icefalls. The hydrograph illustrates the low diurnal amplitude of discharge typical of early season

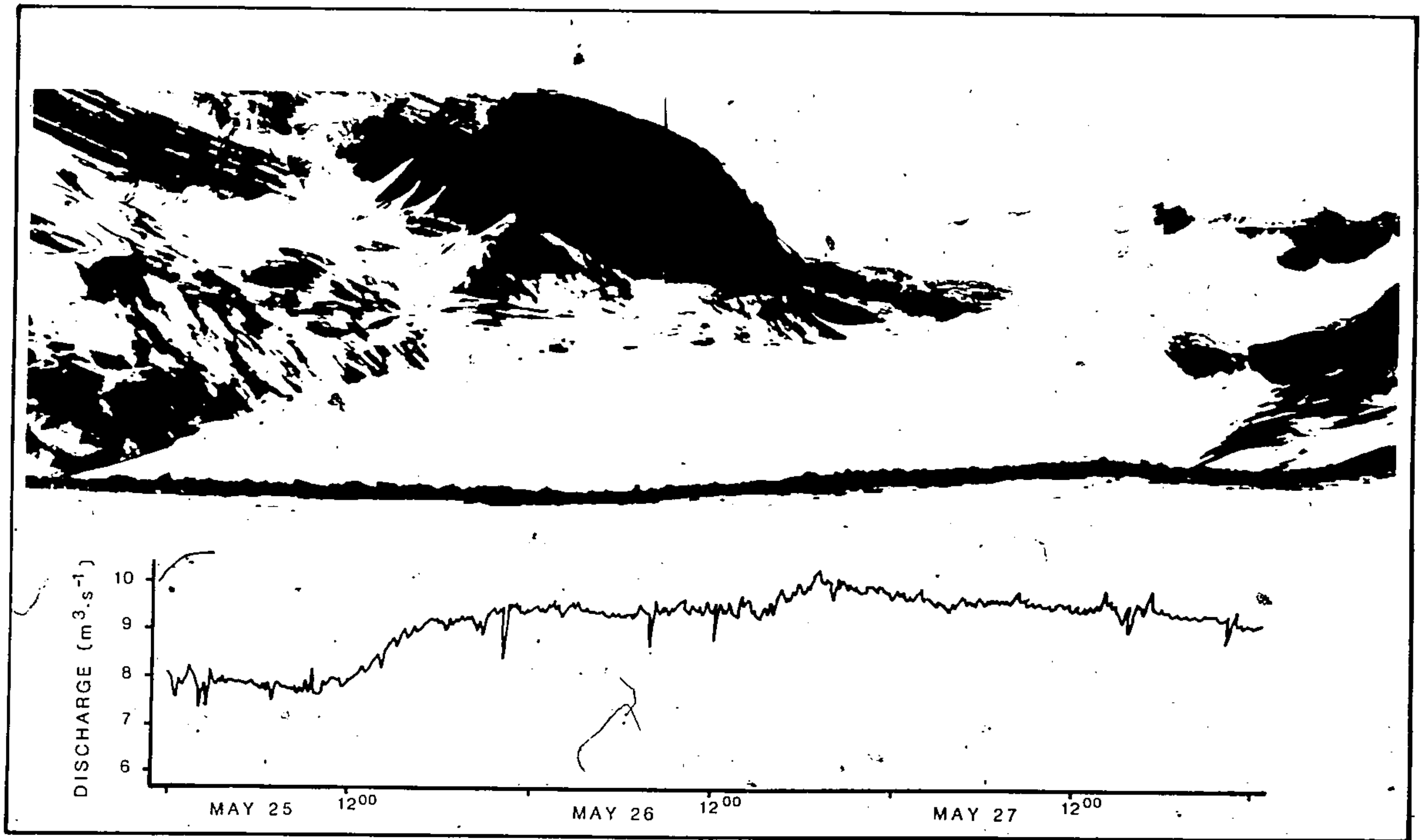

Figure 28 Glaciological conditions and hydrological regime, Peyto Glacier, Alberta, May 26, 1981. Photograph: Y. Carrier, May, 1981.

baseflow events. The peak discharge occurs at approximately 1900 h. Short-term irregularities in the hydrograph are probably due to releases of snow-meltwaters from non-glacial areas. These releases might also be linked to sudden collapse of subglacial channels (e.g., Burkimsher, 1983).

Hydrological conditions remained constant for the baseflow event of June 12 (Figures 29 & 30) but the glacier surface shows signs of increased melt near the icefalls and the medial moraine. In addition, slush formations near the terminus indicate that the water content in the snow is near the saturation point and that lateral movement is commencing.

The glacier snout is 80% bare glacier ice and supraglacial flow is apparent on July 04 (Figure 31). A greater diurnal amplitude of discharge is clearly evident from the hydrograph. The rapid fluctuations in discharge on July 05 probably reflect the opening of a major arterial conduit which is typical of the freshet period.

By July 20 (Figures 32 & 33), the snowline had retreated to an elevation of approximately 2400 m a.s.l. Snow has melted off the glacier tongue except in locations of massive drifting such as the terminus and in major depressions. The diurnal amplitude of discharge continued to increase. The time of peak discharge occurred earlier during the day (1700 h).

Figures 34 and 35 show that the snowline has retreated to the area directly above the icefalls on August

Figure 29 Photograph of Peyto Glacier terminus, June 12, 1981. Photograph: Y. Carrier, June, 1981.

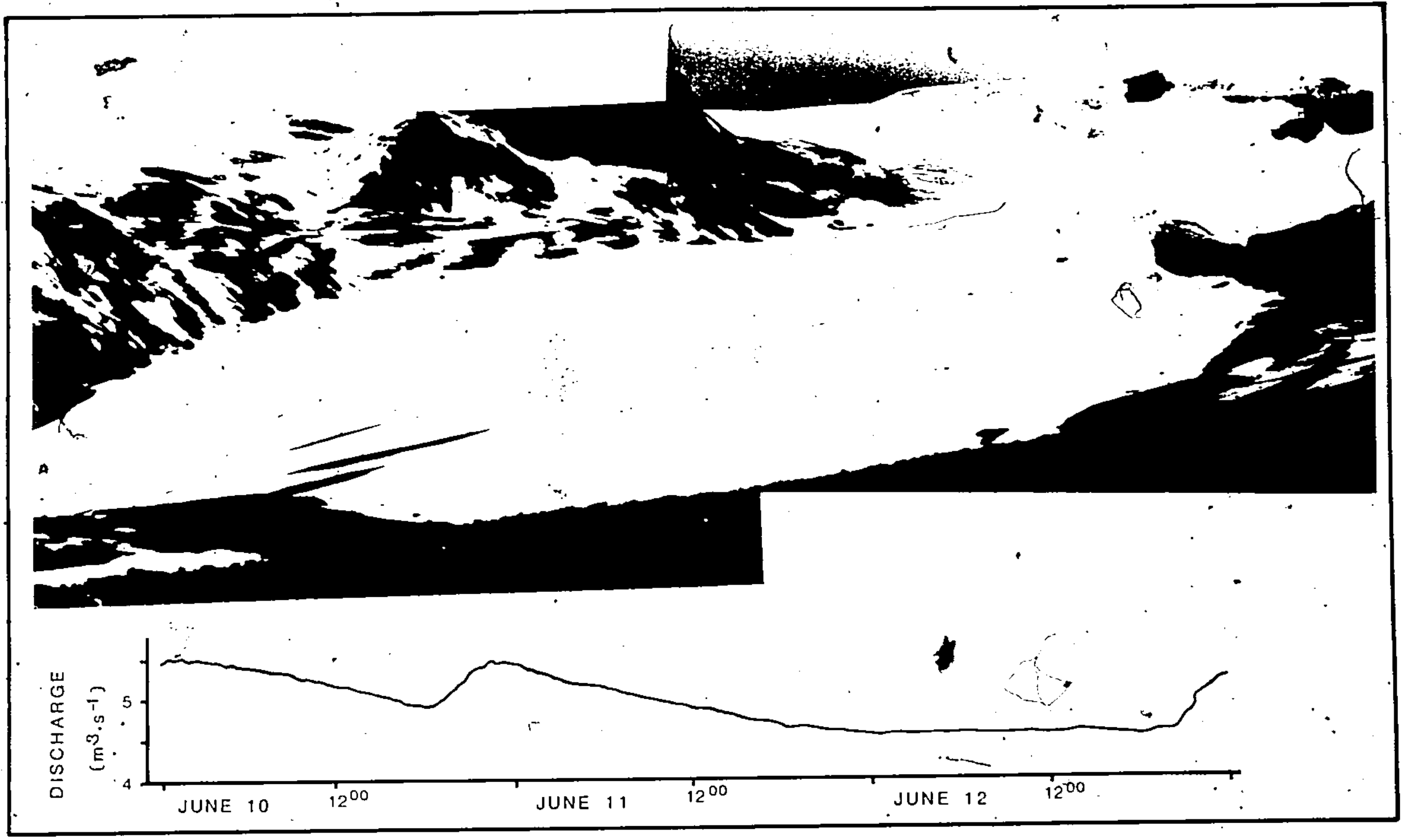

Figure 30 Glaciological conditions and hydrological regime, Peyto Glacier, Alberta, June 12, 1981. Photograph: Y. Carrier, June, 1981.

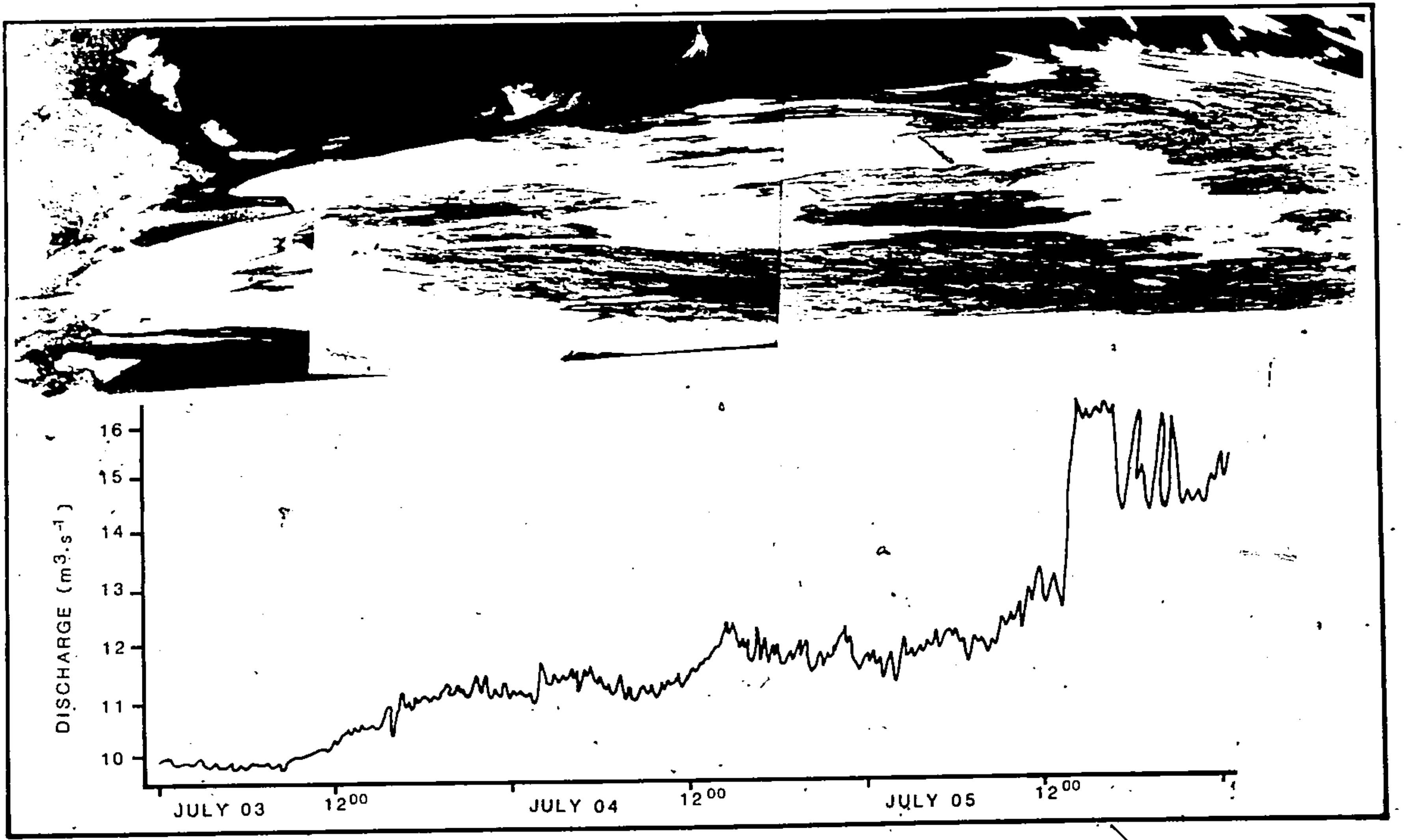

Figure 31 Glaciological conditions and hydrological regime, Peyto Glacier, Alberta, July 04, 1981. Photograph: Y. Carrier, July, 1981.

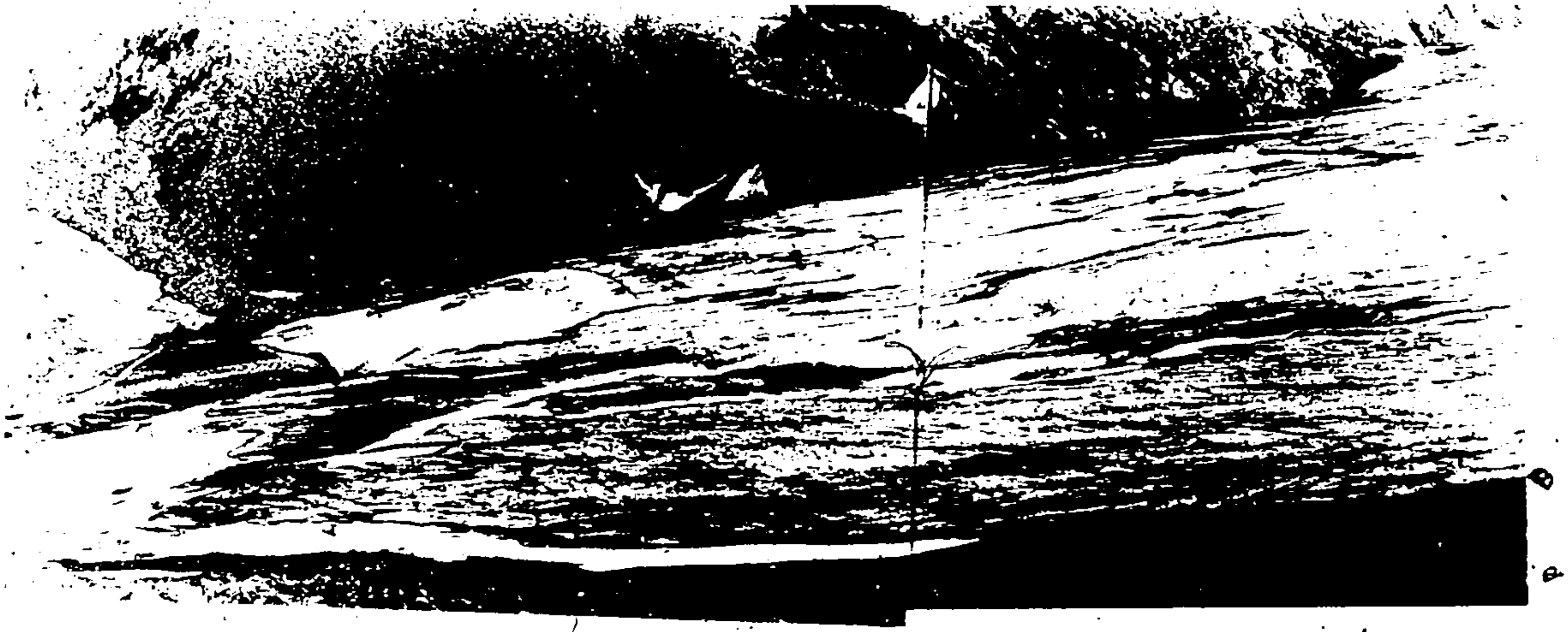

Figure 32 Photograph of Peyto Glacier terminus, July 20, 1981. Photograph: Y. Carrier, July, 1981.

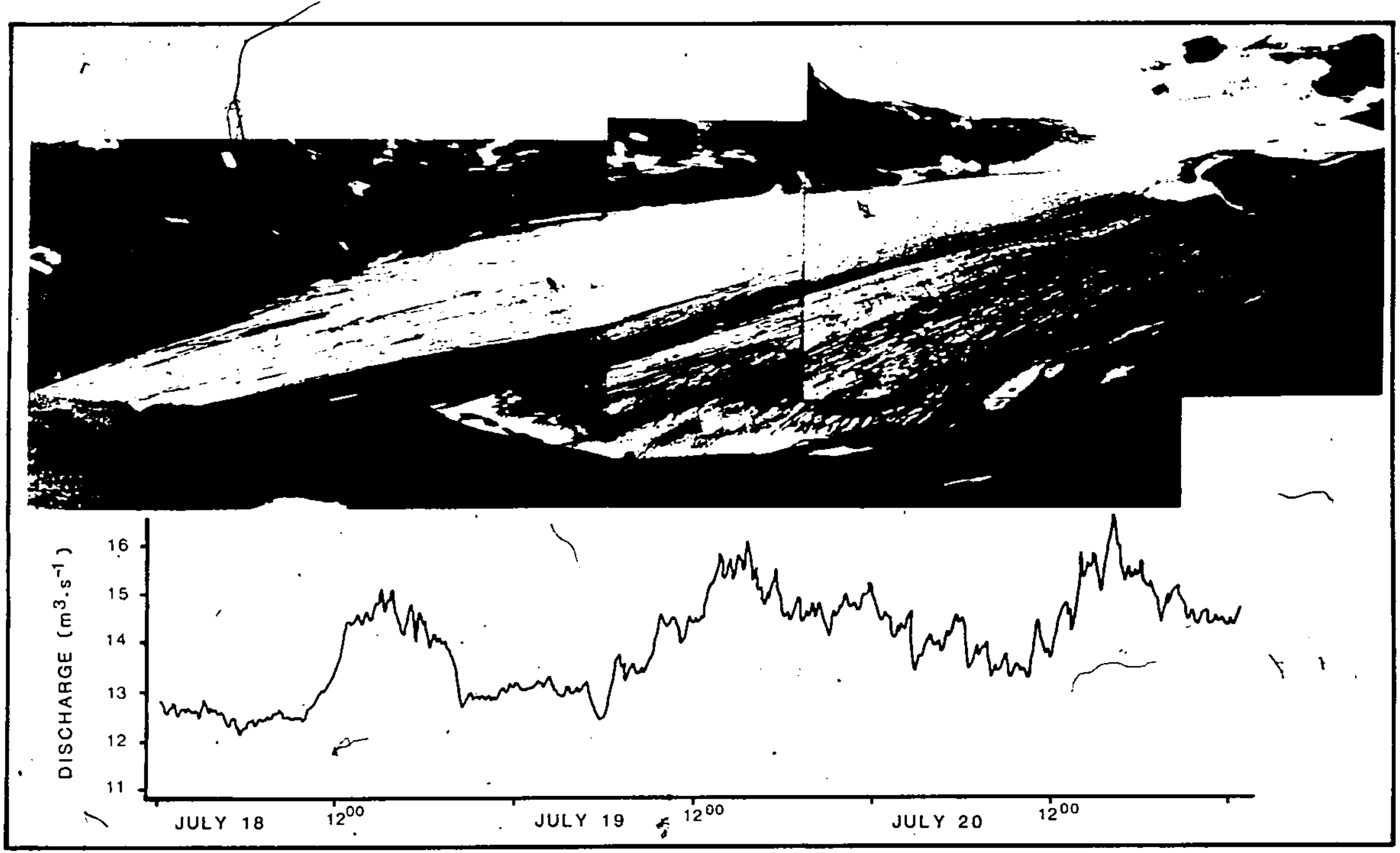

Figure 33 Glaciological conditions and hydrological regime, Peyto Glacier, Alberta, July 20, 1981. Photograph: Y. Carrier, July, 1981.

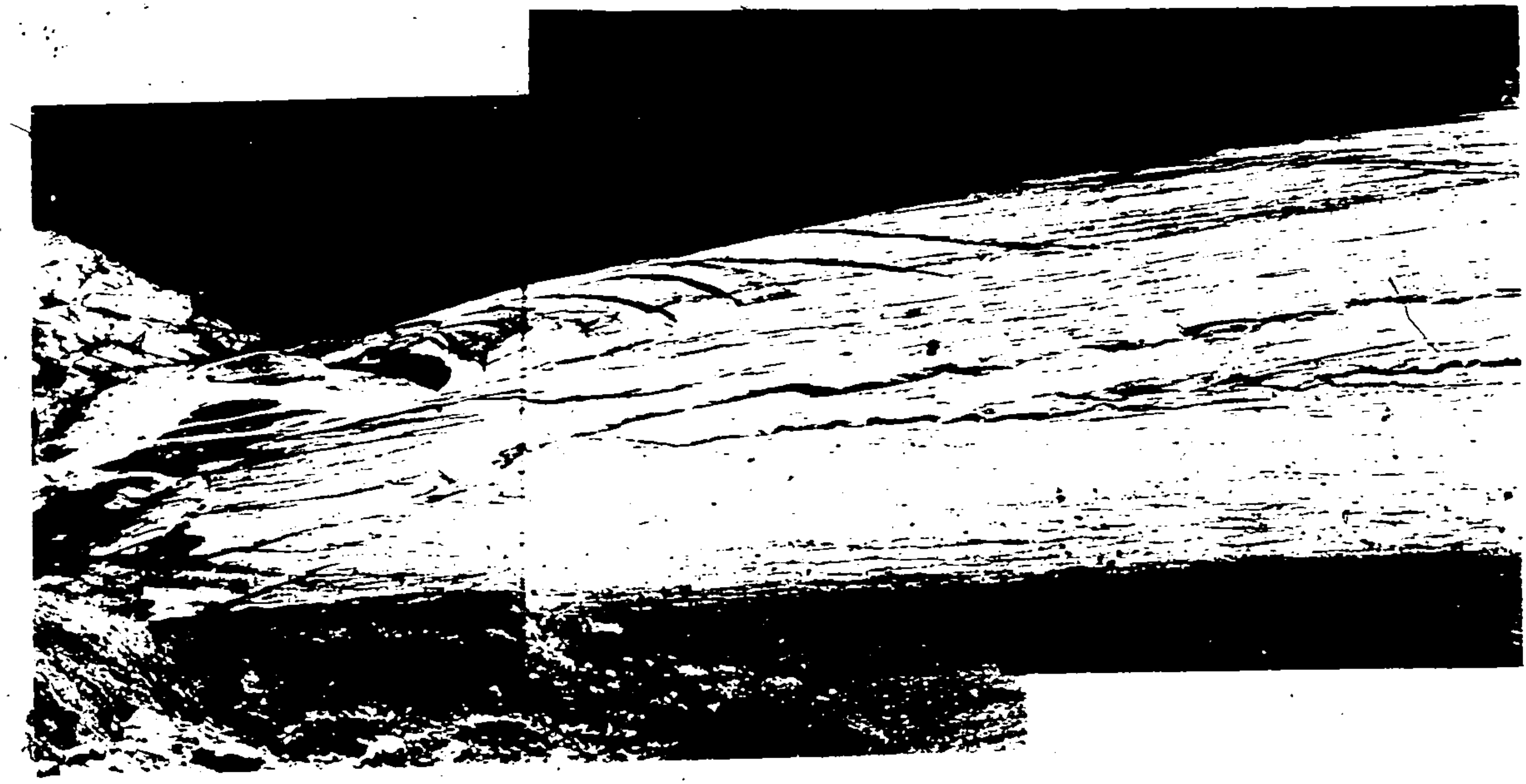

Figure 34 Photograph of Peyto Glacier terminus, August 05, 1981. Photograph: Y. Carrier, August, 1981.

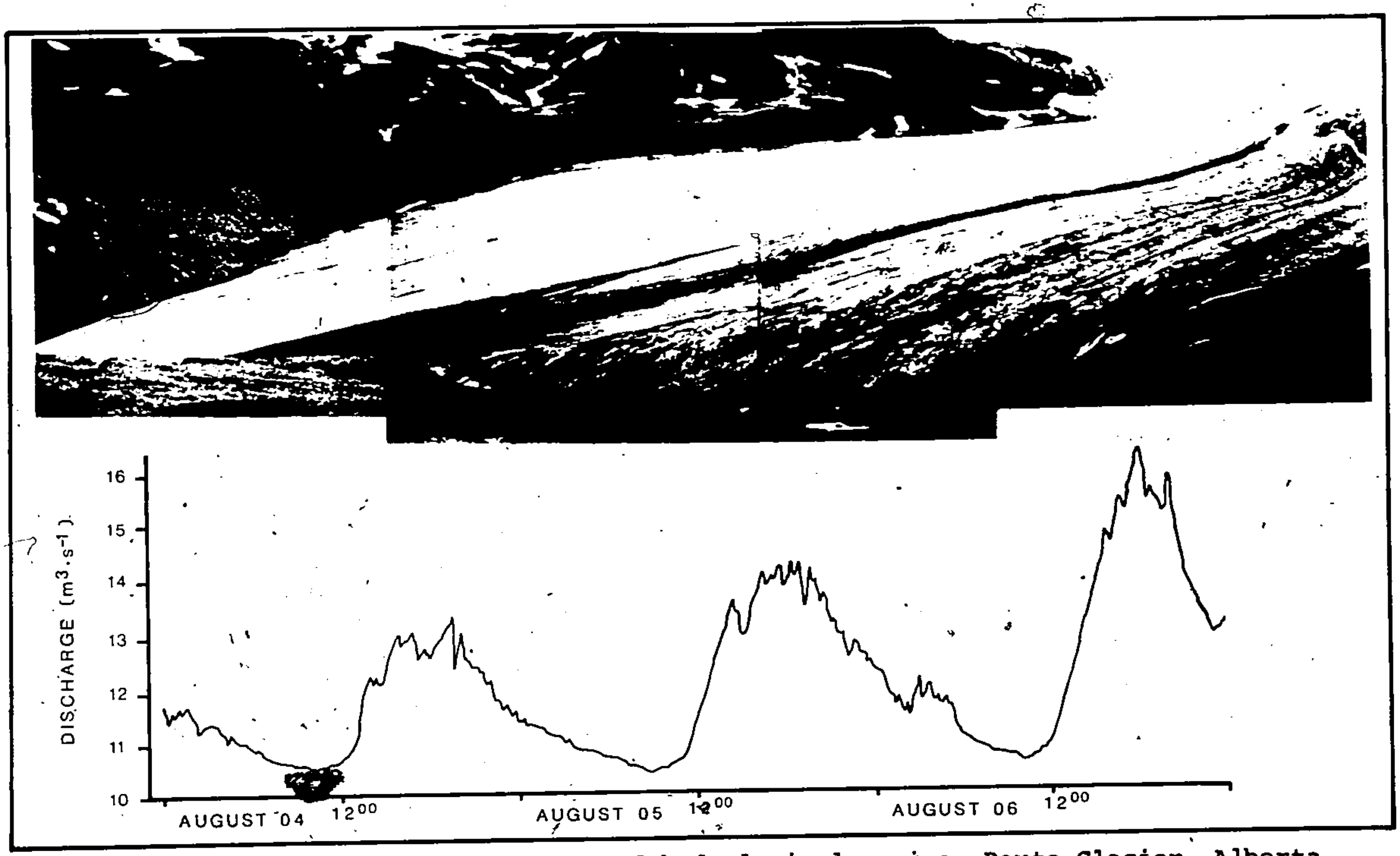

Figure 35 Glaciological conditions and hydrological regime, Peyto Glacier, Alberta, August 05, 1981. Photograph: Y. Carrier, August, 1981.

05. The photograph also illustrates increased downcutting of the supraglacial streams. The diurnal amplitude of discharge continues to increase as the contribution from glacier icemelt increases. The shape of the daily hydrograph reflect the behavior of the meteorological parameters in the basin. Periods of sustained high temperatures resulted in increased meltwater production and discharge amplitude while during colder periods the melt and the discharge amplitude decreased.

The snowline is shown at approximately it's maximum elevation (2750 m a.s.l.) on August 28 (Figures 36 & 37). The diurnal amplitude of discharge has reached its maximum and total daily discharges are high due to the contributions from meltwaters originating in the firn area. During this period, the meltwaters from the accumulation zone reach the glacier portal more rapidly because the upper basin crevasses are completely snow-free as illustrated on the photographs.

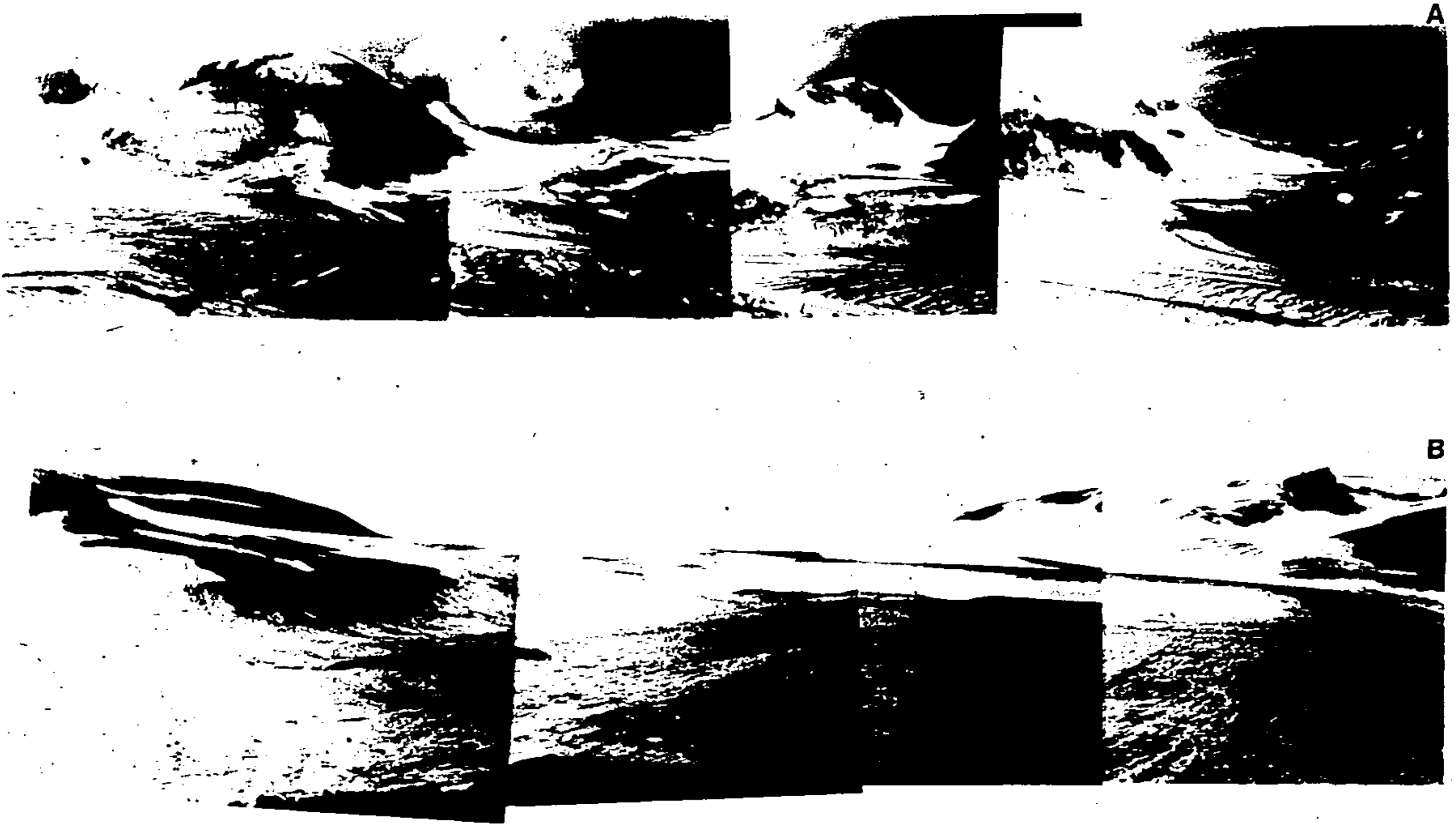

Figure 36 Photographs of upper basin area, Peyto Glacier, Alberta, August 28, 1981. a) west basin, and b) east basin. Photographs: Y. Carrier, August, 1981.

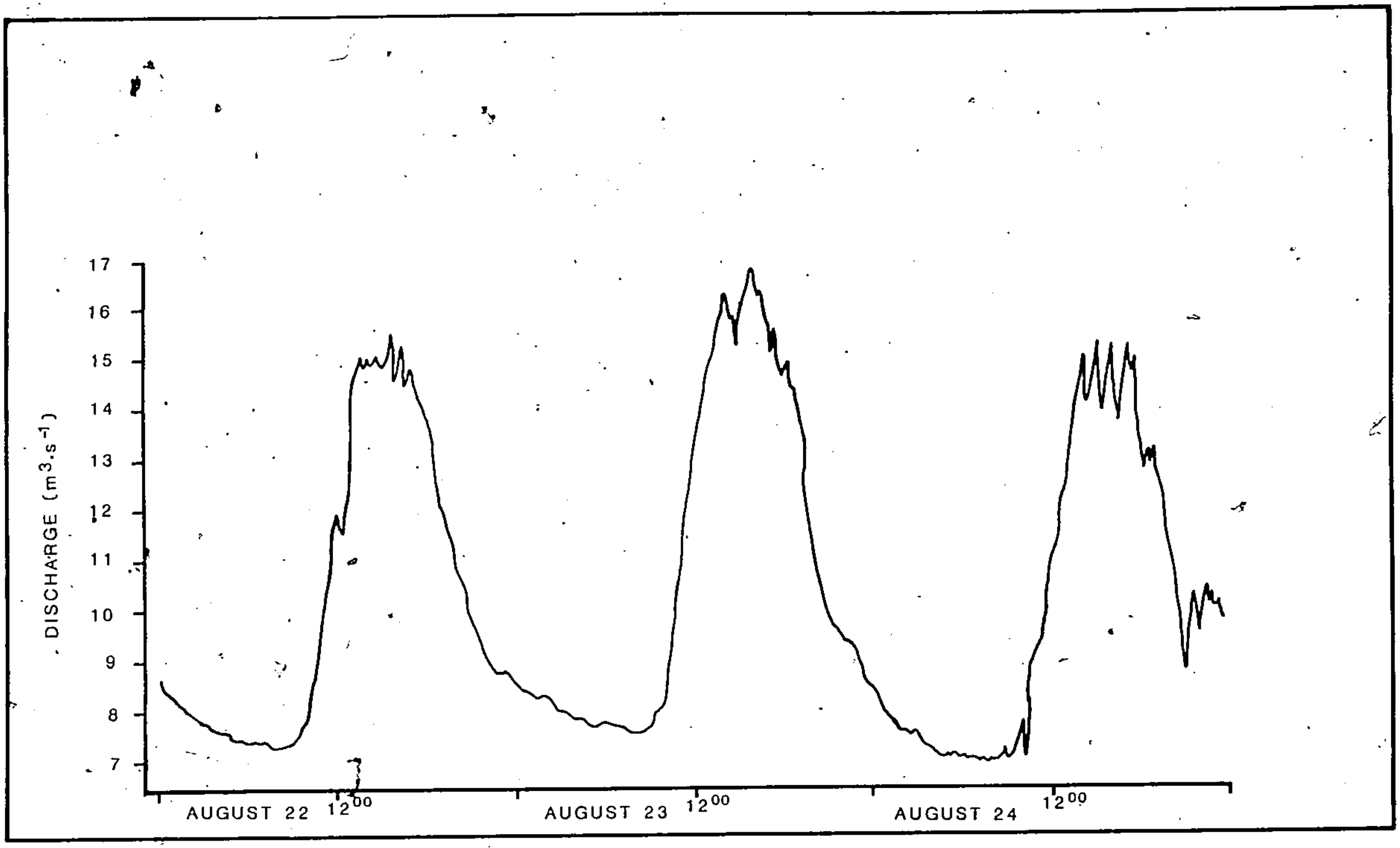

Figure 37 Peyto Creek hydrograph, August 22 to August 24, 1981.

CHAPTER 5

GLACIER HYDROCHEMICAL AND SUSPENDED-SEDIMENT REGIMES: RESULTS AND INTERPRETATION

5.1 Glacier hydrochemistry

5.1.1 Electrical conductivity

The seasonal trend of the electrical conductivity measurements made on Peyto Glacier meltwaters (Figure 27) reinforces the four component hydrological regime proposed in Chapter 4. During the baseflow component, May 19 to June 29, when stream discharges were at their lowest, the highest electrical conductivity values were recorded (52μS - 91μS). Runoff during this time, originated from two main sources, the subglacial zone and the non-glacierised areas. A large portion was probably derived from the subglacial zone where stored meltwaters acquired solutes by travelling through ion-rich lithospheric and morainic material. Since the basin is mostly composed of permeable limestone, subglacial springs may have added solute rich water to the subglacial flow. A spring emerging from a limestone outcrop, located approximately 4 km downvalley from the glacier has been documented (Collins and Young, 1979a, 1979b). Electrical conductivity measurements of the waters indicate that percolation through limestone led to high solute content (Collins and Young, 1979a). No other springs have been located within the basin but the possibility that there may be others does exist. The snow-meltwater runoff from non-glacierised areas was also ion-rich because the waters flowed over morainic deposits and bedrock outcrops.

Conductivity levels decreased rapidly during the freshet reaching 9µS on July 06. This was probably due to a rapid release of "chemically dilute" snow-meltwaters trapped in previously closed ice-walled conduits within the glacier. Water routed englacially retained it's original chemical composition, in contrast to subglacially routed meltwaters because it does not come in contact with debris. Thus, an enormous amount of englacially stored water apparently diluted the solute rich basal flow during this time period.

During the main ice ablation component, the electrical conductivity decreased to a season low of 4µS (July 28-29). The recorded levels varied with the fluctuations of various hydrometeorological parameters. The dilution effect was greater in times of sustained ablation as "chemically dilute" meltwaters from the supraglacial zone were routed through the englacial network of passages. Colder periods caused reduced glacier ablation, which resulted in less "ion-free" meltwater production to dilute the solute rich subglacial flow.

Conductivity levels increased (5 - 30µS) at the end of the study season as baseflow conditions prevailed in response to colder climatic conditions.

The diurnal variations in electrical conductivity for the five hourly sampling periods (June 13-15, June 27-29, July 13-16, August 19-21, September 03-05) are presented in Figures 38 to 42. As expected, the two early season sampling periods (June 13-15, 27-29) (Figures 38 & 39) showed no distinct diurnal trend. This occurred because early season runoff was mostly composed of "chemically rich" baseflow which remained relatively constant during the day. A weak diurnal rhythm was detected for the August 19-21 (Figure 41) and September 03-05 (Figure 42) periods as lower conductivity levels were recorded during the day than at night. This was due to the dilution of the ion-rich subglacial flow by meltwaters that originated from the supraglacial and englacial zones travelling through ice-walled tunnels during the day. However, at night, as the temperature decreased, the surficial meltwater supply was reduced and baseflow prevailed. The results of July 13-16 sampling period (Figure 40) were anomalous. No distinct diurnal pattern was detected and the widest range in electrical conductivity levels were recorded during this period. Although a major snowfall curtailed glacier meltwater production, Peyto Creek discharge remained high. During this storm event, rapid melting of the newly fallen snow from adjacent non-glacier areas and it's subsequent runoff (i.e., slopewash) compensated for the depletion of glacier meltwater production. This slopewash in ion-rich morainic material combined with a reduction in glacier melt resulted in a short-time peak in conductivity.

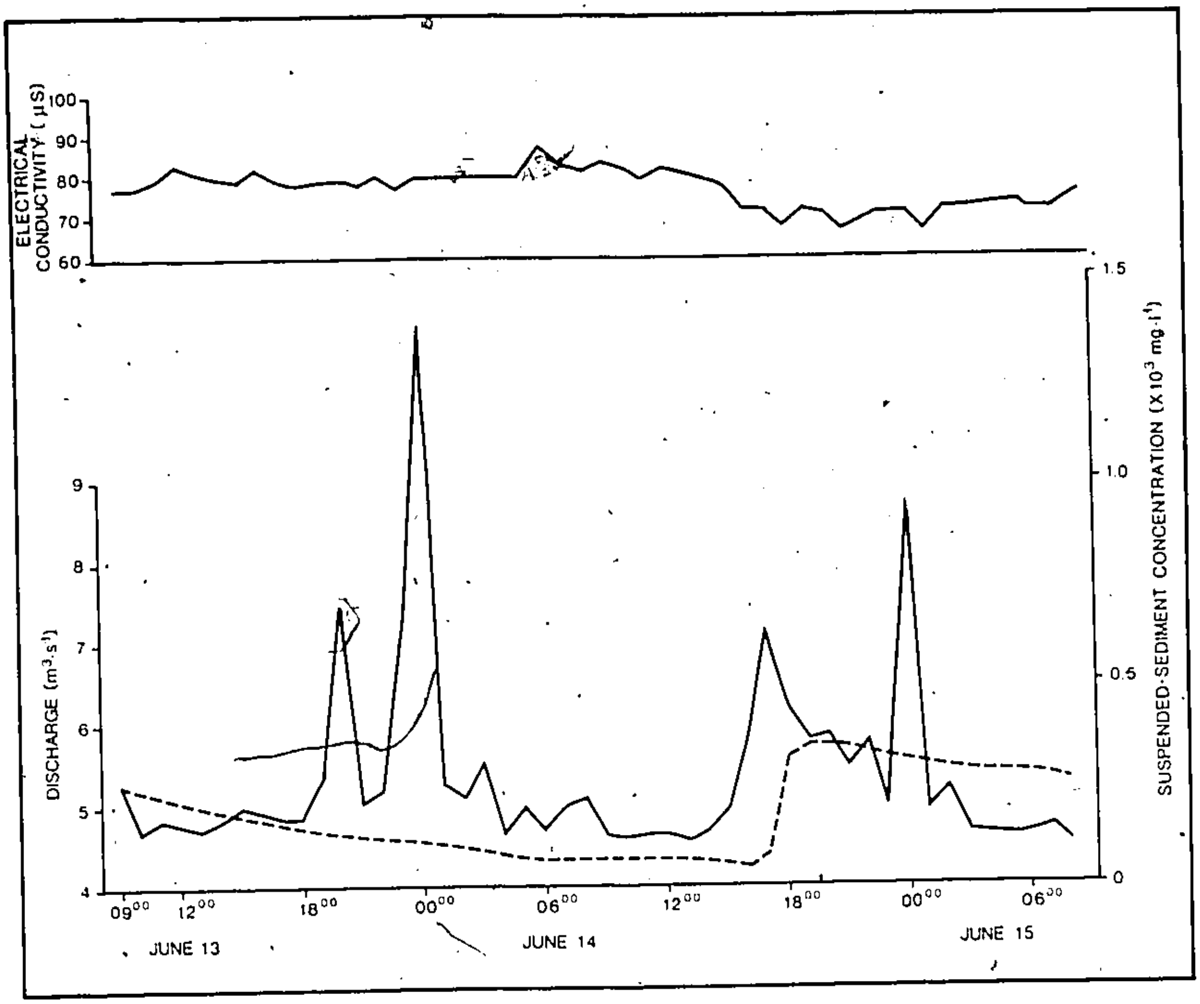

Figure 38. Diurnal variations in electrical conductivity (top), discharge (dashed line) and suspended-sediment concentration (solid line) (bottom), Peyto Creek, June 13 to June 15, 1981.

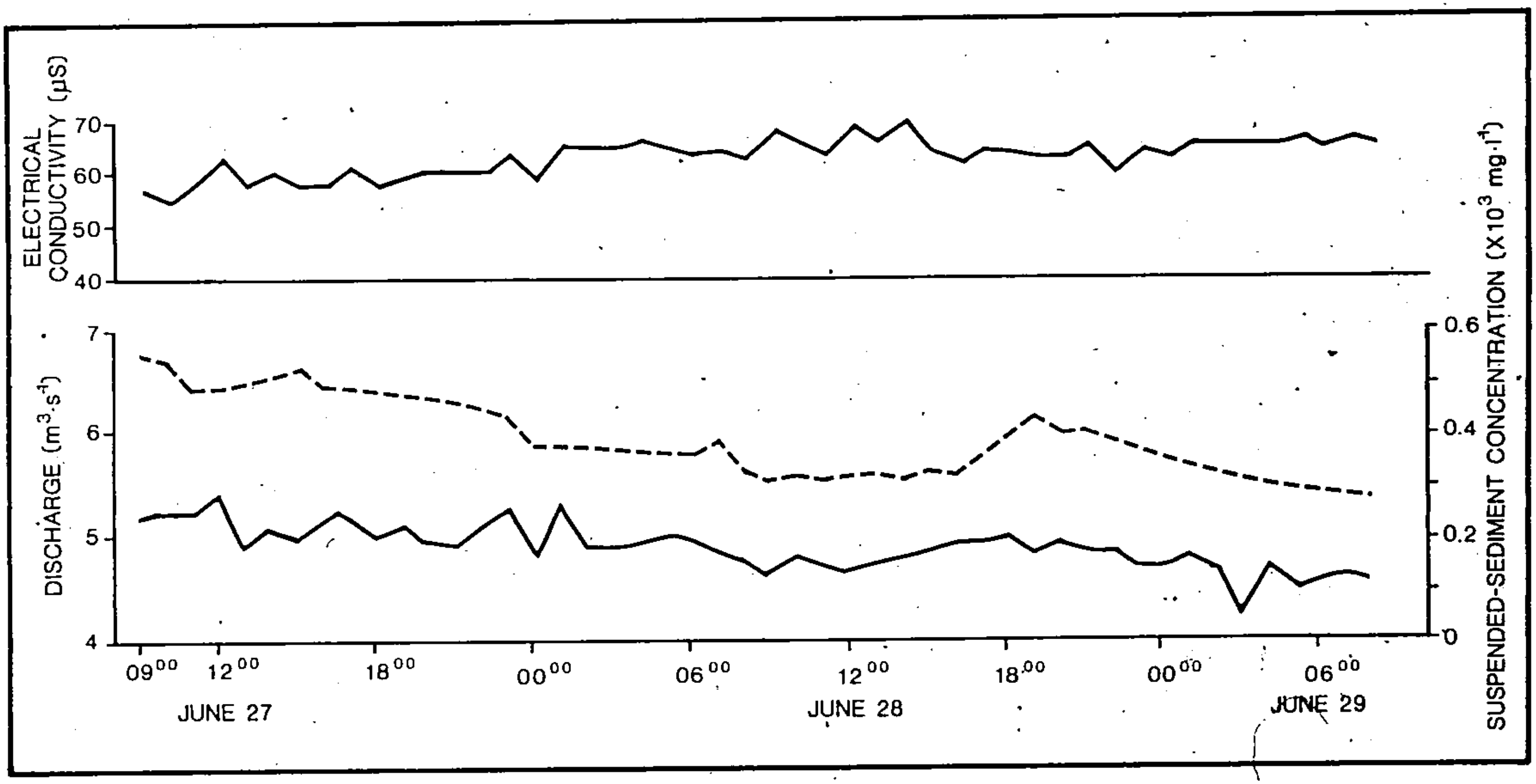

Figure 39 Diurnal variations in electrical conductivity (top), discharge (dashed line) and suspended-sediment concentration (solid line) (bottom), Peyto Creek, June 27 to June 29, 1981.

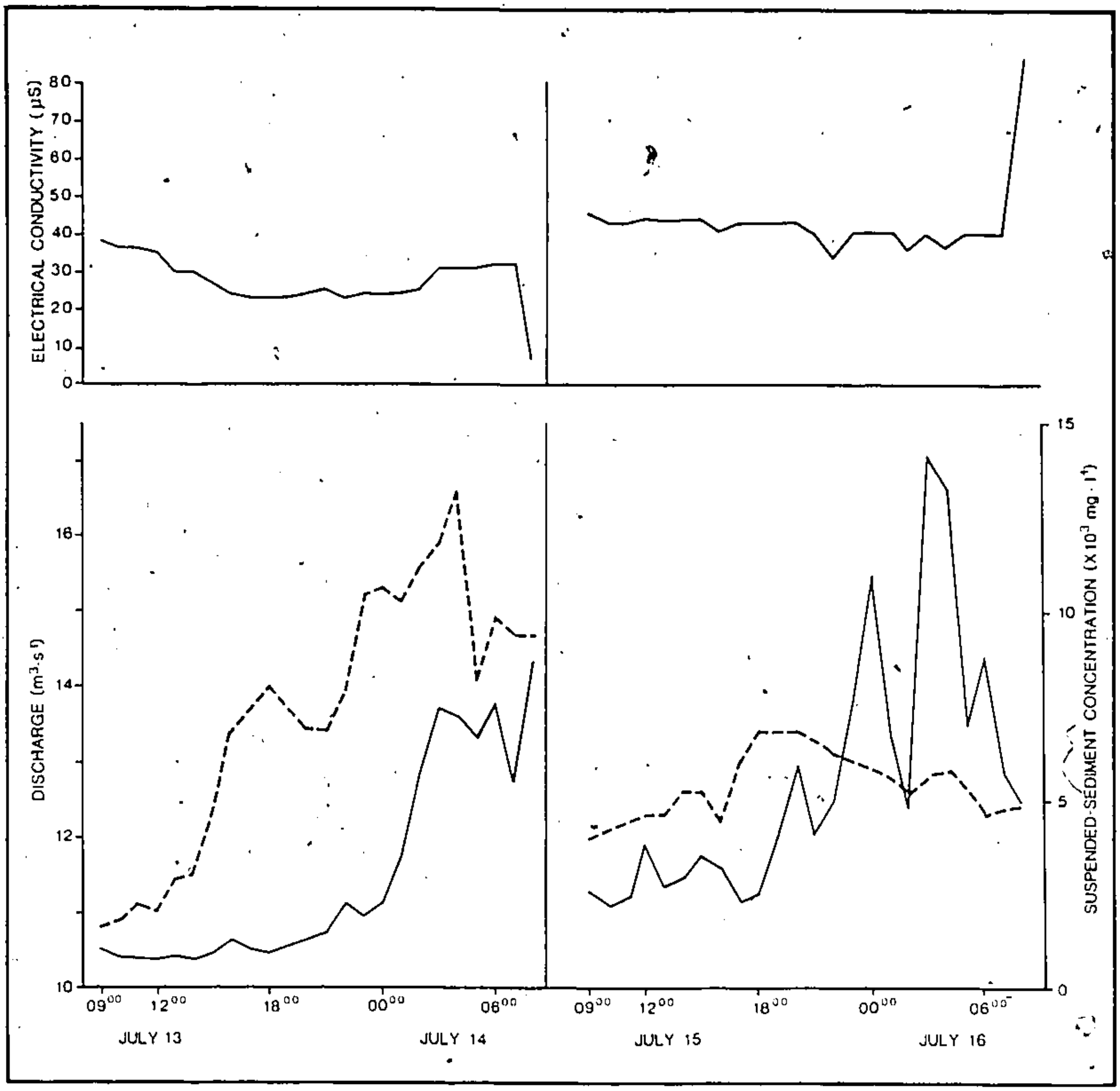

Figure 40 Diurnal variations in electrical conductivity (top), discharge (dashed line) and suspended-sediment concentration (solid line) (bottom), Peyto Creek, July 13 to July 14 and July 15 to July 16, 1981.

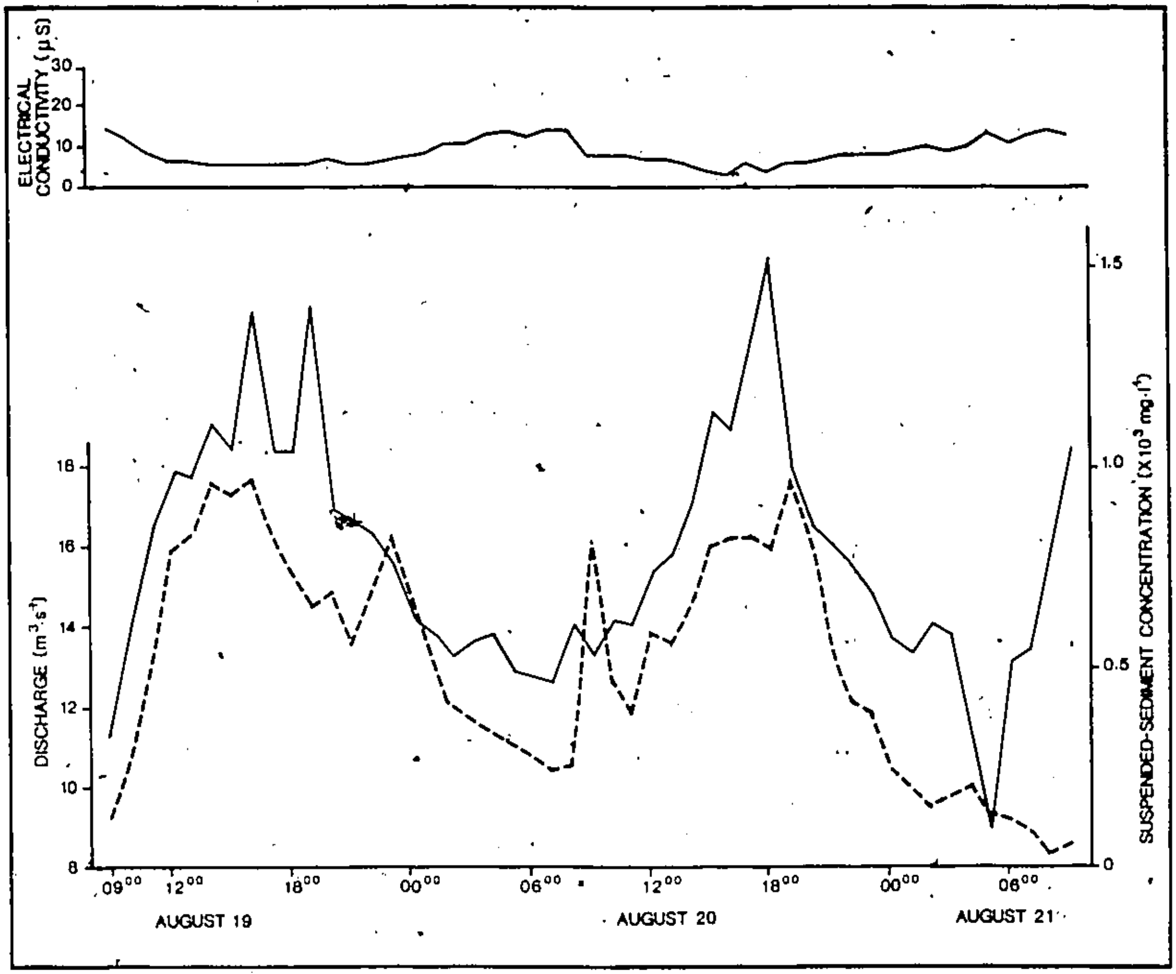

Figure 41 Diurnal variations in electrical conductivity (top), discharge (dashed line) and suspended-sediment concentration (solid line) (bottom), Peyto Creek, August 19 to August 21, 1981.

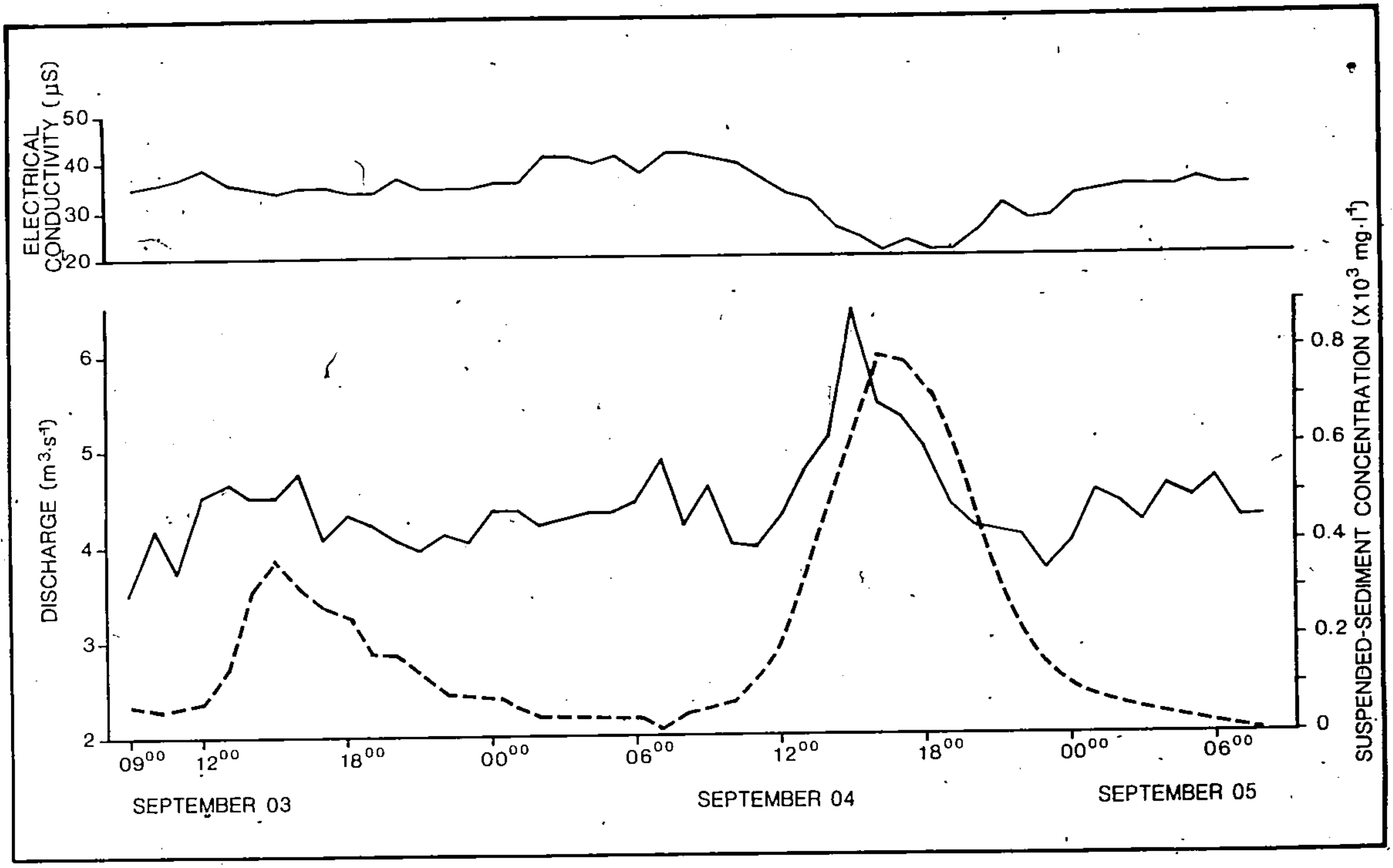

Figure 42 Diurnal variations in electrical conductivity (top), discharge (dashed line) and suspended-sediment concentration (solid line) (bottom), Peyto Creek, September 03 to September 05, 1981.

5.1.2 Solute concentration

The seasonal variation in concentration of the four major cations (Calcium (Ca^{++}), Magnesium (Mg^{++}), Potassium (K^+) and Sodium (Na^+)) follows the general trend of the electrical conductivity regime (Figure 43). Initially the concentration of the individual cations is high, but as the ablation season progresses the concentration decreases, followed by an increase at the end of the study period. These trends are due to the fluctuating dilution effect during the summer. The divalent cations, Calcium (Ca^{++}) and Magnesium (Mg^{++}), show greater absolute fluctuations (2.29 - 8.03 ppm and 1.14 - 6.41 ppm respectively) than the momovalent cations Sodium (Na^+) and Potassium (K^+) (0.93 - 2.56 ppm and 0.04 - 0.34 ppm respectively) but Potassium has the highest proportional variation. The concentration of Ca^{++} and Mg^{++} in meltwaters reflects the importance of limestone dissolution (Lemmens and Roger, 1978) in the Peyto Creek basin. Kodybka (1981) showed that most geological formations in the basin contained over 90% carbonates by weight$\cdot g^{-1}$ and that these strata were highly susceptible to dissolution. The introduction of Ca^{++} by dissolution and it's predominance in glacier meltwaters agrees with results reported by Slatt (1972) from a study of nine Alaskan glaciers. The concentrations observed at Peyto Glacier follow the trend, $Ca^{++} > Mg^{++} > Na^+ > K^+$, reported for other glaciated areas (Eyles *et al.*, 1982; Livingstone, 1963; Lorrain and Souchez,

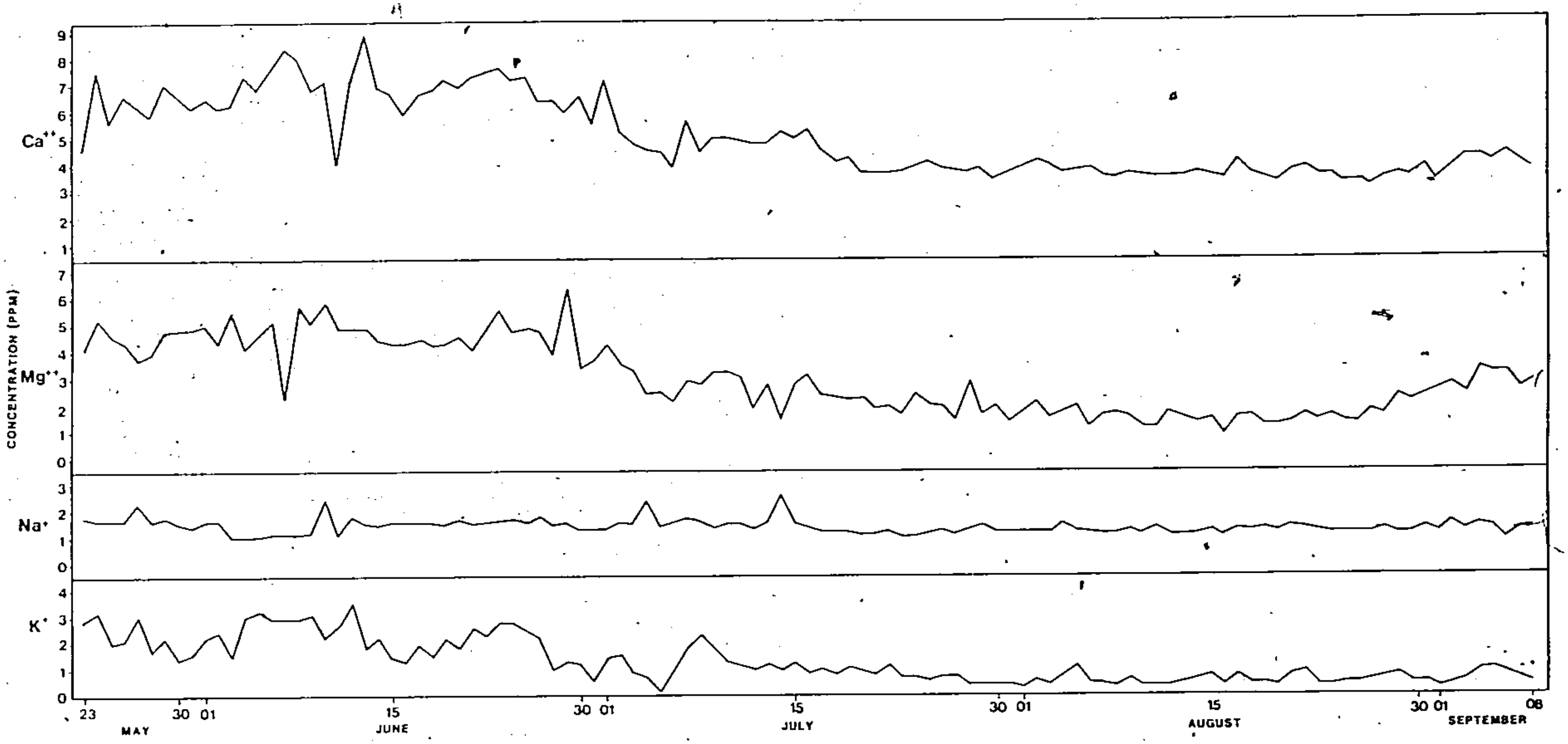

Figure 43 Seasonal fluctuations of the cations: Calcium (Ca^{++}), Magnesium (Mg^{++}), Sodium (Na^+) and Potassium (K^+), Peyto Creek, Alberta, 1981.

1972; Slatt, 1972).

The variations in concentration of the four major cations during the five hourly sampling periods showed no apparent diurnal trends but early season samples generally contained higher concentrations (Table 2). Results of the chemical analysis of rain, ice, supraglacial streams and tributary streams samples are presented in Appendix A.

5.2 Attached cationic concentrations

The adsorption of cations to silt and clay particles in transit is an important process affecting the amount of cations available for potential cation exchanges.

The attached cationic load on suspended-sediment particles from the five hourly sampling periods demonstrated a seasonal trend (Table 3). Initially, in June, the average concentrations of Ca^{++}, Mg^{++}, Na^{+}, K^{+} are at their highest. An important lowering occurred in July which was followed by an increase at the end of the summer (August and September). This suggests that the contact time between the subglacial water supply and the sediment is important. Greater amounts of cations became adsorbed on the early season sediment because they remained in the subglacial environment for a longer period of time due to low discharges. During the main ice ablation period, higher discharges led to an increase in sediment evacuation and

DATE	Ca^{++}	Mg^{++}	Na^{+}	K^{+}
June 13-15	4.38-5.91	2.78-5.91	1.51-2.04	0.11-0.25
June 27-29	4.45-5.83	1.76-3.59	1.30-1.62	0.12-0.22
July 13-14	3.13-5.86	1.28-4.09	1.26-2.43	0.04-0.21
July 15-16	3.21-6.36	2.16-3.32	1.22-1.72	0.06-1.14
August 19-21	1.42-3.68	1.33-3.69	1.13-1.56	0.04-0.08
September 03-05	1.84-3.60	2.81-4.34	1.22-1.60	0.05-0.13

Table 2 - DIURNAL RANGES IN CATION CONCENTRATION (ppm).

Date	Ca^{++}	Mg^{++}	Na^{+}	K^{+}
June 13-15	22-735(328)	1-31(14)	9-124(56)	5- 55(26)
June 27-29	167-891(422)	9-29(17)	27-175(60)	9-101(33)
July 13-14	18-181(90)	1- 7(4)	1- 16(6)	1- 10(4)
July 15-16	10- 73(49)	1- 9(3)	1- 12(3)	1- 7(2)
August 19-21	92-942(199)	3-32(7)	4-105(16)	2- 28(10)
September 03-05	77-262(173)	4-11(8)	8- 94(17)	5- 15(9)

Table 3 - DIURNAL RANGES OF ATTACHED CATIONIC CONCENTRATIONS ($ppm \cdot g^{-1}$)
(daily average in parentheses).

to a decrease in transit-time which therefore resulted in lower concentrations. At the end of the ablation season, discharge decreased in response to colder climatic conditions, thus leading to increased contact times and greater concentrations. The results also indicate that Calcium (Ca^{++}) was the most readily adsorbed cation and Magnesium (Mg^{++}) the least which suggests that adsorption may possibly be a selective process.

The attached load also fluctuated erratically on a daily basis but no apparent diurnal trend could be clearly defined.

The routing of the meltwater and it's suspended-sediment load at the time of sampling are probably the main factors influencing the irregularity of cation attachment in a glacierised basin. This agrees with the conclusions of Bigras (1981) from his study of Grizzly Creek glacier.

In summary, the solute content in Peyto Creek meltwaters progressively decreased during the ablation season. This decrease was the result of dilution by "chemically dilute" meltwaters from the supraglacial and englacial zone mixing with the ion-rich subglacially routed waters. The attached cationic load indicates the routing and the contact time of the sediment through the subglacial system. Calcium (Ca^{++}) is the most abundant cation present in solution and the most readily adsorbed on sediment surfaces.

5.3 Suspended-sediment

5.3.1 Variations in concentration

The variability of suspended-sediment outputs from Peyto Glacier was demonstrated by the daily samples collected at approximately mid-stage throughout the study period (Figure 27). The concentrations range from a low of 19 $mg \cdot l^{-1}$ on June 22-23 to a high of 3379 $mg \cdot l^{-1}$ on June 10 with a mean of 660 $mg \cdot l^{-1}$ and a standard deviation of 594 $mg \cdot l^{-1}$.

Early in the ablation season, suspended-sediment concentrations were low because most of the runoff originated from surface snowmelt which does not make contact with sediment sources. Subglacial flow was low during this period but the occasional slumping of subglacial debris or channel migration into new sources of material led to sudden suspended-sediment pulses (e.g., June 10). During the freshet, the opening of major conduits resulted in the flushing out of great quantities of sediment. As the melt season progressed, the opening of internal channels further up glacier resulted in new sources of sediment to be eroded by meltwaters. Sediment pulses during this time were caused by sediment availability rather than increased stream discharge. For example, the opening of a small conduit directly connected with large supplies of material will lead to high concentrations but the opening of a large channel with high discharge travelling across bare bedrock will transport small quantities of material.

Results from the five 48 hour sampling periods illustrate the diurnal variability of the suspended-sediment concentration being discharged by Peyto Glacier (Figures 38 to 42). These graphs also indicate the timing of the daily suspended-sediment concentration peaks in comparison to the daily water discharge peaks. Three different process responses are visible from these individual plots: 1) the suspended-sediment peak precedes the discharge peak (June 14, August 20, September 03, September 04), 2) the suspended-sediment peak follows the discharge peak (July 13-14, July 15-16, August 19) and 3) no apparent pattern in the suspended-sediment plot (June 13, June 27, June 28). A rapid injection of material followed by rapid exhaustion occurring independently of discharge variations can be inferred from the irregular suspended-sediment pulses. These sudden pulses in suspended-sediment concentration are probably the result of subglacial channel migration. Under changing hydrostatic and ice-overburden pressures, subglacial streams are occasionally diverted into new supplies of easily eroded material. The result is a sudden rise in concentration that is quickly exhausted. In addition, slumping of morainic debris alongside these basal channels also lead to a similar sudden enrichment. This agrees with the findings of Collins (1979a) at the Gornergletscher in Switzerland.

An exception to this would be the July 13-16 sampling period where heavy snowfall and rainfall (Figure 22) may have initiated slopewash alongside the glacier. The material washed down from the lateral moraine found it's way into the subglacial network of conduits and caused a sudden large-magnitude increase in suspended-sediment concentration.

The results of the various fifteen-minute sampling periods are shown in Figures 44 to 47. Fluctuations in concentration greater than 200% over fifteen minute intervals are frequent with a maximum 1900% occurring on June 12 between 1900 h and 1915 h (48-959 mg·l^{-1}). This emphasizes the irregularity in concentration observed in the hourly samples. Two of three different responses of concentration peak to discharge peak are apparent in the individual graphs. The concentration peak of the June 26, August 21-22 and September 05 periods preceeded the discharge peak while the June 12, July 06 and August 23 periods showed no apparent pattern.

5.3.2 Variations in grain size

The grain size characteristics of the suspended-sediment varied throughout the study period. Samples collected during periods of low flow were composed mostly of silt (3.9 - 62.5μ) and fine sand (62.5 - 250μ). Occasionally, at high flow, medium and coarse sand (250μ - 1 mm) were found due to increased stream capacity. Grain size measurements of 14 representative samples (Figure 48) show the variability in composition, particularly in the

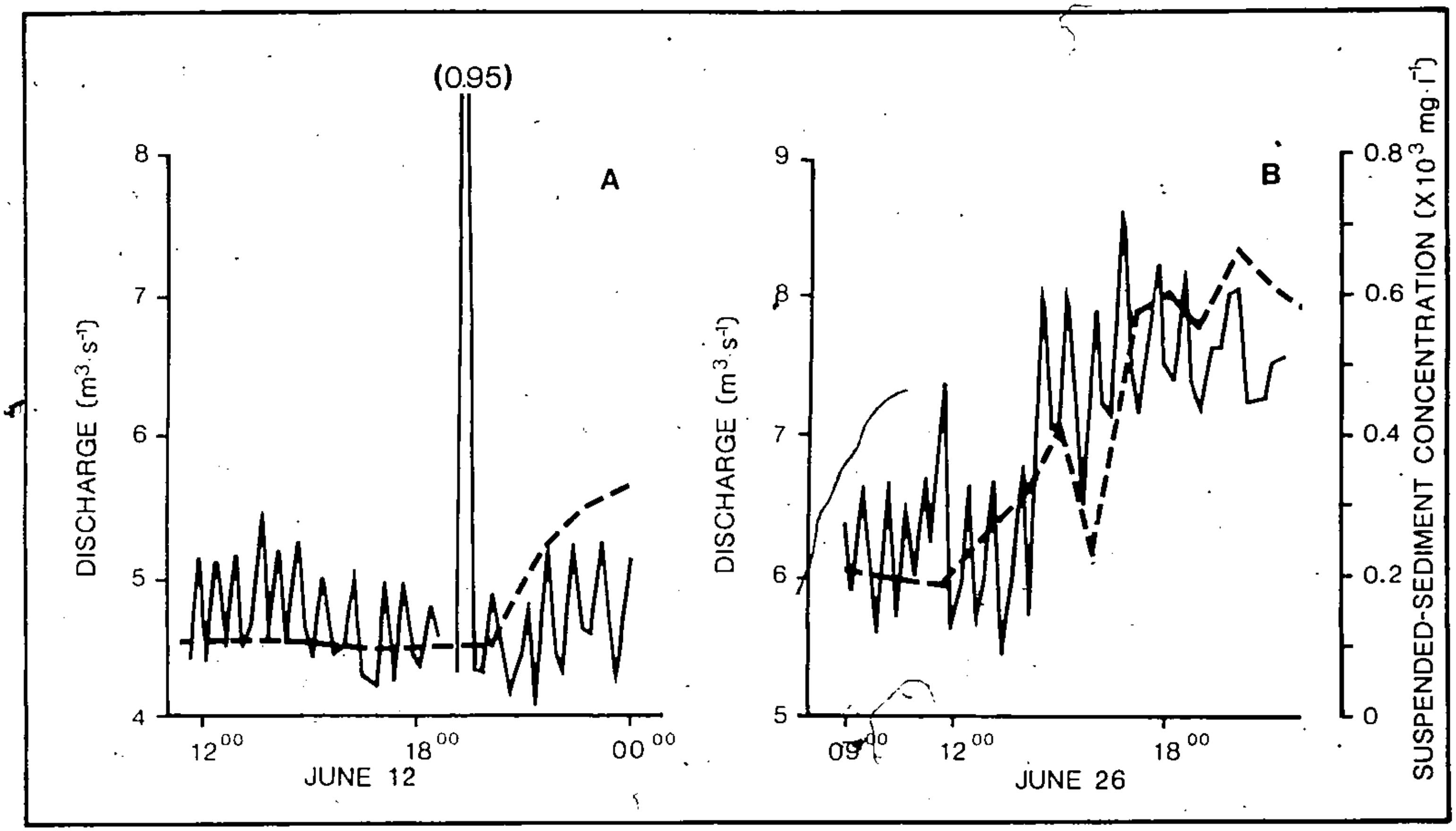

Figure 44 Short-term (15 minutes) fluctuations in discharge (dashed line) and suspended-sediment concentrations (solid line), Peyto Creek, a) June 12, 1981, and b) June 26, 1981.

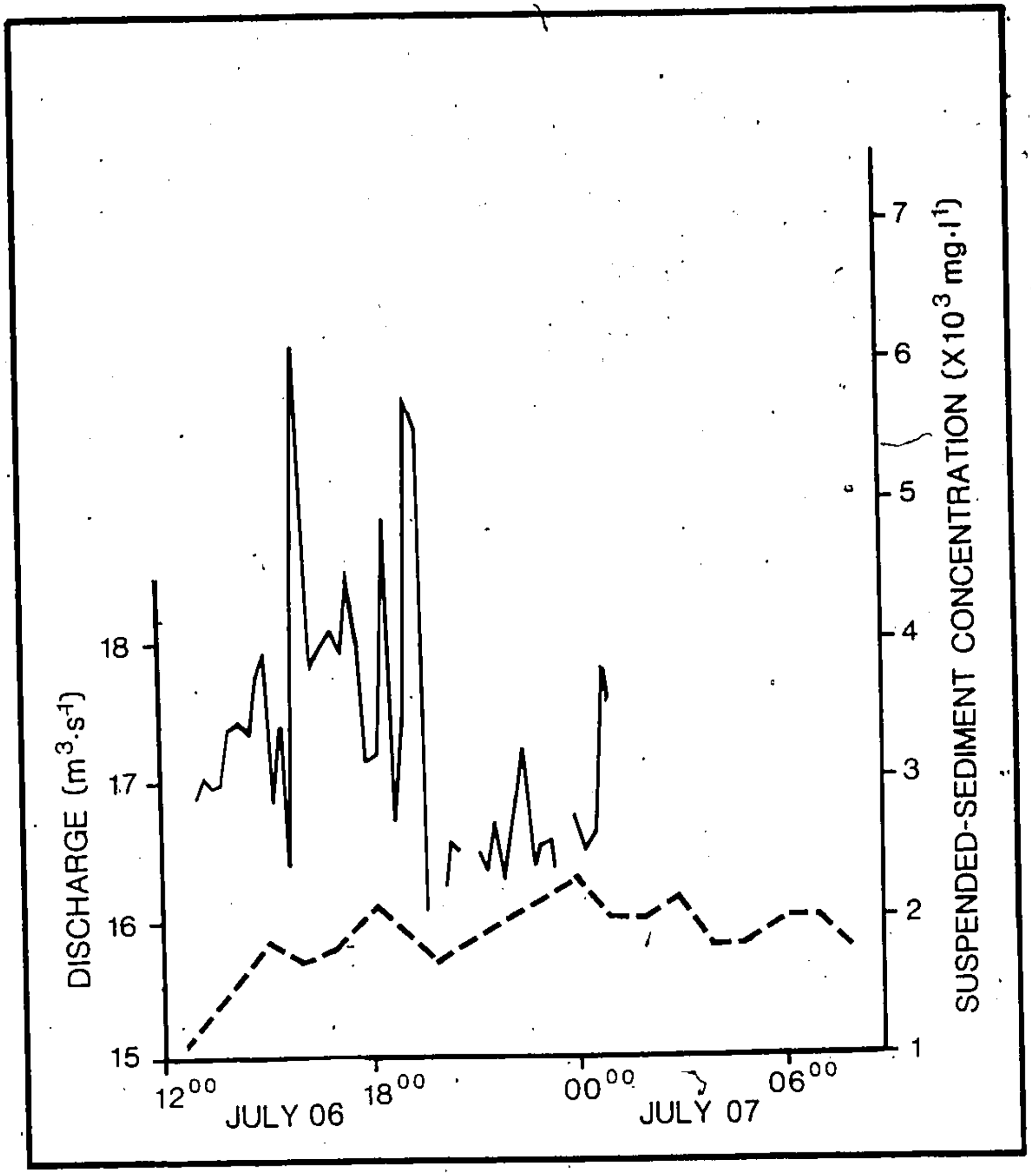

Figure 45 Short-term (15 minutes) fluctuations in discharge (dashed line) and suspended-sediment concentrations (solid line), Peyto Creek, July 06 to July 07, 1981.

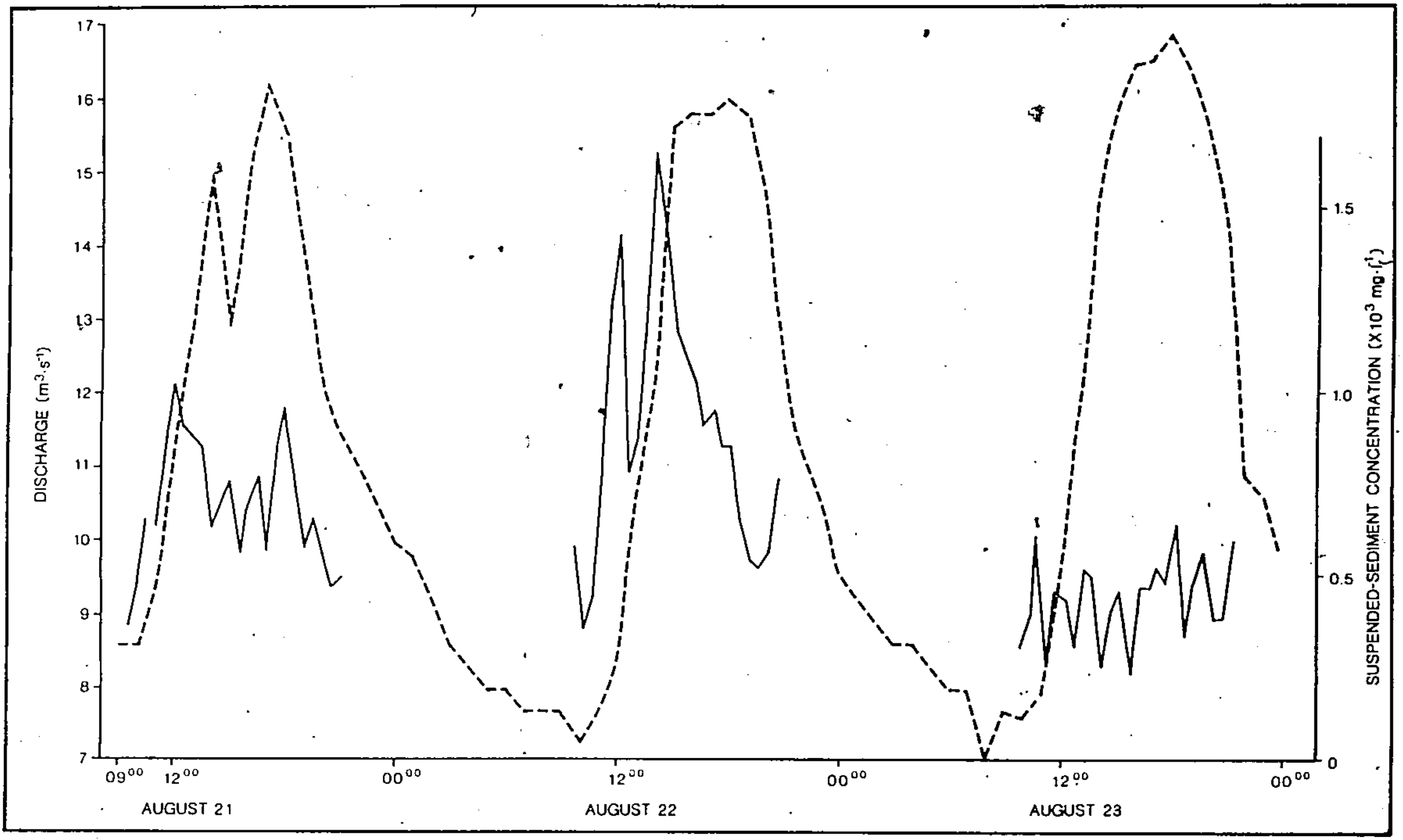

Figure 46 Short-term (15 minutes) fluctuations in discharge (dashed line) and suspended-sediment concentrations (solid line), Peyto Creek, August 21 to August 23, 1981.

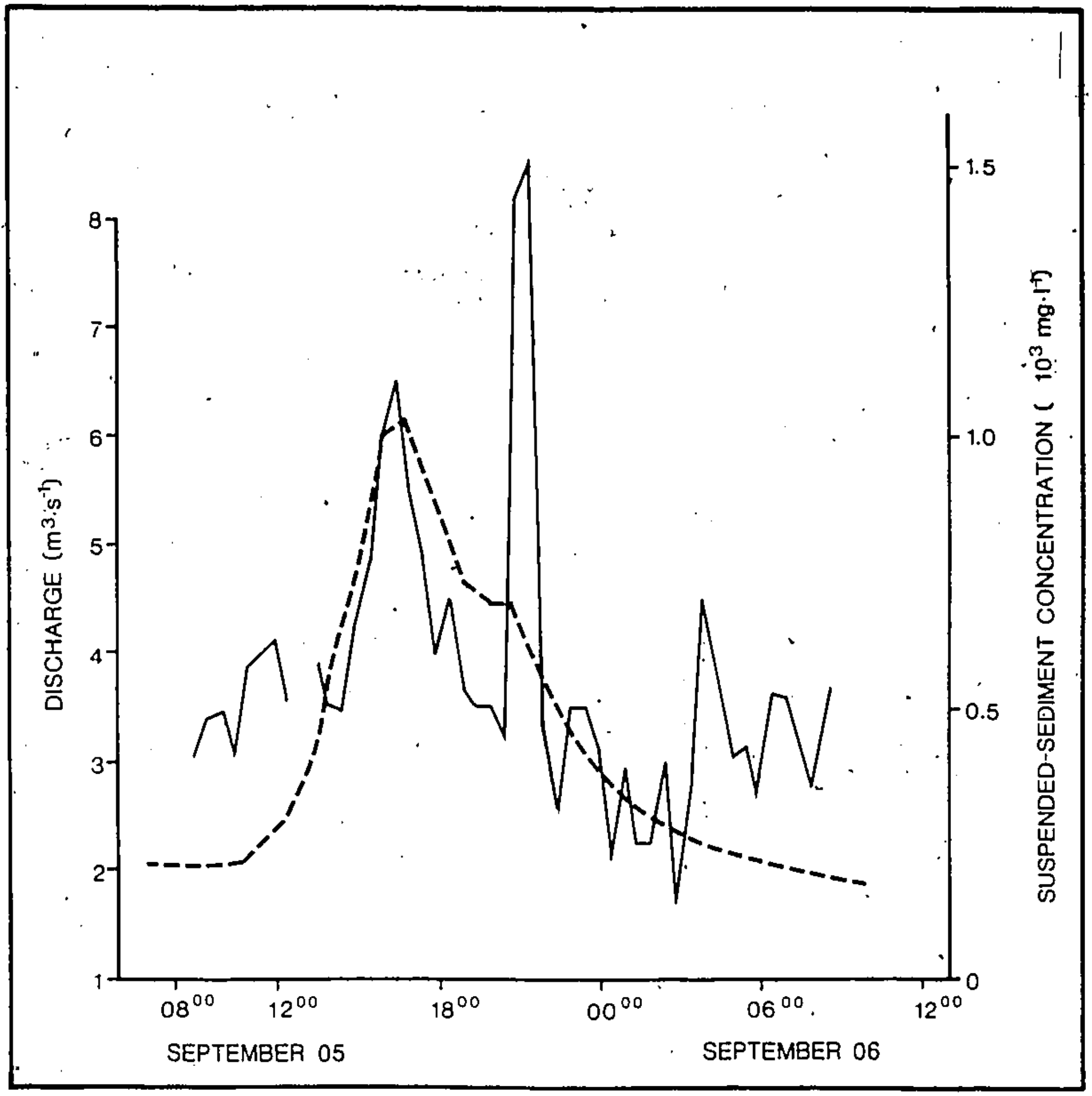

Figure 47 Short-term (15 minutes) fluctuations in discharge (dashed line) and suspended-sediment concentrations (solid line), Peyto Creek, September 05 to September 06, 1981.

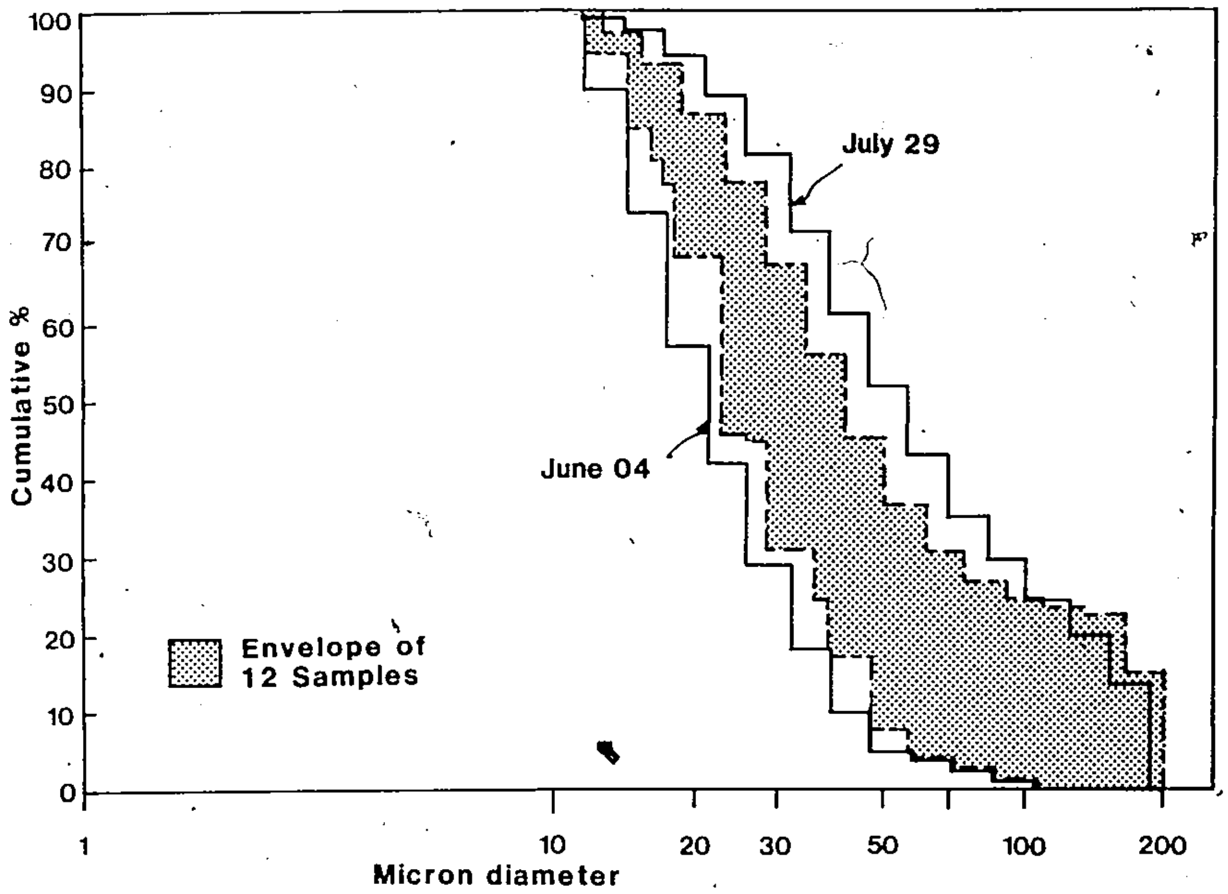

Figure 48 Grain-size distribution of selected suspended-sediment samples, Peyto Creek, Alberta, 1981.

20 - 200μ range. The diagram groups the majority of the samples (envelope of 12 samples) with the two extremes (June 04 and July 29) plotted separately. The hydrological, glaciological and climatological conditions during June 04 and July 29 were not extreme in any respect. This would tend to imply that the grain size characteristics of the suspended-sediment is primarily a function of sediment supply and release mechanisms from the glacier rather than stream capacity. The occasional granule-sized sediment particle (2.0 - 4.0 mm), probably in saltation in the stream, tended to over-estimate the actual conditons in Peyto Creek by showing apparent increases in concentration. The July 13-16 hourly sampling period, in which concentrations range from 719 to 14,002 $mg \cdot l^{-1}$ is a probable example of this over-estimation.

5.3.3 Suspended-sediment concentration versus discharge relationships

The influence of stream discharge on sediment entrainment in a glacierised basin is illustrated by bivariate plots of concentration and discharge for the different sampling periods throughout the season (Figure 49 & 50). Low correlation coefficients (0.44 for all samples collected, 0.38 for daily samples and 0.52 for the combined five hourly periods) indicate the existence of a very weak positive relationship between these variables. This was also observed in samples taken near Peyto Lake by

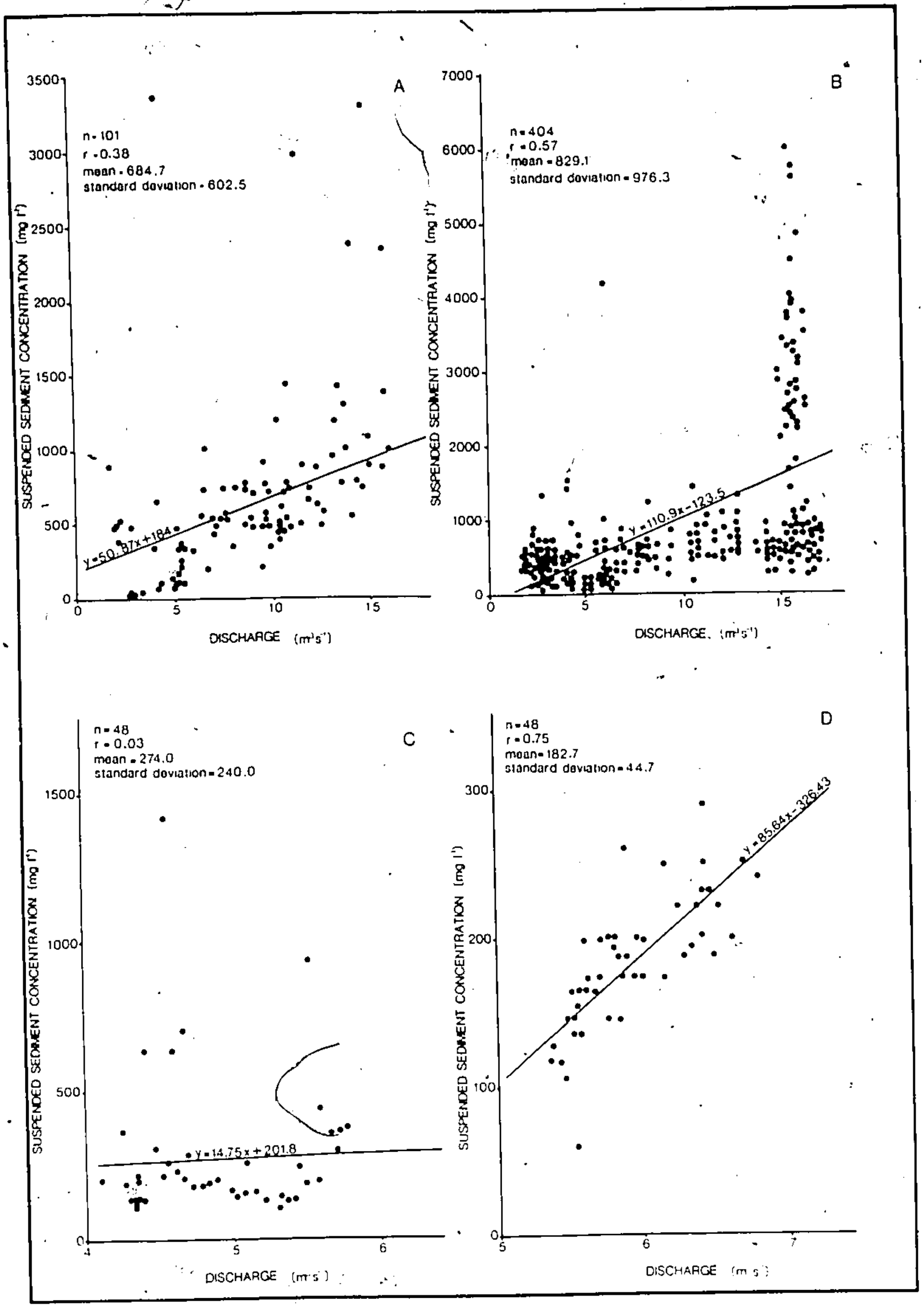

Figure 49 Bivariate plots of suspended-sediment concentration and discharge: a) daily samples, b) short-term (15 minutes) samples, c) June 13 to June 15 (hourly samples) and d) June 27 to June 29 (hourly samples).

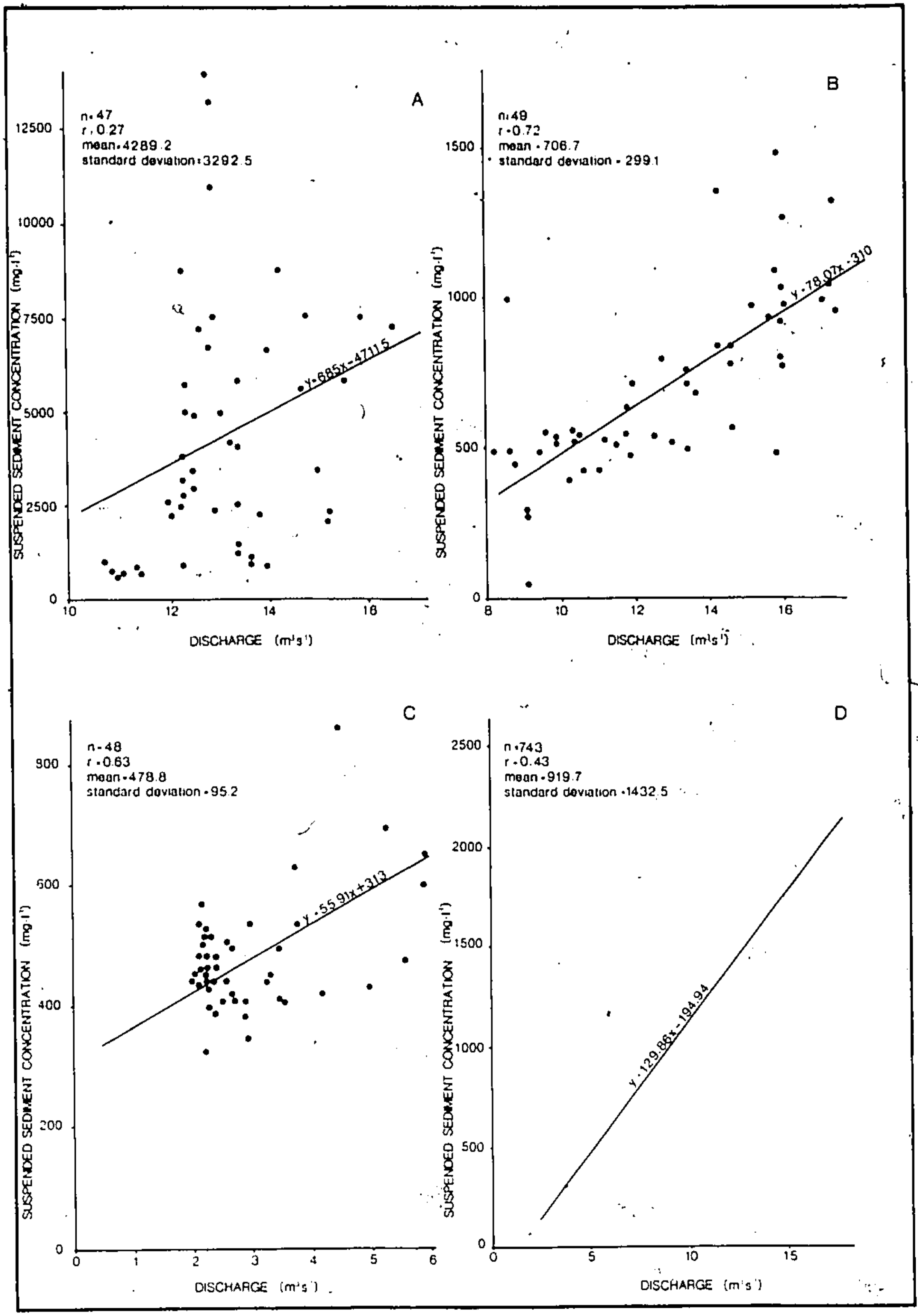

Figure 50 Bivariate plots of suspended-sediment concentration and discharge: a) July 13 to July 14 and July 15 to July 16 (hourly samples), b) August 19 to August 21 (hourly samples), c) September 03 to September 05 (hourly samples) and d) all collected samples.

Vendl (1978). The calculated correlation coefficients for the individual hourly sampling periods also showed weak relationships (0.03 (June 13-15), 0.28 (July 13-16) to highs of 0.76 (June 27-29), 0.73 (August 19-21) and 0.63 (September 03-05)).

The relationship between suspended-sediment concentration and discharge becomes more complex with the presence of a daily hysteresis effect. Clockwise hysteresis loops, which are more frequently found in non-glacier-fed streams and in which the concentration is greater on the rising limb of the hydrograph than at corresponding discharges on the falling limb, were observed on three occasions: June 13-15 (Figure 51), June 27-29 (Figure 52) and September 03-05 (Figure 55). This results from the evacuation of sediment deposited during low flows at the bed of subglacial channels. These graphs also included sub-loops reflecting the irregular sediment pulses from the glacier. On two occasions, July 13-14 and July 15-16 (Figure 53), the daily hysteresis loop was anti-clockwise which probably resulted from the incorporation of material from the slumping of lateral ice-cored moraines during the snowfall. This caused a peak in sediment with no proportional variations in discharge. The August 19-21 sampling period (Figure 54) contained both clockwise and anti-clockwise loops which probably reflect irregular sediment availability at the time of sampling.

These hysteresis phenomena prevented the

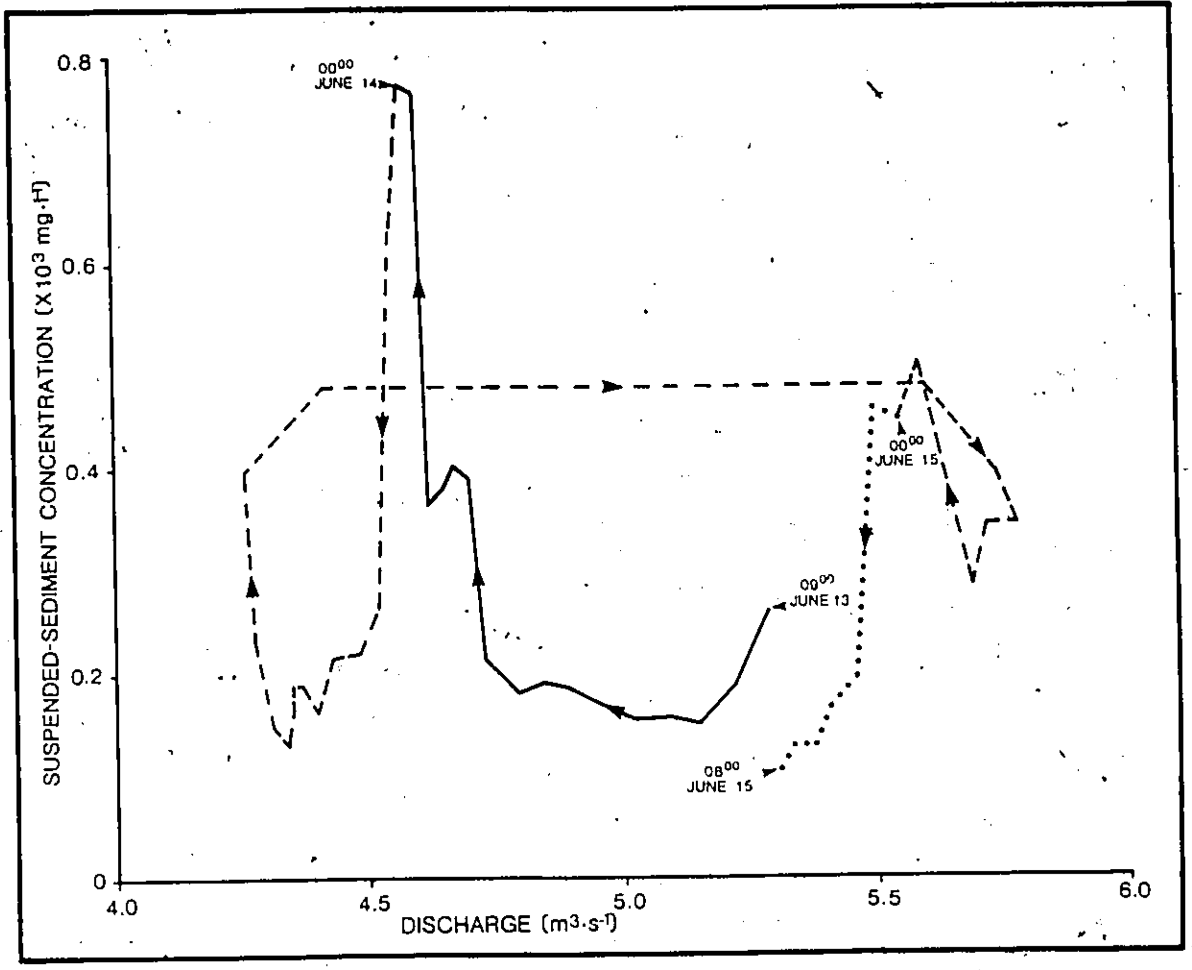

Figure 51 Hysteresis loops for suspended-sediment concentration versus discharge, Peyto Creek, June 13 to June 15, 1981: June 13 (solid line), June 14 (dashed line) and June 15 (dotted line).

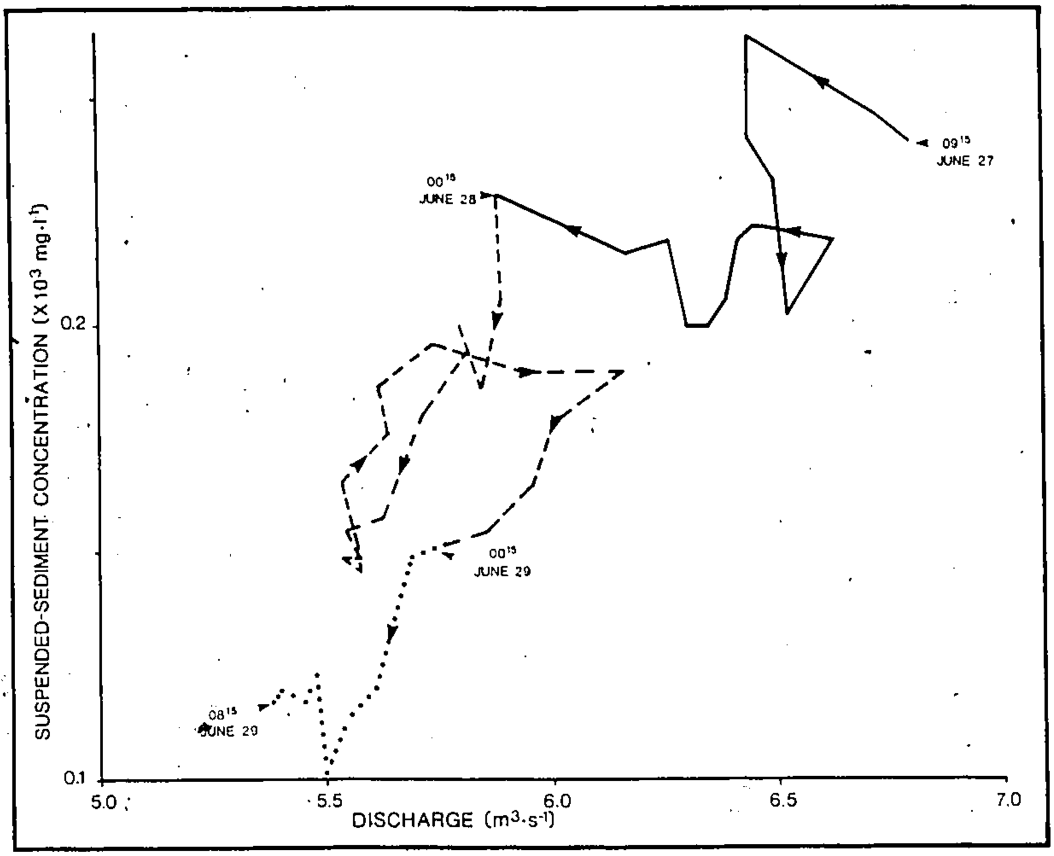

Figure 52 Hysteresis loops for suspended-sediment concentration versus discharge, Peyto Creek, June 27 to June 29, 1981: June 27 (solid line), June 28 (dashed line) and June 29 (dotted line).

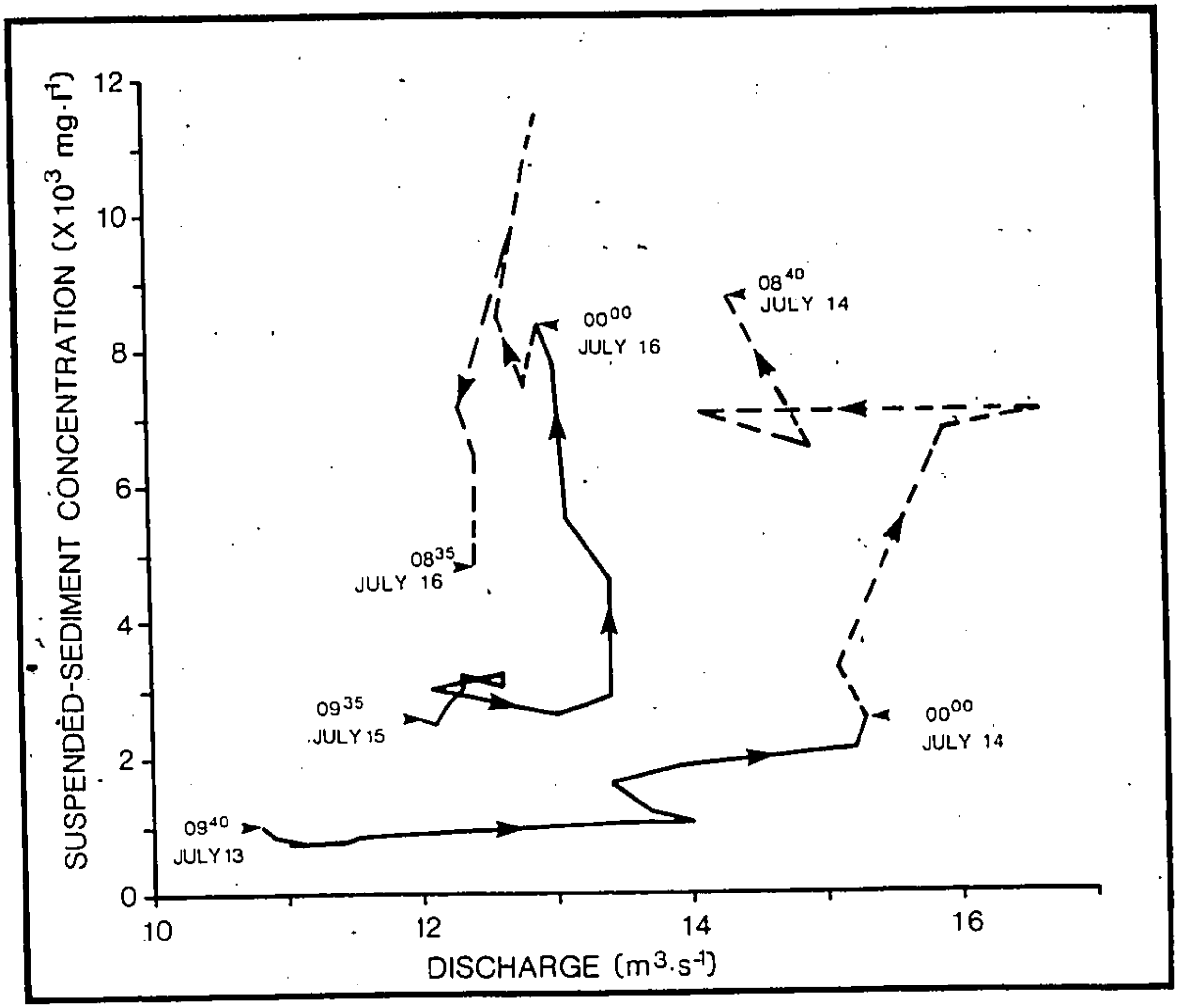

Figure 53 Hysteresis loops for suspended-sediment concentration versus discharge, Peyto Creek, July 13 to July 14 and July 15 to July 16, 1981: July 13 (solid line), July 14 (dashed line), July 15 (solid line) and July 16 (dashed line).

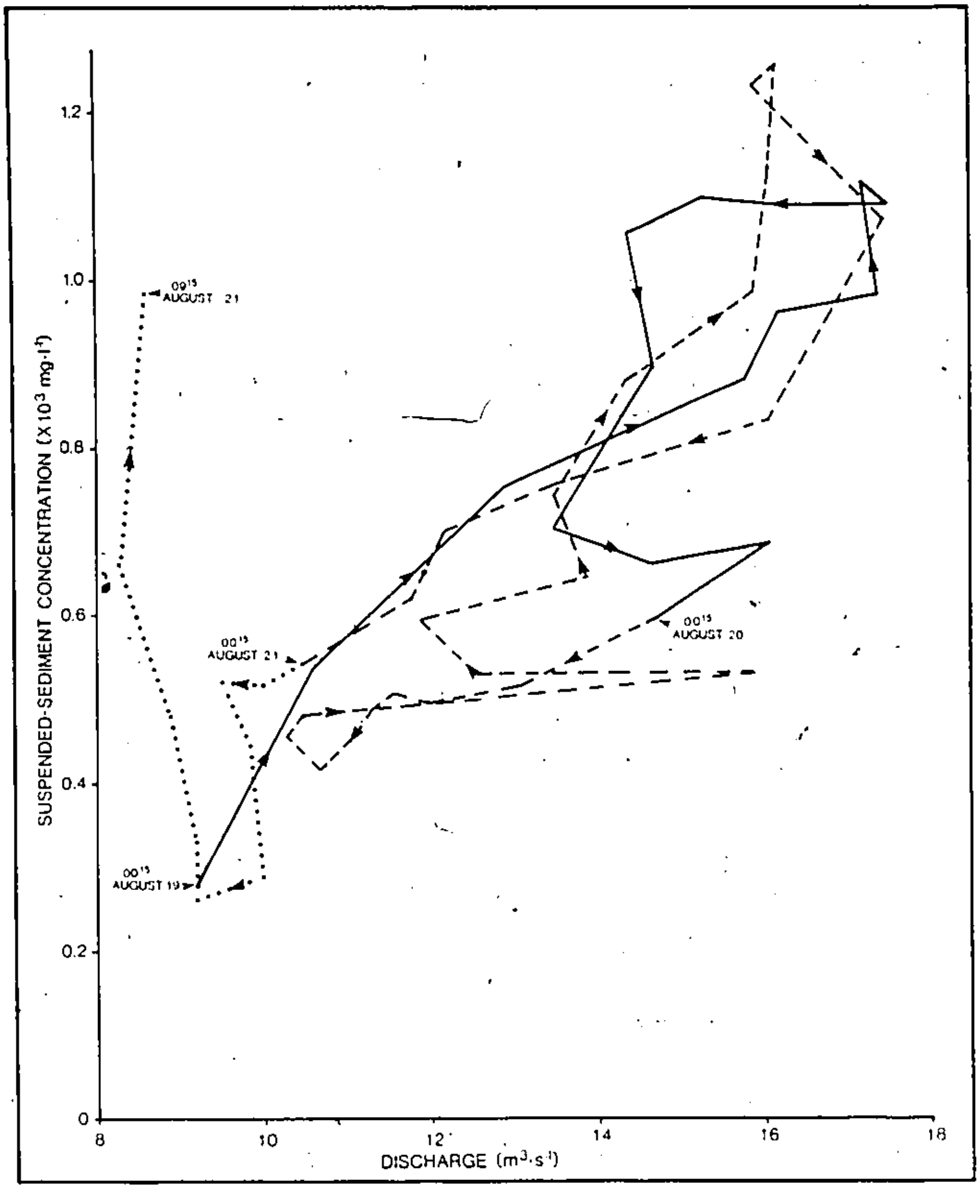

Figure 54 Hysteresis loops for suspended-sediment concentration versus discharge, Peyto Creek, August 19 to August 21, 1981: August 19 (solid line), August 20 (dashed line) and August 21 (dotted line).

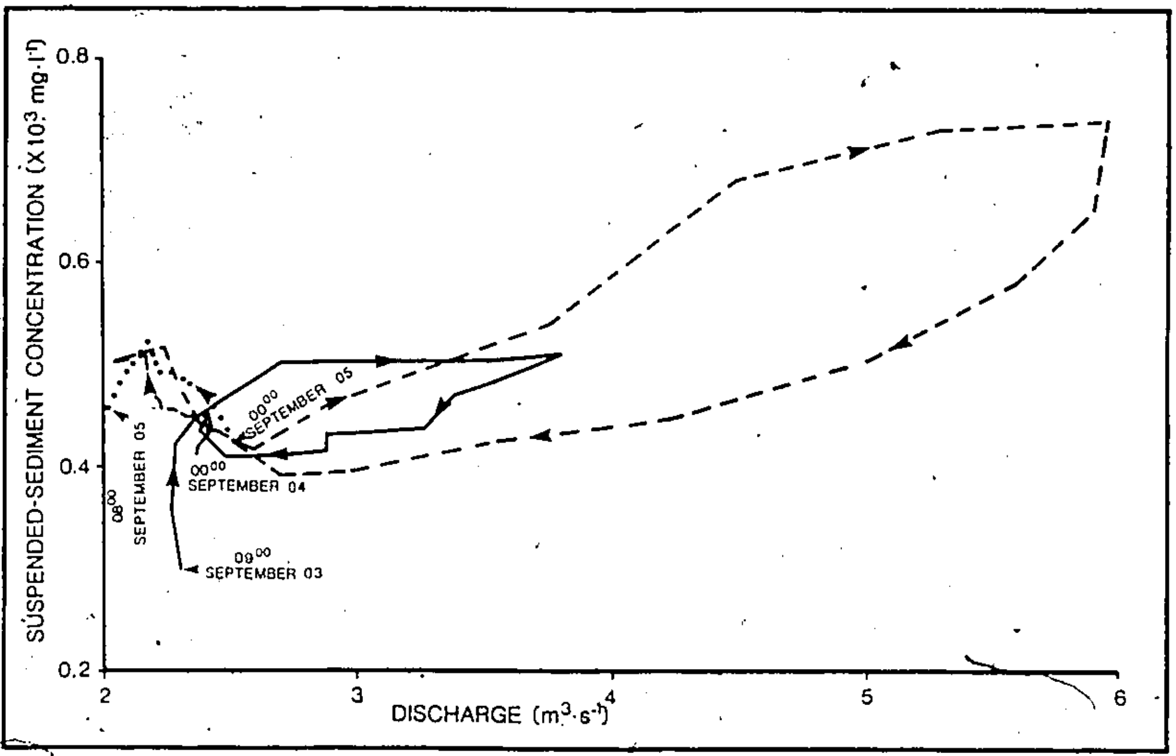

Figure 55 Hysteresis loops for suspended-sediment concentration versus discharge, Peyto Creek, September 03 to September 05, 1981: September 03 (solid line), September 04 (dashed line) and September 05 (dotted line).

formulation of a suspended-sediment concentration versus stream discharge curve of the form, $Sc = aQ^b$ (where Sc is the suspended-sediment concentration, Q is the stream discharge and a, b are estimated parameters) employed in non-glacial streams (i.e., Jasper, 1973). The disparity between the rising and the falling stage of the hydrograph, it's inconsistency (anti-clockwise in some occasions) and the sudden releases of sediment, would result in low degree of fit for such a model. Better correlations have been reported (e.g., Church, 1972; Østrem, 1975a) using the statistically spurious correlation between suspended-sediment load (concentration x discharge) and discharge (Benson, 1965). Walling (1977) has stated that using suspended-sediment rating curves for non-sampling periods could cause serious errors (over or under-estimates) especially with the presence of hysteresis.

5.3.4 Suspended-sediment load

A crude estimate of the glacier's suspended-sediment output for the 1981 ablation season was calculated by taking the product of the sediment concentration (daily sample taken at approximately mid-stage) and the daily total discharge. This estimate, of 68,000 tonnes, is probably much less than the actual production because of the numerous diurnal pulses which are not taken into account. The seasonal load (Figure 56) fluctuates from a minimum of approximately 5 tonnes on June 22 to a maximum of 4,418

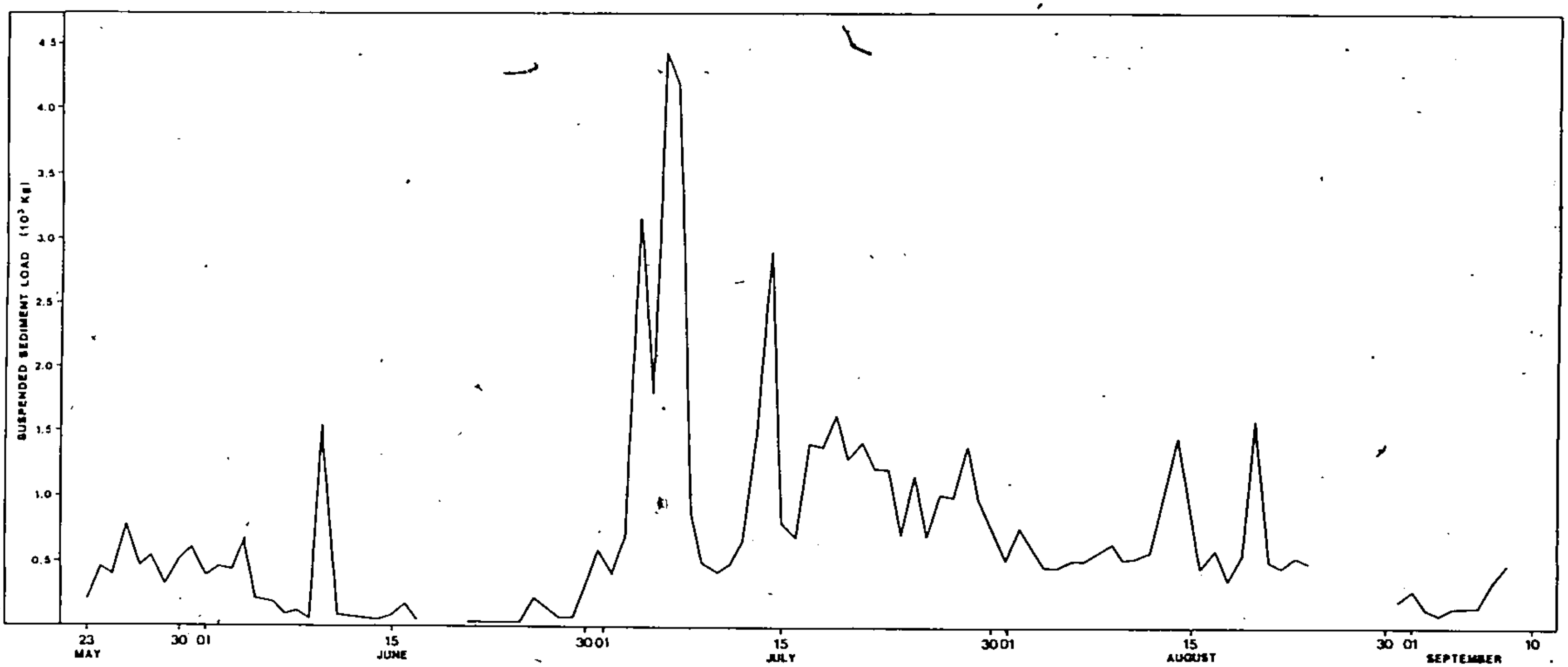

Figure 56 Peyto Glacier suspended-sediment load regime for the 1981 ablation season (May 23 to September 08). Note that breaks in record are due to missing discharge data resulting from instrument malfunction.

tonnes on July 06.

Single daily sample loads in comparison to estimations from several samples taken during the day (summerised in Table 4) indicate that single sample estimations are quite accurate during the baseflow events of June 28 and September 04. However, serious underestimations arose on June 14 and during the main ice ablation period July 13-14, July 15-16 and August 20 due to the flushing out of sediment caused by changes in discharge and channel migration.

Peyto Creek's instantaneous load ($kg \cdot s^{-1}$) was calculated for the five hourly sampling periods (Figures 57 to 59). These graphs illustrate the highly irregular nature of glacier suspended-sediment production, with results ranging from 0.51 $kg \cdot s^{-1}$ at 1330 h on June 14 to 179.23 $kg \cdot s^{-1}$ at 0335 h on July 16.

In summary, no simple relationships seem to exist between suspended-sediment concentration and discharge. Discharge magnitude is not the main factor in influencing suspended-sediment entrainment in a glacier-fed stream but it is instead a combination of availability and changing glaciological conditions (i.e., rate of increase in discharge, the length of time water flows through the sediment source and subglacial channel migration).

DATE	SINGLE SAMPLE ESTIMATION (tonnes·d^{-1})	HOURLY SAMPLE ESTIMATION (tonnes·d^{-1})
June 06	47.2	102.0
June 28	61.3	88.3
July 13-14	1670.0	3718.4
July 15-16	802.2	6021.0
August 20	843.6	1576.7
September 04	152.9	153.4

Table 4 - COMPARISON OF DAILY SUSPENDED-SEDIMENT LOADS ESTIMATED BY SINGLE DAILY SAMPLES AND BY HOURLY SAMPLES.

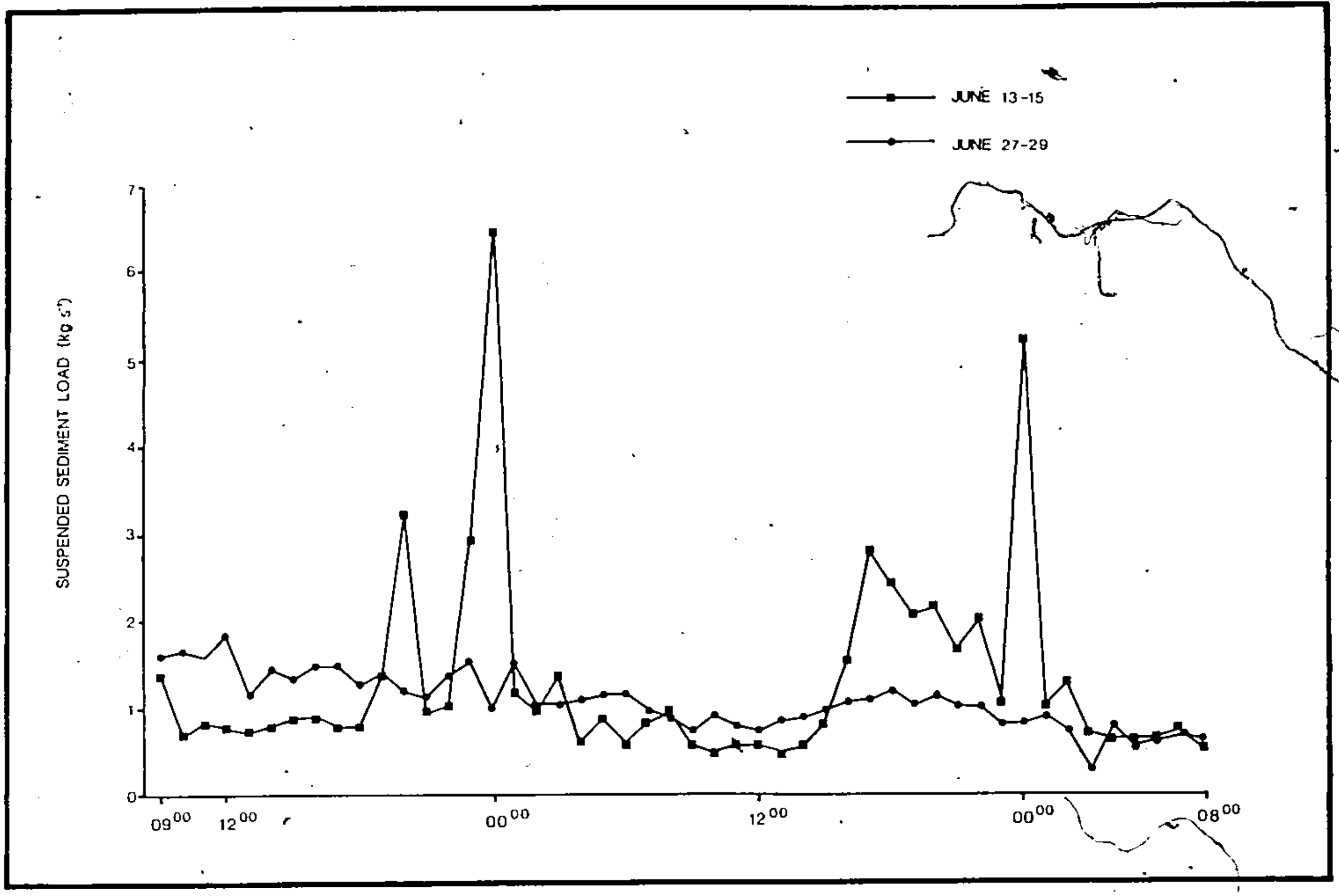

Figure 57 Suspended-sediment loads for the hourly sampling periods of June 13 to June 15 and June 27 to June 29, 1981.

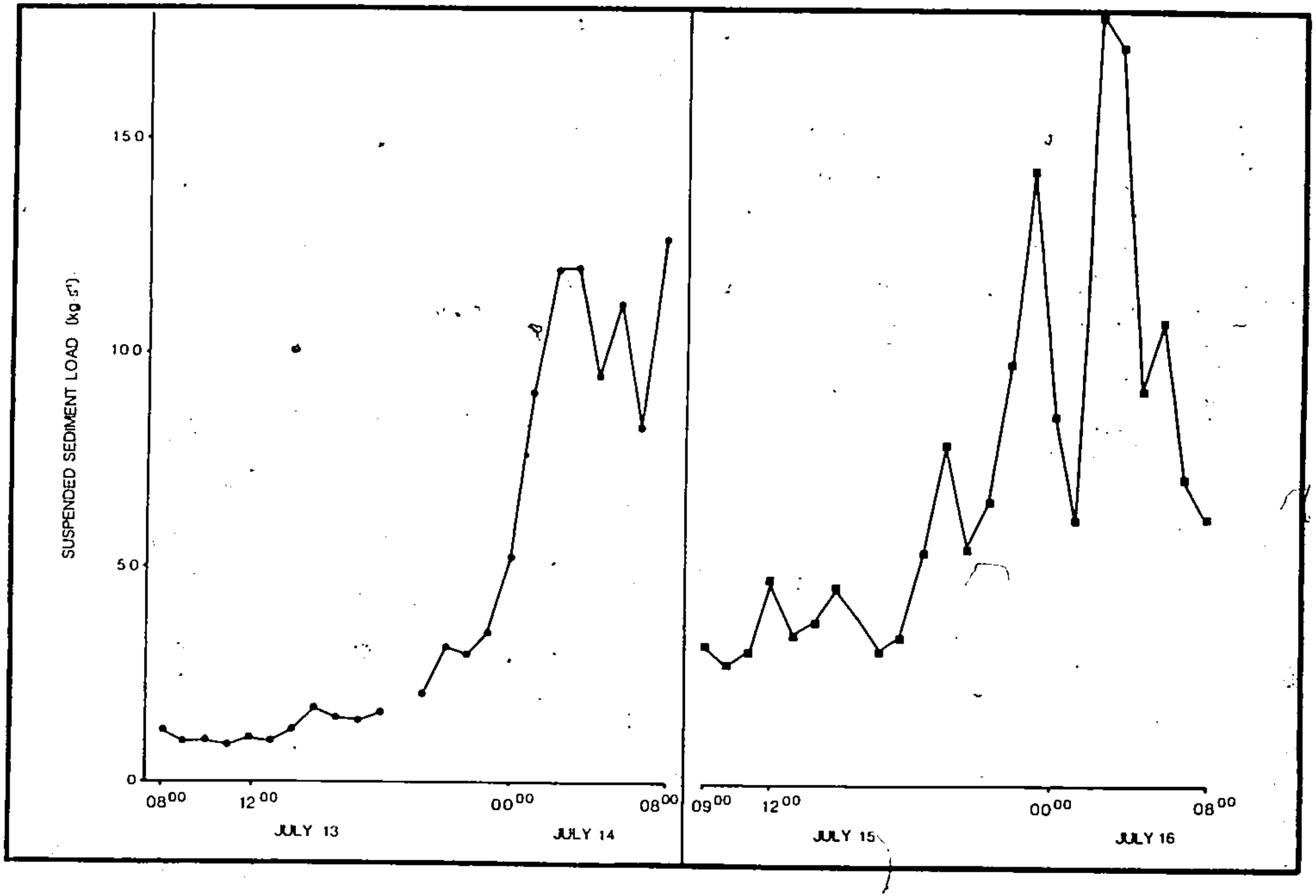

Figure 58 Suspended-sediment loads for the hourly sampling periods of July 13 to July 14 and July 15 to July 16, 1981.

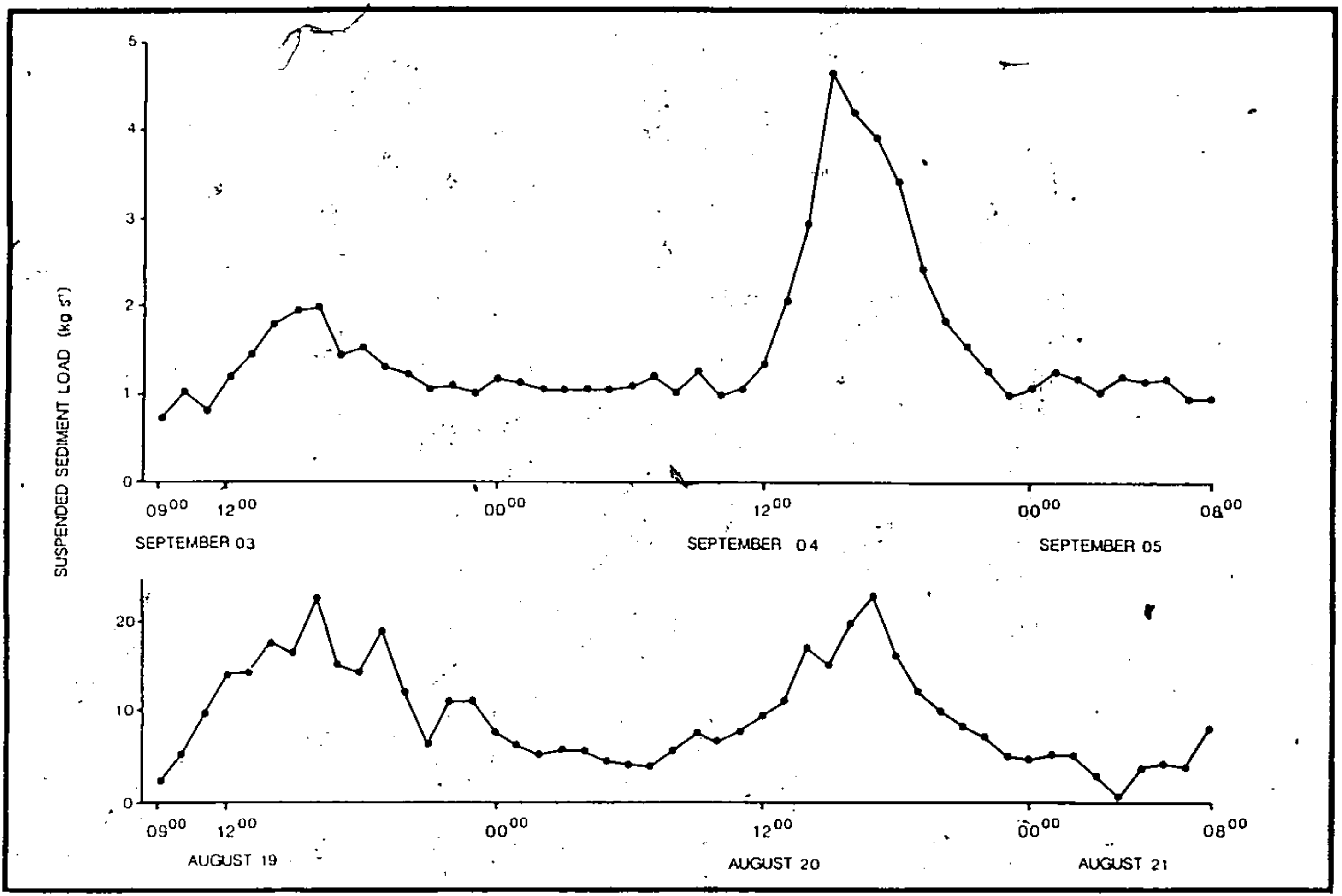

Figure 59 Suspended-sediment loads for the hourly sampling periods of August 19 to August 21 and September 03 to September 05, 1981.

CHAPTER 6

CONCLUSIONS

6.1 Fluvioglacial hydrochemical and suspended-sediment dynamics

This study examined two aspects of importance to the understanding of erosional processes active in a glacierised basin, glacier meltwater hydrochemistry and suspended-sediment characteristics.

A four component hydrological regime based on discharge and meteorological data was proposed in this study.

Peyto Glacier meltwaters show seasonal and diurnal trends in hydrochemistry linked to changing dilution effects. Early season runoff originates from the subglacial zone where meltwaters are enriched by travel over ion-rich basal material, and from non-glacierised areas of the basin. As thaw progresses meltwaters from glacier surface snowmelt and from englacial channels add to subglacial flow and result in lower solute and attached cationic concentrations. At the end of the ablation season, reduced surficial icemelt production results in higher solute concentrations.

The dilution effect is also evident on a diurnal basis since lower concentrations are measured during the day than during the night when melt production is curtailed.

The fluctuations in hydrochemistry do not show any link to the progressive increase in contact with the different geological strata within the basin. This is probably due to the geologic homogeneity of the basin. Thus variations in meltwater hydrochemistry reflect the changing amounts of dilution throughout the ablation season.

The trend in the attached cationic concentration regime is directly related to the contact-time within the glacier system. Early and late melt season sediments have greater amounts of adsorbed cations on their surface because they have longer residence times due to low discharges. Suspended-sediment during the high flow periods in July and August have lower concentrations because of reduced contact-time.

The suspended-sediment regime is irregular and unlike that of non-glacier-fed streams. Greater suspended-sediment concentrations are not proportionally linked to greater discharges and irregular pulses of sediment occur independent of discharge variations. Three patterns of diurnal response are identified. (1) the daily suspended-sediment concentration peak precedes stream discharge peak, (2) it follows the peak, and (3) no distinct pattern was visible. This diversity may be linked to sediment availability. The sediment peak may precede the discharge peak when the opening of the conduits is directly connected with a sediment source but when the channel is not linked to a sediment source the sediment peak will either follow the discharge peak or show no peak at all.

Sediment source areas are normally irregularly distributed within the subglacial zone. The opening of small conduits with very low discharge that are connected to sediment sources will release large pulses while large conduit openings that are not linked to sediment sources will release only small quantities of material.

Subglacial channel re-organisation in response to changing hydrostatic pressures, changing glacier flow regimes and sediment availability are probably the major factors influencing suspended-sediment output from Peyto Glacier. As a result, it is difficult to formulate a predictive model. Any such model will be very site-specific and may not be used for more than one season. This is because the flushing of sediment in any one year might influence the availability of sediment in the next year.

The processes active in the basin are influenced by different controls at different times. Quantification of glaciological controls on suspended-sediment output is difficult but the climatological controls are more easily quantified.

6.2 Recommendations for future research

Detailed investigations are needed to quantify glacier controls on discharge and suspended-sediment output in alpine basins. A complete photographic record taken throughout the ablation season in addition to a dye tracing strategy to determine the glacier drainage system will perhaps lead to a greater insight into glacier dynamics.

Continuous monitoring of electrical conductivity combined with laboratory analysis of the meltwaters will permit researchers to gain information on chemical weathering in alpine basins.

There is a need for more detailed suspended-sediment studies at Peyto Glacier and in other glacierised basins throughout the ablation season to fully understand the processes on both a local and a regional scale. An hourly sampling strategy seems to be the most reasonable time-scale to use. These hourly samples should be taken daily throughout the ablation season to define cyclic trends using more powerful statistical methods (e.g., spectral analysis). A continuous recording turbidity meter should be installed at the sampling site to detect the occurrence of sudden suspended-sediment pulses not recorded using the hourly sampling strategy. This will probably lead to the formulation of a suspended-sediment/discharge rating curve for both rising and falling limbs of the hydrograph.

There is also a need for a detailed geological study in the Peyto Creek basin and the surrounding area.

APPENDIX A

TYPE OF SAMPLE	DATE	Ca^{++}	Mg^{++}	Na^{+}	K^{+}
Rain		0.00	0.30	0.03	0.04
Ice sample (snout)	09-07	0.38	0.24	0.40	0.22
Ice sample (snout)	12-08	0.31	0.22	0.54	0.15
Ice sample (upper basin)	15-08	0.27	0.19	0.51	0.11
Ice sample (upper basin)	15-08	0.19	0.32	0.62	0.14
Snow sample (snout)	18-06	0.00	0.14	0.00	0.00
Snow sample (upper basin)	18-06	0.00	0.19	0.09	0.09
Supraglacial stream	20-07	0.00	0.24	0.29	0.05
Supraglacial stream	02-08	0.09	0.19	0.22	0.04
Tributary stream	20-07	4.23	3.24	1.13	0.08
Tributary stream	02-08	7.40	6.28	1.74	0.19
Tributary stream	08-09	5.18	2.01	1.08	0.05

Table A-1 - CHEMICAL ANALYSIS: RAIN, ICE, SUPRAGLACIAL AND TRIBUTARY STREAMS (ppm)

REFERENCES

Ambach, W., Eisner, H., Elsässer, M., Löschhorn, U., Moser, H., Rauert, W. and Stichler, W.
1976: Deuterium, tritium and gross-beta-activity investigations on Alpine glaciers (Ötztal Alps); Journal of Glaciology, V. 17, no. 77, p. 383-400.

Ambach, W., Kuchlechner, P., Moser, H. and Stichler, W.
1982: Seasonal variations of deuterium concentration in runoff from a glacierised basin; Hydrological Sciences Journal, V. 27, p. 29-34.

Angino, E.E. and Billings, G.K.
1967: Atomic absorption spectrometry in geology; Elsevier, Amsterdam, 144p.

Arnborg, L., Walker, H.J. and Peippo, J.
1967: Suspended load in the Colville River, Alaska, 1962; Geografiska Annaler, V. 49A, p. 131-144.

Behrens, H., Bergmann, H., Moser, H., Rauert, W., Stichler, W., Ambach, W., Eisner, H. and Pessl, K.
1971: Study of the discharge of Alpine glaciers by means of environmental isotopes and dye tracers; Zeitschrift für Gletscherkunde und Glazialgeologie, Bd. 7, Ht. 1-2, p. 89-102.

Behrens, H., Bergmann, H., Moser, H., Ambach, W. and Jochum, O.
1975: On the water channels of the internal drainage system of the Hintereisferner, Ötztal Alps, Austria; Journal of Glaciology, V. 14, no. 72, p. 375-382.

Belyea, H.R.
1964: The story of the mountains in Banff National Park; Geological Survey of Canada, Miscellaneous Report, no. 1, 73p.

Benson, M.A.
1965: Spurious Correlation in Hydraulics and Hydrology; Journal of the Hydraulics Division, American Society of Civil Engineers, V. HY-91, no. 4393, p. 35-42.

Bigras, S.C.
1982: Hydrological investigation of glacial runoff components and their separation through hydrochemical analysis; M.A. Thesis, Department of Geography, University of Ottawa, Ottawa, 154p.

Bogen, J.
1980: The hysteresis effect of sediment transport systems; Norsk Geografisk Tidsskrift, V. 34, no. 1, p. 45-54.

Borland, W.M.
1961: Sediment transport of glacier-fed streams in Alaska; Journal of Geophysical Research, V. 66, no. 10, p. 3347-3350.

Bryan, M.L.
1972: Variations in quality and quantity of Slims River water, Yukon Territory; Canadian Journal of Earth Sciences, V. 9, p. 1469-1478.

Burkimsher, M.
1983: Short-term irregularities of discharge of glacial melt-water streams; Journal of Glaciology, V. 29, no. 101, correspondence, p. 198-199.

Carter, R.L.
1954: Study of glaciers in Banff and Jasper National Parks, 1952 and 1954; Report no. 2160-(52 & 54), Dominion Water and Power Bureau, Forests and Scientific Services Branch, Department of Mines and Resources, Calgary, Alberta, manuscript, 32p.

Church, M.
1972: Baffin Island sandurs: a study of Arctic fluvial processes; Geological Survey of Canada, Bulletin 216, 208p.

1974: On the quality of some waters on Baffin Island, Northwest Territories; Canadian Journal of Earth Sciences, V. 11, p. 1676-1688.

Church, M. and Gilbert, R.
1975: Proglacial fluvial and lacustrine environments: in: Glaciofluvial and glaciolacustrine sedimentation, editors A.V. Jopling and B.C. McDonald; Society of Economic Palaeontologists and Mineralogists, Special Publication 23, p. 22-100.

Church, M. and Kellerhals, R.
1970: Stream gauging techniques for remote areas using portable equipment; Inland Waters Branch, Energy, Mines and Resources, Technical Bulletin 25, 89p.

Church, M. and Ryder, J.M.
1972: Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation; Geological Society of America Bulletin, V. 83, p. 3059-3072.

Colby, B.R. and Scott, C.H.
1965: Effects of water temperature on the discharge of bed material; United States Geological Survey, Professional Paper 462-G, 25p.

Collins, D.N.
1977: Hydrology of an Alpine glacier as indicated by the chemical composition of meltwater; Zeitschrift für Gletscherkunde und Glazialgeologie, Bd. 13, Ht. 1-2, p. 219-238.

1979a: Sediment concentration in melt waters as an indicator of erosion processes beneath an Alpine glacier; Journal of Glaciology, V. 23, no. 89, p. 247-257.

1979b: Quantitative determination of the subglacial hydrology of two Alpine glaciers; Journal of Glaciology, V. 23, no. 89, p. 347-362.

1979c: Hydrochemistry of meltwaters draining from an Alpine glacier; Arctic and Alpine Research, V. 11, no. 3, p. 307-324.

1980: Hydrochemical characteristics of runoff in glacierised mountain catchments, Rocky Mountains, Alberta and British Columbia; Report on contract OSS79-00029, Environment Canada, Glaciology Division, 54p.

1981: Seasonal variation of solute concentration in meltwaters draining from an Alpine glacier; Annals of Glaciology, V. 2, p. 11-16.

1982: Flow-routing of meltwater in an alpine glacier as indicated by dye tracer tests; Beitraege Zur Geologie Der Schweiz-Hydrologie, Bd. 28, Ht. 2, p. 523-534.

Collins, D.N. and Young, G.J.
1979a: Hydrochemical separation of components of discharge in alpine catchments; Proceedings of the 47th Western Snow Conference, p. 1-9.

1979b: Separation of runoff components in glacierised alpine watersheds by hydrochemical analysis; Proceedings of the Canadian Hydrology Symposium, Vancouver, Canada, May 1979, p. 570-581.

1981: Meltwater hydrology and hydrochemistry in snow- and ice-covered mountain catchments; Nordic Hydrology, V. 12, p. 319-334.

Cook, D.G.
1975: Structural style influenced by lithofacies, Rocky Mountain main ranges, Alberta-British Columbia; Geological Survey of Canada, Bulletin 233, 73p.

Day, T.J.
1977: Field procedures and evaluation of a slug dilution gauging method in mountain streams; Journal of Hydrology, V. 16, no. 2, p. 113-133.

Derikx, L.
1973: Glacier discharge simulation by ground-water analogue; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 29-40.

Derikx, L. and Loijens, J.S.
1971: Model of runoff from glaciers; Proceedings of the Hydrology Symposium no. 8, National Research Council, Associate Committee on Geodesy and Geophysics, sub-committee on hydrology, Quebec City, May 1971, V. 1, p. 153-199.

Dincer, T., Payne, B.R., Florkowski, T., Martinec, J. and Tongiorgi, E.
1970: Snowmelt runoff from measurements of tritium and oxygen-18; Water Resource Research, V. 6, p. 110-124.

Elliston, G.R.
1973: Water movement through the Gornergletscher; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 79-84.

Environment Canada
1981: Snow cover data, Canada, 1971-1980; Atmospheric Environment Services, Downsview, Ontario.

1982a: Canadian climate normals, 1951-1980, Volume 2, temperature; Atmospheric Environment Services, Downsview, Ontario, 306p.

1982b: Canadian climate normals, 1951-1980, Volume 3, precipitations, Atmospheric Environment Services, Downsview, Ontario, 602p.

Eyles, N., Sasseville, D.R., Slatt, R.M. and Rogerson, R.J.
1982: Geochemical denudation rates and solute transport mechanisms in a maritime temperate glacier basin; Canadian Journal of Earth Sciences, V. 19, no. 8, p. 1570-1581.

Fahnestock, R.K.
1963: Morphology and hydrology of a glacier stream,, White River, Mount Rainier, Washington; United States Geological Survey, Professional Paper, 422-A, 70p.

Feth, J.H., Roberson, C.E. and Polzer, W.L.
1964: Sources of mineral constituents in water from granitic rocks, Sierra Nevada, California and Nevada; United States Geological Survey, Water-supply Paper 1535-I, 70p.

Field, W.O. Jr. and Heusser, C.J.
1954: Glacier and botanical studies in the Canadian Rockies, 1953; Canadian Alpine Journal, V. 37, p. 128-140.

Flemming, G. and Poodle, T.
1969: Particle size of river sediments; Journal of the Hydraulics Division, American Society of Civil Engineers, V. HY-96, Proceedings Paper, no. 7068, p. 431-439.

Foessel, D.G.
1974: An analysis of the temperature distribution over Peyto Glacier, Alberta; M.Sc. Thesis, Guelph University, Guelph, 137p.

Föhn, P.M.B.
1973: Short-term snowmelt and ablation derived from heat and mass balance measurements; Journal of Glaciology, V. 12, no. 65, p. 275-289.

Ford, D.C., Fuller, F.G. and Drake, J.J.
1970: Calcite precipitates at the soles of temperate glaciers; Nature, V. 226, no. 5244, p. 441-442.

Freeze, R.A. and Cherry, J.A.
1979: Groundwater; Prentice Hall, New Jersey, 604p.

Golubev, G.N.
1973: Analysis of the runoff and flow routing for a mountain glacier basin; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 41-50.

Goodison, B.
1970: The relation between ablation and global radiation over Peyto Glacier, Alberta; in: Glaciers, Proceedings of the International Hydrological Decade Workshop Seminar, 1970, Vancouver, British Columbia, Canadian National Committee for the International Hydrological Decade, p. 39-42.

1972a: The distribution of global radiation over Peyto Glacier, Alberta; Inland Waters Directorate, Water Resources Branch, Scientific Series no. 22, Ottawa, 22p.

1972b: An analysis of climate and runoff events for Peyto Glacier, Alberta; Inland Waters Directorate, Water Resources Branch, Scientific Series no. 21, Ottawa, 29p.

Gottlieb, L.
1980: Development and applications of a runoff model for snwocovered and glacierized basins; Nordic Hydrology, V. 11, p. 255-272.

Gurnell, A.M.
1983: The dynamics of suspended sediment concentration in an Alpine pro-glacial stream network; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on the Hydrological aspects of alpine and high mountain areas, Exeter, July 1982, I.A.S.H.-A.I.S.H. Publication no. 138, p. 319-330.

Guy, H.P.
1970: Fluvial sediment concepts; Techniques of water-resources investigations of the United States Geological Survey, Book 3, Application of hydraulics, Chapter C1, 55p.

Hallet, B.
1975: Subglacial silica deposits; Nature, V. 254, no. 5502, p. 682-683.

1976: Deposits formed by subglacial precipitation of CaCO3; Geological Society of America Bulletin, V. 87, no. 7, p. 1003-1015.

Hjulström, F.
1939: The principles of construction of instruments for procuring samples of water containing silt; Geografiska Annaler, V. 21, p. 67-71.

Jasper, J.N.
1973: Suspended sediment and dissolved material transport in "Twisty Creek", a small subarctic watershed; in: Hydrologic aspects of northern pipeline development, Editor D.K. Mackay, Department of the environment, p. 645-664.

Johnson, P.G.
1971: Ice-cored moraine formation and degradation, Donjek Glacier, Yukon Territory, Canada; Geografiska Annaler, V. 53A, p. 198-202.

Kennedy, V.C.
1965: Mineralogy and cation-exchange capacity of sediments from selected streams; United States Geological Survey, Professional Paper 433-D, 28p.

Kobybka, R.J.
1981: Erosion of Paleozoic bedrock in the terminal zone of Yoho Glacier, British Columbia; M.Sc. Thesis, Department of Geography, Memorial University of Newfoundland, St John's, 193p.

Kol, E.
1942: The snow and ice algae of Alaska; Smithsonian Miscellaneous Collections, V. 101, no. 16,1, 36p.

Krimmel, R.M. and Tangborn, W.V.
1974: The moderating influence of glaciers on runoff; Proceedings of the 42nd Western Snow Conference, Anchorage, Alaska, April 1974, p. 9-13.

Krimmel, R.M., Tangborn, W.V. and Meier, M.F.
1973: Water flow through a temperate glacier; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on the Role of snow and ice in hydrology, Banff, September 1972, I.A.H.S.-A.I.S.H. Publication no. 107, V. 1, p. 401-416.

Lang, H.
1973: Variations in the relation between glacier discharge and meteorological elements; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 85-94.

Lang, H., Schädler, B. and Davidson, G.
1977: Hydroglaciological investigations on the Ewigschneefeld, Great Aletschgletscher; Zeitschrift für Gletscherkunde und Glazialgeologie, Bd. 12, Ht. 2, p. 119-124.

Lemmens, M. and Roger, M.
1978: Influence of ion exchange on dissolved load of Alpine meltwaters; Earth Surface Processes, V. 3, p. 179-187.

Liestøl, O.
1967: Storbreen Glacier in Jotunheimen, Norway; Norsk Polarinstitutt, Skrifter, Nr. 141, 63p.

Livingstone, D.A.
1963: Chemical composition of rivers and lakes; United States Geological Survey, Professional Paper 440-G, 7p.

Loijens, H.S.
1974: Streamflow formation in the Mistaya River Basin, Rocky Mountains, Canada; Proceedings of the 42nd Western Snow Conference, Anchorage, Alaska, April 1974, p. 86-95.

Lorrain, R.D. and Souchez, R.A.
1972: Sorption as a factor in the transport of major cations by meltwaters from an Alpine glacier; Quaternary Research, V. 2, p. 253-256.

Male, D.H.
1980: The seasonal snowcover; in: Dynamics of snow and ice masses, editor Samuel C. Colbeck, Academic Press, New York, p. 305-395.

Male, D.H. and Gray, D.M.
1981: Snowcover ablation and runoff; in: Handbook of snow, editors D.M. Gray and D.H. Male, Pergamon Press, Toronto, p. 360-436.

Martinec, J.
1970: Recession coefficient in glacier runoff studies; International Association of Scientific Hydrology Bulletin, V. 15, no. 1, p. 87-90.

Mathews, W.H.
1964: Sediment transport from Athabaska Glacier, Alberta; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on Land erosion, precipitations, hydrometry and soil moisture, Berkeley, August 1963, I.A.S.H. Publication no. 65, p. 155-165.

May, R.D., Blair, R.V. and Harry, R.M.
1950: Study of glaciers in Banff and Jasper National Parks, 1950; Report no. 2160-(50), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Calgary, Alberta, manuscript, 34p.

McCoubrey, A.A.
1938: Glacier observations, 1936 and 1937; Canadian Alpine Journal, V. 25, p. 113-116.

McFarlane, W.T.
1945: Study of glaciers in Banff, Yoho and Jasper National Parks, 1945; Report no. 2160-(45), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Vancouver, British Columbia, manuscript, 23p.

1946: Study of glaciers in Banff and Jasper National Parks, 1946; Report no. 2160-(46), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Vancouver, British Columbia, manuscript, 34p.

1947: Study of glaciers in Banff and Jasper National Parks, 1947; Report no. 2160-(47), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Vancouver, British Columbia, manuscript, 40p.

1960: Survey of glaciers in Banff and Jasper National Parks; Department of Northern Affairs and Natural Resources, Water Resources Branch, Ottawa, 30p.

McFarlane, W.T., Blair, R.V. and Ozga, W.J.
1949: Study of glaciers in Banff and Jasper National Parks, 1949; Report no. 2160-(49), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Calgary, Alberta, manuscript, 34p.

McFarlane, W.T. and May, R.D.
1948: Study of glaciers in Banff and Jasper National Parks, 1948; Report no. 2160-(48), Dominion Water and Power Bureau, Surveys and Engineering Branch, Department of Mines and Resources, Calgary, Alberta, manuscript, 32p.

McPherson, H.J.
1971: Dissolved, suspended and bed load movement patterns in Two O'clock Creek, Rocky Mountains, Canada, Summer, 1969; Journal of Hydrology, V. 12, p. 222-233.

Meek, V.
1948: Glacier observations in the Canadian Cordillers; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the General Assembly of Oslo, I.A.S.H. Publication no. 30, V. 2, p. 264-275.

Mills, H.H.
1979: Some implications of sediment studies for glacial erosion on Mount Rainier, Washington; Northwest Science, V. 53, no. 3, p. 190-199.

Moser, H. and Stichler, W.
1975: Deuterium and oxygen-18 contents as an index of the properties of snow covers; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on Snow mechanics, Grindelwald, Switzerland, April 1974, I.A.H.S.-A.I.S.H. Publication no. 114, p. 122-135.

Munro, D.S.
1975: Energy exchange on a melting glacier; Ph.D. Thesis, McMaster University, Hamilton, 182p.

Munro, D.S. and Davies, J.A.
1977: An experimental study of the glacier boundary layer over melting ice; Journal of Glaciology, V. 18, no. 80, p. 425-436.

Munro, D.S. and Young, G.J.
1982: An operational net shortwave radiation model for glacier basins; Water Resources Research, V. 18, no. 2, p. 220-230.

Nakamura, R.
1971: Runoff analysis by electrical conductance of water; Journal of Hydrology, V. 14, p. 197-212.

Nielsen, S.A. and Hansen, E.
1973: Numerical simulation of the rainfall-runoff process on a daily basis; Nordic Hydrology, V. 4, p. 171-190.

Nye, J.F.
1973: Water at the bed of a glacier; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 189-194.

Nye, J.F. and Frank, F.C.
1973: Hydrology of the intergranular veins in a temperate glacier; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 157-161.

Oerter, H., Behrens, H., Hibsch, G., Rauert, W. and Stichler, W.

1980: Combined environmental isotope and electrical conductivity investigations of the runoff at Vernaglferner (Ötztal Alps); Materialy Glyalsiologicheskikh Issledovanity Khronika Obsuzhdeniya, V. 39, p. 157-161.

Ommanney, C.S.L.

1972: Glacier surveys by district personnel of the water survey of Canada; 2. Peyto Glacier; Glacier inventroy note no. 7, Glaciology Division, Water Resources Branch, Inland Waters Directorate, Department of the Environment, Ottawa, 20p.

1984: Canadian glacier variations and mass balance changes, 1975-1980; Quadrennial report to the permanent service on the fluctuations of glaciers, Unesco, 255p.

Østrem, G.

1959: Ice melting under a thin layer of moraine and the existence of ice cores in moraine ridges; Geografiska Annaler, V. 41, p. 218-230.

1962: Ice-cored moraines in the Kebnekajse area, Sweden; Bulletyn Perygl Norsk, V. 11, p. 271-278.

1964a: Ice-cored moraines in Scandinavia; Geografiska Annaler, V. 46, p. 282-337.

1964b: A method of measuring water discharge in turbulent streams; Geographical Bulletin, V. 6, no. 21, p. 21-43.

1966: Mass balance studies on glaciers in western Canada; Geographical Bulletin, V. 8, no. 1, p. 81-107.

1975a: Sediment transport in glacial meltwater streams; in: Glaciofluvial and glaciolacustrine sedimentation, editors A.V. Jopling and B.C. McDonald; Society of Economic Palaeontologists and Mineralogists, Special Publication 23, p. 101-122.

1975b: Sediment transport studies at selected glacier streams in Norway, 1969; in: Fluvial processes: Cueillette et analyse des données, editor P.G. Johnson, Proceedings of the Third Annual Colloquium of the Department of Geography and Regional Planning, March 24-25, 1972, Occasional Papers, no. 3, Department of Geography and Regional Planning, University of Ottawa Press, Canada, p. 5-23.

Østrem, G. and Arnold, K.
1970: Ice-cored moraines in southern British Columbia and Alberta, Canada; Geografiska Annaler, V. 52A, p. 120-128.

Østrem, G., Bridge, C.W. and Rannie, W.F.
1967: Glacio-hydrology, discharge and sediment transport in the Decade Glacier area, Baffin Island, Northwest Territories; Geografiska Annaler, V. 49A, p. 268-282.

Østrem, G. and Stanley, A.
1966: Glacier mass balance measurements: a manual for field and office work; Canadian Department of Energy, Mines and Resources and the Norwegian Water Resources and Electricity Board, 129p.; Canadian edition published as Inland Waters Branch reprint series, no. 66, Department of the Environment, Ottawa, Canada, 118p.

Paterson, W.S.B.
1981: The physics of glaciers, 2nd edition; Pergamon Press, Oxford, Great Britain, 380p.

Power, J.M. and Young, G.J.
1979a: Application of the UBC watershed model to Peyto Glacier basin; Proceedings of the Canadian Hydrology Symposium, Vancouver, Canada, May 1979, p. 570-581.

1979b: Application of an operational hydrological forecasting model to a glacierized research basin; Proceedings of the Third Norther Research Basin Symposium Workshop on The state of the art in transposable watershed models, Quebec City, Quebec, 10-15 juin, 1979, Abstract, p. 11.

Prantl, F.A. and Loijens, H.S.
1977: Nuclear techniques for glaciological studies in Canada; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on Isotopes and impurities in snow and ice, Grenoble, August/September 1975, I.A.H.S.-A.I.S.H. Publication no. 118, p. 237-241.

Quick, M.C. and Pipes, A.
1977: UBC watershed model; Hydrological Sciences Bulletin, V. 22, no. 1, p. 153-161.

Rainwater, F.H. and Guy, H.P.
1961: Some observations on the hydrochemistry and sedimentation of the Chamberlin Glacier area, Alaska; United States Geological Survey, Professional Paper 414C, 14p.

Reynolds, R.C. and Johnson, N.M.
1972: Chemical weathering in the temperate glacial environment of the Northern Cascade Mountains; Geochimica et Cosmoschimica Acta, V. 36, no. 5, p. 537.554.

Roaas, J.
1973: Sedimentransportens kortvarige sesongmessigne variasjoner i ulike delfelt; Unpublished Thesis, Department of Geography, University of Oslo, Oslo, Norway.

Röthlisberger, H.
1972: Water pressure in intra- and sub-glacial channels; Journal of Glaciology, V. 11, no. 62, p. 177-203.

Sedgwick, J.K.
1966: Geomorphology and mass budget of Peyto Glacier, Alberta; M.A. Thesis, McMaster University, Hamilton, 165p.

Sedgwick, J.K. and Henoch, W.E.S.
1975: Peyto Glacier. Interpretive information on glaciers with special reference to Peyto Glacier; Glaciology Division, Environment Canada, Ottawa, 32p.

Shreve, R.L.
1972: Movement of water in glaciers; Journal of Glaciology, V. 11, no. 62, p. 205-214.

Skibinski, J.
1967: Bedload transport at flood time; International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on River Morphology, Bern, September, 1967, I.A.S.H. Publication no. 75, p. 41-47.

Slatt, R.M.
1972: Geochemistry of meltwater streams from nine Alaskan glaciers; Geological Society of America Bulletin, V. 83, p. 1125-1132.

Smith, N.D., Vendl, M.A. and Kennedy, S.K.
1982: Comparison of sedimentation regimes in four glacier-fed lakes of western Alberta; <u>in</u>: Research in glacial, glacio-fluvial and glacio-lacustrine systems, Proceedings of the 6th Guelph Symposium on Geomorphology, 9-10 May, 1980, editors R. Davidson-Arnott, W. Nickling and B.D. Fahey, Geographical Publication no. 6, Department of Geography, University of Guelph, Geo Books Norwich, Geo Abstracts, Norwich, p. 203-238.

Souchez, R.A.
1971: Ice-cored moraines in south-western Ellesmere Island, Northwest Territories, Canada; Journal of Glaciology, V. 10, no. 59, p. 245-254.

Stanley, A.D.
1970: A pilot study for the inventory of the glaciers in the Rocky Mountains: Inventory of glaciers in the Waputik Mountains; in: Perennial ice and snow masses: A guide for compilation and assemblage of data for a world inventory, Unesco/ I.A.S.H. Technical Papers in Hydrology, V. 1, p. 36-46.

Statham, I.
1977: Earth surface sediment transport; Clarendon Press, Oxford, Great Britain, 184p.

Stenborg, T.
1965: Problems concerning winter run-off from glaciers; Geografiska Annaler, V. 47A, p. 141-184.

1969: Studies of the internal drainage of glaciers; Geografiska Annaler, V. 51A, p. 13-41.

1970: Delay of runoff from a glacier basin; Geografiska Annaler, V. 52A, p. 1-30.

Stenning, A.J.
1980: Synoptic controls on katabatic layer characteristics above a temperate alpine-type glacier, Peyto Glacier, Alberta; M.Sc. Thesis, Department of Geography, Memorial University of Newfoundland, St John's, Newfoundland, 193p.

Stenning, A.J., Banfield, C.E. and Young, G.J.
1981: Synoptic controls over katabatic layer characteristics above a melting glacier; Journal of Climatology, V. 1, no. 3, p. 309-324.

Straub, L.G.
1955: Effect of water temperature on suspended-sediment transport in an alluvial river; Proceedings of the 6th General Meeting of the International Association of Hydraulic Research, Proceeding Paper D-25, 5p.

Straub, L.G., Anderson, A.G. and Flammer, G.H.
1958: Experiments on the influence of temperature on the sediment load; United States Army Corps of Engineers, Missouri River Diversion, Sediment Series no. 10, 36p.

Tangborn, W.V., Krimmel, R.M. and Meier, M.F.
1975: A comparison of glacier mass balance by glaciological, hydrological and mapping methods, South Cascade Glacier, Washington; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on Snow and ice, Moscow, U.S.S.R., August 1971, I.A.H.S.-A.I.S.H. Publication no. 104, p. 185-196.

Van Loon, J.C.
1980: Analytical atomic absorption spectroscopy: selected methods; Academic Press, Toronto, 337p.

Vendl, M.A.
1978: Sedimentation in glacier-fed Peyto Lake, Alberta; M.Sc. Thesis, University of Illinois at Chicago Circle, Chicago, Illinois, 96p.

Vivian, R.A.
1970: Hydrologie et érosion sous-glaciaires; Revuede géographie Alpine, V. 58, p. 241-264.

1977: Tourism, summer ski-ing, hydroelectricity and protection of the public in the French Alpine glacial area: the development of an applied glaciology; Journal of Glaciology, V. 19, no. 81, p. 639-642.

Vivian, R.A. and Zumstein, J.
1973: Hydrologie sous-glaciaire au Glacier d'Argentière (Mont-Blanc, France); International Union of Geodesy and Geophysics, International Association of Scientific Hydrology, Proceedings of the Symposium on the Hydrology of glaciers, Cambridge, 7-13 September, 1969, I.A.S.H. Publication no. 95, p. 53.64.

Walling, D.E.
1977: Assessing the accuracy of suspended-sediment rating curves for a small basin; Water Resources Research, V. 13, no. 3, p. 531-538.

Warner, L.A.
1968: Fluorometry in water survey; Unpublished internal report, Water Survey of Canada, 40p.

Weertman, J.
1964: The theory of glacier sliding; Journal of Glaciology, V. 5, no. 39, p. 287-303.

1966: Effect of a basal water layer on the dimensions of ice sheets; Journal of Glaciology, V. 6, no. 44, p. 191-207.

Wendler, G., Trabant, D. and Benson, C.
1973: Hydrology of a partly glacier-covered arctic watershed; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on the Role of snow and ice in hydrology, Banff, September 1972, I.A.H.S.-A.I.S.H. Publication no. 107, V. 1, p. 417-435.

Wilcox, W.D.
1909: The Rockies of Canada; Putnan, New York, 300p.

Wilson, J.F. Jr.
1968: Fluorometric procedures for dye tracing; United States Geological Survey, Techniques of water-resources investigation, Book 3, Applications of Hydrolics, United States Department of the Interior, 31p.

Young, G.J.
1970: Mass balance measurements related to surface geometry on Peyto Glacier, Alberta; in: Glaciers, Proceedings of the International Hydrological Decade Workshop Seminar, 1970, Vancouver, British Columbia, Canadian National Committee for the International Hydrological Decade, p. 11-20.

1974: Glacier mass-balance and terrain shape, a methodological study; Ph.D. Thesis, Department of Geography, McGill University, Montreal, 320p.

1975: Accumulation and ablation patterns as functions of the surface geometry of a glacier; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on Snow and ice, Moscow, U.S.S.R., August 1971, I.A.H.S.-A.I.S.H. Publication no. 104, p. 134-138.

1976: An approach to glacier mass-balance analysis utilizing terrain characterization; Inland Waters Directorate, Water Resources Branch, Scientific Series no. 60, Ottawa, 34p.

1977a: Relations between mass-balance and meteorological variables on Peyto Glacier, Alberta, 1967-1974; Proceedings of the Symposium on the Dynamics of temperate glaciers, Munich, Germany, 6-9 September, 1977, Zeitschrift für Gletscherkunde und Glazialgeologie, Bd. 13, Ht. 1-2, p. 111-125. Also - EOS, Transactions, American Geophysical Union, V. 58, no. 9, Abstract, 903.

Young, G.J.
1977b: The seasonal and diurnal regime of a glacier-fed stream, Peyto Glacier, Alberta; Proceedings of the Alberta Watershed Research Program Symposium, compilers R.H. Swanson and P.A. Logan, 31 August - 2 September 1977, Edmonton, Alberta, Northern Forest Research Centre, Information Report NOR-X-176, Forestry Service, Fisheries and Environment Canada, p. 111-126.

1980: Streamflow formation in a glacierized watershed in the Rocky Mountains, Canada; Date of Glaciological Studies, Chronicle, Discussion, Section of Glaciology of the Soviet Geophysical Committee and Institute of Geography, Academy of Sciences of the U.S.S.R., Moscow, July 1980, no. 39, p. 134-139.

1981: The mass balance of Peyto Glacier, Alberta, Canada, 1965 to 1978; Arctic and Alpine Research, V. 13, no. 3, p. 307-318.

1983: Hydrological relationships in a glacierized mountain basin; International Union of Geodesy and Geophysics, International Association of Hydrological Sciences, Proceedings of the Symposium on the Hydrological aspects of alpine and high mountain areas, Exeter, July 1982, I.A.S.H.-A.I.S.H. Publication no. 138, p. 51-59.

Zeman, L.J. and Slaymaker, H.O.
1975: Hydrochemical analysis to discriminate variable runoff source areas in an alpine basin; Arctic and Alpine Research, V. 7, no. 4, p. 331-340.

ABSTRACT

Hydrological, hydrochemical and suspended-sediment regimes at Peyto Glacier, Alberta (116° 33'W, 51° 40'N) during the 1981 ablation season showed significant seasonal and diurnal trends.

The seasonal hydrograph (May 19 - September 09) is divided into four components. Initially, during the months of May and June, as glacier snowmelt is retained in the snowpack and in blocked crevasses and conduits, runoff consists of a steady baseflow and snowmelt from non-glacierised areas. A freshet component, in late June and early July, results from a rapid release of meltwaters from major arterial conduits and from the snowpack. During July and August, the main ice ablation component, hydrological events occur in response to precipitation and icemelt events. Peaks in discharge coincide with periods of sustained high temperature or precipitation. A return to a steady baseflow takes place in late August and September as unfavorable climatic conditions curtail icemelt and runoff.

Hydrochemically, the meltwaters are initially "chemically-enriched" as they originate from the "ion-rich" subglacial zone. But as the ablation season progresses, "chemically-dilute" meltwaters from the supraglacial and

englacial zones are added to the subglacially routed waters resulting in lowering of the overall concentration by dilution. This dilution effect is also apparent in the electrical conductivity regime. Divalent cations, calcium (Ca^{++}) and magnesium (Mg^{++}) are the most abundant cations in Peyto Creek meltwaters.

The attached cationic concentration displays a seasonal trend in response to changing contact-times within the glacier system. Early and late season concentrations are high because low discharges, lead to increased contact-time while the high discharges of July and August result in decreased transit-time and lower concentrations. Calcium (Ca^{++}) is the most readily adsorbed cation.

The glacier suspended-sediment regime is very irregular seasonally and diurnally. Greater suspended-sediment concentrations are not linked to proportionally greater discharges and irregular pulses of sediment occur independently of discharge variations. These sudden releases produce peaks which occur both before and after the daily discharge peak. On certain occasions no apparent trend is visible. Thus, subglacial channel re-organisation under changing hydrostatic pressures and sediment availability are hypothesised to be the major factors influencing suspended-sediment output from Peyto Glacier.

RESUME

L'analyse estivale des régimes hydrologique et hydrochimique, et celle des sédiments en suspension, démontre des tendances saisonnières et journalières significatives au glacier Peyto en Alberta (116° 33'O, 51° 40'N).

L'hydrogramme saisonnier (mai 19 - septembre 09) se divise en quatre composantes. Pendant les mois de mai et de juin, le débit comprend un écoulement régulier de la zone sous-glaciaire et un écoulement issu de la fonte de la neige des zones non-englacées. L'eau de fonte de la neige à la surface du glacier est à cette époque accumulée dans les crevasses et les moulins bloqués de neige. Au début du mois de juillet, une crue printanière se produit. Elle est dûe à la libération soudaine des eaux de fonte piègées dans le glacier. La troisième composante, la période de l'ablation de la glace, se produit en juillet et en août. Ses principaux évènements hydrologiques sont dépendants des fluctuations climatiques. Les débits maximums se produisent pendant les périodes assez longues de températures élevées ou de précipitations. Enfin, à la fin du mois d'août et en septembre, des conditions climatiques non-favorables à la fonte de la glace entrainent un retour à l'écoulement régulier provenant de la zone sous-glaciaire tel qu'observé au début de la saison.

Les eaux de fontes du glacier sont originalement enrichies chimiquement car elles proviennent de la zone sous-glaciaire. Pendant l'été, ces eaux deviennent diluées par l'addition d'eau "chimiquement pure" des zones supra-glaciaires et inter-glaciaires. Cette dilution est également évidente dans le régime saisonnier de la conductivité électrique. Les cations bivalents, soit le calcium (Ca^{++}) et le magnésium (Mg^{++}) sont les plus abondants dans les eaux du ruisseau Peyto.

La concentration en cations adsorbés à la surface des sédiments en suspension démontre une tendance saisonnière. Les concentrations du début et de la fin de la saison sont élevées dû au temps de contacte plus long résultant du faible débit. L'inverse se produit en juillet et en août car les débits sont élevés. Le calcium (Ca^{++}) est le cation adsorbé en plus grande concentration.

Le régime du débit des sédiments en suspension est variable de façon saisonnier et journalier. Les fluctuations du débit n'amènent pas des variations de concentration en sédiment en suspension de tailles similaires. Des injections de sédiment se produisent indépendamment du débit. Des fluctuations soudaines de sédiments en suspension produisent des pointes soit avant ou après la crue journalière. A certaines occasions aucun patron est évident. Les causes probables de cette irrégularité semblent être la réorganisation des ruisseaux sous-glaciaires dû à des changements de pressions hydrostatiques et la disponibilité des sources en sédiments.