RECENT GEOMORPHIC CHANGES IN THE SNOUT AND PROGLACIAL ZONE OF THE WHITE AND THOMPSON GLACIERS, AXEL HEIBERG ISLAND, NORTHWEST TERRITORIES.

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ABSTRACT

Current geomorphic processes and recent morphological changes were investigated in the lower ablation and proglacial zones of the White and Thompson glacier complex, Axel Heiberg Island, Northwest Territories. Study of glacier front evolution and frontal moraine development over the last three decades (1959-1989) is based on photographic, cartographic and geodetic information acquired by researchers since the late 1950's updated by surveys of glacier-distal moraine perimeter position in the summer of 1989. Even though both glaciers are juxtaposed in the lowermost ablation zone, it was found that the White Glacier has receded circa 100 m while the Thompson Glacier front has progressed downvalley by approximately 500 m. Other findings include: (1) the uneven retreat of the White Glacier ice front; (2) the shrinking widthwise of the White Glacier and lengthwise of its frontal moraine due to the pushing action of the advancing Thompson Glacier and (3) the asymmetric development of the Thompson Glacier frontal moraine.

A series of measured transects and comparative photography for 1989 and 1990 provided information on short-term morphologic changes occurring within and beyond the moraine complex. In the case of the White moraine, dramatic changes were found to be associated with thermokarst processes enhanced by catastrophic drainage of an ice-dammed lake. Current processes in the push moraine composed of stacked up slabs of outwash material resulting from glaciotectonic activity and lying ahead of the Thompson Glacier were found to corroborate the asymmetric development trend toward the southwest that had been noted in earlier studies. This study also suggests that deep seated thrusting (rather than simple bulldozing) is the main formative process for the Thompson Glacier push moraine.

RESUME

La dynamique récente de la zone d'ablation inferieure du complexe glaciaire formé par les glaciers White et Thompson (île Axel Heiberg, Territoires du Nord-Ouest) ainsi que les processus géomorphologiques actifs au droit de la zone proglaciaire constituent le propos du present memoire. L'étude de l'évolution du front glaciaire et du développement des moraines frontales au cours de la période 1959-1989 s'appuie sur une mise en commun de renseignements de nature photographique, cartographique et geodésique glanés par divers chercheurs depuis la fin des années 50 ainsi que sur des données d'arpentage ayant trait à la position du périmètre des moraines acquises à l'été 1989. En dépit du fait que les deux glaciers reposent l'un contre l'autre dans leur partie inférieure, on a noté un retrait du front du glacier White d'environ 100 m, mais une progression d'environ 500 m du front du glacier Thompson. On a également mis en évidence (1) le retrait inégal du front du glacier White, (2) le rétrécissement du glacier White et de sa moraine frontale par la poussée du glacier Thompson et enfin (3) le développement asymétrique de la moraine frontale du glacier Thompson.

Les changements morphologiques sur une courte periode dans le complexe morainique et dans la zone d'épandage ont été étudiés par des mesures sur le terrain et mis en exergue par des photographies prises en 1989 et en 1990. On impute au cumul des processus de thermokarst et d'érosion fluviatile (notamment la débâcle causée par le drainage rapide d'un lac de barrage glaciaire) la dégradation marquee de cette masse riche en glace qui constitue la moraine d'ablation frontale du glacier White. Les manifestations sur le terrain de l'évolution récente de la moraine de poussée formée par la structure d'empilement édifiée immédiatement à l'aval du glacier Thompson dans du matériel fluvioglaciaire par des processus glaciotectoniques indiquent le caractère contemporain du développement asymétrique vers le sud-ouest tel que proposé dans des études antérieures. Les observations permettent enfin d'affirmer que les mécanismes qui produisent la structure d'empilement ne sont pas de simples poussées horizontales de surface, mais bien des poussées qui originent en profondeur.

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FIGURE 0.0 The M[c]Gill High Arctic Research Station on Axel Heiberg Island, Northwest Territories. A meteorological station was set up in the early days of the Jacobsen-M[c]Gill Arctic Expedition near the upper (right) cabin. This station is referred to in work published by the expedition as "Base Camp" (1 July 1990).

CHAPTER 1: INTRODUCTION

1.0 INTRODUCTION

Studies pertaining to many aspects of earth science including glaciology, geology, geomorphology, climatology, hydrology, limnology and botany have been conducted since the late 1950's in the Expedition Fiord area of Axel Heiberg Island, Northwest Territories. Most of this scientific work, which was carried out in conjunction with research programs operated by Dr. F. Muller prior to his death in 1980, was ultimately published in a number of publications known as the Axel Heiberg Island Research Reports (e.g. ADAMS 1966, KALIN 1971). A number of papers were also published in a variety of scientific journals (e.g. MULLER 1962, OHMURA 1982).

During the first half of the 1980's, scientific activity in the Expedition Fiord area suffered from the departure and death of Fritz Muller and from the combination of increased costs and lower support. As a result, research activity in this area was at a much lower level during the last decade than it had been in the previous 20 years (ADAMS 1987). Despite these problems, efforts to revive the M^c^Gill High Arctic Research Station in the more recent past have contributed to a new and stimulating atmosphere of scientific interest and cooperation involving researchers from several universities and government agencies. The present thesis is a direct outcome of this renewed momentum.

1.1 STUDY OBJECTIVES

The general objective of this dissertation is to investigate the range of geomorphic processes influencing the glacier snout and the terminal moraine area of the White and Thompson glaciers and to assess their relative rates of activity by comparison with data from an earlier phase of research in this area. A direct consequence of this research will be the updating of the database concerning glacier extent and terminal processes available for this area. In view of recent concerns for the implications on the cryosphere of an eventual climate amelioration, there is a need to maintain long-term records and research programs on glaciers as a basis for statistical interpretation and detection of global warming.

Accordingly, the specific aims for this research are:

(1) estimate ice front displacement over the period for which information is available (roughly the last 30 years);

(2) investigate geomorphic changes in the proglacial zone due to ice front displacement;

(3) determine the most active geomorphic processes currently affecting the proglacial zone;

(4) assess present and future trends in the evolution of the lower ablation and proglacial zones in light of field evidence.

1.2 THESIS STRUCTURE

The problem investigated in this paper can be summarized in the two following questions: (1) how has the snout area of the White and Thompson glacier complex evolved during these last three decades of intermittent observations (roughly from 1960 to 1990) and (2) what are the most significant geomorphic processes currently operating in the moraine complex? An ultimate goal of this study is to assess the ways current processes bear any relationship or consequence with the long term snout processes and evolution.

The methods used together with a review of literature are presented in the second chapter. The third chapter focuses on the general evolution of the snout area over the last 30 years, while chapters 4 and 5 comprise field observations on present-day geomorphic processes pertaining to more specific subzones of the glacier snout area.

The factual approach used in this thesis fits in well with the fundamental aim of the early expedition (hence the name Expedition Fiord) to Axel Heiberg Island, which was to "... study the evolution of the mountainous and strongly glacierized and glaciated area of the central part of western Axel Heiberg Island" (MULLER 1961a, p.2). The geographical names used in the text (except for those within inverted commas) were proposed by the early expedition and most of them had been officialized by the mid 1960's by the Canadian Permanent Committee on Geographical Names (now the Canadian Board on Geographical Names) (MULLER 1963a). They were used on virtually all the published maps and reports pertaining to the Expedition Area of Axel Heiberg Island.

1.3 STUDY AREA

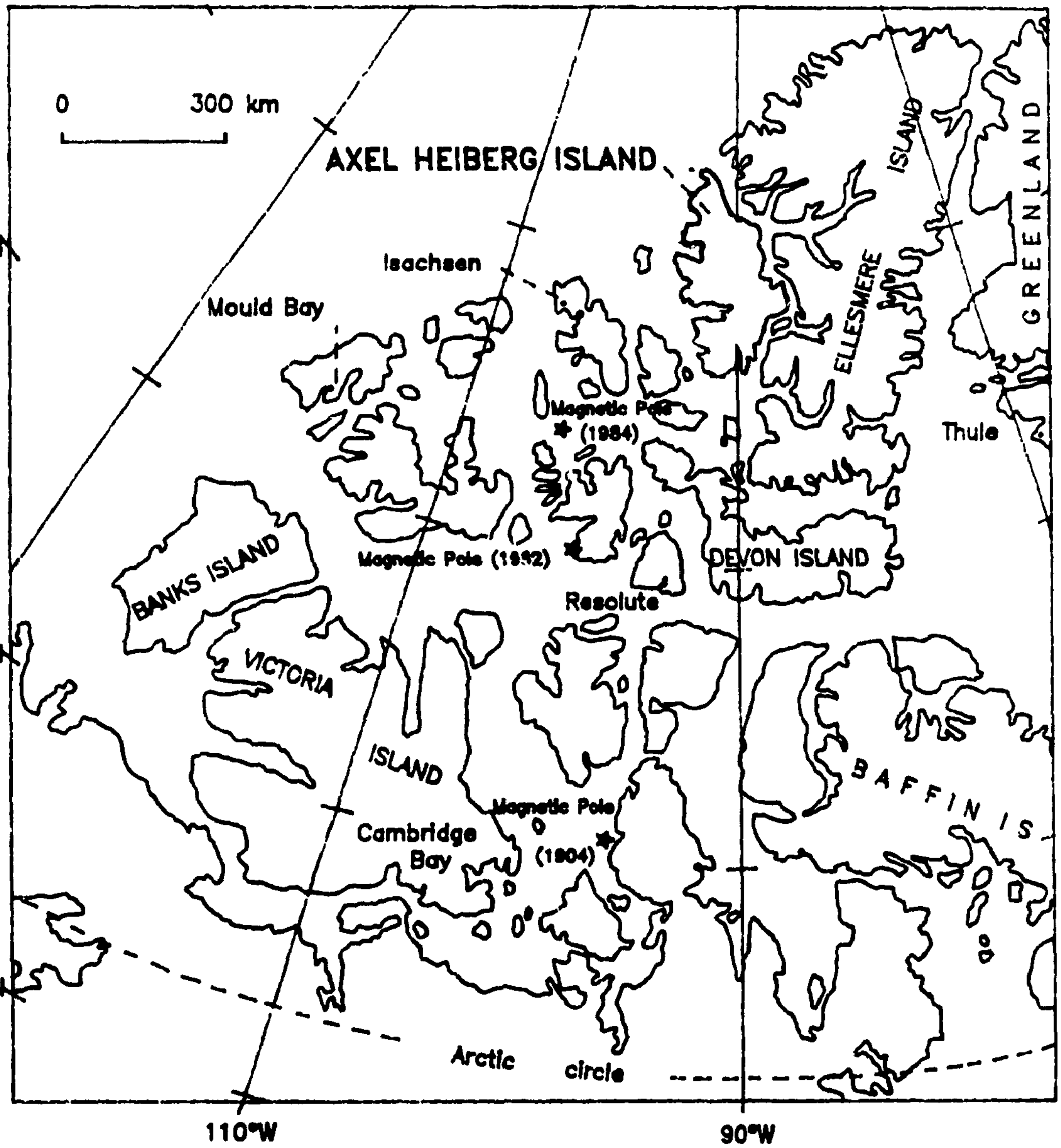
1.3.1 GENERAL SETTING

Axel Heiberg Island is the second most northerly of the larger islands in the Canadian High Arctic (figure 1.1). It is located within the Sverdrup Basin (or Islands) geological region, and is part of the Queen Elizabeth Archipelago. It extends from 78^0 to 81^0 N and from 84^0 to 96^0 W.

The Expedition Fiord area is located in central south-western Axel Heiberg Island (figure 1.2). It is in the "axial part of the Sverdrup Basin", which is characterized by N-S trending structures that are linked to a major orogeny that occurred during the Tertiary period (FRICKER 1963, p.4). Although the total vertical sedimentary sequence contains units dating from the Upper Paleozoic to the Tertiary, only the Mesozoic and Tertiary stratigraphic formations are observable in the mountainous landscape of the Expedition Fiord area (FRICKER 1963). Outcrops of Upper Paleozoic rocks are found in the form of anhydrite and gypsum diapiric intrusions. According to Hoen (1964 p.1), "the Expedition area and the region immediately west and south of it contain the greatest concentration of anhydrite diapirs in the Canadian Arctic Archipelago". At least one such intrusion, which is associated with highly mineralized perennial springs, is located immediately southeast of the McGill High Arctic Research Station.

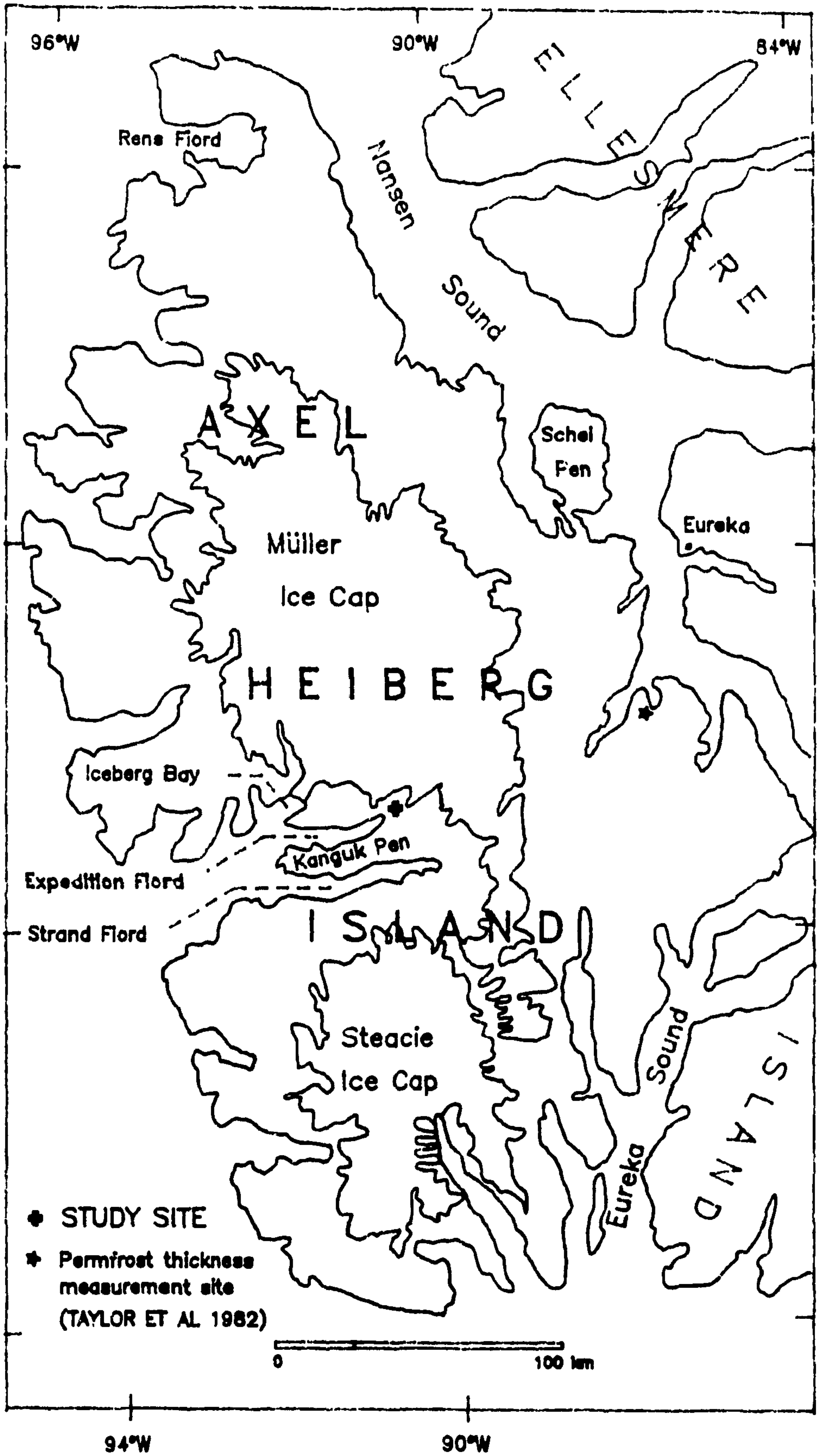
Axel Heiberg Island is roughly 370-km long and 190-km wide and it entirely lies within the Polar Desert area of the High Arctic (TEDROW 1977), even though the more lush parts (like the Expedition Valley) may be associated with

FIGURE 1.1 GENERAL LOCATION MAP



NOTE: Magnetic pole position from NEWITT and NIBLETT (1986)

FIGURE 1.2 AXEL HEIBERG ISLAND



the tundra zone.

The climate of the Expedition Fiord area is best approximated by the data pertaining to Eureka, a weather station operated by Atmospheric Environment Service and located a little more than 100 km northeast of Base Camp (see figure 1.2) on the west coast of Ellesmere Island. Temperature normals computed for Eureka (80^0 0'N 85^0 56'W) for the 1951-1980 period are presented in the first part of figure 1.3.

Mean monthly temperature values averaged over the 1960 to 1973 period for Base Camp (79^0 26'N 90^0 46'W) are available from early spring to end of summer (ALLAN et al 1987). They are shown in the second part of figure 1.3 to correspond very closely to data compiled for Eureka. However air temperature data for more recent years are only available for limited and discontinuous periods of time. Mean daily temperatures were computed for the period of occupation of the station in 1989 and 1990 by averaging the minimum temperature recorded between 19:00 to 7:00 and the maximum recorded between 7:00 and 19:00 (local time). Mean monthly temperatures were derived by averaging the mean daily temperatures and they are included in the second part of figure 1.3. The coldest temperature for the 1989-1990 winter recorded about 0,5 km downvalley from the White Glacier (at the station identified as "Outwash Plain" in HAVENS ET AL [1965, p.2]) was -64^{0}C. For the 1988-1989 winter, the minimum recorded was -58,5^{0}C. Summer highs recorded at the Base Camp station were 13,5^{0}C (sometime between 16 July and 20 August 1989) and 17^{0}C on 27 June

1- MEAN MONTHLY TEMPERATURE (^{0}C) FOR EUREKA (80^{0} 0'N 85^{0} 56'W)

Normal values averaged for the 1951-1981 period.

Month	Mean monthly temperature
JAN	-36,4
FEB	-38,0
MAR	-37,4
APR	-27,6
MAY	-10,7
JUN	1,8
JUL	5,4
AUG	3,3
SEP	-8,3
OCT	-22,1
NOV	-31,5
DEC	-34,8

Mean annual air temperature for the 1951-1981 period is -19,7 degrees Celsius.

SOURCE: CANADA (1982)

2- MEAN MONTHLY TEMPERATURES (^{0}C) FOR BASE CAMP (79^{0} 26'N 90^{0} 46'W) EXPEDITION FIORD, AXEL HEIBERG ISLAND, NWT.

	MAY	JUNE	JULY	AUGUST
1960-1973 *	-10	1,3	5,8	3,6
1989 **	--	--	1,8	--
1990 ***	--	6,8	4,9	--

* Average values, between 1960 and 1973; from Allan et al 1987.

PARTIAL DATA, SPRING AND SUMMER OF 1989 AND 1990.

** Based on 11 days of measurement, between 5 and 15 July.

*** Based on last 24 days of June and first 20 days of July.

FIGURE 1.3 TEMPERATURE DATA FOR EUREKA AND BASE CAMP.

1990.

Two ice caps as well as at least 26 minor highland ice fields and a few smaller lowland ice sheets together with their outlets occupy about one-third of the total island area of 37 200 km^2 (MULLER 1961b). The biggest of the two ice caps, the Muller Ice Cap (formerly named M'Gill Ice Cap and still earlier referred to as the Akaioa Ice Cap according to MERCER 1975), covers an estimated area of 7250 km^2 in the central north portion of the island (REDPATH 1965). The Steacie Ice Cap (5100 km^2) lies in the southern part of the island (see figure 1.2).

Geomorphic processes on the island as a whole are dictated by the presence of glaciers and by the glacial and periglacial environments they create. Large outlet glaciers emanating from highland ice fields which are developing (or are maintained?) on the island's highest reaches (up to 2000 m in the central mountain range, the Princess Margaret Range) together with a variety of smaller glaciers directly or indirectly influence the landscape evolution of a significant proportion of the island's unglaciated areas. Not only does the presence of glaciers affect those areas covered by ice, but it also dictates geomorphic evolution in vast proglacial zones. The latter zones can be subdivided into (1) the areas subject to the actual movement of ice masses and (2) the areas influenced by the action of meltwater.

Indirectly, glaciers determine the landscape evolution of the whole island by virtue of their effect on climatic conditions. Frost action, mainly evidenced in the field by the shattering of rock outcrops and the sorting of material, combines with a variety of concurrent geomorphic processes, most important of which in the Expedition Area are slope processes, to produce characteristic periglacial landforms such as ice-wedge polygons, mudboils, solifluction lobes, stripes and felsenmeer. In one of the few studies on the geomorphology of the island ever to have been conducted, Robitaille (1961) viewed the Expedition Area as belonging to the central mountainous zone (one of the five morpho-structural zones he had defined for the whole island), a zone which is characterized by a wide variety of periglacial environments that depend mainly on the intensity of slope processes and amount of vegetation cover.

Permafrost studies in the Expedition Area are scarce. The data obtained are mostly related to active layer depth and do not form exhaustive records. An active layer thickness of at least 1 m was reported by Kalin (1971) for outwash gravel. Maximum thaw depths on the order of 80-90 cm (by early August) were recently measured in large high-centred ice-wedge polygons occurring in the study site (POLLARD 1991, personal communication). In the summer of 1990, a fresh trench in stabilized outwash material lying a few decameters ahead of the White Glacier terminal moraine showed the top of an ice wedge to lie at 1,2 m below surface.

Even though no thermal profile of the upper few meters of the ground is available, it is obvious from the high latitudinal position of the island that permafrost is continuous. A permafrost thickness of over 500 m was documented in an exploration well (see figure 1.2) on the east side of Axel Heiberg, roughly 80 km from Expedition Fiord (TAYLOR ET AL 1982). However, there may be important local differences with regards to permafrost depth and thickness in the Expedition Area owing to the proximity of the ocean and to the presence of geothermal anomalies. The presence of springs (apparently geothermal in origin) about 3 kilometers downriver from the glacier terminus illustrates the potential for thermal disturbances in the permanently frozen material of the Expedition Area.

Over the winter, the mineral springs (which emerge from the southeast flank of Gypsum Hill, the northwestern outcrop of the Expedition anhydrite diapir [HOEN 1964]), form a vast 1,5 to 2-meter thick icing that progrades toward the center of the Expedition River (figure 1.4). The springs are conspicuous in the landscape by their noticeable H_2S emanations and also by the accumulations of gypsum precipitate that form white and yellowish patches. A large icing also forms every winter (at least during the 1987-1988, 1988-1989 and 1989-1990 winters) next to the front of the Thompson Glacier, immediately west of the western corner of the Thompson Glacier moraine. Although it is not known whether this last icing owes its presence to a subglacial discharge or to geothermal springs, it should be apparent that permafrost conditions in the Expedition Area are most probably variable on a local scale.

1.3.2 STUDY SITE

The study site lies about 8 kilometers inland from the

FIGURE 1.4 Icing formed by discharge from perennial springs occurring near the base of Gypsum Hill (13 June 1990).

head of Expedition Fiord, on the central west coast of the island. It lies within a 3 X 1 km rectangle that extends from latitudes 79^0 24'N to 79^0 26'N -- which approximately corresponds to the northernmost extents of Siberia -- and longitudes 91^0 30'W and 91^0 45'W -- which in more meridional terms corresponds to a location about 180 km east of Winnipeg. It encompasses the termini of two (or more?) merging glaciers as well as the moraine complex they produce. Elevations vary from 225 m on the Thompson Glacier down to about 30 m asl at the toe of the frontal moraine of the same glacier. Figure 1.5 shows the site location.

The largest ice body is the Thompson Glacier, which is a 35-km long and 3-km wide outlet glacier (OMMANNEY 1969) that originates from the western rim of the Muller Ice Cap. It has an estimated area of 230 km^2 and it flows towards the south at an average gradient of 3 per cent (KALIN 1971). In its lower half, however, a gradient of only 1 percent was estimated by Redpath (1965). The Thompson Glacier is joined along its sides by a number of smaller valley glaciers that coalesce with the main stream. In its lower ablation area, the Thompson Glacier is met by the White Glacier, which is a 15-km long and 1-km wide ice stream that is considered to be an alpine glacier because of the clear delineation of its accumulation zone and of the distinctiveness of the latter from the accumulation zone of the Thompson Glacier, the Muller Ice Cap (MULLER 1961b). Upstream from the junction of the two glaciers, an ice-dammed lake named Between Lake (figure 1.6) forms every summer as meltwater accumulates. It has been witnessed to drain as a jokulhlaup almost every summer during the first half of the 1960's (MAAG 1969).

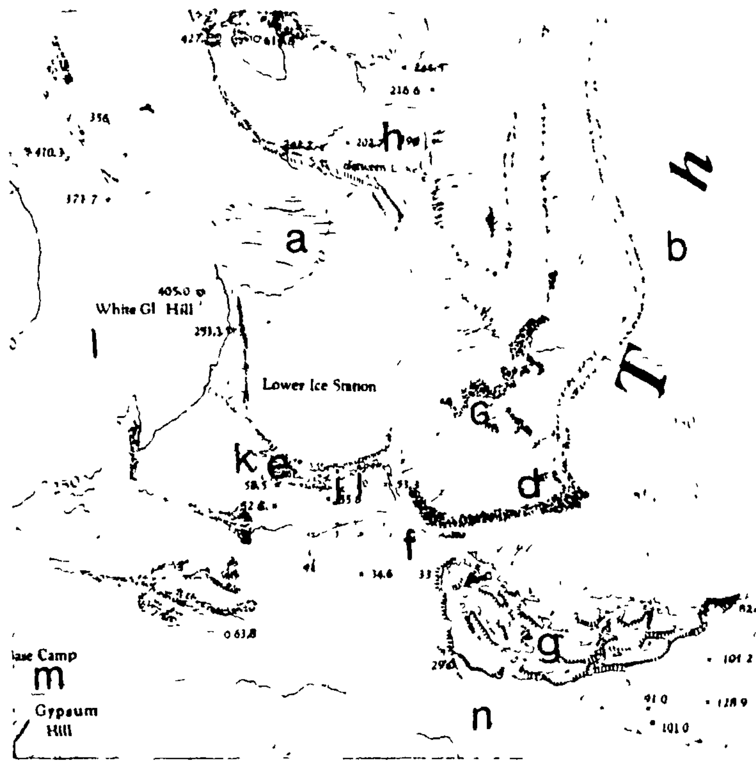


FIGURE 1.5 Map of the site location (portion of CANADA 1962a at a scale of 1: 50 000) including a list of features that will be referred to in this thesis: (a) White Glacier; (b) Thompson Glacier; (c) "W-shaped" moraine; (d) "S-shaped" moraine; (e) White Glacier moraine; (f) moraine-free zone; (g) Thompson Glacier moraine; (h) Between Lake; (i) Yellow Cairn Channel; (j) Stevenson Channel; (k) Ermine River; (l) White Glacier Hill; (m) Gypsum Hill and (n) Expedition River sandur. Since this map portrays the situation as of 1959, the features discussed in this thesis are either not illustrated or cannot be positioned accurately.

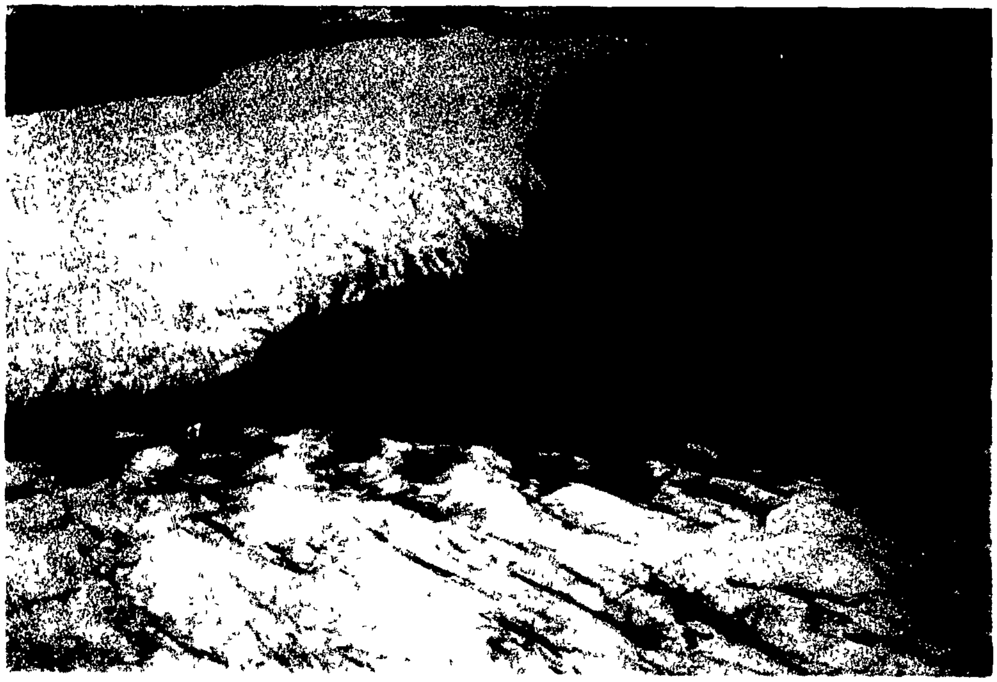


FIGURE 1.6 Between Lake at an intermediate stage. The White Glacier extends from the top of the photo and the Thompson Glacier is in the near foreground. Note the higher water levels (marked by an arrow) along the shore of the lake (16 July 1989).

The White Glacier extends from 1600 to 80 m asl (BLATTER 1985) and has a gradient averaging 10 per cent (REDPATH 1965). This average gradient, however, hides a much greater variability in slope angles than in the case of the relatively uniform Thompson Glacier. In some serac areas, for instance, slopes are well above 10 percent, whereas in other places it may only be 4 or 5 percent. The initial southeasterly flow of the White Glacier changes to correspond with the southerly flow of the much more massive Thompson Glacier upon meeting it in its lower ablation area. The difference in size between the two glaciers is best conveyed in the estimated values of ice volume: 115 km^3 for the Thompson Glacier compared to 7,6 km^3 for the White Glacier (OMMANNEY 1969).

At the snout, the merging glaciers form a 4-km wide ice tongue (figure 1.7). This body of ice is not homogeneous, however, as both contiguous glaciers are separated by a relatively narrow trench that may have been formed and/or maintained over the years by the catastrophic emptying of Between Lake.

The western portion of the ice terminus is occupied by the White Glacier. It is currently about 0,8 km wide and its front presents medium to high slopes. Seismic investigations along a transect located about 4 kilometers upvalley from the position of the glacier front in the early 1960's showed ice thicknesses on the order of 200 m (REDPATH 1965). In the eastern portion of the glacier complex, the Thompson Glacier lies quite substantially ahead (south) of the western portion and it displays an ice cliff and

FIGURE 1.7 View of the 4-km wide terminus of the Expedition glacier complex formed by the merging of the White Glacier (left) and Thompson Glacier, looking north. Tributary glaciers in the center-right portion of the photograph are about 5 km from the ice front. Note the presence of surficial moraines on the Thompson Glacier. The left and right moraines on the photo are respectively referred to in the text as the "W-shaped" and "S-shaped" moraines. Figure 5.1 shows a vertical view of these moraines (24 June 1990).

sometimes an overhang over 40 m high. Ice depths on the order of 500 m were reported about 8 kilometers up from the position of the glacier front in the early 1960's (REDPATH 1965). Using gravity measurements, Kalin (1971) found ice thicknesses on the order of 250 m about 1,5 km up from the current position of the glacier front.

The glacier foreland consists of a moraine complex divided into two portions that are separated by a moraine-free zone (figure 1.8). To the west, the ablation moraine of the White Glacier shows a rolling topography extending about 300 m in front of the glacier terminus in its central zone. It has an average height (relative to the floodplain) on the order of 10 m.

To the east, a much more impressive frontal moraine complex composed of glacially-thrust frozen outwash material occurs. The Thompson Glacier moraine is shaped in the form of a crescent grossly corresponding to the shape of the ice front. It displays a rugged topography with its highest peaks (on the order of 100 m in altitude) rising about 10 m above the glacier terminus. Thrusting structures and other indicators of glaciotectonic activity along the outer edge of the moraine (especially in the southwestern portion) testify of recent downvalley progression of the moraine. In terms of size, the Thompson Glacier moraine (the term "moraine" will be used in this paper as a strictly descriptive term for the Thompson Glacier frontal deposits) is about two and a half times as wide and twice as long (length being parallel with the ice front) as that of the White Glacier.

FIGURE 1.8 View of the moraine complex, looking east. Note the difference in surface relief between the terminal moraine of the White Glacier (foreground) and that of the Thompson Glacier (center). The two moraines are separated by a moraine-free zone (11 May 1989).

From the above description, it is apparent that the study area can be divided into two geomorphological zones, namely that of the retreating White Glacier and that of the advancing Thompson Glacier snouts. This basic dichotomy constitutes the analytical framework of this paper.

CHAPTER 2: BACKGROUND AND METHODS

2.0 INTRODUCTION

Geomorphological changes and processes in the snout area of a glacier complex are investigated in this thesis. Before entering the discussion on the results per se, a logical first step is to present a review of pertinent literature as well as an overview of methods.

The first part of this chapter presents a literature review pertaining to (1) general processes and landforms at ice fronts, with a special emphasis on retreating (or stagnant) glaciers and (2) glaciotectonism and other processes related to advancing glacier fronts. Since the overriding factor of landform evolution in the study area is the downvalley progression of the better portion of the glacier complex (it will be shown later in this thesis that the front of the glacier complex under consideration is partly retreating and partly advancing), greater care was given in reviewing the literature on frontal processes at the terminus of advancing glaciers.

The second part of this chapter presents an overview of methods both relating to field work and to data analysis. Specific methods are mentioned in the result chapters.

2.1 REVIEW OF LITERATURE

2.1.1 GENERAL PROCESSES AT NON ADVANCING GLACIER FRONTS

The wide variety of glacial processes can be divided into two groups: (1) erosional and (2) depositional. No attention will be payed here to erosional or "destructive" processes since they are best observed after the glaciers have disappeared. Thus only depositional or "constructive" processes will be considered.

A number of papers about glacial processes and deposition at the front of stagnant or retreating glaciers were published. Terminal depositional features and processes at currently retreating glaciers were and are studied in many areas of the world (e.g. KARLEN [1973] in Northern Scandinavia, BOULTON and VAN DER MEER [1989] in Spitzbergen, CHINN [1985] in the dry valleys of Antarctica etc). Mapping of ice-cored terminal moraines in western Canada was performed by Kupsch (1962). Aspects of drainage and sedimentology in terminal glacial deposits were investigated in papers like Lawson (1979) and Boulton and van der Meer (1989).

2.1.2 PROCESSES AT THE FRONT OF ADVANCING GLACIERS

2.1.2.1 Glaciotectonism

So far as this thesis is concerned, papers on glacial processes at the front of advancing glaciers are more important, for the driving mechanism which is at the source of most geomorphological changes in the proglacial zone of the White and Thompson glacier complex has been the downvalley progression of the Thompson Glacier and the edification of a glaciotectonic structure in the rounded sandur deposits.

Modern literature on structures related to glaciotectonic activity places a great deal of emphasis on Pleistocene examples both in consolidated and in unconsolidated material (e.g. papers by Cowan [1968], Dredge and Grant [1986], Hicock and Dreimanis [1985], Kupsch [1962], Mackay [1959], Moran [1971] and Rutten [1960]). Although the mechanics that gave rise to Pleistocene structures may be similar to those that are responsible for currently developing features, severe limitations on comparative analogies are imposed by the fact that Pleistocene structures are often an order of magnitude greater than recent structures.

Fundamental ideas regarding the classification and description of glaciotectonic structures are found in Aber (1988), where five genetic types of "constructional glaciotectonic landforms" are presented. These forms are: (1) "large composite-ridges", (2) "small composite-ridges", (3) "cupola hill", (4) "flat-lying megablock" and (5) "hill-hole pair". Among these, however, the "hill-hole pair" is identified as the basic combination of ice-scooped basin and ice-pushed hill of which all glaciotectonic landforms are variations.

Among the five genetic types presented above, the "composite-ridges" category best describes the Thompson Glacier push moraine. Composite-ridges are often arcuate, concave up-ice and are presumably the result of ice shoving. According to Aber, the terms "composite-ridge" or "ice-thrust ridge" are preferable to the many alternative denominations found in the literature (e.g. stauchmorane, push moraine, ice-thrust moraine etc) since they do not carry any structural connotation and do not include the often misused word moraine. Furthermore he adds:

> "The folds and thrust blocks that form ridges have usually been detached, transported some distance, and stacked up in an imbricated structure. Composite-ridges are, thus, allochtonous in a glaciotectonic sense, and it may be possible to recognize the up-ice source from whence (sic) material in the ridges was derived" (ABER 1988, p.283).

Cut-off values between "large" and "small" composite ridges are proposed where a large structure is at least 100 m in height, 5 km in width and 50 km in length.

An extensive treatment of the five glaciotectonic structural types using the "case-history" method is found in Aber et al (1989). For the authors, "... push-moraines are a restricted subset of small composite-ridges that consists largely or wholly of glaciogenic strata" (ABER et al 1989, p.47). Hence, they argue, "composite-ridges that contain appreciable non-glacial material should not be called push-moraines." The theoretical considerations on glaciotectonic structure formation presented in Aber et al (1989) will be introduced in chapter 5.

Problems relating to terminology are illustrated in a number of papers. The morphologic classification of moraines found in Goldthwait (1988) conveys the type of ambiguity with which specialists of Quaternary deposits are confronted. For Goldthwait, a "push moraine" (Stauchmorane) is defined as a "belt of low hills, generally crescentic, raised above ground moraine" or as "any soft pre-glacial or glacial material raised and deformed by ice-edge thrusting". This definition is "subtly different from [the definition of] thrust moraine", which is defined as "dragged older basement crescentic lead edge of slabs with till or till-on-bedrock blocks" (GOLDTHWAIT 1988, p.274).

The question of the role of permafrost in ice-thrust ridging was mentioned in a number of papers. Although it was demonstrated in recent studies (e.g. SCHLUCHTER 1983) that permafrost is not necessary for the preservation of moving structures in a push moraine as a glacier advances (this conclusion had already been proposed by MACKAY and MATTHEWS 1964), it is difficult to envisage the formation of such a huge structural landform as the Thompson Glacier moraine, which is built from non cohesive openwork gravel, without the presence of permafrost. In New Zealand, some glaciers were noted to push into unconsolidated outwash gravels but glaciotectonic structures were not found to be preserved (SOONS 1990, personal communication).

The argument that development and preservation of large deformation structures in unconsolidated material most likely require the ground to be in a permanently frozen condition is expressed in Humlum (1985) and Rutten (1960). The implication in this argument is that the role of permafrost (or more suitably of ice bonding) in the edification of ice-thrust moraines is basically one of making the stratigraphic succession of unconsolidated sediments more competent to transmit the stresses that will cause deformation.

Lately, a number of studies have concentrated on describing recent glaciotectonic phenomena in soft proglacial material. Seven of these studies are particularly interesting within the context of the present research.

Boulton and van der Meer (1989) report cases of "glacially-pushed" sediment in western Spitzbergen. Deformation structures are described and a host of related information, namely on sedimentary and structural characteristics of materials, is presented. The specific case they are studying, however, is one of a glacier that produced a push moraine in material with a relatively high proportion of fines sometime in the 19th century, but which is currently decaying in its lower ablation zone.

Eybergen (1987) describes a 100-m long by 40-m wide "complex of lobate ridges more or less parallel to the glacier margin" at the Turtmannglacier in Switzerland. Processes responsible for the formation of this complex of ridges are summarized by the author as follows:

> "Apart from the suggested thrusting of mainly outwash deposits during the advance in the western part, the process of bulldozing (largely being a horizontal pushing event) probably played a minor role in the formation. Strictly, it can only account for the displacement of frontal material resting against a moving ice front" (EYBERGEN 1987, p.227).

Boulton (1986) reports interesting cases of short-term fluctuating glacier fronts (retreating in the summer and advancing in the winter), a process which induced the formation of "push moraines". Examples of the sedimentological implications of longer-term glacier front advances are also reported. Similarly, Worsley (1974) describes " `annual' moraine ridges" that formed each winter between 1957 and 1970 due to the advance of the Austre

Okstrindbreen Glacier in Northern Scandinavia. The ridges are thought to have been formed primarily by ice push, but the hypothesis of a squeeze process could not be rejected.

An "imbricate push moraine" a few decameters in width with a maximum height of 10 meters along the front of the Hofdabrekkujokull in Iceland is described in Humlum (1985). The following quote illustrates Humlum's view on the formation of this particular moraine:

> "As the glacier overrides areas with glaciofluvial net sedimentation, it pushes into proglacial sediment and, by thrusting, a slab of frozen sediment is raised in the glacier foreland. As it rises, it bends to slide along the undisturbed proglacial surface farther away from the glacier ... Thus the low frontal ridge is formed. During the continuing advance, the thrust slab is slowly rotated and pressed "backward" up the glacier front, while new slabs are produced at the glacier toe. Gradually an imbricated structure is formed, and individual slabs may be somewhat tilted, deformed, and fractured. As the push moraine grows in height, it tends to deform by creep due to its own weight. Folds and small overthrusts may be generated by this process. Other folds may be the result of the sediment being compressed between the uppermost slabs and the sediment above" (HUMLUM 1985, p.191-193).

The readvance of the Findelengletscher in Switzerland during the late 1970's and early 1980's (which was measured to be 136 m between October 79 and October 81) is described in terms of its sedimentological implications, namely a "low production of 'new till' but a voluminous remobilisation of older glacial deposits at the lateral and frontal ice margin" in Schluchter (1983 p.95).

A last but important paper about currently developing moraines in proglacial material is that of Kälin (1971) published as a Axel Heiberg Island Research Reports. This paper constitutes the only substantial research dealing specifically with the Thompson Glacier moraine. The data presented in Kalin's work are most interesting in that they contain a great deal of precise surveying measurements concerning the moraine during the mid 1960's (see next chapter). This report will be referred to on many occasions throughout this thesis for comparative purposes.

2.1.2.2 <u>Apron entrainment</u>

Apron entrainment constitutes another aspect of glacial processes at the front of advancing glaciers. Such processes were noted to occur all along the Thompson Glacier front. The only paper reviewed for this subsection is that of Evans (1989), where apron entrainment at the front of glaciers in northwestern Ellesmere Island is described.

2.2 **METHODS**

2.2.0 <u>INTRODUCTION</u>

Meeting the objectives stated in section 1.1 required the collection and analysis of various types of data. Determining the amount and nature of change in the glacier snout area implied a thorough investigation of all published work (mainly the Axel Heiberg Island Research Reports), maps and air photographs. Surveying work was performed in the summer of 1989 so as to provide up-to-date information on the position of the distal edge of the moraine complex. A map containing all the pertinent information was then produced. It forms the basis of chapter 3. Field observations and measurements as well as photographic material collected in 1989 and especially in 1990 helped portray current trends in the geomorphic evolution of the moraine complex. Those observations are synthesized in the last three chapters of this paper.

2.2.1 DETERMINATION OF RECENT LANDSCAPE EVOLUTION

2.2.1.1 Fieldwork and preparation

Although air photo coverage of the area is extensive (see Appendix 1 for a full listing), variations in scale and in overall picture quality, resolution and area covered made its use overly complex and unreliable for overlaying and comparative mapping. The photos are, however, used to illustrate the structural evolution of the Thompson Glacier moraine in chapter 5. Instead, it was decided to survey the position of the distal edge of the moraines in relation to points that had been first surveyed in 1960 by D. Haumann of the Photogrammetric Research Section of the National Research Council of Canada. The results of the 1960 survey were used as reference points on a map compiled from a series of 1959 air photographs taken by the Royal Canadian Air Force. (Other photographs acquired in the summer of 1959 by the department of Energy, Mines and Resources constitute the first set of good quality vertical air photographs of the Expedition glacier complex taken by a non military organization.) A reproduction of this map at a scale of 1: 50 000, which was done by the Army Survey Establishment in 1962 (CANADA 1962a), was used as the reference map for overlaying the 1989 survey data. Figure 2.1 shows the portion of the 1: 250 000 map of Axel Heiberg Island (CANADA 1967) that covers the Expedition Area.

The grid superimposed on the 1962 topographical map (CANADA 1962a) is an XY reference system, determined by

FIGURE 2.1 The Expedition Fiord Area; part of Canada (1967). Scale is 1: 250 000.

surveying in the early 60's (HAUMANN 1961), in which one unit is equal to one meter. This local grid is also tied in with geographical coordinates by referencing the X and Y units of the grid (which are respectively sets of user-defined longitudes and latitudes) to two locations in the Thompson Glacier area for which precise geodetic information is known. Unfortunately, precise survey data are found in Haumann (1961) for only two locations in that portion of the map which covers the study area. One of those locations was no longer existing in 1989 because it was overriden by the Thompson Glacier sometime in the last 30 years. The remains of the second location were found during the 1990 field season, after all the surveying work had been completed.

Nevertheless, two rock cairns which are identified on the 1962 reference map were found in the field. These two locations, identified as Station 3 and Point 9 for the 1989 survey exercise, were graphically transposed onto figure 3.1 by digitizing their position from the reference map. Mapping errors were computed by comparing surveyed versus map-determined distances between those two locations. The line between the two locations was also used as an absolute reference for positioning all surveyed locations on figure 3.1.

Surveying was performed with a Sokkisha Set 4 total station. A triple prism was used to reflect the infrared beam emitted by the station. This instrumentation allowed measurement of distances up to 2,1 km with an accuracy of 1 mm. Angle measurement accuracy was 5 seconds. The aim of the surveying exercise was to obtain the present position of the distal edge of the moraines. Due to logistical constraints, surveying could not be extended to the eastern Thompson Glacier moraine. The most important surveying data are included in Appendix 2.

2.2.1.2 Mapping the data

Figure 3.1 constitutes the basic map from which all the other maps in this thesis were derived. It was produced using a Geographical Information System (GIS) called Atlas Graphics (release 3.00). Before using this package, however, the relevant portion of the reference map (solid line on figure 3.1) was photoenlarged and subsequently digitized using a software package called Atlas Draw (release 2.0). Employing the reference grid determined by Haumann (1961) as a user-defined projection in Atlas Draw allowed for the overlaying of data for comparative purposes, as will be discussed later.

Errors resulting from the digitizing process were investigated by comparing computer-determined against field-measured distances and locations. The distance between the graphically determined (digitized) positions of Station 3 and Point 9 (referred to as "baseline" on figure 3.1) was computed by the software to be 1131,9 m. By comparison, the value measured in the field between the same two points was 1121,954 m.

A similar test was performed on the two field locations for which precise surveying data was available, namely the points identified 52,6 (x = 31756,61 and y = 61687,59) and 53,3 (x = 32523,93 and y = 61826,39) in Haumann (1961).

Those points lie along the distal edge of the White Glacier moraine, but they were not reported on figure 3.1. The first point was located by the software to lie at x = 31765,94 and y = 61675,08 while the second point was found to be located at x = 32532,4 and y = 61821,0. As for the baseline length, the error is smaller than 10 units (i.e. 10 meters). Such errors are within the resolution of the maps used throughout this paper. For instance, the width of the finest pen (diameter = 0,3 mm) used for drawing figure 3.1 represents approximately 8,5 meters in the field.

Two additional sets of data were overlaid onto the digitized reference map to produce figure 3.1. They are: (1) the position of the glacier snout as well as of the distal edge of the whole White Glacier moraine and of the eastern portion of the Thompson Glacier moraine determined by L. King during the summer of 1988 using a geodetic camera (KING 1988) and (2) the locations surveyed in the summer of 1989 along the distal edge of the whole of the White Glacier moraine and of the western and central portions of the Thompson Glacier moraine. Because those data sets were referenced to the grid system that had been devised by Haumann in the early 60's, a relatively accurate overlay of the information could be achieved. The two data sets are represented in all the maps included in this thesis by circles and squares respectively.

It should be noted at this point that the graphic overlaying of data collected by different persons using different techniques introduces an amount of relative error that could ultimately affect the overall accuracy of figure

3.1. The definition of what constitutes the contact between the glacier and the glacier-proximal moraine or between the glacier-distal moraine and the sandur is at the heart of the problem. This issue will be discussed in greater detail in the next chapters.

2.2.2 SPECIFIC FIELD METHODS

2.2.2.1 Defining the moraine perimeter

It was mentioned in the previous section that the accuracy of the maps presented in this thesis may suffer from the overlaying of data from diverse sources. Both the 1959 and 1988 data sets originate from the interpretation of photographs (vertical air photographs in the first case and geodetic camera shots in the second case), whereas the 1989 data set consists of surveying data. Care was taken in 1989 to position the reflecting prism as close as possible to the break of slope so as to obtain the most exact position of the distal edge of the main body of the moraine. Double checking of how representative of the distal edge position were the surveyed points revealed that all were at the break of slope except points number 4, 5, 6 and 7 (see figure 4.1) which were found to lie a little upvalley from the actual position of the break of slope. Tracing the position of the distal edge from photographs could easily lead to different results, especially if the contact between the moraine edge and the forelying zone were obscured by the presence of a few morainic boulders located ahead of the main edge line.

Surveyed locations were selected so that they best represented the distal edge of the main body of the moraine complex. In the case of the White Glacier moraine, this meant that a 1,5-meter high hump lying some 30 m ahead of surveyed points number 4 and 5 was not considered a part of the moraine. This could explain why the difference between the 1988 and 1989 data sets is greatest at the locations of those two points. The explanation for the discrepancy from surveyed point number 6 eastward, however, seems to lie in the difference between the methods used to determine the distal limit of the moraine and maybe also in the subjective evaluation of moraine perimeter location by individual researchers.

This problem of determining moraine perimeter location also arose for the Thompson Glacier moraine. In this case, the 1988 data (from KING 1988) were not included for the western portion of the moraine, where the problem of defining the edge is compounded by the many small new thrust ridges that lie sometimes quite far away from the distal edge of the main body of the moraine.

2.2.2.2 Collection of directional data

A fair proportion of the data collected around the Thompson Glacier moraine was directional in nature. In spite of all the unreliability related to the use of a magnetic compass in the Canadian High Arctic (NEWITT 1990), measurements of the orientations of fractures, depositional surface dips and long axes of pebbles were performed with a Brunton pocket transit model 5008. The main reason for the use of the compass was that alternative methods for determining orientation are cumbersome and their use could not be envisaged within the limits of the present work. Another reason, however, pertains to the fact that measurements with the compass during the 1990 field season did not seem to be as unreliable as originally expected.

It is recognized that using a magnetic compass in areas that are located close to the North Magnetic Pole (NMP) is unreliable for precise bearing calculations. The relatively short distance that separates Expedition Fiord from the NMP (about 250 km, as shown on figure 1.1) has two important consequences. First, because the very small horizontal component of the magnetic field (1180 nT [nanoteslas] according to NEWITT 1990, personal communication) is apparently too weak to overcome the frictional forces in a normal compass, the needle is not free to align with the true direction of the horizontal component of the Earth's magnetic field. Second, it is believed that fluctuations in the instantaneous location of the NMP could bring about declination changes of up to 20 degrees (from the mean declination of 102^0 45'W) over the course of one day (NEWITT 1990: personal communication).

However the relative consistency of measurements obtained in the field during the summer of 1990 revealed that the fears expressed above did not apparently materialize so dramatically as predicted. Tests relative to needle sensitivity were conducted by repeating measurements twice or three times or by comparing the readings with another compass. The consistency of bearings obtained in repeated field tests tended to infirm the statement that the compass needle is not sensitive enough to align with the horizontal component of the Earth's magnetic field.

Repeated readings of the position of the sun at solar noon (this measurement was performed as a check on each day the compass was used) tended to disprove high fluctuations of the magnetic declination on a day to day basis. Readings varied from 178 to 185^0. Fluctuations of magnetic declination on the course of a few to several hours were investigated by fixing the compass on a tripod and by monitoring changes in bearing. Three tests were performed (see Appendix 3).

Figure 2.2 shows the results of such monitoring expressed as a time series over a 6-hour period (from 12:00 to 18:00 local time, on 8 July 1990) during which bearing was noted at five minute intervals. Care was taken to jostle the instrument before each reading so as to allow free needle settling. Variations are shown to be within 5 degrees. The detailed results for a 12-hour period given in Appendix 3 show a 5,5-degree variation. Such a level of variation was found to be quite acceptable for the purposes of the present work and therefore it was decided to use the compass without restrictions. To minimize the effects of diurnal variations, measurements were generally taken within a period of time not exceeding 6 hours, most often in the late morning and afternoon.

2.2.2.3 <u>Complementary data</u>

As a complement to field data, one site was selected for pebble fabric analysis in both the Thompson and the White moraines. Pebbles were selected for measurement according to common criteria (e.g. HARRIS [1969]. The ratio between the long and intermediate axes of pebbles

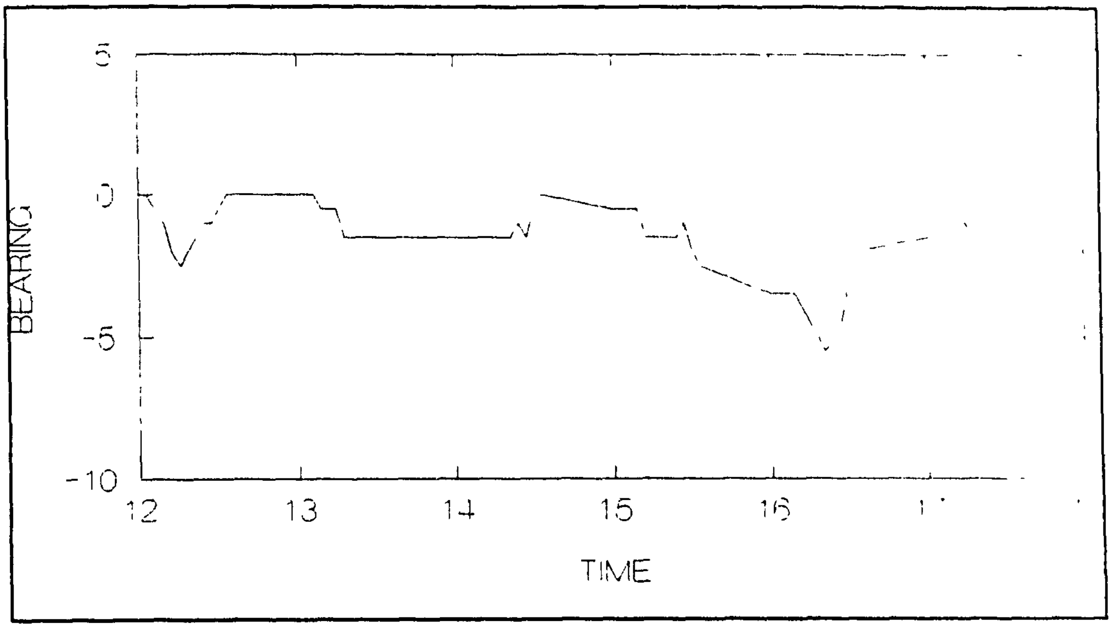


FIGURE 2.2 Fluctuation of compass bearing, 8 July 1990.

(respectively the A and B axes) had to be equal to or greater than 1,5 : 1, while the length of the long axis had to be between 2 and 64 cm.

Finally, grain size analysis was performed on four representative samples of the material in the Thompson Glacier moraine using the traditional sieving method.

CHAPTER 3: EVOLUTION OF THE GLACIER COMPLEX TERMINUS

3.0 INTRODUCTION

One of the most spectacular features in the upper Expedition Fiord and Expedition River area is the 4-km wide glacier wall, formed by the merging of the White and Thompson glaciers. The six glaciology reports published as a product of the Jacobsen-M^c^Gill Expedition constitute the most important subsection, in numerical terms, of the series of Axel Heiberg Island Research Reports. All but one of those glaciology reports deal specifically with either the White Glacier or the Thompson Glacier. The large number of publications generally arising from research at the M^c^Gill High Arctic Research Station possibly makes the Expedition Area one of the most intensively studied areas in the Arctic.

A goal of the present thesis is to provide an update of the spatial arrangement of both the glacier snouts and the perimeter, or distal edge, of the moraines. Besides the study conducted by Kalin in the 1960's in which the advance of the Thompson Glacier and resulting changes in its frontal moraine were documented (KALIN 1971), there have been no other studies focusing on landscape evolution related to the Expedition glacier complex. This chapter presents a summary of landscape evolution in the lower ablation area and proglacial zone of the glacier complex over the last 30 years.

3.1 **RESULTS**

3.1.0 INTRODUCTION

The data presented in figure 3.1 are consistent with the conclusions that had been reached in the reports published by the Jacobsen-M^{c}Gill Expedition, namely that the snout of the White Glacier is retreating whereas that of the Thompson Glacier is progressing downvalley. An immediate consequence of such changes in the glacial landscape is the spatial reorganization of the frontal moraine complex.

3.1.1 WHITE GLACIER

Figure 3.1 shows that the lower ablation zone of the White Glacier has undergone two major changes over the last 30 years. Firstly, it was shrunk from the east by the inexorable advance of the Thompson Glacier. This resulted in a maximum loss in width (measured toward 270^0) on the order of 200 meters at the snout. Secondly, the glacier front has receded by unequal amounts depending on location.

Surveying of the position of the glacier front between 1959 and 1962 revealed that the central-western portion retreated approximately 15 m in that 3-year period (MULLER 1963b). Recent data concerning front position (KING 1988) show increasing retreat distances from east to west. From negative values in the easternmost zone of the front, total retreat over the last 30 years increases to a maximum of c. 250 m in the west. Higher retreat values of the western front are probably linked in part to the fact that this portion of the glacier is exposed to the afternoon sun. Field observations revealed two additional factors that may contribute to enhanced ablation in the western front: (1)

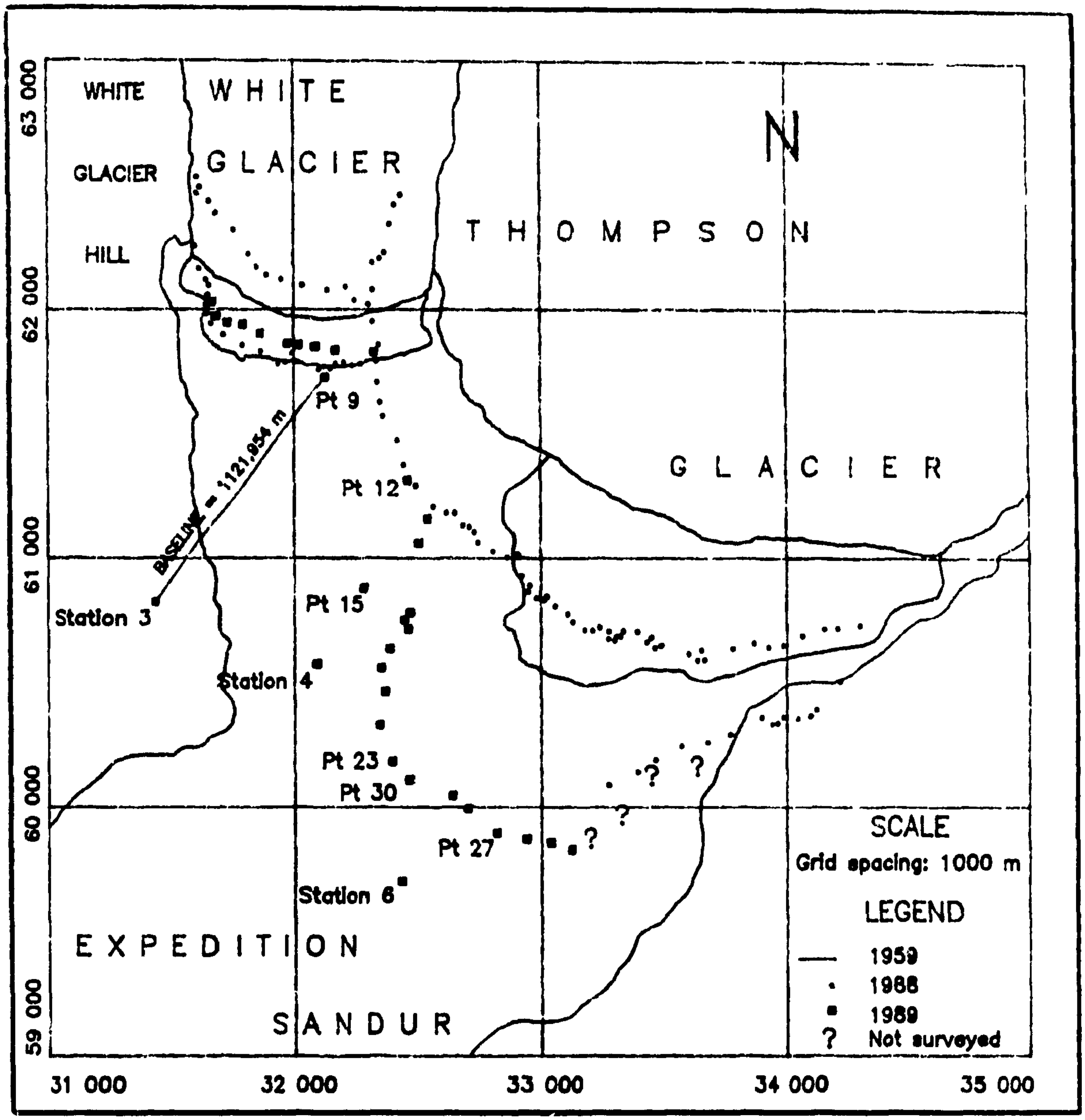


FIGURE 3.1 Evolution of the glacier complex between 1959 and 1989. 1959, 1988 and 1989 data are respectively from CANADA 1962a, KING 1988 and from field survey data. The 1988 data depict both the ice front and the distal perimeter of the eastern moraine. 1989 data depict the position of the moraine distal perimeter only.

the overall lower albedo of the frontal glacial debris deposited in the west and (2) the intense lateral erosion and undercutting by the Ermine River (cf figure 1.5), which flows along the west margin.

Lack of uniformity, or at least of symmetry with respect to the central ice flow line, in frontal retreat suggests that the shift in the White Glacier front position depends not only on "normal" ablation processes (melting, evaporation and calving), but also on other factors. One is then led to conclude that some other process has been offsetting the impact of ablation more and more as one proceeds eastward. The deformation of the eastern side of the White Glacier front by the advancing Thompson Glacier seems a plausible explanation. Evidence for this is illustrated in figure 3.1, where one can note a displacement towards c. 250^0 (i.e. a net forward progression) of the 1959 location of the eastern junction between the White Glacier and its frontal moraine.

A variety of field observations also support the theory that the eastern White Glacier has been physically displaced by the Thompson Glacier. The squeezing of the White Glacier described earlier involves a large mass of ice. Since the better part of the compressed ice could not have been lost only to the ablation processes of melting, evaporation and calving, then an important quantity of ice must have been displaced. The consequence of such displacement would be either a shift in the **z** direction (i.e. an increase of the mean ice surface elevation along the contact between the adjacent glaciers) or a change in the **x** and/or **y** directions (i.e. a shift in the glacier front position).

Figure 3.2 shows that general ice surface elevation increases along a west to east transect in the lowermost portion of the White Glacier tongue. Evidence of the compression is found on both sides of the contact between the glaciers in the form of humpback-shaped relief elements rising a few meters above the mean elevation of the glacier surface.

Compression is evidenced on the Thompson Glacier by the squeezing of the "W"-shaped surface moraine located near the contact between the glaciers. Air photos indicate a decrease in the distance between the two apices of the "W" from c. 330 m in 1959 to c. 230 m in 1977 (the "W"-shaped moraine is visible on figures 5.1 and 1.7). The zone that is apparently affected by compression lies west of the "S"-shaped supraglacial medial moraine (which extends east of the "W"-shaped moraine as two parallel one-clast-thick strips of very angular material) and extends about two-thirds of the way to Between Lake from the front. Linear debris patches expelled at the surface of the lower eastern White Glacier from compressive flow were noted to align grossly southeast-northwest, indicating flow direction towards the southwest. Such a direction is believed to be caused by the northeast to southwest compressive action of the Thompson Glacier on the White Glacier.

Photographs and maps depicting conditions in the early 1960's do not show such a marked increase in surface elevation of the White Glacier from west to east. Instead,

FIGURE 3.2 Terminal moraine and snout of the White Glacier, looking north. Note an increase in elevation of the ice surface toward the eastern glacier (marked by an arrow) (15 July 1989).

they indicate an increase from the western margin to the center of the glacier followed by a more or less constant elevation up to the contact with the Thompson Glacier (CANADA 1962b). Such a profile, however, is indicative of an already substantial compressive action exerted by the Thompson Glacier in the early 1960's.

The stresses related to the actual dragging of the eastern White Glacier are evidenced in a number of ways. The slope of the glacier front increases from about 30^0 in the west to near vertical in the central and central-eastern zones and to vertical and overhanging in the east. Following the hypothesis that advancing glaciers are characterized by vertical ice fronts and that retreating glaciers display low frontal slopes (SUDGEN and JOHN 1967), then the slope variations along the snout of the White Glacier suggest increasing amounts of forward movement (retreat can be considered as negative forward movement) from west to east. Earlier data on the slope of the White Glacier front show that maximum slope values (which were also measured at the easternmost front) were only on the order of 45^0 (CANADA 1962b).

The area of greatest stress in the easternmost portion of the front is also characterized by a zone of complex folding and fracturing of the ice. This area, shown in figure 3.3, is also the only zone where oversteepening and calving along the White Glacier front are observed. Ice breccia, which is indicative of calved block remobilization, was also noted at the base of the junction between the two glaciers. The Thompson Glacier snout also shows evidence of

FIGURE 3.3 Zone of calving and severe deformation located near the junction between the White and Thompson glaciers. Ice blocks more than 1 500 m^3 lying up to 40 m away from the front were documented (9 July 1990).

stress. For instance, one observes a shift of ice strata dips from upglacier near the contact between the glaciers to downglacier as one progresses along the front east of the White Glacier.

In summary, it is obvious both from field observations and from maps depicting change in ice front position that the White Glacier has shrunk from the east and was dragged downvalley by the compressing Thompson Glacier. The amount of deformation along the White Glacier front decreases rapidly westward and ablation becomes the most important process controlling temporal front evolution. The final result is that the front of the White Glacier has effectively been both translated and rotated rather than simply translated upvalley.

As a consequence of the unequal retreat along the White Glacier front since 1959, the terminal ablation moraine has correspondingly increased its width (width being parallel to glacier flow direction) by unequal amounts. A more detailed investigation of the White Glacier moraine is presented in the following chapter.

3.1.2 THOMPSON GLACIER

The compressive action exerted on the White Glacier by the westernmost section of the Thompson Glacier is in itself obvious evidence for the downvalley movement of the Thompson Glacier snout. Estimating the total displacement of the Thompson Glacier front, however, is not as straightforward as it appears. Even though figure 3.1 shows the positions of the ice margin in 1959 and 1988, it does not lend itself to a quick calculation of the glacier front progression. The problem of estimating glacier front displacement is linked with the problem of defining the direction of flow lines at specific locations along the glacier front.

A theoretical prediction of the orientation of displacement vectors appears virtually impossible because of the complexity in the interaction between flow as would be predicted by physical laws and various interfering elements (like the mobile boundaries that constitute the White Glacier to the west and the frontal moraine to the south). Fortunately, flow directions at the Thompson Glacier snout and at locations within the moraine were measured by Kalin (1971) between 1963 and 1968. Although measurements are scarce and only confined to the western Thompson Glacier, they provide the only sound basis for estimating total glacier movement.

Kalin (1971) measured a flow direction towards 230^0 near the 1967 location of the western junction between the glacier and the moraine. From his data, azimuths decreased towards the east by some 5^0 on the 400-meter long stretch along which he measured glacier flow velocities and directions. This information constitutes the closest approximation to current glacier flow direction, even though on average the flow lines have probably shifted slightly to the west since the late 1960's because of the constant realignment towards a most westerly attitude of the glacier front that is evidenced in figure 3.1.

Kalin's data are reported on figure 3.4. Glacier

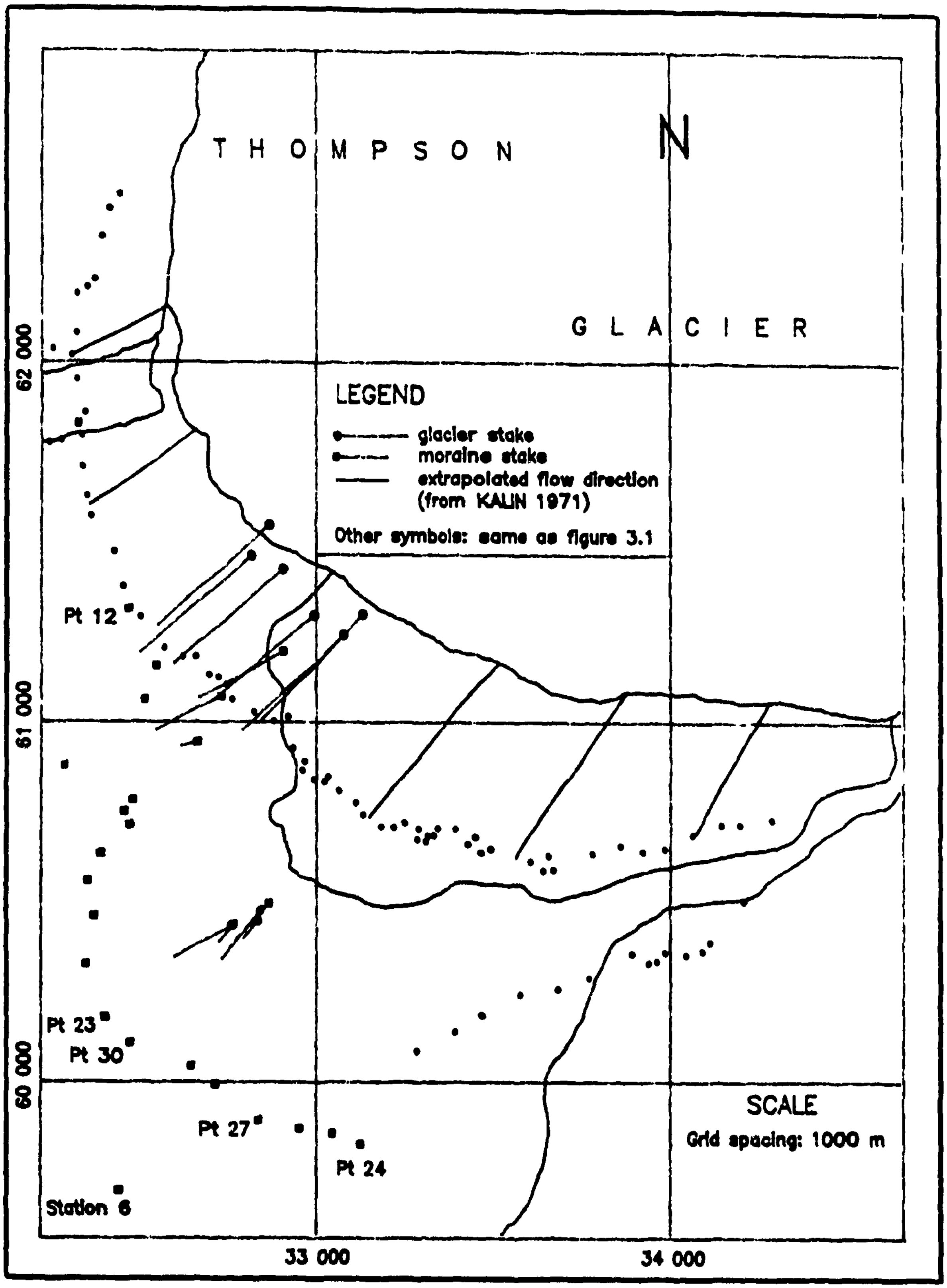


FIGURE 3.4 Glacier front displacement vectors between 1959 and 1988. Front displacement was sketched from data published in KALIN (1971).

stakes are depicted as circles and moraine stakes as squares. The direction and relative rate of movement of those stakes are shown by the orientation and length of the lines attached to the stake symbols. All the glacier stakes were monitored between 1967 and 1968. The reason why all but one of those glacier stakes are not located on the glacier in figure 3.4 is that the glacier front position depicted is from 1959. Because the rate of movement decreases dramatically as the glacier stakes progress towards the front, their much greater movement rates in comparison with the moraine stakes shall not be given too much importance. Orientation is of greatest concern. The moraine stakes were monitored for a period of one to five years between 1963 and 1968.

Using Kalin's data for glacier stake motion and considering as a constant the decrease in azimuth toward the east of about 5^0 per 400 meters that he had measured in the central-western glacier, the extrapolated directions of glacier flow shown on figure 3.4. were obtained. Figure 3.4 indicates that the prograding distance of the glacier front between 1959 and 1988 reaches a maximum of c. 550 m in the central zone. The zone of maximum displacement extends from center to center-east and estimated values decline sharply to approximately half of the maximum value in the easternmost portion of the front. Thus mean glacier front velocities over that 29-year period vary from c. 19 m/year in the center and center-east to about 9 m/year in the east. By comparison, glacier front position was estimated to have moved in a relatively uniform manner toward a mean direction of 210^0 between 1960 and 1967 at a much higher average velocity of 23 to 26 m/year (KALIN 1971). The discrepancy between the rates of glacier front progression obtained for the 1960 to 1967 and the 1959 to 1988 periods suggests that glacier front progression has possibly slowed during the last two decades.

As illustrated in figure 3.4, the forward progression of the Thompson Glacier has brought about a translation as well as a change in the shape of the forelying moraine. As was the case for estimating glacier front movement, estimating the direction of the translation movement of the moraine is met with a number of difficulties. The dynamic nature of the progradation process implies that no structural references in the moraine can be monitored for movement with any degree of reliability. Therefore, without data pertaining to progradation rates for various parts of the moraine, it is impossible to calculate displacement vectors. The problem is particularly acute for the distal edge, where tectonic and fluvial dynamics constantly modify landforms (cf chapter 5, section 5.2.4.2).

Kalin's data show that stakes in the western moraine were moving towards a noticeably greater azimuth value than the glacier stakes located straight upice. However, the movement of the cluster of stakes he had set up in the central distal moraine of 1967 (shown on figure 3.4 to lie ahead of the central distal edge of the 1959 moraine) showed a parallel alignment with the extrapolated glacier flow direction. At the time of Kälin's work, it appears that the central moraine was effectively moving in a direction grossly parallel to ice flow, but it was also developing both forward and sideways (westward) in its western sector.

Even though Kalin (1971) did not monitor movement in the eastern moraine, a general statement about moraine development in the 1960's could be that the moraine was developing generally parallel to ice flow in its center, but that it was developing along diverging directions on either side of the central zone. Recent data on dips of depositional surfaces presented in chapter 5 (section 5.2.3) support this hypothesis.

Relative evolution among the different sectors of the moraine are illustrated in figure 3.4. From 1959 to 1988, the width of the eastern moraine has decreased slightly. During the same period of time, the width of the central moraine has increased by a factor of approximately 1,5 while the western moraine has also increased widthwise but by a slightly smaller factor. It then seems as though the eastern moraine has been "left behind" by the fast advancing central and western zones.

This is evidenced by the concave-downvalley reentrant in the otherwise convex-downvalley shape of the 1988 distal edge of the moraine east of the last surveyed point (Pt # 24). Such a dent is indicative of a rapid decrease in progradation rates eastward. Field observations in this zone of changing progradation rates during the summer of 1990 revealed the presence of large subdued fractures parallel to glacier flow direction and cutting through medial and distal moraine structures. Large open fractures were observed in the central eastern zone a few decameters west of survey point # 24. The presence of these apparently younger fractures west of the zone of rapid progradation rate changes defined by the concave-downvalley outline of the moraine perimeter may be indicative of a shift to the west of the zone of rapid progradation rate changes. Such a shift is concordant with the theory that the advancing Thompson Glacier is constantly shifted to the west by topography. Similar fractures were also noted a few decameters up from the front in the central-eastern zone of the Thompson Glacier. Those fractures may also reflect the stresses caused by the rapidly varying progradation rates.

3.1.3 SHORT-TERM GLACIER DYNAMICS

Short-term glacier dynamics were tentatively investigated using a time-lapse camera (focal length = 35 mm) set up on the eastern flank of the White Glacier Hill, which borders the lower ablation area of the White Glacier to the west. The camera was set up to take three consecutive shots daily at solar noon for a period of over one year. The experiment failed because the cable linking the camera to the power source was gnawed by wildlife. Fortunately, a number of slides were taken from the time-lapse site using a 70-mm lens mounted on a normal 35-mm camera.

Two of those shots picture the glacier terminus on 14 July 1989 (figure 3.5a) and 16 June 1990 (figure 3.5b). The field of view on those two pictures covers the central portion of the field of view "seen" by the time-lapse camera. Notwithstanding a slight shift in perspective, it is apparent from those two photos that the lower ablation

FIGURES 3.5A AND 3.5B A section of the glacier front (White Glacier in the foreground): upper photo taken in July 1989, lower in June 1990. Note a slight change in ice front shape (center) indicative of forward movement.

zone of the Thompson Glacier advanced during this 11-month period. Although it was not quantified, a definite forward progression of the Thompson Glacier front at the junction with the White Glacier was also observed during the 1990 field season. Precise measurements could not be obtained because of constantly falling debris that landed up to 50 m away from the snout.

CHAPTER 4: THE WHITE GLACIER MORAINE

4.0 INTRODUCTION

The evolution of the position of the White Glacier front over the last three decades was discussed in the previous chapter. It was shown that the front has retreated substantially with respect to its 1959 position in the west, but that it has been dragged downvalley along its contact with the Thompson Glacier. This chapter focuses on the geomorphic processes currently acting on the White Glacier moraine in relation to its past, present and future evolution.

4.1 CHANGES IN THE AERIAL EXTENT OF THE MORAINE

As illustrated in figure 4.1, two major modifications to the 1959 aerial extent of the White Glacier moraine have been (1) the loss of a 200-meter long portion in its easternmost end due to the incursion of the Thompson Glacier and (2) the variable gain in width due to differential glacier snout retreat. Figure 4.1 suggests another important change, namely a noticeable retreat of the whole distal edge of the moraine, with a maximum that matches the maximum glacier front retreat in the west. It is suspected however that, because of the technical problems inherent to overlaying data from different sources, the amount of distal edge retreat may not be as important as depicted on figure 4.1.

Note that on figure 4.1 both the 1988 and 1989 data sets indicace increasing backwasting of the distal edge of the moraine toward the west compared with the 1959 position

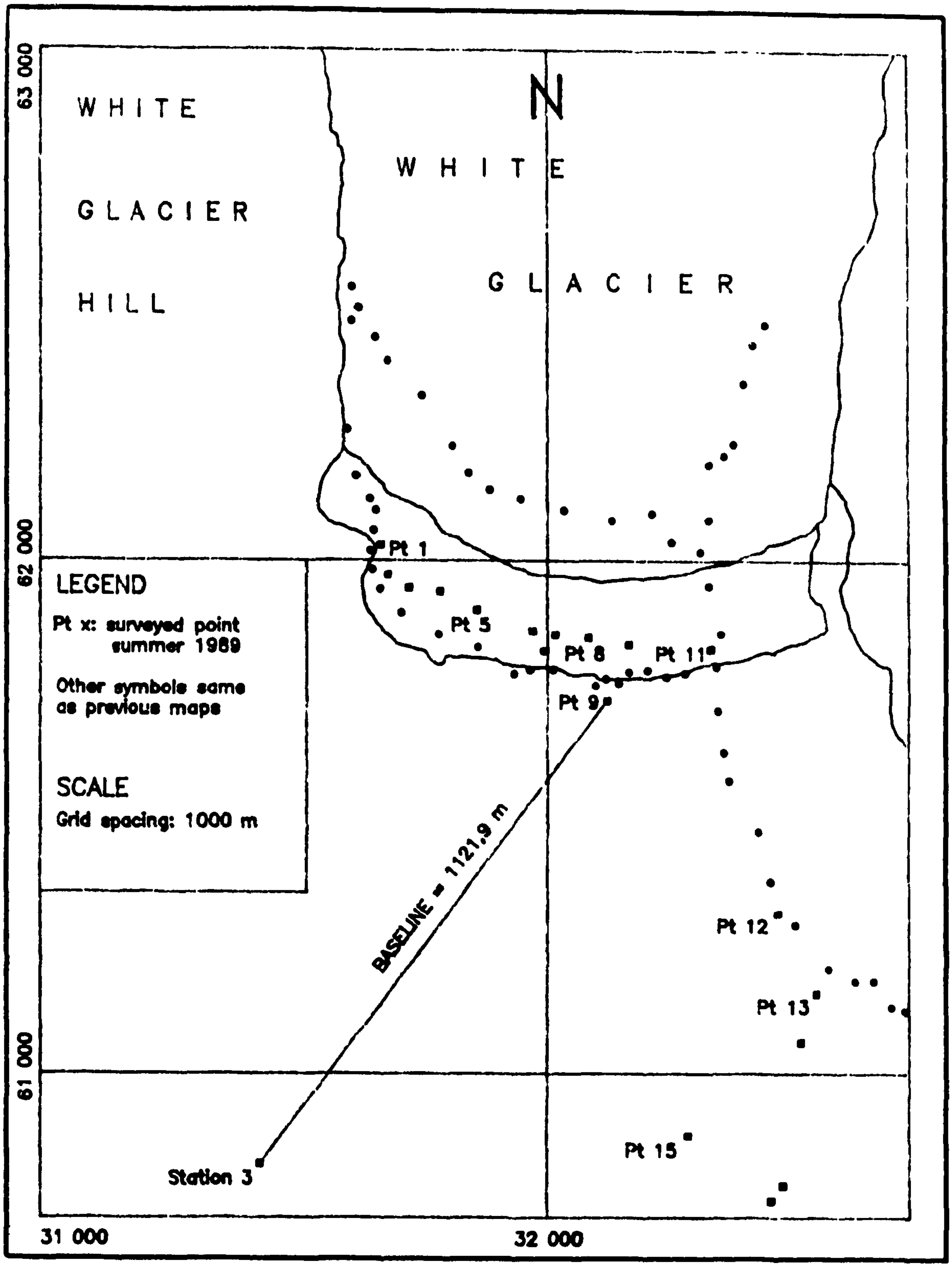


FIGURE 4.1 Changes in the White Glacier snout area between 1959 and 1989.

(solid line). Backwasting along the westernmost section of the distal edge of the White Glacier moraine was found to be currently operating due to thermoerosion along the western lateral and frontal edges. A definite proof of such lateral erosion is the fact that the small rock cairns set up in 1989 as markers for survey points number 1, 2 and 3 were not found during the 1990 field season (just a little under a year after they had been set up) while all the other cairns indicating survey locations along the moraine remained intact. Evidence for longer term thermoerosion in the westernmost moraine is noted by a decrease in lichen cover along a west to east transect parallel to moraine length in the zone lying west of the present position of Ermine River (the present moraine lies east of the river). Following the west to east migration of the river over the last 30 years, lichen cover of rock surfaces was found to decrease steadily toward the east from a maximum of approximately 20 % in the extreme western moraine.

The very idea that the distal edge of the moraine as a whole may have retreated over the last 30 years is evidenced by the presence of thermokarst scars along the distal slope of the moraine edge. It should be noted, however, that no active thaw slump processes that would promote distal edge retreat were noted during the 1989 and 1990 field seasons except in the westernmost section. Field observations therefore suggest that localized backwasting of the distal edge is a plausible process, but that it is likely to operate at a relatively slow pace except in the westernmost moraine. The big difference noted on figure 4.1 in the position of the distal edge of the moraine among the three data sets and especially between the 1988 and 1989 sets is not supported by field observations.

Thus it appears that the only way to verify the hypothesis of substantial distal edge retreat of the White Glacier moraine in its central and eastern portions would be to survey the edge position over a period of a few years. The only hypothesis that may be retained now to explain the discrepancies in figure 4.1 relates to the discussion on overlaying data from different sources presented in section 2.2.2.1. Of prime importance here are problems related to defining the exact location of the contact between the moraine and the forelying sediment.

4.2 GEOMORPHOLOGY AND MATERIALS

The White Glacier moraine is an ice-rich landform 10-15 meters in height covered by a thin veneer of loose debris (figure 4.2). In the central moraine, the blanket of ice-free material was found to increase from about 20 cm or less near the front to about 1 m in the medial and distal moraine. Because there is no apparent increase in the thickness of this blanket from medial to distal even though the distal portion of the moraine is older than its medial portion, it is believed that downwasting of the moraine (which may correspond with the gradual stabilization of the active layer) mostly occurs within a few years or decades after initial deposition. During the summer of 1990, downwasting processes in the proximal moraine were found to be enhanced by thermal-mechanical erosion by small meltwater streams flowing along the contact between ice-rich and ice-free material. One such stream was observed to cut through

FIGURE 4.2 Section cut by fluvial erosion into the White Glacier moraine near its contact with the glacier. Note the upglacier dipping stratification and the high ice content of the landform (28 June 1990).

the side of a natural trench in the moraine at the ice-rich/ice-free contact in a matter of minutes.

The White Glacier moraine is currently about 600 m in length and 300 m in width in its central zone. In the central zone, the surface of the moraine apparently corresponds with the upper limit of the layer of dirty basal ice observed at the ice front (figure 4.3). This relationship and the upice dipping stratification shown in figure 4.2 suggest that the White Glacier moraine is formed by the lowermost debris-laden ice layers of the White Glacier. Downwasting and backwasting rates of the debris-laden basal ice are much lower than backwasting rates of the glacier front due to the insulating effect of the surface blanket of ice-free material that develops as the glacier front recedes. A profile along moraine width in the central and central-east zones would show a gently rolling topography as illustrated on figure 4.4.

The hummocky topography in the westernmost sector of the moraine is characterized by the presence of small ice-cored ridges normal to glacier flow that are similar in their appearance to the sharp and well defined structures of the Thompson Glacier moraine (figure 4.5). The ridges typically consist of an ice core covered by a blanket of material that is thickest at the crest. The formation of these ridges was not observed in the present study, but it is believed that the shape of the ridges is linked to differential ablation rates along the debris-rich glacier front. During the 1990 field season, the western portion of the glacier front showed the highest concentration of

FIGURE 4.3 Glacier/moraine contact, central White Glacier. Note the concordance between upper limit of dirty basal ice layers at the glacier front and surface of moraine. Same location as figure 4.2 (20 July 1990).

FIGURE 4.4 View of the White Glacier moraine, looking west. Note the gently rolling topography of the eastern (center) and central moraine (11 July 1990).

FIGURE 4.5 Ridgy and hummocky surface morphology, western White Glacier moraine. The ridges are ice-cored (26 June 1990).

surface debris patches originating from debris layers and brought to the surface by compressive flow. In one instance, a 4-5 cm thick band of material produced a 2-3 m wide patch of debris at the surface of the moderately sloping glacier. Figure 4.6 depicts the snout area on 21 July 1990.

Clast textures at the surface of the moraine range from very fine material (silt and clay) to boulders over 1 m^3 in size. In terms of roundness, particles cluster in the subrounded to subangular groups. Lower mean grainsize and overall darker appearance were noted in the western portion of the moraine. The relatively brighter appearance of surface material in the central and eastern moraine is mainly due to the abundance of highly resistant quartzite blocks. In the west, the moraine is covered by a great many shattered blocks of black shale as well as by gabbros and diorites. A fair proportion of the blocks lying at the surface of the moraine were striated and many typical glacial blocks like the one shown on figure 4.7 were found. Material provenance was more thoroughly investigated during the summer of 1990 by M. Parent (GSC, Québec city).

4.3 **PROCESSES**

4.3.1 GENERAL OBSERVATIONS

The moraine has been mostly subjected to degradation over the last 30 years. The basic causes for degradation are (1) the impinging of the Thompson Glacier from the northeast, (2) thermokarst processes and (3) fluvial erosion. The only constructive geomorphic process from the point of view of moraine formation has been the retreat of

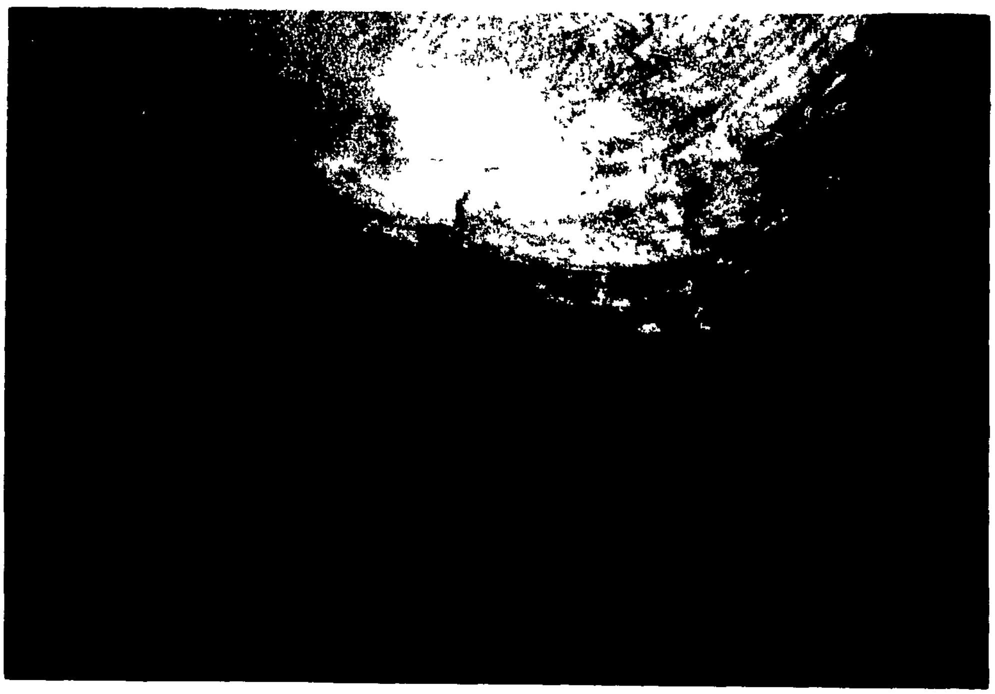


FIGURE 4.6 Quasi-vertical view of the White Glacier moraine. Note the generally darker appearance of surface material in the western moraine (left) and the degradation caused by fluvial processes in the central and eastern moraine. Note also the asymmetric shape of the glacier front and the relatively high concentration of surface debris patches in the western portion of the glacier terminus (21 July 1990).

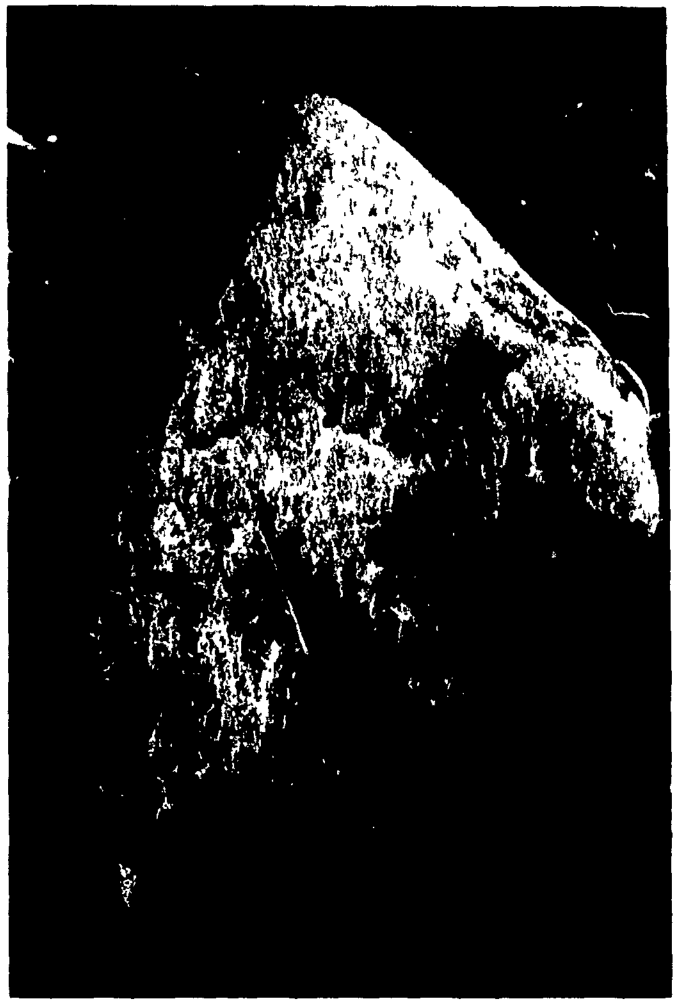


FIGURE 4.7 Typical subrounded and striated glacial boulder found at the surface of the White Glacier moraine. Black lens cap for scale.

the White Glacier front, but this retreat also brought about the shifting east of Ermine River (the west lateral stream) and hence the gouging of the western moraine along its lateral perimeter.

Frontal perimeter retreat and moraine downwasting appear to have been relatively minor degradational processes over the last three decades. A determinant erosional process, the first occurrence of which is noted on the 1977 air photographs, has played a major role in the degradation of the White Glacier moraine in recent years. This process is the shifting of the proglacial section of the outlet stream that drains Between Lake (referred to in the literature [e.g. MAAG 1969] as "Between River") from its traditionally observed "between-the-glaciers" location to a current location more than 200 m west of the present junction point between the two glaciers. The erosional action of the meltwater flowing across the White Glacier moraine was extremely intense during the sunny and warm summer of 1990, but significantly less so during the cool and cloudy summer of 1989.

The primary source of meltwater that is currently eroding the core of the moraine (as opposed to eroding it along the lateral edges) is Between Lake, an ice-dammed water reservoir that builds up about 1,5 km upstream from the present glacier terminus at the confluence of the two glaciers (see figures 1.5 and 1.6). The lake forms as summer progresses from the accumulation of spring meltwater that flows along the northeastern side of the White Glacier and the western side of the Thompson Glacier.

The particularly impressive erosive power of the lake drainage stems from the fact that the lake empties as a jokulhlaup. Between 1959 and 1965, the lake emptied every year except in 1964 (MAAG 1969). In 1963, maximum surface area and maximum water volume of the lake were estimated to be respectively 410 000 m^2 and 7 500 000 m^3. The estimated maximum discharge for the 1961 and 1963 flash floods were respectively 40 m^3/s (KALIN 1971) and 140 m^3/s (MAAG 1969). According to Maag (1969 p.14), the "modus of emptying" of the lake was "supraglacial over the lowest point of the damming glacier". The earliest and latest recorded beginning of the jokulhlaup events during the first half of the 1960's were 3 July (in 1962) and 23 July (in 1961 and 1963). The time lapse from the moment lake drainage was initiated until the moment it was two-thirds empty (which is the criterion used by Maag 1969) varied from less than two days in 1963 to over 10 days in 1965.

Between 1958 and 1962, a westerly shift of Between River was observed on the glacier. By the time the rushing water arrived at the front however, it was falling off the glacier front and was directed in the main proglacial channel between the two glaciers. Pictorial evidence of the subaerial character of Between River along its entire glacial section during the 1960's is found in Muller (1977).

Ice-cored mounds covered by glaciofluvial material and rising a few meters above mean ice surface that may be remnants of earlier catastrophic drainage events were found near the present contact between the White and Thompson glaciers, a few decameters up from the front. The humpback-shaped mounds are aligned grossly parallel to glacier flow and are topped by sediment that may have been left by the old supraglacial (or englacial?) Between Channel. The thickness of this insulating blanket of material was on the order of one to a few decimeters. Thus during the 1960's water flowing out of Between Lake was eroding the White Glacier moraine along its western flank even though the glacial portion of Between River was shifted west as the Thompson Glacier was compressing the White Glacier from the east.

The air photograph record shows that the proglacial section of Between River moved from its original position immediately east of the White Glacier moraine to a location that is referred to on figure 4.8 as "Yellow Cairn Channel" (named after the yellow rock cairn [survey point #9] that lies west of the channel near the distal edge of the moraine) sometime between 1973 and 1977. This shift towards the central White Glacier moraine resulted in a different and maybe more intensive type of fluvial erosion than had been observed during the 1960's, as evidenced by the substantial widening and deepening of both the glacial and proglacial sections of the outlet channel over the one year period between 1977 and 1978. In 1978 the flow both for the glacial and the proglacial sections of the river was subaerial. The distance between the steep river banks of the Yellow Cairn Channel was estimated from the air photographs to be 11 m (in the medial moraine), whereas it was on the order of 130 m in 1990.

Unfortunately, photographic information after 1978 is

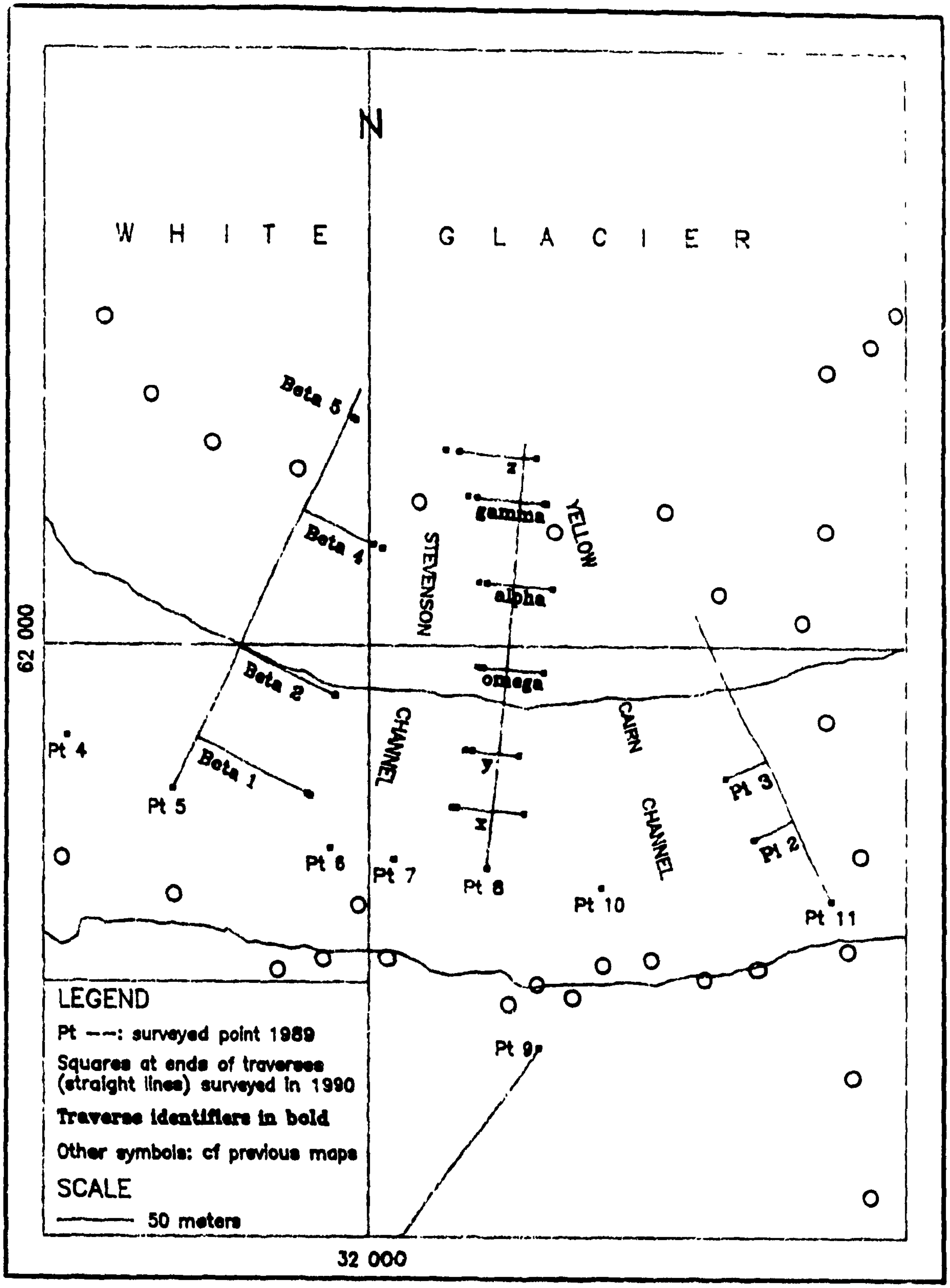


FIGURE 4.8 Close up view of the eastern and central White Glacier moraine (cf figure 4.1 for a general view).

nonexistent except for a new series of photographs that were taken on 5 August 1990. The subglacial trickle emanating from the head of Yellow Cairn Channel in 1990 most likely indicates that Between River was at one time exiting the glacier subglacially at the location of Yellow Cairn Channel. However no evidence of a former opening in the White Glacier front was apparent.

In 1989, Between Lake drained sometime during the first half of August and was unfortunately not monitored. In late August, the presence of stranded ice blocks on the dry bottom of a channel referred to on figure 4.8 as "Stevenson Channel" (the channel lies east of the Stevenson screen that was set up by the early Jacobsen-McGill Expedition in the 1960's and referred to in HAVENS ET AL [1965] as the "Outwash Plain" site of meteorological observations) provides a strong indication that the lake had drained via that channel. In comparison with the mild and sunny summer of 1990, the less significant geomorphic effect of the 1989 jokulhlaup noted in late summer was probably due to cool and cloudy weather conditions.

A completely different situation occurred in 1990. The very warm and sunny spring of 1990 (see figure 1.3) resulted in a quick filling of Between Lake (figure 4.9). The lake drained between 0:00 and 7:00 (local time) on 28 June, the earliest date recorded for the onset of the jokulhlaup event. Such an early drainage, however, is thought to have occurred partly because the lake area and volume have been noticeably reduced between 1963 and 1990 by the southwesterly advance of the Thompson Glacier. As a result

FIGURE 4.9 Between Lake on 26 June 1990, roughly two days before drainage. Note the eventual high water level as indicated by the water line after drainage (marked by an arrow). Note also the high water level relative to water level shown on figure 1.6 (figure 1.6 depicts conditions almost a month later in the melt seaso

it is expected that a faster filling and overflow of Between Lake will continue. Figures 4.10a and 4.10b show lake water levels approximately 12 and 60 hours following initiation of drainage.

Two moulins over 30 m deep in the ice along the channel path testified to the definitely englacial nature of Between River. However, the supraglacial modus of emptying as described by Maag (1969) was still a valid formulation for qualifying lake drainage in 1990. Figure 4.11 shows the head of Between River approximately 12 hours after the onset of overflow. The water level at the overflow point was observed to drop as the emptying progressed. This entails that the deeply incised path of Between River down the White Glacier is the result of repeated episodes of mechanical and thermal erosion related to the jokulhlaup events.

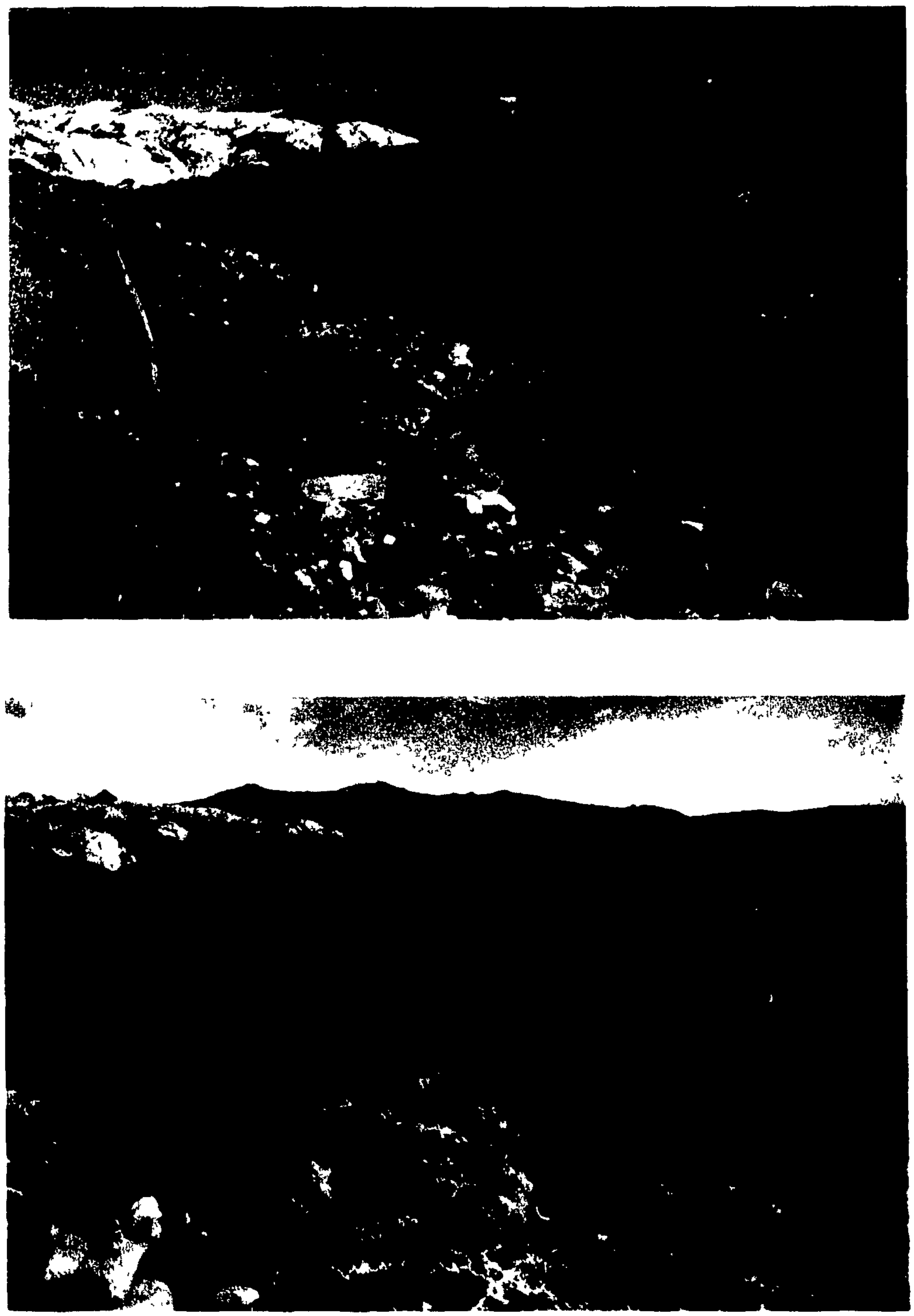
In 1990, Between River exited the glacier subglacially via a 10 to 15-m high and 7 to 10-m wide Rothlisberger channel carved in the central glacier front (figure 4.12). Meltwater was flowing out of the base of the glacier and across the moraine via Stevenson Channel as one big stream and eventually branched out in several smaller streams in the sandur. As of 1990, the width of the channel (distance between opposing river banks) was on the order of 80 meters in the medial moraine.

The geomorphic impact of the jokulhlaup is conveyed by the series of photographs (figures 4.13a and 4.13b) depicting conditions at the distal edge of Stevenson Channel both before and during the flood event. The staggering

FIGURES 4.10A AND 4.10B Between Lake approximately 12 and 60 hours after onset of emptying. Arrow indicates maximum water level (cf figure 4.9).

FIGURE 4.11 Supraglacial modus of emptying, upper Between River. Thermal and mechanical erosion caused the water level to go down as lake drainage was progressing.

FIGURE 4.12 Subglacial discharge of Between River at the glacier front, central White Glacier moraine. Note the continuity of foliation between the moraine and the basal ice of the glacier (28 June 1990)



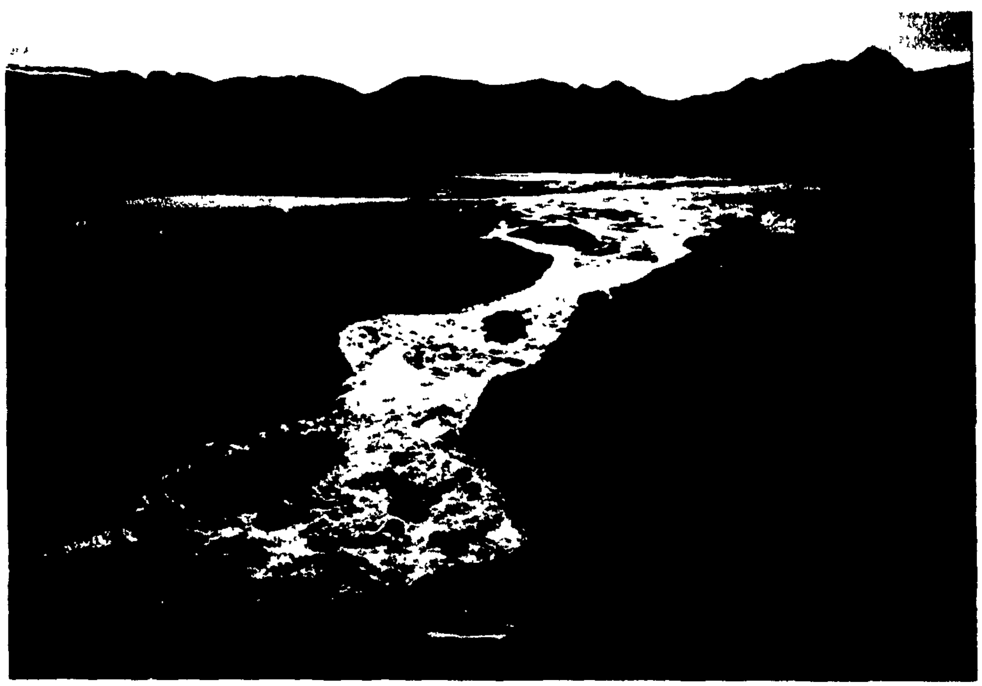
FIGURES 4.13A AND 4.13B Morphological impact of the annual emptying of Between Lake at the distal edge of the White Glacier moraine. Pictures taken at a few days interval.

erosive power of the meltwater cutting through the moraine is illustrated in figures 4.14a and 4.14b, which show the evolution of channel morphology over a one year period. Even though there is a slight change of perspective that makes the channel relatively wider in the second (most recent) photograph, there is no doubt that the channel had widened between the two shots. A pictorial history of the 1990 flood event is contained in the series of photographs presented below (figures 4.15a to 4.15d).

4.3.2 QUANTITATIVE OBSERVATIONS

Quantitative monitoring along Yellow Cairn and Stevenson channels both in their moraine and outwash sections was quite instructive as to the erosive power of meltwater within the moraine. Peak discharge in 1990 was estimated by multiplying the velocity of a piece of wood (averaged over a 50-m stretch) by an estimated value of channel cross-section. An approximate value of 50 m^3/s was thus obtained. This is only about one-third of the value of 140 m^3/s reported by Maag (1969) for the 1963 jokulhlaup, but about the same as the value reported by Kalin (1971) for the 1961 jokulhlaup. The presence of many floating ice blocks (some reaching 0,125 m^3 in size) at the beginning of the flood event suggests that the emptying of the lake was linked to the collapse of an ice plug. Short episodes of river swelling generally lasting less than an hour and accompanied by floating ice were noted on two other occasions later in July. Those sudden and short-lived peaks in discharge were also apparently linked to the collapse of ice plugs deeper in the glacier as summer was progressing and Between River was carving its way down.

FIGURES 4.14A AND 4.14B Morphological impact of Between River flowing across the White Glacier moraine: upper photo taken in 1989, lower in 1990.



FIGURES 4.15A AND 4.15B Pictorial history of the 1990 jokulhlaup: upper photo 21 June, lower 28 June 1990. Terrace levels on the sandur testify of earlier flood events at a time when channel bottom was shallower.

FIGURES 4.15C AND 4.15D Pictorial history of the 1990 jokulhlaup (continued): upper photo 30 June, lower 9 July 1990.

Three transects were measured across the moraine from survey points # 5, 8 and 11 up to the 1990 position of the snout (figure 4.8). Each transect was oriented at right angles with a baseline between the survey point from which the transect originated and a previous survey point.

The transects shown on figure 4.8 were measured using a tape (as opposed to a theodolite) and they reach positions that extend too far upglacier from the 1988 glacier front position (depicted by the circles). Most of the discrepancy can be attributed to mapping and overlaying errors. Nevertheless, the dimensions among the three transect lines are proportionately correct. Hence even though the position of the 1990 glacier front as defined by the proximal ends of the transects is too far upglacier on figure 4.8, the curve described by the 1990 position of the glacier front adequately depicts the current shape of the glacier front in relative terms. In other words, it is believed that a good approximation of the absolute 1990 glacier front position could be obtained by a simple translation of the curve along the vertical axis of figure 4.8. The translation and rotation of the 1990 position of the glacier front compared to the 1988 position indicates the retreat along the central front and the dragging downvalley of the eastern front mentioned in the previous chapter.

Networks of survey stations were laid along traverse lines parting at right angles from the transects to monitor headwall retreat of the channel banks. Also monitored were survey points #6 and #10 as well as a small rock cairn on the west bank of Stevenson Channel, approximately 50 m downvalley from the distal edge of the moraine. The distances between the 2 squares at the end of each traverse lines (figure 4.8) show the total bank retreat over the period of observation (from mid June to end July 1990). More detailed data about the transects are given in Appendix 4.

A vivid illustration of the erosive power of Between River is conveyed in figures 4.16 and 4.17. Those figures summarize the data given in Appendix 4, but only relative locations (in terms of proximal, medial and distal) along the channels are given. Negative retreat values are included to highlight the absence of retreat meant by a zero value. Figure 4.16 shows that the well stabilized and generally convex upward slopes of the old Between Channel (Yellow Cairn Channel) have undergone virtually no morphological change in terms of headwall retreat during the mid summer period of 1990. Some retreat was monitored in the proximal west bank of the channel and at survey point #10. Quite surprisingly, the westerly exposed east bank did not show any movement except again in the proximal zone where a retrogressive thaw slump cutting through the transect showed some activity.

Figure 4.17 illustrates the radically different situation monitored along the current Between Channel (Stevenson Channel). In the same period of time, retreat rates of over 40 cm/day were observed at the proximal east bank of Stevenson Channel. The general picture along Stevenson Channel was one of actively retreating headwalls, with more pronounced rates along the east bank. The two

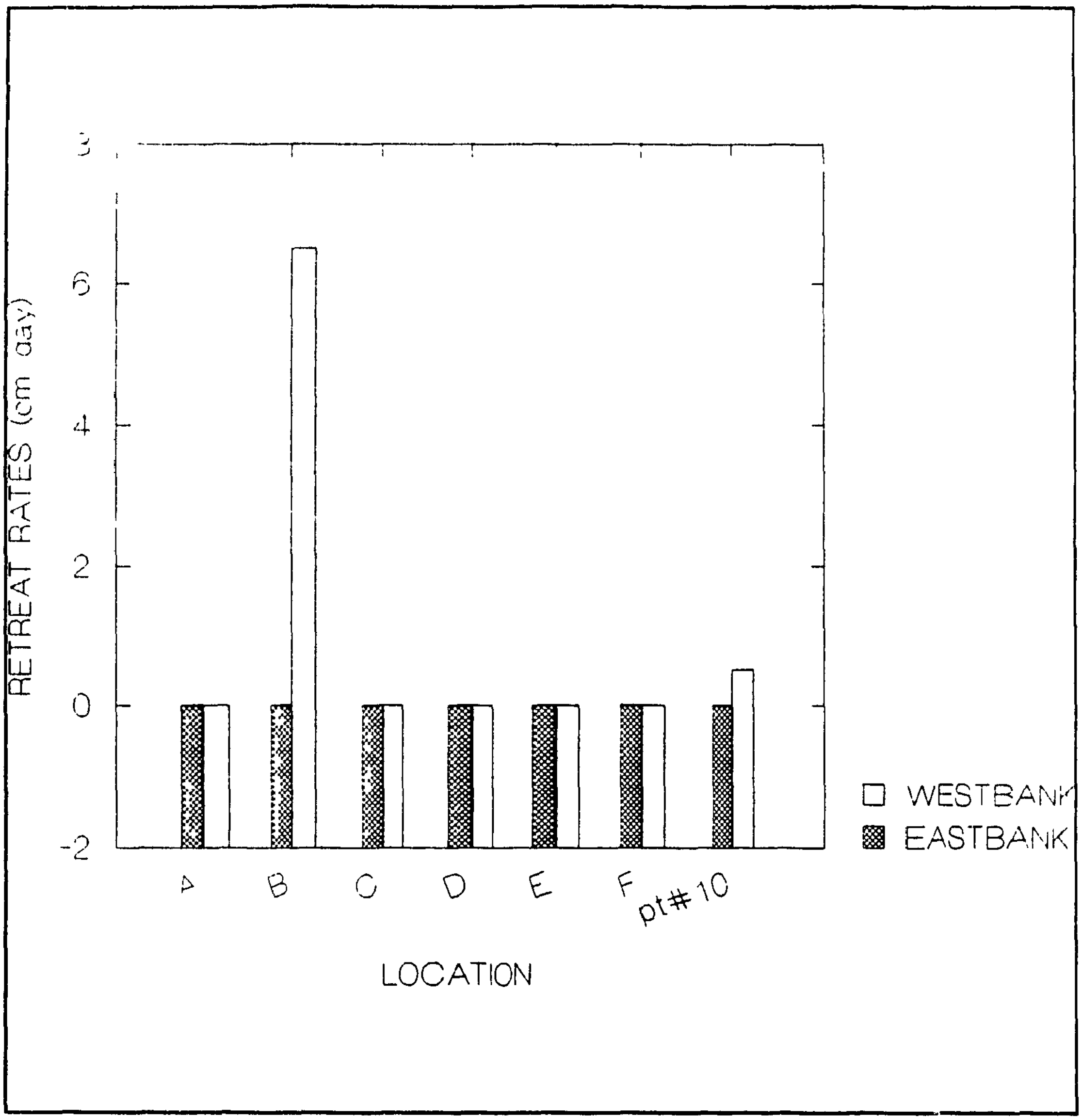


FIGURE 4.16 Retreat rates for Yellow Cairn Channel, June and July 1990. Letters on the x-axis refer to relative locations in the moraine, "A" being a proximal location and "F" a distal location. "Pt#10" refers to a location on the outwash plain (the coarse outwash material of the Expedition sandur has low ice content).

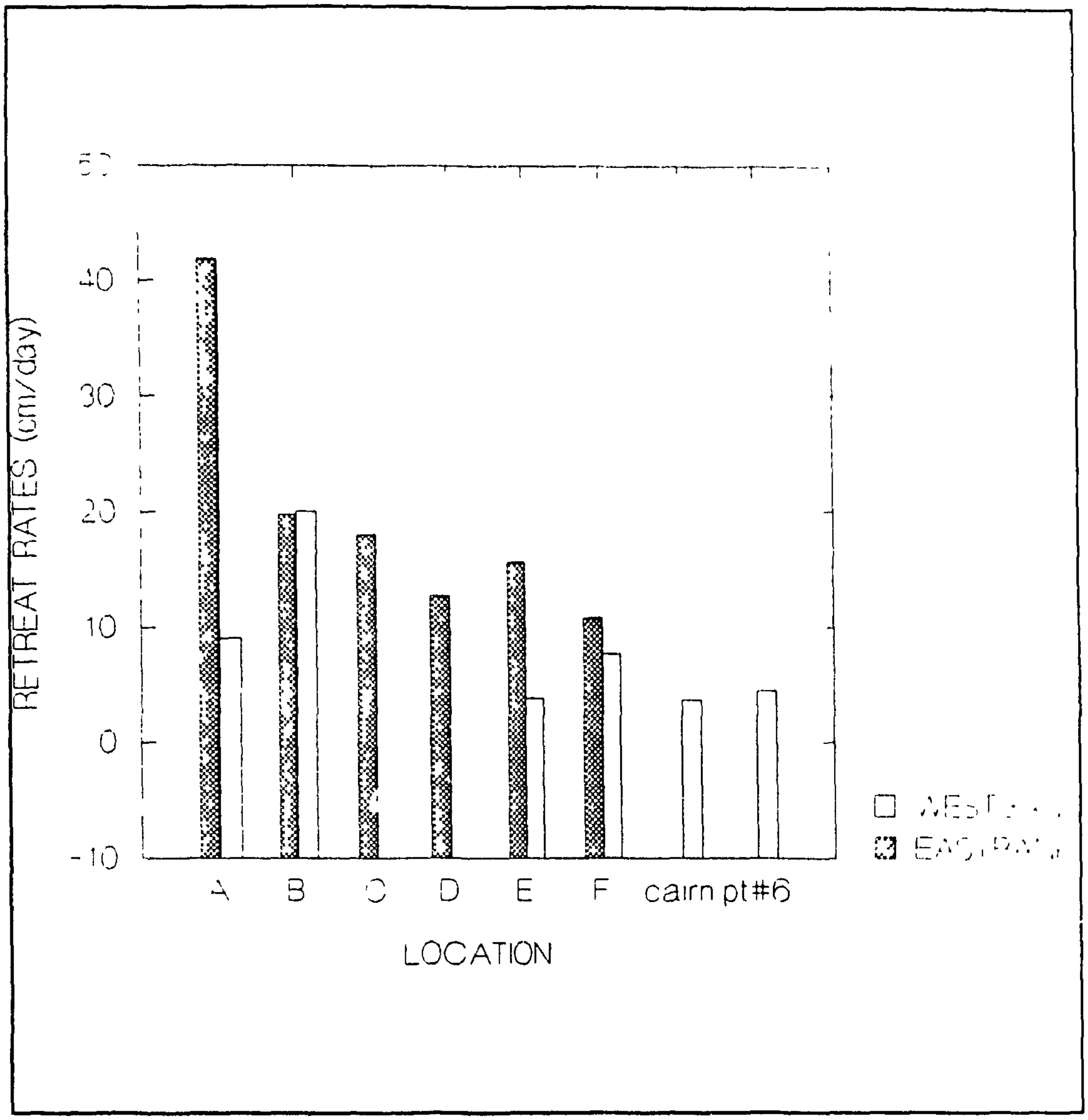


FIGURE 4.17 Retreat rates for Stevenson Channel, June and July 1990. Letters on the x-axis refer to relative locations in the moraine, "A" being a proximal location and "F" a distal location. "Cairn" and "Pt#6" refer to locations on the outwash plain (the coarse outwash material of the Expedition sandur has low ice content).

locations monitored in the outwash section of the channel (point #6 and "cairn") showed much slower retreat rates. Figure 4.6 shows the two channels.

Some conclusions may be drawn from a comparison of figures 4.16 and 4.17. First, higher colluvial activity (showed by higher bank retreat rates) is closely linked to the intensity of fluvial processes. By constantly removing material that accumulates at the base of slopes and sometimes by undercutting the bank, running water maintains relatively high slopes and hence the potential for colluvial activity. If Stevenson Channel were to become a dry channel (in the event, for example, that Between Channel is shifted west again), colluvium produced by thermokarst processes would begin to accumulate at the base of slopes. This would lead to the clogging of the channels used by colluvium and hence to the slowing down of colluvial activity. Eventually, a residual layer of thawed material would form an effective protection against further degradation and slopes would stabilize at a relatively low angle value, as is the case now at Yellow Cairn Channel.

A second conclusion is that the incidence of meltwater erosion is far more important in ice-rich than in ice-free material. Regarding this last statement, however, the data set presented in figures 4.16 and 4.17 is somewhat less obvious than it was for the first conclusion mentioned above. Figure 4.17 indicates that retreat rates at "point #6" and "cairn" are quite comparable with retreat rates in the distal moraine. Although this is true, it does not portray the situation very well. The small rock piles that constituted "point #6" and "cairn" were located on stratified and relatively ice-free outwash material in a zone where Between River was deeply undercutting the bank. The retreat rates for those two points then reflect only the extreme situation of a vertical bank of relatively friable material being eroded from the base. The retreat rate value observed at "point #10" (figure 4.16) is more representative of the intensity of retreat along the outwash portion of the channels.

Figure 4.17, which depicts retreat rates along the current Between Channel, shows that rates are generally higher along the east bank. A preliminary conclusion would be to attribute this difference to the fact that the east bank is exposed to afternoon solar radiation. Hidden in the data presented, however, is the fact that the manner in which colluvial activity occurs along both banks is different. Most of the time, material collapse along the west bank involved several cubic decimeters of material flowing down as bodies of quite varying viscosities along defined channels. Along the east bank, material was falling off from higher and steeper slopes as individual blocks or as small block slides. Typically, the steeper slopes were undercut by the stream. Questions as to whether this difference in the type of colluvial mechanism between the two sides of the channel is due to the different solar inputs or whether the difference in mechanism is really meaningful in explaining the observed differences in retreat rates are beyond the scope of this paper.

4.4 COMPLEMENTARY DATA

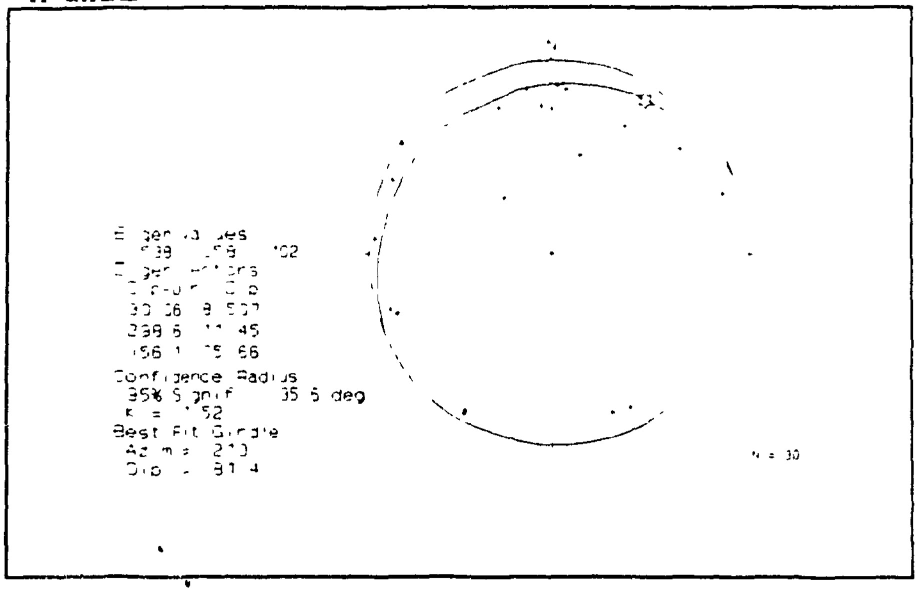
As a complement to the study, pebble fabric analysis was performed near point #6 using a magnetic compass. The site selected for fabric analysis was located on the west bank of Stevenson Channel at the distal edge of the moraine, where morainic material is ice-free and safely accessed. The face from which the pebbles were extracted was 1 m wide by 0,3 m high. Figure 4.18 shows the location of the face.

The abrupt and unconformable sedimentological contact between the upper till and the lower stratified outwash material is clearly visible. A 5-cm thick discontinuous horizon of buried organic matter composed mainly of roots was found in the summer of 1990 at the moraine/outwash contact in the central distalmost moraine. The corrected radiocarbon date of the sample was determined to be 180 +/- 60 years BP. This date represents a good estimate of the last glacier maximum and also a maximum age for till deposition, for the material sampled was located in the distalmost moraine. The age obtained for this recently found sample compares well with the age of 240 +/- 100 years BP obtained for a sample extracted in the early 60's at the same moraine/outwash contact, but in the eastern proximal moraine (MULLER 1963c).

A-axis and C-axis orientations of pebbles in the upper sedimentological unit (till) are shown on figure 4.19. The software used to plot the data was developed by van Everdingen and van Gool (1990). Because of the relatively small sample size and also because fabric data is complementary to other information in this paper, complex

FIGURE 4.18 Contact between outwash material (lower unit) and morainic material. The location of fabric analysis is marked by an arrow. Red ice axe measures 80 cm.

A axis



C axis

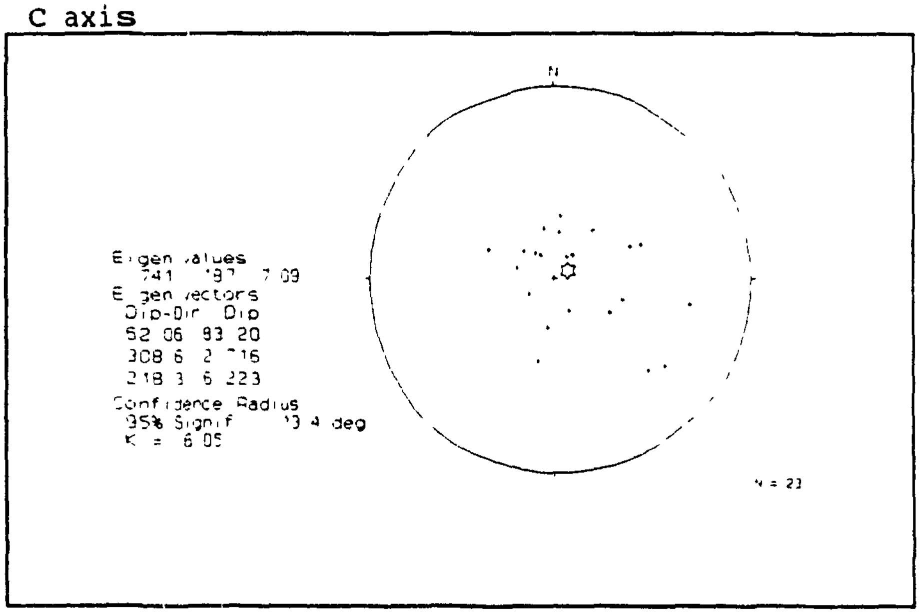


FIGURE 4.19 Pebble fabric data from the central distal White Glacier moraine, lower hemisphere projection: A-axis and C-axis orientations are shown respectively in the upper and lower illustrations. Star indicates position of first eigenvector. Dotted line delimits 95 % confidence zone for first eigenvector position.

statistical analysis of the data was not undertaken and only scatter plots are presented. Detailed fabric data is presented in Appendix 5.

The most interesting data pertains to the orientation of the plane defined by the two largest dimensions of the pebbles (the A and B axes). The orientation of this plane is given by the normal to the plane (the C-axis). The set of intersections of the C axes with a lower hemisphere depicted on figure 4.19 shows a weak tendency for the $A \wedge B$ planes of pebbles to be inclined downvalley towards 242^0. This direction does not correspond with the flow direction of the last section of the White Glacier, which is generally due south (180^0). However, it may reflect a secondary component of flow direction imposed by the NE-SW push of the Thompson Glacier. Additional fabric data from the medial and proximal moraine would be needed to confirm this hypothesis.

CHAPTER 5: THE THOMPSON GLACIER MORAINE

5.0 INTRODUCTION

The basic purpose of this chapter is to present field evidence that supports the evolutionary trends of the Thompson Glacier moraine proposed in chapter 3. A second purpose is to discuss some of the most active geomorphic processes that are currently operating in the Thompson Glacier moraine.

5.1 MORAINE DEVELOPMENT ASSESSED FROM AIR PHOTOGRAPHS

Between 1960 and 1967, the Thompson Glacier moraine was compressed along its length but its basal area increased mainly due to the increase in overall moraine width (KALIN 1971). During the same period of time, the surveying of stakes in the western sector both on the glacier and the moraine indicated that the mean direction of moraine development was about 10 degrees more towards the west than the mean direction of glacier flow (240^0 vs 230^0, according to Kalin 1971). Development trends over the last 30 years as evidenced by the data presented in chapter 3 can be summarized as follows: the length of the moraine has more or less remained unchanged, but the width noticeably decreased in the east whereas it substantially increased in the central and central-western zones.

The development of the Thompson Glacier moraine at three stages over the last 30 years is illustrated in the series of three pictures (figures 5.1a to 5.1c) depicting the moraine in 1959, 1972 and 1990. It is evident from the series of figures that the moraine has grown asymmetrically

FIGURES 5.1A AND 5.1B Moraine complex in 1959 (series A16864 Nos 36 or 37) and 1972 (series A23057 Nos 4 or 5).

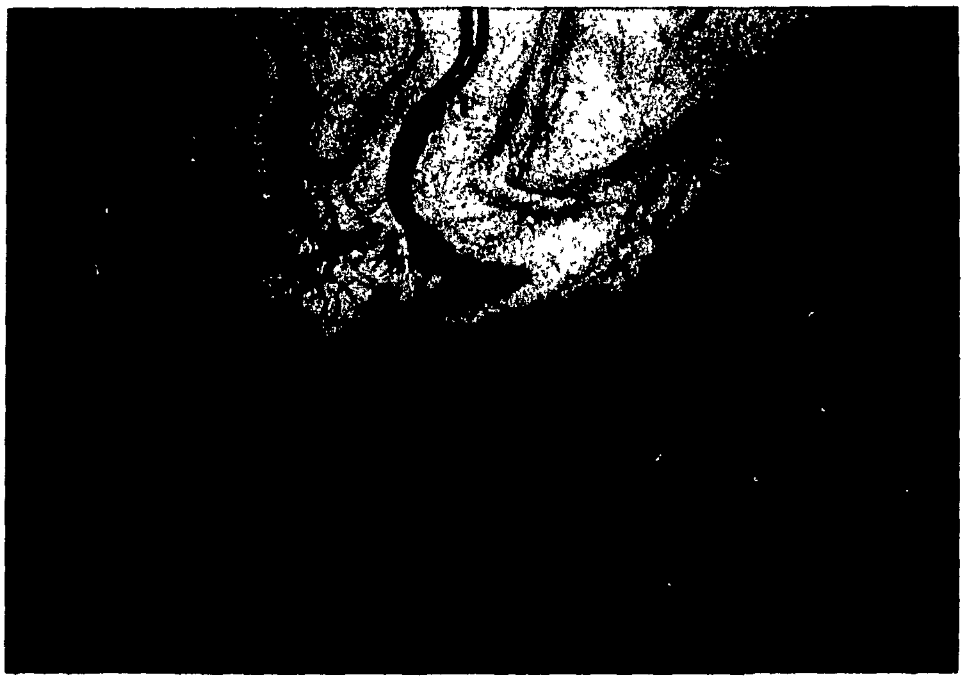


FIGURE 5.1C Moraine complex in 1990. The area shown is a portion of a photograph temporarily identified as PCSP-4 (see Appendix 1 for detail). The series of figures (a to c) shows the widening and shortening (lengthwise) of the White Glacier moraine as well as the asymmetric development of the Thompson Glacier moraine toward its central and western sectors. Note also the relatively good preservation of ridge structures in the central and western proximal moraine.

over the last 30 years. Maximum development occurred in the central and central-western zones, a conclusion that confirms the results presented in chapter 3.

5.2 **FIELD OBSERVATIONS**

5.2.1 EVOLUTION OF THE SURVEY PERIMETER

Field evidence is unequivocally supportive of faster development in the central and central-western moraine. On 15 June 1990, the only cairns indicating survey locations east of the present limit of the White Glacier moraine that could still be found were # 16, 30, 29, 28, 25 and 24. It is quite possible that cairns # 12 and 13 were washed away by meltwater, just as was witnessed for cairns # 16 and 24 later in the summer. However, all the other cairns along the distal edge of the moraine which were not found in 1990 had been so positioned in 1989 that they could not have been washed away. The implication then is that they were consumed by the prograding moraine after being buried by the incessant collapse of blocks along the distal edge.

In an attempt to quantify moraine development along the western, central and central-eastern perimeter, a group of four linear networks of orange-painted stones were laid perpendicular to the distal edge of the moraine at a few locations east of survey point # 16. The networks consisted in four stones separated by a distance of 25 cm, with the first stone being positioned right against the distal edge of the moraine. Over the period from mid-June to mid-July 1990, only one network located near point # 23 and another one near point # 16 were disrupted. The monitoring period was not long enough to allow for a quantitative assessment of moraine progradation rates at the distal edge. However these observations suggest that activity is occurring along the central and western portions of the distal edge.

5.2.2 DIRECTIONAL DATA: FRACTURES

The development of a group of fractures in the sandur beyond the distal edge of the southwestern moraine also lends support to higher activity in that portion of the moraine. The geometrical arrangement made by the fractures and the level of activity measured in the summer of 1990 discredit the hypothesis that the fractures may originate from thermal contraction.

All the directional data collected in the Thompson Glacier moraine area are presented in figure 5.2. The fractures are drawn to scale and are positioned as closely as possible to their absolute position in the field as of June 1990. Data pertaining to the dips of depositional surfaces are also included, but the locations on the map are accurate in only relative terms.

Figure 5.2 shows that there is a positive correlation between fracture density and fracture length. The 1990 fracture system extended from the central and southwestern moraine perimeter, between survey points # 21 and 26. However the highest concentration of fractures was located in the southwestern sector bordered by survey points # 21 and 30. Within this zone an even smaller area between points # 22 and 23 contained the three longest fractures in the whole system (fractures # 3, 4 and 5 on figure 5.2). The length of these fractures was on the order of 70 m, and

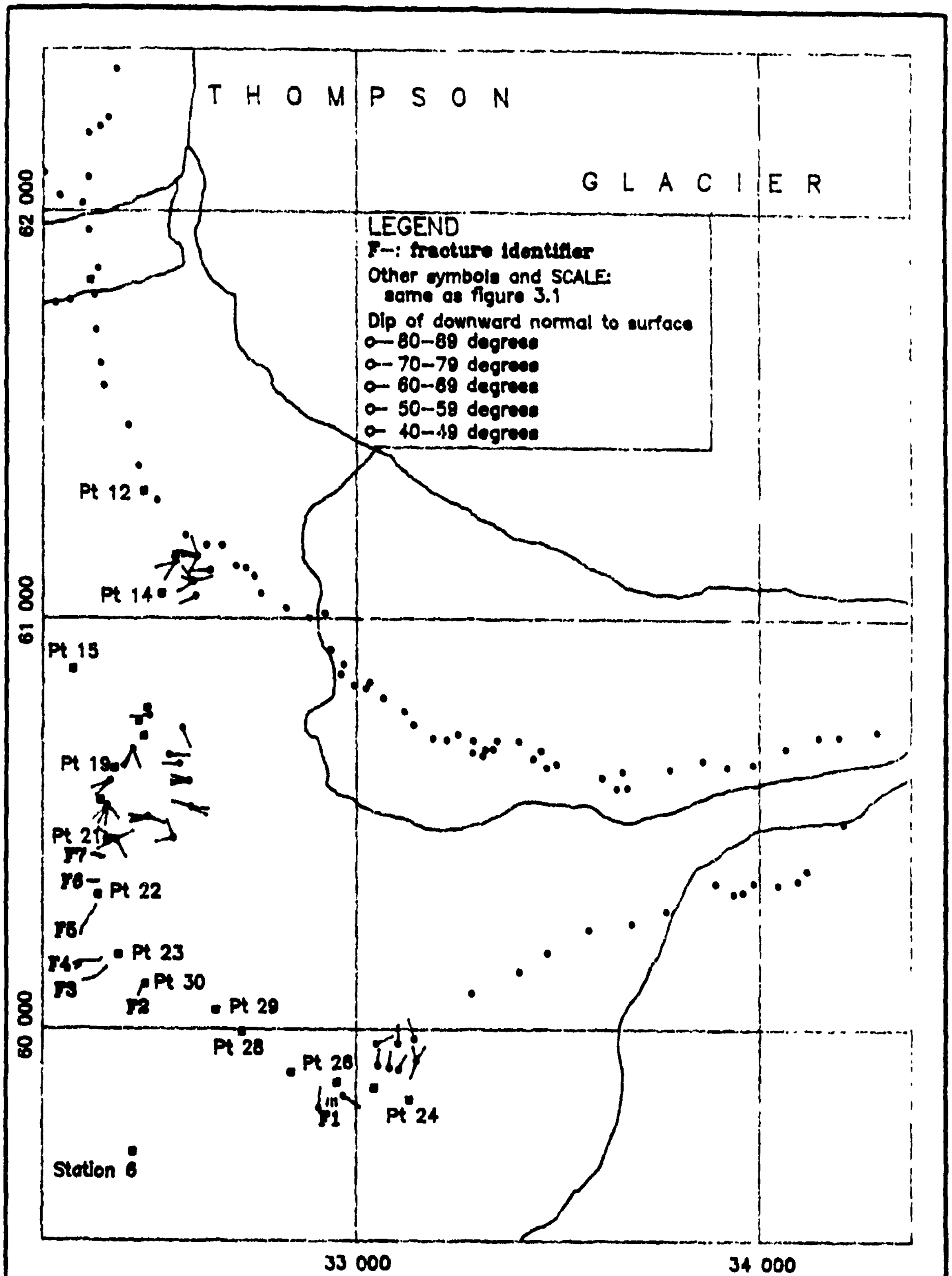


FIGURE 5.2 Map of directional data collected in the Thompson Glacier moraine: orientation of sandur fractures and of depositional surfaces.

the proximal ends of the fractures lay between 5 and 20 meters away from the moraine edge. Bulging on the sandur was only noted at the distal ends of those three fractures. Fissures emanating almost perpendicular to the main fractures were also a common occurrence in this zone. Figure 5.3 shows a portion of one of the three long fractures.

In an attempt to monitor relative movement between sides of fractures, a number of small transects of painted rocks were set up across the fractures at arbitrarily determined locations along the fractures. Horizontal movement between the ledges was not monitored, but relative vertical displacement was measured. Angular measurements between two fixed points on both sides of the fractures were recorded at transect locations during the one month period of observation. The data were transformed into vertical displacements and are presented in figure 5.4. More general information about the fractures is included in Appendix 6.

Figure 5.4 shows that no movement was detected in the group of three small fractures located near point # 26 (fracture 1 on figure 5.2) as well as along the fracture originating from point # 30 (fracture 2). All the fractures off the southwestern moraine (except # 5, for which the readings were found to be erroneous) showed relative vertical movement of the ledges varying from a few millimeters up to 3 centimeters during the one month period. However, no movement pattern could be identified along individual fractures. At some transects, the relative vertical distance between the ledges increased while at

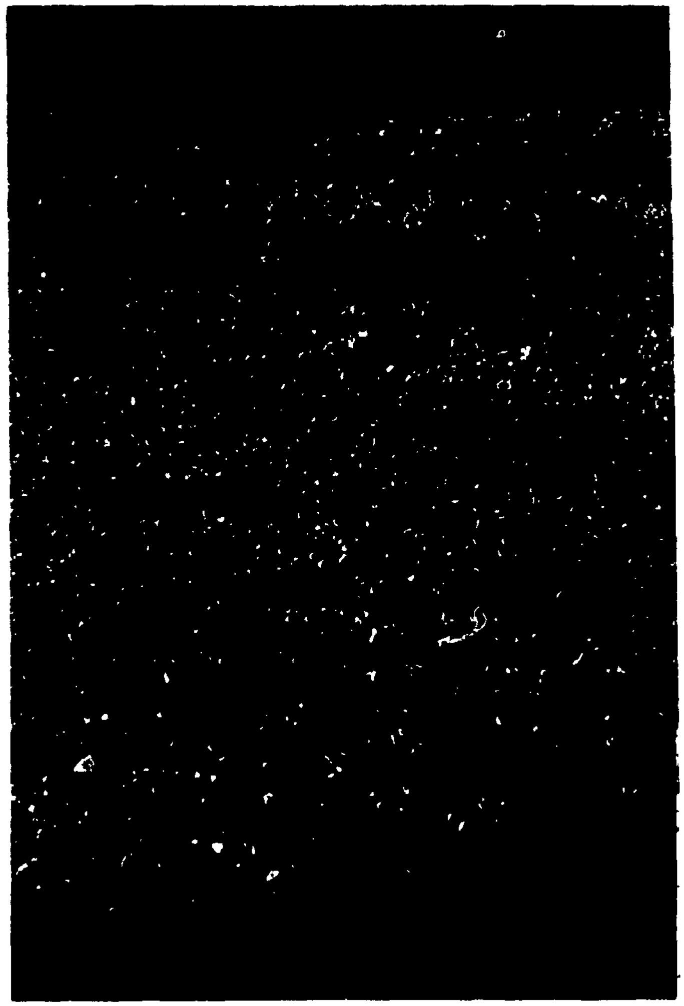


FIGURE 5.3 Sandur fracture linked to glaciotectonic activity beyond the southwestern Thompson Glacier moraine. The ski pole (foreground) and the blue backpack are approximately 10 meters apart.

FRACTURE NUMBER*	TOTAL VERTICAL DISPLACEMENT (cm)		
	increase	**decrease**	**inversion**
1	-------- No displacement -------		
2	-------- No displacement -------		
3	1.8		
		0.45	
	1		
	0.38		
		0.1	
4	0		
	0		
			3.1
		1.8	
	0.3		
	0.3		
5	------------ No data -----------		
6	1.4		
		1	
		negligible	
7	0.95		
		0.24	

* Refer to figure 5.2 for location.

FIGURE 5.4 Relative vertical displacement between fracture ledges at arbitrarily determined locations measured from mid-June to mid-July 1990 on the sandur near the Thompson Glacier moraine. Individual measurements are on separate lines.

other transects it decreased and in one instance the relative displacement brought about an inversion (i.e. the lower side had become the upper side). Fracture activity was also documented by the collapse down into the furrow of two painted rocks that had been position at fracture edges. Throughout the observation period, other small cracks appeared in the sandur between survey point # 16 and fracture #7.

The enhanced level of activity along the fractures located beyond the southwestern moraine further substantiates the observation that glaciotectonic processes are most active in the southwestern moraine. Corroborative data regarding higher glaciotectonic activity in the southwest had also been obtained at the end of the 1989 winter, when the only evidence of block cracking and thrusting was actually observed off the southwestern moraine perimeter. Figure 5.5 shows a block of frozen outwash material approximately 20 cm thick rotated upglacier. The full length of a 1,5-m long ski pole could be driven in the opening. Such open cracks were not observed anywhere else on the sandur and were not noted during summertime, a fact that suggests that evidence of glaciotectonic activity is best observed during winter when the active layer is still frozen.

Fracturing in the sandur appears to be a relatively recent phenomenon. No fractures were reported in the sandur in the 1960's except for one narrow 10-m long fissure located about 1 km downvalley from the central distal edge of the moraine (KALIN 1971). The total absence of fractures

FIGURE 5.5 Evidence of thrusting: open crack in the sandur off the southwestern Thompson Glacier moraine. The 20-cm thick slab is tilted upglacier.

for that period is rather astonishing, especially given the fact that it had been demonstrated at the time that the moraine was an advancing feature developing asymmetrically towards the southwest. An explanation one could provide is that overall distal moraine development rates in the southwest were significantly lower then than they are now. This explanation, however, contradicts the statement in section 3.1.2 to the effect that glacier progradation rates have apparently slowed after the 1960's.

5.2.3 DIRECTIONAL DATA: DIP OF DEPOSITIONAL SURFACES

The Thompson Glacier moraine is made up of a series of arcuate ridges produced by the folding and thrusting of blocks of glaciofluvial deposits lying ahead of the glacier snout. The presence of old braided channels on some of the blocks in the moraine suggest that these blocks used to be portions of the floodplain surface. It then seems logical that the present attitude (strike and dip) of such former floodplain surfaces (that we call depositional surfaces) may yield some valuable information on current processes dictating moraine development.

Dips of depositional surfaces were included in figure 5.2 to complement fracture data. The measured depositional surfaces were arbitrarily chosen in terms of their representativity of the general local trend of anticlinal or monoclinal surface attitudes. The surfaces which did not appear to be the result of tectonic activity (e.g. slopes produced by colluvial activity) were excluded.

Most measurements were taken in the distal zone of the moraine on what appeared to be the top portion of large scale anticlinal folds that were fractured open at the top. According to Aber (1988 p.63), this type of fold is common in the distal area of ice-thrust structures where "some thrusts die out upward into fold structures". Folded beds, however, were not studied in detail. The fractures cutting through the folds were strongly oriented into two perpendicular sets, one of which was parallel to fold (and ridge) axis. Except in the western corner of the moraine, the set of fractures that parallel ridge axis was not better developed than the other set (see figure 5.6).

A typical fold cross-profile would show relatively low angle slopes near the tension fractures and slightly increasing slope values for both limbs of the fold, especially the upice limb. In some cases, especially between survey point # 20 and 23, the wedge shaped fractures parallel to ridge axes reached 3 to 4 m in width at the fold apex and up to 2 m in depth. Widths and depths reaching 10 and 4 m respectively were measured for fractures aligned perpendicular to the fold axial plane. This last set of fractures is parallel to the set of sandur fractures described in the previous section. As for the sandur fractures, horizontal and lateral displacement for the distal moraine fractures were not apparent in the field. However, vertical differences on the order of a few decimeters between the surfaces of the ledges were noted.

On figure 5.2, the surface dips of the blocks defined by the fracture network (two blocks in the case of a single fracture, but three or four where two fractures meet) are

FIGURE 5.6 Extension cracks in distal fold structures, southwestern Thompson Glacier moraine. Note the two sets of fractures oriented parallel (from left to right) and perpendicular (from top to bottom) to ridge (or fold) axis. The intersections of these fracture systems delimit 2, 3 and 4-block structures the slopes of which diverge from intersection locations.

shown as groups of two or more lines originating from a common point (represented by a circle). For draughting purposes, the magnitude and orientation of the dip values on figure 5.2 relate to the downward normal direction to the plane defined by the measured surfaces. The magnitude of the dip of that normal direction is the complement of the true dip of the depositional surface and its orientation is shifted 180^0 with respect to the orientation of the dip of the depositional surface. Practically, this entails that the dip of a horizontal surface (0^0) is represented by a value of $(90 - 0)^0$. A surface dipping 10^0 toward 45^0 is shown on figure 5.2 as a line dipping $(90 - 10)^0$ toward $(180 + 45)^0$.

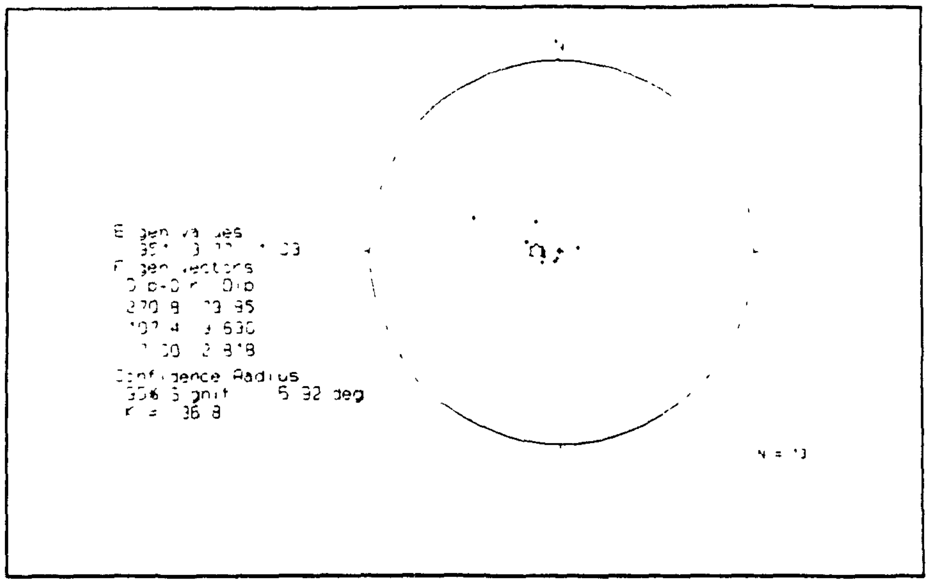
The distal and medial-distal portions of the western and southwestern moraine are characterized by the 2, 3 and 4-block structures which are directly associated with folding. Figure 5.6 shows an example of such structures in the southwestern distal moraine. On figure 5.2, some structures show block surface dips both upvalley and downvalley, but most structures show all individual blocks to be tilted upvalley. (It should be noted that since the general surface of the sandur is not horizontal but gently dipping downvalley toward the southwest [by a value of about 2^0 toward 230^0, which would translate on figure 5.2 as a line dipping 88^0 toward 50^0] a horizontal surface in the southwest should be considered as a surface slightly dipping upvalley). It can also be noted on figure 5.2 that structures are generally monoclinal and rocked downvalley in the distal eastern moraine. The difference in distal structures between the western and eastern moraine is interesting and whether it is a consequence of differences in moraine development, material or flow regime is problematic.

Two trends are apparent if one considers the dip data shown in figure 5.2 as four spatial clusters, namely the western corner, the southwestern distal zone, the southwestern medial-distal zone and the eastern distal zone. A first trend is a decrease in azimuth as one proceeds east along the moraine. A second trend is also a decrease in azimuth, but this time as one goes from a medial to a distal position in the moraine. The first trend can be explained by spatial variations of the stress field within the moraine. The second trend is indicative of variations in the stress field over time at a specific location. This suggests that the main stress orientations rotate from south to west as structures initially deformed in the southwestern distal moraine are becoming more and more proximal over time due to the glacier advance. In addition, figure 5.2 reveals that structures in the medial moraine do not show a net increase in the amount of upvalley tilt with respect to distal structures. This implies that blocks initially thrust in the distal moraine are apparently not further subjected to significant tilting while they are being stacked up and incorporated in the medial moraine. Four scatter plots (figure 5.7) present dip data for each of the four spatial clusters in a graphical form.

5.2.4 <u>CURRENT GEOMORPHOLOGY AND PROCESSES</u>

5.2.4.1 <u>Surface morphology</u>

The distal edge of the moraine was very well defined in



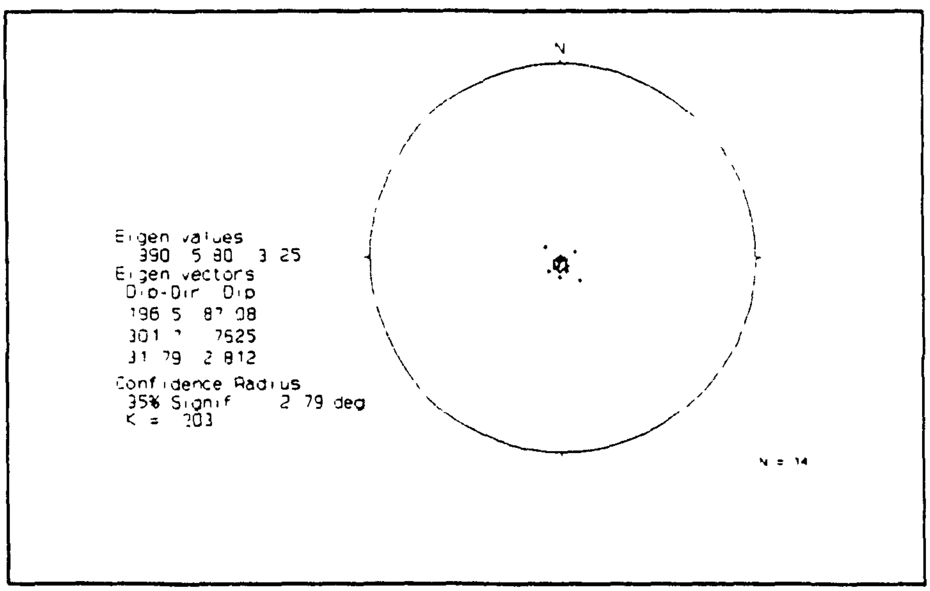
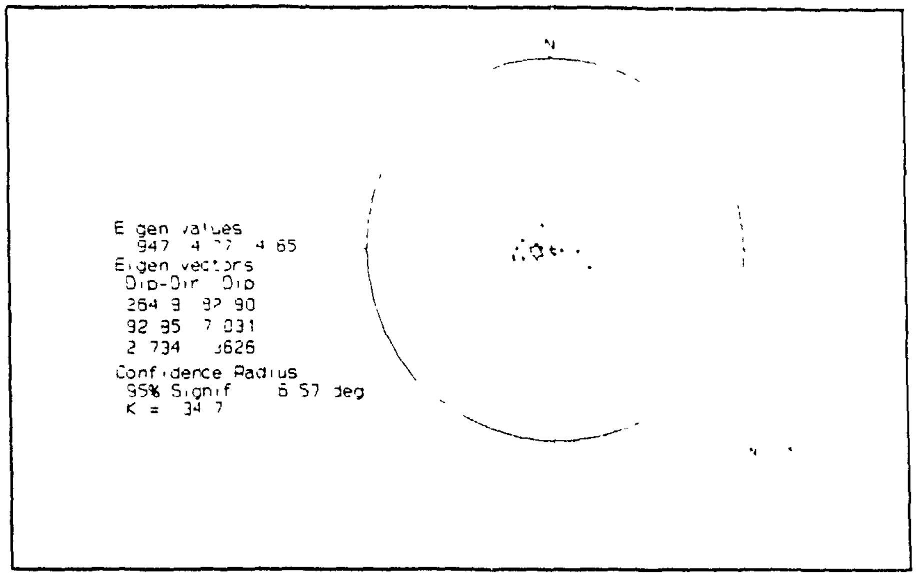


FIGURE 5.7 Lower hemisphere intersection of poles from planes defined by depositional surfaces, western corner (upper illustration) and southwestern distal zone (lower illustration), Thompson Glacier moraine. Star indicates position of first eigenvector. Dotted line delimits 95 % confidence zone for first eigenvector position.



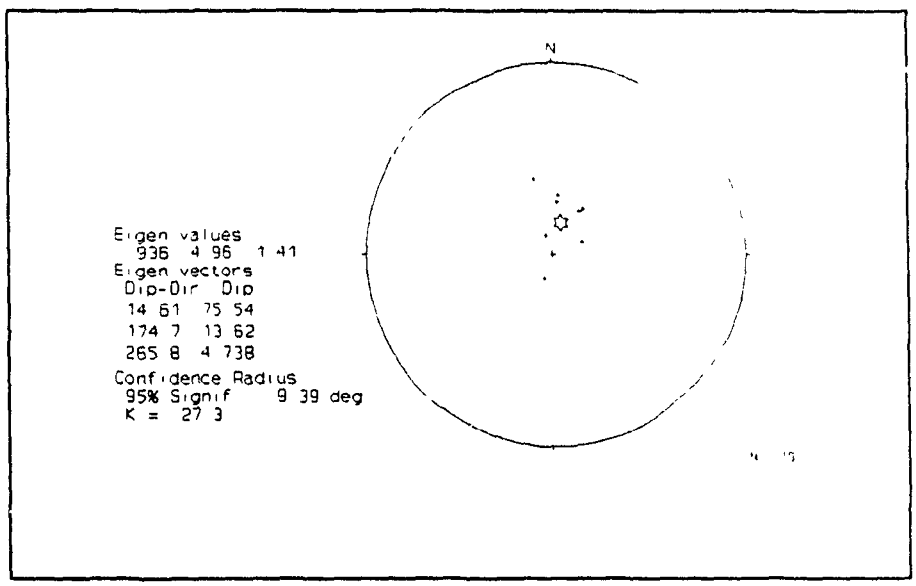


FIGURE 5.7 (continued) Lower hemisphere intersection of poles from planes defined by depositional surfaces, southwestern medial (upper illustration) and eastern distal (lower illustration) zones, Thompson Glacier moraine. Star indicates position of first eigenvector. Dotted line delimits 95 % confidence zone for first eigenvector position.

the east by an abrupt 30 to 40-m rise of the distalmost ridge. In the west, moraine limits were not as clear due to the presence of growing ridges at various locations in the sandur off the distal edge of the main landform.

The general surface appearance of the moraine also changes substantially from west to east. West of survey point # 24, moraine topography is characterized by very angular peaks and sharp crest lines whereas more subdued relief elements are observed in the east. The roughly semi-circular arrangement of structures, which is obvious in the distal zone, becomes increasingly blurred toward the front. A transect from distal to proximal in the western moraine would show important differences in relative height among individual relief elements and a generally increasing mean altitude with a maximum value a few decameters ahead of the glacier front. East of point # 24, a similar transect would show an abrupt rise at the moraine edge and relatively small altitude oscillations around a much higher mean level than in the west. This situation of a relatively high density of small relief elements lacking spatial organization in the eastern sector is most likely a result of the compressing of the moraine by the progressing glacier front.

The difference in surface morphology between the western and the eastern portions of the moraine is illustrated in figure 5.8. The absence of well defined structures in the eastern moraine is apparent. Future evolution of this part of the moraine would be interesting to monitor as it appears that the lateral eastern perimeter of the moraine will be pushed against the flanking hillside

FIGURE 5.8 Surface morphology of the Thompson Glacier moraine. Note the relatively high mean elevation and the small size of individual relief elements in the eastern portion of the moraine (foreground) compared with the topography of the western portion (upper central zone).

in the near future. Figures 5.9a and 5.9b show the progression of the glacier and moraine towards the valley side over a period of one year. Note on the central right portion of figure 5.9b the presence of freshly deposited humps of material on the valley side. Those humps are ice-cored conical structures a few meters in height which were deposited during the 1989-1990 winter. Similar humps of material were not reported in earlier literature.

5.2.4.2 Active processes

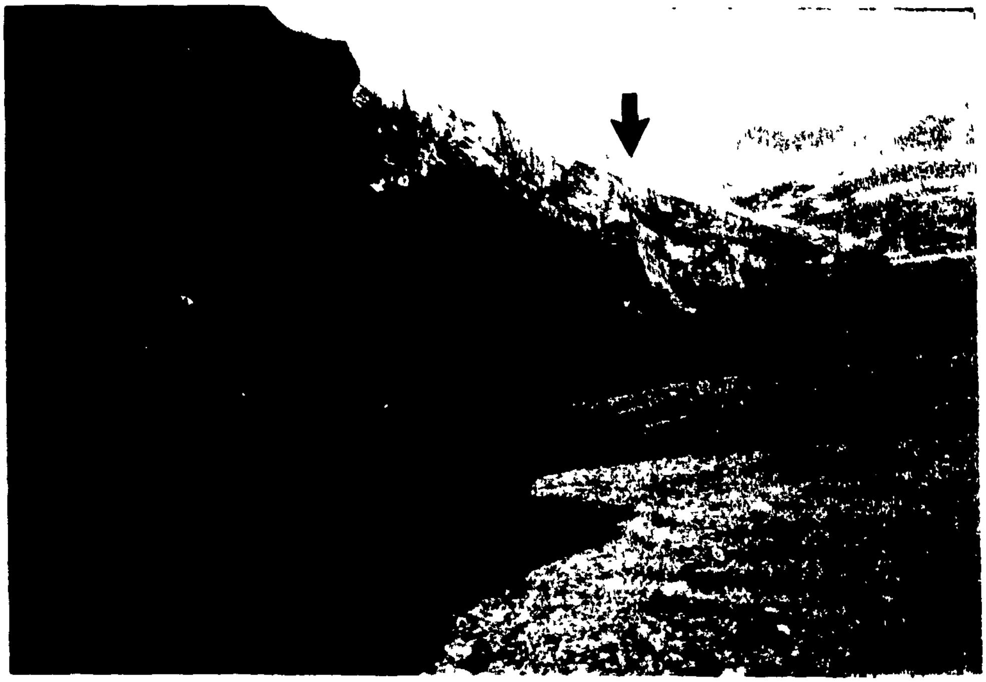
Tectonic activity together with colluvial and fluvial processes form the three basic geomorphic processes currently operating in the Thompson Glacier moraine. The topic of tectonic processes was introduced earlier and will be given a full treatment in a later section.

5.2.4.2.1 Colluvial processes

During the 1989 and 1990 summers, observed colluvial processes in the moraine consisted almost exclusively of individual particle slides. A fundamental difference with individual debris slides in the White Glacier moraine, however, is that most slides were not due to thermokarst processes. Particles were tumbling down as a dry slide under the sole impetus of gravity. In 1989 however, a fresh retrogressive thaw slump scar (similar to the slumps observed on the west bank of Stevenson Channel, in the White Glacier moraine) was found in one of the few zones of fine material in the Thompson Glacier moraine (figure 5.10).

5.2.4.2.2 Fluvial processes

Kälin (1971 p.23) noted that "water is the dominant



FIGURES 5.9A AND 5.9B View of the development of the eastern Thompson Glacier and moraine toward the hillside: upper photo July 1989, lower July 1990. Arrows indicate a landscape reference.

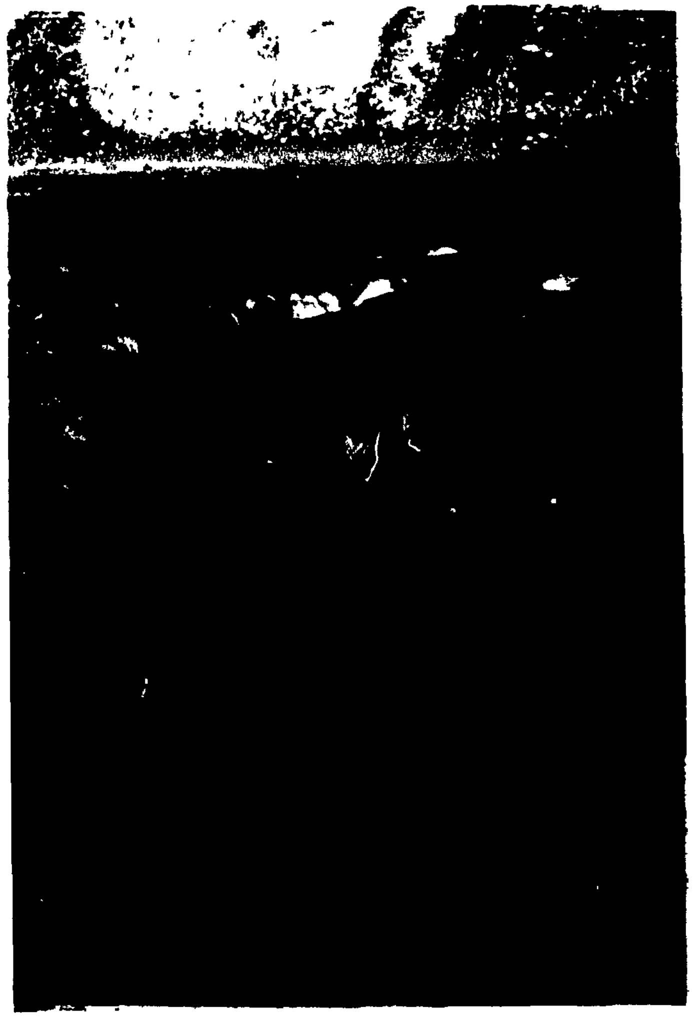


FIGURE 5.10 Retrogressive thaw slump in the Thompson Glacier moraine that developed in ice-rich fine-grained material (probably old lake bottom sediments) following fluvial excavation.

agent modifying the push moraine morphology". He observed that most of the water exiting the moraine originated from supraglacial meltwater streams that were cascading over the front. Water was crossing the moraine either directly or through small lakes and many streams were not continuous in the landscape. The higher number of sources compared to sinks suggested to him that "the water in the push moraine flows close to the surface in veins which have a tendency to branch out". The general hydrology in the Thompson Glacier moraine at present would still be aptly characterized by Kalin's description.

Figure 5.1c shows the entire moraine system as it appeared on 5 August 1990 and provides a clear view of glacial drainage through the moraine. Across the length of the Thompson Glacier, seven main meltwater streams were active during the summers of 1989 and 1990. Four of those channels were exiting the moraine at the location of the four outwash fans visible on figure 5.1c.

In the west, a first channel made up of a number of small streams falling off the Thompson Glacier front in the moraine-free zone was flowing along the ice margin and down along the western edge of an icing located on the sandur at the western corner of the moraine. In both 1989 and 1990, this icing occupied an area of over 10 000 m^2 (at its maximum extent in the early summer) north and west of survey point # 14. The icing is not observable on any of the air photographs prior to the 1990 series and its presence was not reported in earlier reports. On the 1978 air photos, however, a large outlet over 10 m wide was emerging subglacially from the snout of the Thompson Glacier about 75 m west of the western corner of the moraine. This stream began to flow "intra- or sub-glacially" in 1967 (KALIN 1971, p.9) and apparently captured part of the flow of the eastern lateral drainage channel. The stream may have been partially blocked by the forward movement of both the glacier and the moraine, a situation which could explain the formation of the icing. Large blisters at the surface of the icing also suggest the presence of a subglacial discharge.

Figure 5.11 shows a view of the icing and of its location relative to the glacier edge, the western corner of the moraine and the westernmost outwash fan on 16 July 1989. An icing located along the eastern distal perimeter was noted in the 1960's (KALIN 1971), but not in 1989 or 1990.

A second meltwater stream flowing west along the glacier/moraine contact exited at the western corner and was flowing over top of the icing and along the moraine edge out to Expedition River. Four streams flowed through the moraine. They emerged from the moraine at the locations of the four alluvial fans visible on figure 5.1c. A last major stream flowed along the eastern lateral ice margin and along the moraine edge.

Another important aspect of the Thompson Glacier moraine hydrology is the presence of many bodies of stagnant water. Kalin (1971) numbered over 80 "lakes" in the moraine. An updated count was not made for this thesis, but it was recognized in the field that many of the structural

FIGURE 5.11 View of the icing (looking north) near the western corner of the Thompson Glacier moraine. The icing is limited to the south by the westernmost alluvial fan (center). For a relative location of the icing, refer to figures 1.7 and 1.4. Note the presence of a stream exiting the western corner of the moraine and flowing along the eastern side of the icing.

troughs in the moraine were occupied by water. No lakes were observed in the compressed eastern portion of the moraine, east of survey point # 24.

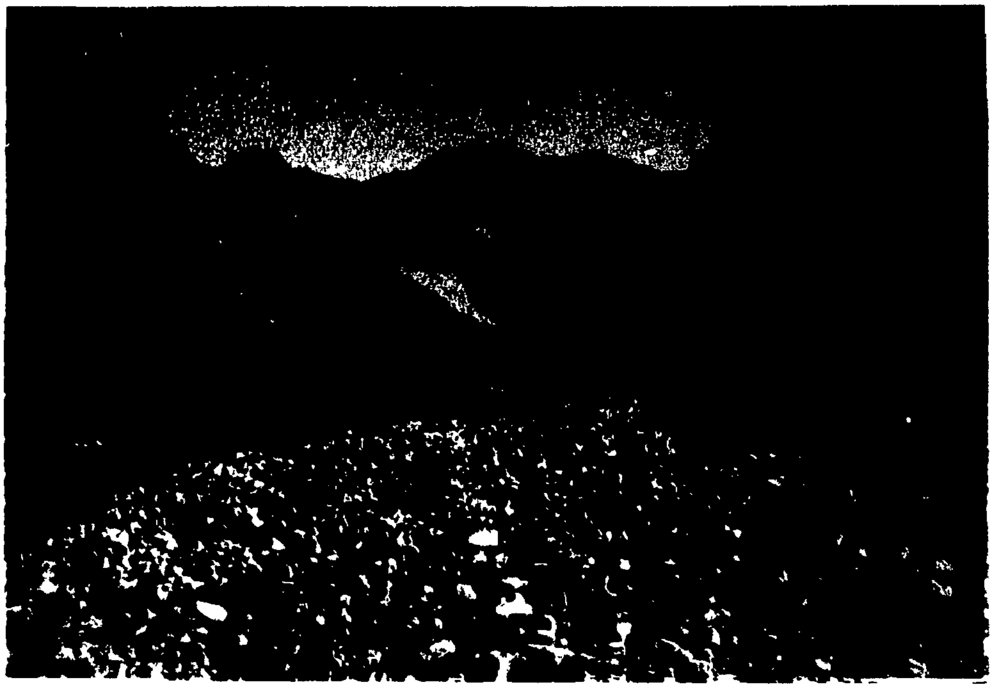
The majority of lakes were not linked with any stream, at least at the surface. Furthermore, as illustrated in the series of air photos depicting moraine evolution over the last three decades (figures 5.1a to 5.1c), many of the larger lakes in the southwestern moraine remained intact despite the significant forward progression of the moraine as a unit. This further buttresses the hypothesis (presented at the end of section 5.2.3) that structures are not greatly disrupted in the medial zone after they were first formed in the distal zone.

The role of the lakes was not studied in this thesis. An interesting avenue of research, however, would be to investigate the relationship between the lakes and ice in the moraine, or the relationship between the lakes and the rather common occurrence of fine sediment accumulations in the moraine.

During the period of study, and especially during the warm and sunny summer of 1990, fluvial processes were found to be responsible for most of the morphologic changes in the Thompson Glacier moraine. The most spectacular changes were observed along the southwest distal edge of the moraine, at the location of the westernmost outwash fan.

The series of five pictures (figures 5.12a to 5.12e) shows the evolution of the fan between July 1989 and July

FIGURES 5.12A AND 5.12B Refer to second next page for description.



FIGURES 5.12C and 5.12D Refer to next page for description.

FIGURES 5.12A TO 5.12E Evolution of the westernmost alluvial fan (for a relative location of the fan, see figures 5.11 and 5.1c). The sequence shows the landscape on: 15 July 1989 (A), 15 June 1990 (B), 19 June 1990 (C), 23 June 1990 (D) and 5 July 1990 (E). The very incised channel of 1989 (5.12A) was filled by sediment by the beginning of the 1990 summer (5.15B) and incised again within a few days in 1990. Note the vertical ice-filled fracture (which is the focus of figure 5.15) in the right-hand side hill shown in figures 5.12B, C and D. Arrows indicate a mobile (?) landscape reference.

1990. The last four pictures cover the period from 15 June 1990 to 5 July 1990. Note the dramatic changes in channel morphology and the formation of terrasses (figure 5.12e) within a few days. Similar changes were also witnessed later in the summer at the location of the central eastern fan. Following an abrupt shift of the stream to the west via a fault underneath a hill located about 50 meters upstream from the distal edge of the moraine, a 3-m deep and 4-m wide channel was carved along the west side of the fan. The cairn that marked the position of survey point # 24, which bordered the fan to the west, was washed away in the process. Such dramatic changes in the short term morphology of the moraine perimeter are not reported in previous literature.

The constantly changing nature of the network of water conduits underneath the moraine was also observed during the summer of 1990. About mid-July, both the streams coming out of the western and central western fans were reduced to mere trickles while discharge in the stream flowing around the west corner of the moraine and along the eastern edge of the icing increased by an order of magnitude. A bubble of upwelling water about 1 meter in diameter at the western corner of the moraine showed the existence of a major underground tunnel or seepage zone emerging as a vertical resurgent source. On figure 5.11, the stream is shown in its much less impressive form in 1989.

In terms of landscape evolution, stream capture, which may lead to the formation of powerful short-lived torrents, has a dramatic effect along the perimeter of the moraine.

By the end of the 1990 field season, the 2-week torrent at the western corner of the moraine had gouged an impressive trench along the north and west limits of the westernmost alluvial fan. A fair amount of material that had been previously deposited on the alluvial fan was eroded and redeposited further downvalley, ready for another possible cycle of incorporation in the moraine.

5.2.5 PERMAFROST AND GROUND ICE

The presence of shallow underground seepage and flow paths in material that lacks cohesion in a thawed state leads one to question the role of permafrost and ice in the moraine. Unlike the White Glacier moraine, the Thompson Glacier moraine is not massively ice-cored. In many occurrences however, concentrations of pure ice were observed in the moraine (as evidenced for example in figure 5.10). The origin of moraine ice is one focus of research of this student's supervisor.

Kalin's (1971 p.16) classification of ice in the moraine into two types, namely (1) congelation ice (which comprised "lake ice" and "ice fillings of faults") and (2) metamorphous ice ("glacier ice" and "ice along thrust surfaces") has only limited application. During the 1990 field season, ice was observed in four different types of occurrences: (1) glacier ice, (2) vertical bodies of massive ice, (3) horizontal bodies of massive ice and (4) intergranular ice.

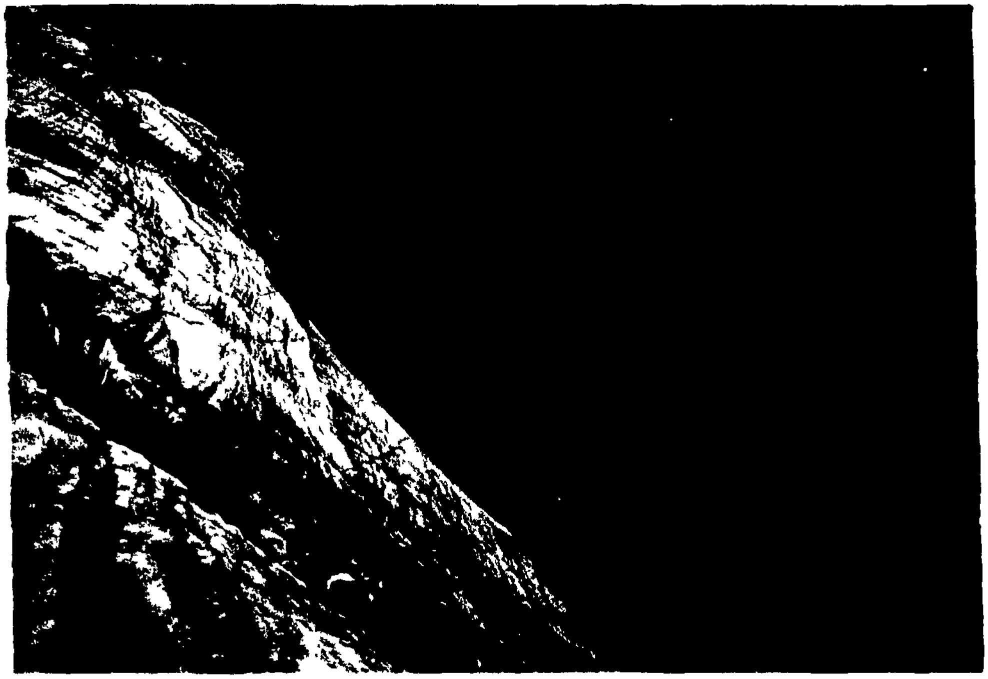
Field observations suggest that glacier ice may underlie a significant portion of the moraine. The best evidence supporting the presence of buried glacier ice was observed at the glacier/moraine contact in the central-eastern moraine (figure 5.13). In addition, large ice bodies possibly of glacial origin at the base of many hills were observed through lake water (figure 5.14). The presence of what appeared to be cryoconite holes at the surface of those ice bodies suggests a glacial provenance. Further investigations would be needed to establish a more reliable interpretation.

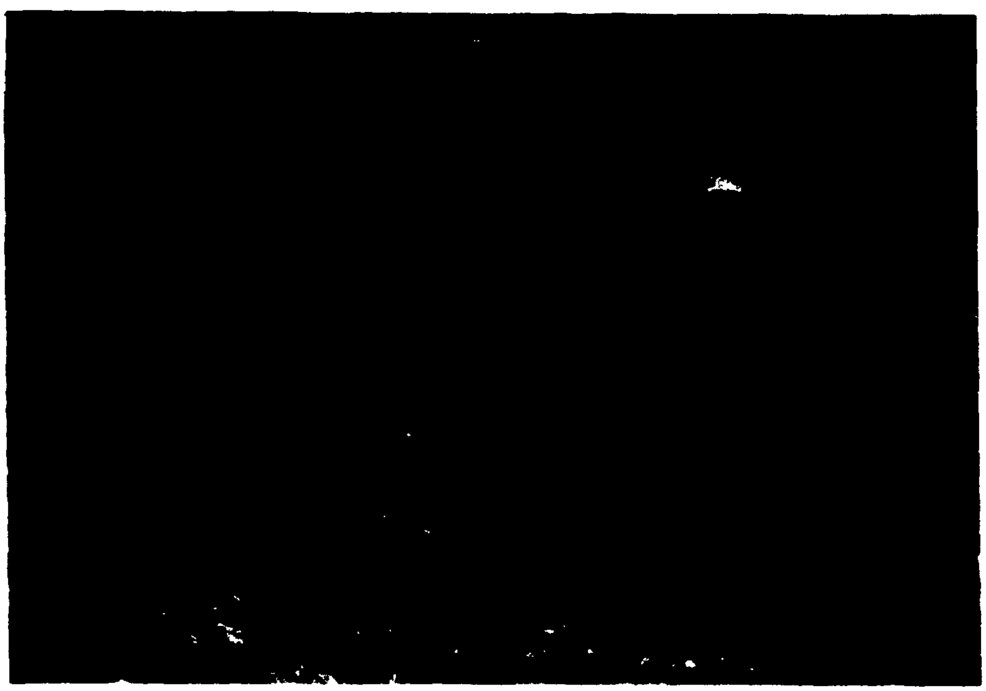
The presence of large vertical and horizontal bodies of ice was also noted at several locations in the moraine (e.g. figure 5.15). Intergranular ice films were also observed around individual particles.

The relatively widespread occurrence of buried snow (figure 5.16) along the distal edge of the southwestern moraine observed in 1990 is not mentioned in the earlier literature concerning the Thompson Glacier moraine. Besides constituting additional evidence of moraine instability and progradation, the burial of snowbanks could be responsible for the formation of massive bodies of ice.

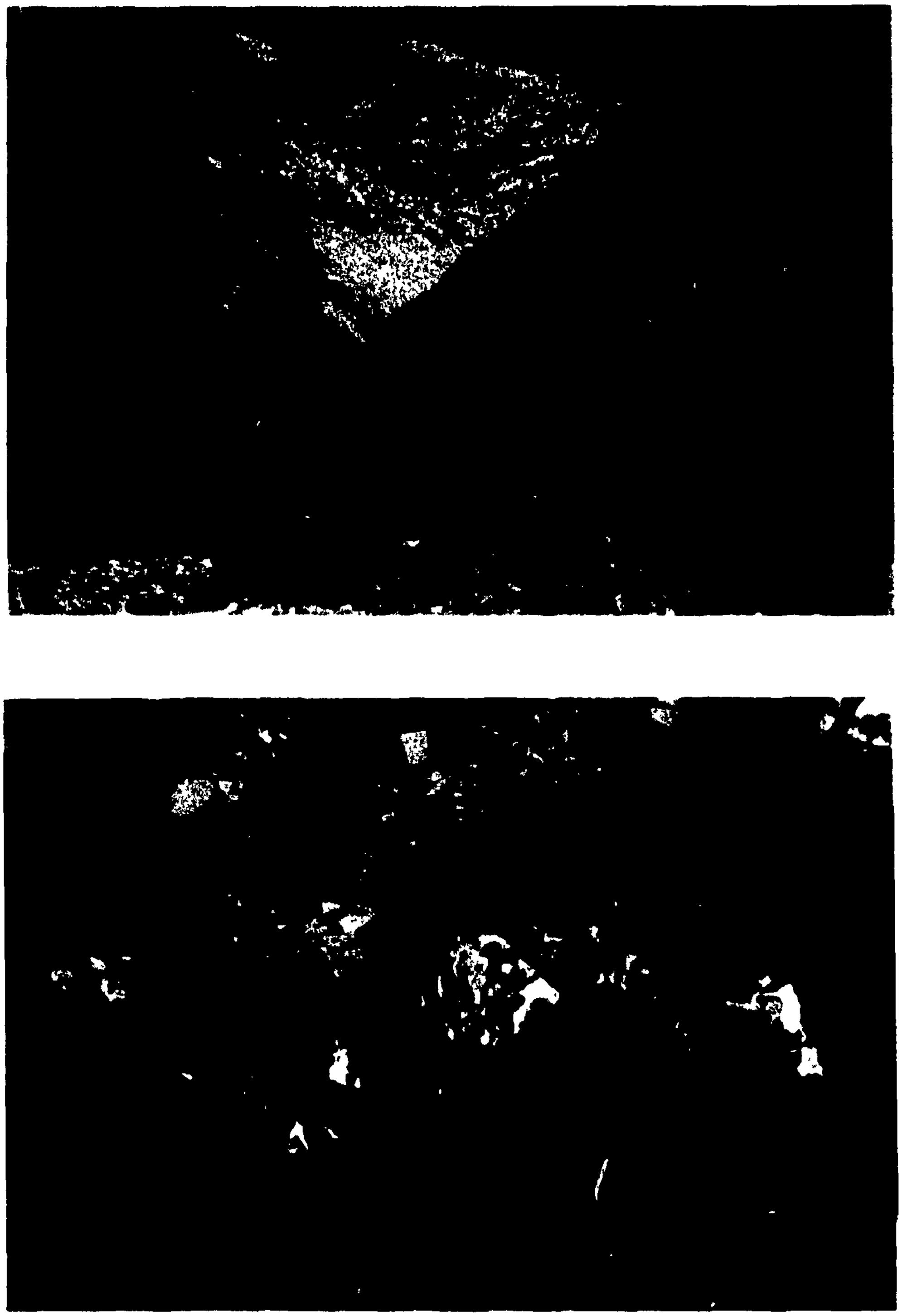
5.2.6 CURRENT MORAINE FORMATION PROCESSES

An earlier conclusion concerning the presence of "morainic material" in the central Thompson Glacier along the moraine/glacier contact was that the Thompson Glacier front had probably been receding there, whereas a few hectometers east it would have been an advancing glacier (ROBITAILLE et GREFFARD 1962, p.92). Data in this thesis show no evidence of such dramatic differences in terms of





FIGURES 5.13 AND 5.14 Occurrences of ice in the Thompson Glacier moraine: glacier ice underlying the central eastern proximal moraine (5.13) and glacier (?) ice underlying a hill (5.14) in the medial western zone.



FIGURES 5.15 AND 5.16 Occurrences of ice in the Thompson Glacier moraine (continued): massive body of ice (5.15) and buried snow (5.16), distal western zone.

movement along the glacier front.

Theory about the formation of ice-thrust structures identifies three basic processes: (1) bulldozing of the forelying material by compressive ice flow; (2) cracking of slabs of material due to differential stress fields created by the superincumbent weight of the ice followed by the upturning of the slabs and incorporation in the moraine and (3) deposition of slabs of debris frozen to the glacier sole and released at the front due to upward compressive flow (ABER ET AL 1989).

Hypothesis 3 can be ruled out at once. The large extent of the Thompson Glacier moraine makes it improbable for the moraine to be a mere deposition of upturned slabs of basal ice. Even at the glacier front no evidence of this process was observed.

Field observations also invalidate the bulldozing hypothesis of moraine formation. For this hypothesis to be plausible, one would expect the moraine to be opposing the forward progression of the glacier front and hence one would expect different processes to occur at the front along the moraine and in the moraine-free zone. Field observations suggest that the type of process at the front does not depend on the presence or absence of the moraine. For example, apron entrainment evidenced by gravel bands and augen structures at the ice front and calving processes occurring along the front in the moraine-free zone (figure 5.17) are observable at the glacier/moraine contact as well, just as if the presence of the moraine hardly interfered

FIGURE 5.17 Apron entrainment at the Thompson Glacier front, in the moraine-free zone. Note the overhanging (or "C") shape of the front.

with processes occurring at the front. Furthermore, the front of the Thompson Glacier shows downglacier dipping ice strata both in the moraine-free zone (except near the White Glacier) and along the moraine. This apparent absence of change in processes throughout the entire width of the glacier is an argument for eliminating the role of bulldozing processes in the formation of the Thompson Glacier push moraine.

Another fact that invalidates the bulldozing process that would be responsible for the formation of a "push" moraine per se relates to the gap that is observed between the glacier front and proximal moraine structures. This gap, which is on the order of a few decameters, was observed along about one half of the glacier/moraine contact. Since it is not logical that a pushed body not be against the pushing body, then bulldozing can be ruled out as the fundamental process responsible for the formation of the Thompson Glacier moraine. Whether an ice keel underneath the apparent floor of the proximal moraine could effectively push the moraine is a possibility, but conclusive evidence of such ploughing was not observed.

An additional argument against the bulldozing hypothesis relates to the preservation of structures in the moraine as a whole (with the notable exception of the easternmost moraine, where the glacier has overriden the proximal moraine) over the last three decades. The preservation of structures is illustrated in the plan views of the moraine for 1959, 1972 and 1990 (figures 5.1a to 5.1c). Lastly, it is doubtful that bulldozing alone could explain how the distal edge of the central and western moraine was translated downvalley at least as much as the glacier front was over the last 30 years.

Instead, field observations suggest the cracking and thrusting of slabs of permafrost (hypothesis number 2 above) is the dominant formative process in the Thompson Glacier moraine. Evidence for the very small scale cracking and rocking back of slabs was presented in section 5.2.2 (figure 5.5). Evidence in support of the thrusting mechanism was also obtained during the summer of 1990.

The thrusting and incorporating in the moraine of slabs of material is visible on the sandur-facing slope of the southwestern distal edge. Over time, those processes lead to the stacking of thrust blocks with the older ones being at the top of the sequence. This situation is described in Klassen (1982 p.373) and in Park (1989 p.71). The resulting topography is an increase in altitude along a distal to proximal transect (figure 5.18).

The stacking of thrust blocks was visible in the field by the vertical succession of jutting blocks of horizontally bedded fluvial gravel in otherwise structureless heaps of gravel. Stratified units along the slopes in the southwestern moraine were often highlighted by the presence of water, which caused a darker appearance of the stratified blocks. The presence of water is very significant, since its role as a lubricant is a key element in the thrusting process (ABER ET AL 1989). Blocks of stratified material along slopes in the eastern moraine did not display the

FIGURE 5.18 Photo showing the decreasing mean altitude of the Thompson Glacier moraine from proximal (right) to distal.

darker colour indicative of wetness. Figure 5.19 shows a portion of the southwestern sandur-facing distal slope.

Examination of this slope made it apparent that blocks of stratified material were being thrust during the summer of 1990. The typical profile downslope of a protruding dark stratified unit shows a vertical face below which the slope is generally concave upward due to the increasing thickness of loose material. This increase in colluvial material as one proceeds downslope from a thrusting block (evidenced in the field by the increasing "softness" of the material when climbing down) was associated with a marked increase in mean grain size. This situation suggested that the jutting blocks of stratified material were sources of colluvial material.

In order to help support the hypothesis that the thrusting of blocks was the main operating building process in the Thompson Glacier moraine, it was decided to determine the origin of the rock slides that produce the accumulations of loose material at the base of slopes. The frequency of block slides was found to be higher in the western moraine, again testifying of the higher activity in this portion of the moraine.

Over a two-hour period on 15 July 1990, 13 rock slides were observed along a portion of the southwestern sandur-facing distal slope pictured on figure 5.19. Ten of those slides involved relatively long (both spatially and temporally) displacements of a group of pebbles and cobbles. All of those slides originated from blocks of stratified

FIGURE 5.19 Blocks of stratified gravel (horizontal patches) jutting out of the otherwise structureless slope in the southwestern distal Thompson Glacier moraine. Scale is given by the man in the upper right corner.

material. The three other slides did not originate from the blocks, but they appeared to be simple resettling of minor quantities of material. This small experiment reinforces the idea that colluvial activity is mainly a result of the melting and collapsing of stratified blocks of material as they are pushed out in a fashion similar to when material oozes at the surface of a glacier due to compressive flow.

Structural evidence of thrusting is increasingly obscured as one proceeds into the moraine along a distal to proximal transect. The repeated action of glaciotectonic processes on the brittle slabs of frozen gravel together with colluvial and eluvial processes significantly alter the structures originally deformed in the distal zone. However the presence of numerous openings between and sometimes even within individual structural elements testifies of the tectonic origin of the moraine.

Many such openings were "accidentally" found in May of 1989, when the ground was still completely frozen. A good example of an opening found in the summer of 1990 is shown on figure 5.20. The hole shown is located at the junction between two small hills in the eastern moraine. Its original appearance in the field was an insignificant looking opening about 10 cm in diameter. Excavation of the original hole revealed a 30-cm wide near vertical ice-walled cave estimated to be at least 5 m deep and extending around and under one of the hills.

The tectonic origin of the moraine is also demonstrated by the straight edges and angular corners of a number of

FIGURE 5.20 Surface hole leading to a 5-m deep and 30-cm wide ice-walled cave in the medial eastern Thompson Glacier moraine.

lake edges. The typically very high length/width ratio of those lakes is a further indication of the structural origin of many troughs in the moraine.

Although a great deal of field observations in the distal zone substantiate the thrusting hypothesis, one fact remains that casts some uncertainty as to the processes acting in the very proximal moraine, namely the decreasing height of the glacier cliff from west to east.

The observed decrease in cliff height (from a maximum of 40 to 50 meters in the moraine-free zone down to about 10 to 20 meters in the central and eastern front) was also noted in the early 1960's (ROBITAILLE et GREFFARD 1962). It is apparently associated with a general increase in moraine floor height. However the series of vertical air photos shows that the central-eastern and especially the easternmost moraine was overriden by the Thompson Glacier. Hence the decrease in apparent ice thickness at the front seems to be related to the overriding process, a process which was not investigated in the present research.

Figure 5.21 shows a representation of what the glacial/proglacial contact may be like in the moraine-free zone and in the eastern Thompson Glacier moraine. The "C" shape of the glacier front (side view) in the moraine-free zone illustrated in figure 5.21 and visible on figure 5.17 was not observed in the 1960's. Photographic information rather indicates the front was vertical (and not overhanging). It is beyond the scope of this thesis to verify whether figure 5.21 is a correct representation of

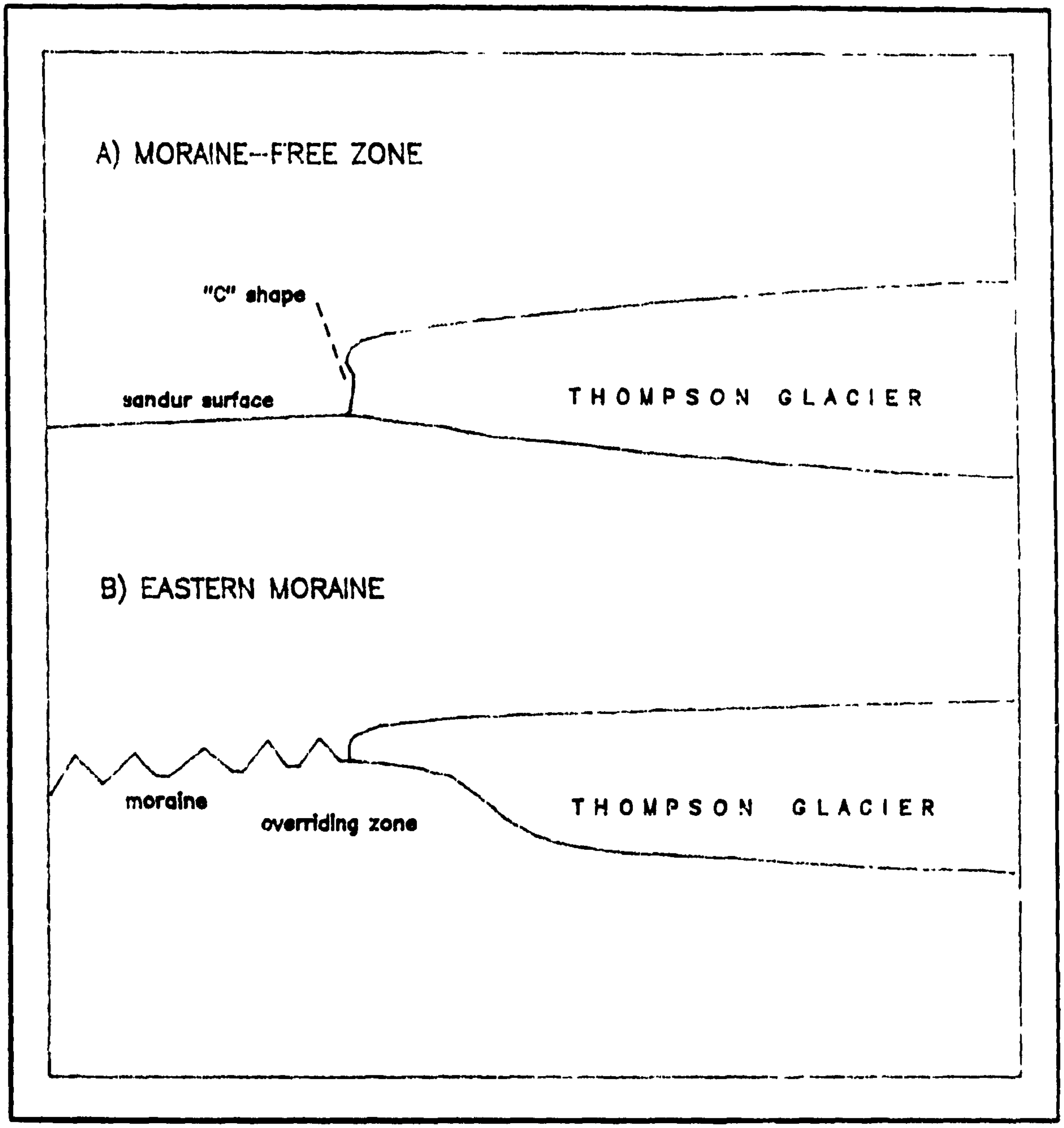


FIGURE 5.21 A possible representation of the glacial/proglacial contact in the moraine-free zone and the eastern Thompson Glacier moraine.

reality, for such a verification would require, among other things, a knowledge of ice thickness near the front across the whole glacier.

5.2.7 PROPOSED MODEL OF MORAINE FORMATION

On the basis of field evidence and from the discussion presented above, a scheme is proposed for ice-thrust ridge formation at the terminus of the Thompson Glacier. The scheme is synthetically represented in figure 5.22.

The key element in figure 5.22 is the proposed cycle of materials in the moraine. As blocks of undisturbed outwash material are deformed and progressively integrated in the prograding moraine, some of the material is inevitably pulled down by gravity. Depending on where this material falls, it either stays in the moraine by settling in a dry depression or it is progressively carried by streams out to the distal zone and eventually out of the moraine (where it settles on the alluvial fans formed at the moraine perimeter). Material that sets in a dry depression may remain still (relative to the sliding of the whole moraine) or be remobilized. Material deposited on the alluvial fans may either remain still (and eventually be subject to a new phase of ridge formation) or intermittently be carried far away down the river by powerful torrents. Figure 5.23 schematically represents the develcpment of the central and western sectors of the Thompson Glacier moraine over time.

5.2.8 COMPLEMENTARY DATA

Fieldwork of more general interest was also carried out in the Thompson Glacier moraine. Pebble fabric analysis was

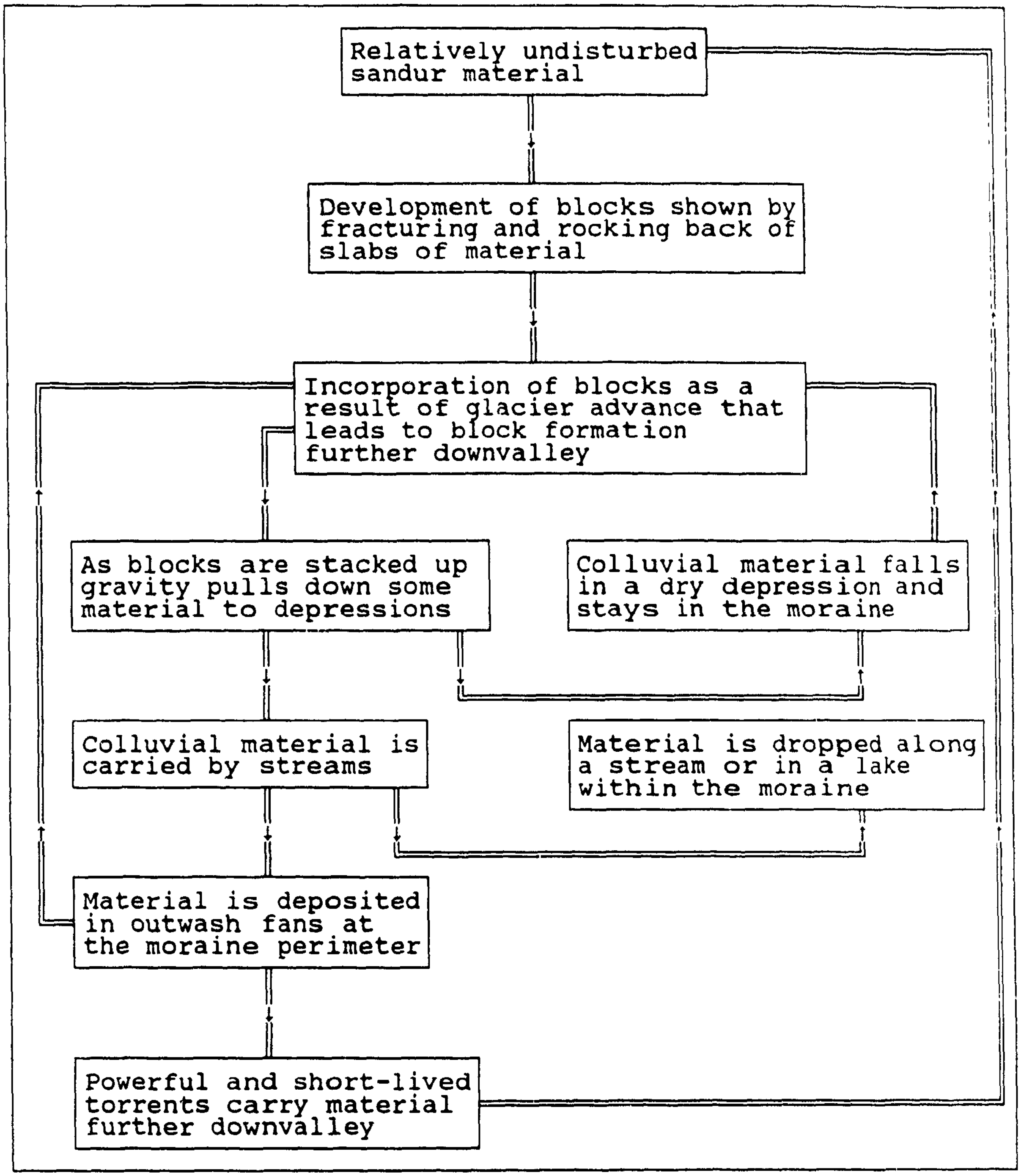


FIGURE 5.22 Posited stages in ice-thrust ridge formation, Thompson Glacier moraine, Axel Heiberg Island.

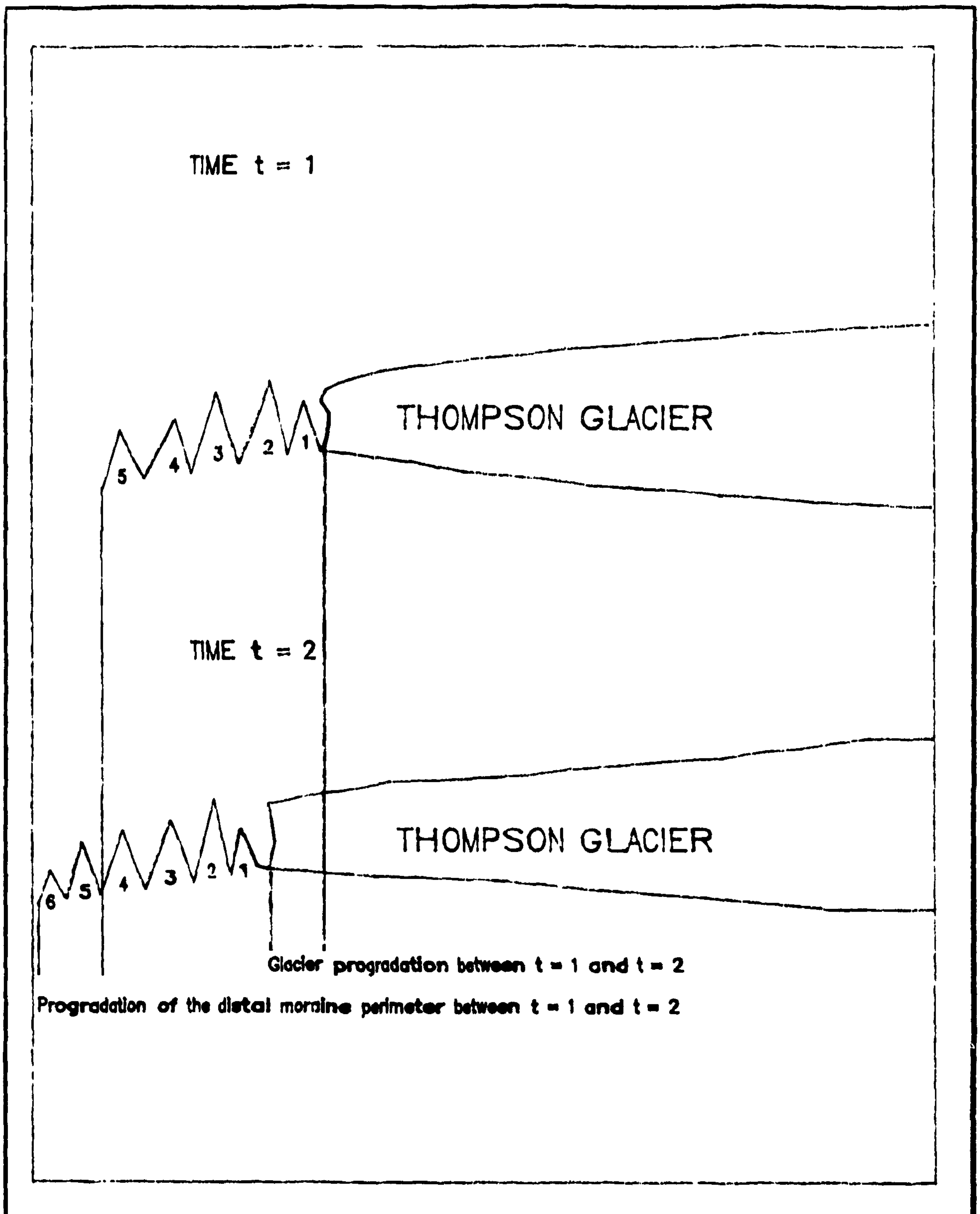


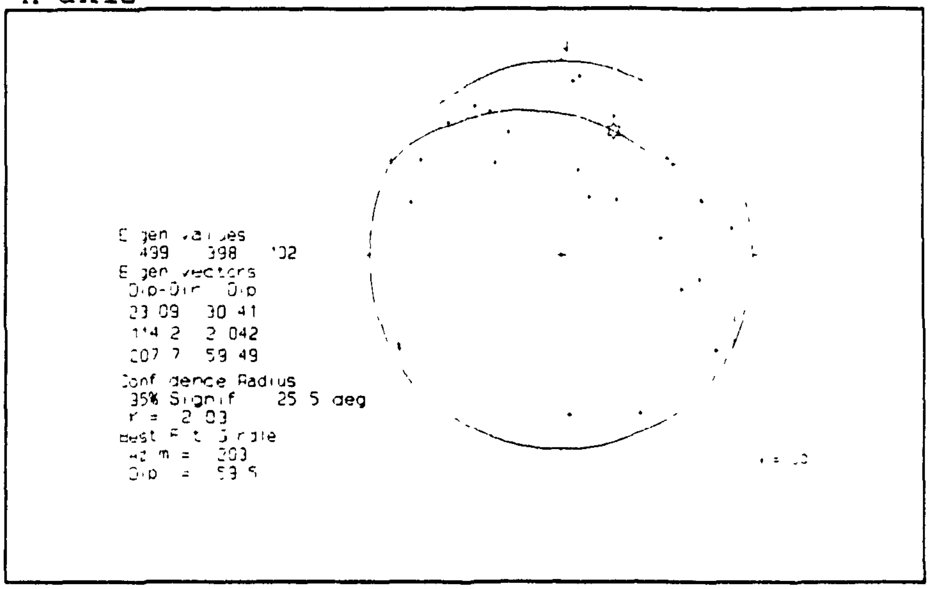
FIGURE 5.23 Development of the Thompson Glacier moraine over time. The moraine is sliding as a whole and structures are grossly preserved. At time t = 2, a new distal ridge (arbitrarily numbered) developed.

performed in what appeared to be deposited glacial till at the glacier/moraine contact about 300 m east of the 1990 position of the western corner of the moraine. The results again reiterate the usefulness of C-axis data for interpreting glacier flow direction from pebble orientation.

The fabric site was located at the contact between the till and the outwash material of the moraine. As for the analysis performed in the White Glacier moraine, the vertical dimension of the area from which pebbles were extracted was kept to a minimum in order to avoid comparing two different till deposition episodes. The lateral dimension was 1,5 m.

Figure 5.24 shows lower hemisphere projections of the A and C axes of the pebbles. Once again, clustering is obvious only for the C-axis data. However, it is interesting to note that the eigenvectors computed for the two sets of data are within three degrees of a common direction (23,11 - 203,11 for the A axes and 205,4 - 25,4 for the C axes). Both scatter plots show an overall upglacier imbrication of individual pebbles. The estimate of glacier flow direction suggested by C-axis data (205^0, with a 95-% confidence interval ranging from 188 to 222^0) is conservative in comparison with interpolated values using surveying data published in Kalin (1971). However, an orientation of 25^0 for ice strata dip was measured about halfway across the glacier and some 1,5 km up from the glacier front. This suggests that central ice flow direction is towards 205^0, a direction which agrees with eigenvector number 1 in the C-axis scatter plot. Specific

A axis



C axis

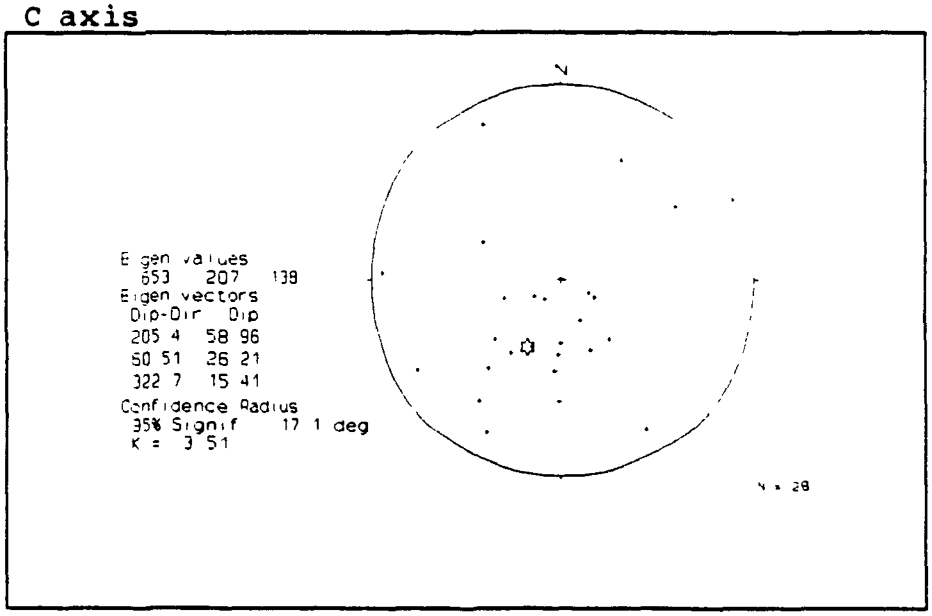


FIGURE 5.24 Pebble fabric data from the central western proximal Thompson Glacier moraine, lower hemisphere projection: A-axis and C-axis orientations are shown respectively in the upper and lower illustrations. Star indicates position of first eigenvector. Dotted line delimits 95 % confidence zone for first eigenvector position.

measurements of present glacier flow would be needed to further investigate the relationship between glacier flow direction and mean orientation of the C axes of pebbles. Detailed fabric data are included in Appendix 7.

Four samples were collected throughout the moraine for grain size analyses including a sample of the till from the fabric site (identified on figure 5.25 as sample A). About 75 meters west of the fabric site, samples of the till and the outwash on both sides of the till/outwash contact that extends in a discontinuous manner along the glacier front were collected (samples D and C respectively). A sample of a patch of the finest material observed in the moraine was also collected (sample B). Cut off points between classes on figure 5.25 are: GRAVEL (> 2mm or -2 phi), XCORSAND (between 1 and 2 mm or > -1 phi), CORSSAND (between 0,42 and 1 mm or approx. > 0 phi), MEDSAND (between 0.250 and 0.42 mm or > 1phi), FINESAND (between 0,063 and 0,25 mm or > -4 phi) and FINES (< 0,063 mm or < -4 phi).

Figure 5.25 shows that grain size distribution in the two till samples (D and A) are quite similar. It should be noted, however, that a true volumetric sample would have somewhat increased the proportion of very coarse material (cobbles and boulders). This also applies, although to a lesser extent, to the outwash sample (sample C). Samples collected in the early 1960's throughout the moraine revealed that material contained 5 % boulders ("blocs"), 65 % cobbles ("galets"), 10 % pebbles ("granules"), 15 % sand and 5 % silt and clay (ROBITAILLE et GREFFARD 1962, p.89). Kalin (1971) found a mean grainsize of 3,7 cm with a

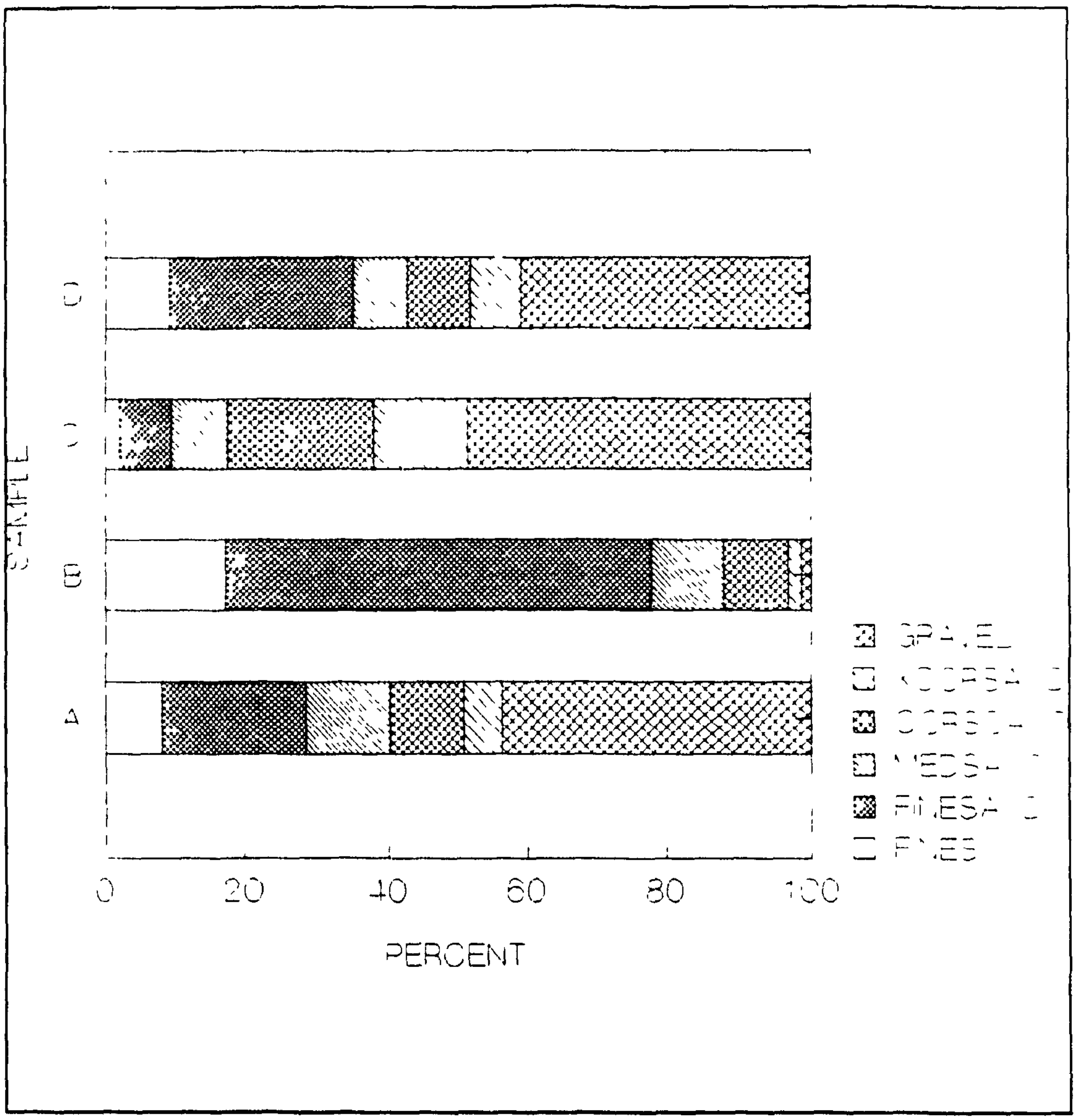


FIGURE 5.25 Grainsize composition of four samples of material collected in the Thompson Glacier moraine.

standard deviation range of 0,58 to 24 cm for outwash gravel. He estimated that about 5 % of the particles exceeded a diameter of 80 cm.

The main difference between the till and outwash samples is the substantially smaller proportion of fines (fine and very fine sand under the category "FINESAND"; silt and clay under the category "FINES") in the outwash material. Other differences between till and outwash material relate to the generally more angular nature of clasts in the till as well as to the absence of striated blocks in the outwash material. Overall, morphometric studies by Robitaille et Greffard (1962) showed that 30 % of cobbles were subangular, 50 % were rounded and 20 % were ovoids. Sample B is a true volumetric sample of the finest type of material that was found at a few locations in the moraine.

Finally, a muskox femur of surprisingly small size was found at the surface of the central Thompson Glacier about 2 km up from the present front position by M. Parent (GSC, Québec city). Detailed information concerning this bone is not yet available. Interested readers should contact Dr. Michel Parent, a research scientist at the Centre géoscientifique de Québec (which is a GSC branch).

CHAPTER 6: CONCLUSIONS AND DISCUSSION

6.0 SUMMARY OF FINDINGS

The basic conclusion from the present research is that the White Glacier has been retreating while the Thompson Glacier has been advancing over the last 30 years. The most important geomorphic process has been the advance of the Thompson Glacier which, because of the length of time for which it has been occurring, can be qualified as a major glacier advance (or readvance?) caused by long-term changes in mass balance. This forward progression of the Thompson Glacier affected the whole the lower ablation and proglacial zones of the Expedition glacier complex.

More specifically, it was shown that the ablation moraine of the White Glacier has been widening at increasing rates towards the west due to increased backwasting of the glacier front, while the eastern front has actually shown an advance. Sometime between 1973 and 1977, the proglacial section of Between Channel shifted west probably in response to the pushing action of the Thompson Glacier and began flowing across the middle of the White Glacier moraine. This phenomenon brought about aggressive erosion of the moraine which in turn contributed to accelerate thermokarst processes. Further degradation has also occurred along the ends of the moraine, by thermal and mechanical erosion due to meltwater in the west and by the impinging of the Thompson Glacier coupled with meltwater erosion in the east. Some backwasting of the moraine frontal perimeter was noted, but this process was found to have had relatively minor importance.

Estimated displacement vectors along the Thompson Glacier front suggest that the presence of the Thompson Glacier moraine had apparently (based on the data presented previously) a limited impact on the forward progression of the glacier. This implies that processes that formed the Thompson Glacier moraine have little to do with bulldozing. This statement is supported by a number of observations including: (1) the preservation of structures in the moraine (even in the proximal zone), (2) the equal amount of displacement of the central and western moraine perimeter in comparison with glacier front displacement and (3) the fact that less than half of the Thompson Glacier front in the moraine section is physically in contact with the proximal structures of the moraine. The most important geomorphic processes at the glacier edge in the moraine-free zone are calving and apron entrainment. These processes were also noted along the glacier front in the moraine section.

The most likely process forming the Thompson Glacier moraine is the thrusting of slabs of forelying material along décollement surfaces due to the pressure field created by the superincumbent weight of the glacier. The spatio-temporal evolution of this pressure field brought about the displacement of the central and western moraine as a whole sliding unit, thereby explaining why the glacier has not engulfed the proximal moraine over the last 30 years. Processes at the glacier/moraine contact in the east, however, include overriding of the moraine. A proposed scheme for moraine edification is contained in the model presented in the previous chapter (figure 5.22).

The variation in progression rates of the Thompson Glacier front across the entire width of the glacier over the last 30 years has resulted in a differential development of the forelying moraine. A gross correspondence between the zone of fastest glacier displacement and the zone of greatest moraine development can be established on the basis of estimated directions of glacier movement, as suggested in section 3.1.2. The asymmetric development of the Thompson Glacier moraine towards the southwest reported in the 1960's was also found to be a characteristic of moraine development over the last 30 years. Field observations, including fracture networks in the sandur near the moraine perimeter, imply higher development rates in the southwestern moraine. The presence of fractures in the sandur (fractures were not observed between 1962 and 1968) suggests that current development rates in the southwestern moraine are higher than they were during the 1960's.

Another important trend in the development of the Thompson Glacier moraine is the compression of its width in the east, and thus a corresponding increase in elevation. In addition, degradational processes were documented to have a much greater incidence on the landforms in the proglacial zone during warm and sunny summers. The great difference between the cool 1989 summer and the warm 1990 summer illustrates the important year to year variability in the magnitude of geomorphic processes in the glacier snout area.

6.1 ABOUT GLACIER DYNAMICS

One of the puzzling questions about the glacier dynamics in the Expedition Area can be formulated as follows: why are the snouts of the White and Thompson glaciers showing opposite dynamic trends? A partial answer can be proposed on the basis of theoretical considerations.

The White Glacier is a valley glacier draining its own accumulation zone whereas the Thompson Glacier is an outlet glacier draining a portion of the Muller Ice Cap. According to Sudgen and John (1967) valley glaciers are systems by themselves, but outlet glaciers are not. In the Expedition Area, the dynamics of the smaller system impose retreat of the glacier front whereas dynamics of the bigger system dictate forward progression. Besides differences in accumulation between the two glaciers, a topic which has apparently never been investigated, differences in resilience (or inertia) may help explain the opposite trends in glacier front displacement.

The faster reaction time of the White Glacier is confirmed in Iken (1977 p.32): "The White Glacier ... showed very large diurnal fluctuations [in glacier flow velocities] ... but at the Thompson Glacier a gradual velocity increase lasting a few days with no fluctuations was observed". Following this, one is led to believe that the front of the White Glacier is responding to more recent conditions while the Thompson Glacier front is responding to earlier conditions. Recent field investigations suggest that the large glaciers of the High Arctic are presently at their maximum Holocene position. According to Evans (1989), the large glaciers would be advancing under the impetus of the increased accumulation during the mid-Holocene warm period. Observations about recent glacier readvance in the Disraeli Fiord area of northern Ellesmere Island are found in Lemmen (1990). Recent glacier movement at the Thompson Glacier front apparently tie in well with this regional trend.

The faster response of the White Glacier may also help explain why the White Glacier is not a simple tributary like all the other glaciers that join the Thompson Glacier further upvalley, but a separate body of ice. The septum along the two glaciers suggests that the White Glacier did not flow into the Thompson Glacier, but rather that the Thompson Glacier flowed into the White Glacier. The former orientation of the lower ablation zone of the White Glacier parallel to that of its upper ablation and accumulation zones is suggested by the presence of remains of a former northeastern lateral moraine ridge of the White Glacier across Between Lake (figure 6.1).

The northeast-southwest trend of pebbles in the central distal White Glacier moraine reported in section 4.4 can hardly be explained by a simple sliding of the White Glacier against the Thompson Glacier, which would have resulted in a fabric oriented parallel to the N-S flow of the lower ablation area of the White Glacier. Also, the presence of a high proportion of quartzite blocks in the central and central-eastern White Glacier moraine for which the only apparent source is located more than 10 km upvalley along the western margin of the Thompson Glacier according to the geological map presented in Fricker (1963) further suggests that the White Glacier was pushed to the side by the

FIGURE 6.1 Old lateral moraine of the White Glacier lying across the present location of Between Lake. The orientation of the moraine suggests that the White Glacier was at one time a straight southeasterly oriented valley glacier. Figure 1.6 depicts the same scene at a higher oblique angle. Height of the ice cliff (center left) is on the order of 40 m.

advancing Thompson Glacier. The presence of the White Glacier in a zone that was later occupied by the Thompson Glacier could be explained by a faster response time of the smaller glacier.

Following this scenario, the White Glacier would have subsequently been pushed out of the way (as it has been over the last 30 years) and would have in the process reached a maximum downvalley expression outlined by the present moraine perimeter. A date of circa 1850 for the most recent White Glacier maximum is proposed in Beschel (1961). The radiocarbon date of a buried root sample collected in the summer of 1990 at the outwash/moraine stratigraphic contact in the central distal White Glacier moraine, which is unfortunately not available at the present time, will provide a good indication of the time at which maximum glacial extent was attained.

Data presented in this paper suggest that retreat of the White Glacier was initiated circa 1900. This is based on the assumption that the estimated rate of central White Glacier front retreat of 100 m over the last 30 years (i.e. approximately 3.3 m per year) has been constant since the onset of retreat. It follows that a period of about 90 years would have been needed for the central White Glacier to attain its present width of 300 m, hence the proposed date of retreat onset.

At the moment no explanation has been proposed for the retreat of the White Glacier. Recent investigations of englacial temperatures in the accumulation zone of the White

Glacier indicate a general warming trend probably beginning early this century (BLATTER 1985). The initiation of the warming trend corresponds with the estimated date of glacier retreat onset mentioned above. If this warming trend did induce retreat of the White Glacier, but not of the Thompson Glacier, then it must be assumed that the longer term glacial dynamics of the White Glacier have been constant during the last century (at least) and such that increased frontal ablation due to warming could not be offset.

A second fundamental question that arises from the results presented in this thesis relates to the absence of a frontal moraine along the western Thompson Glacier front. Kalin (1971 p.33) presented three hypotheses to explain what he termed the "missing portion" of the Thompson Glacier moraine. The first was that the static load of the glacier was unevenly distributed across the width of the glacier (i.e. ice thickness in the west would be "less than the critical value needed to cause the stress field necessary to overcome the strength of the ground"). Geophysical investigations carried out across the Thompson Glacier showed that the "lower surface of the glacier seems to have a fairly circular shape, but towards the White Glacier it ascends in steps" (KALIN 1971, p.38). The location of these steps appears to coincide with the western boundary of the moraine. The two other hypotheses relate to a higher overall strength of the ground on the western side and to the possible presence of bedrock as one or several terrasses beneath the western side of the proglacial sandur. These last two hypotheses could not be verified by geophysical methods (KALIN 1971).

The uneven distribution of the glacier load seems to constitute the most likely explanation for the absence of a moraine ahead of the westernmost Thompson Glacier front. However, it has never been demonstrated that the smaller stresses due to the thinning of the glacier towards the west were indeed smaller than the critical value needed to overcome the strength of the forelying sandur material. If it is accepted that stress levels in the west could be sufficient to induce thrusting in the forelying outwash sediments, then another hypothesis need to be developed.

It was mentioned in the previous section that the White Glacier is thought to have been across the path of the advancing Thompson Glacier. The length of the glacier tongue that would have been across the path of the Thompson Glacier is unknown, but from the considerations on long term dynamics of the White Glacier expressed above, it could most likely not have been much greater than the maximum position outlined by the current moraine perimeter. This implies that only the western front of the prograding Thompson Glacier could have come into contact with the White Glacier. If those initial conditions are accepted, then an alternative explanation for the absence of a moraine in the west can be proposed.

Considering that the progradation rate of the central Thompson Glacier front remained constant at approximately 0,5 km per 30 years (which is a value derived from the data presented in section 3.1.2), then the initial contact between the White and the Thompson glaciers would have occurred about 180 years ago. This is based on the fact that the present location of the Thompson Glacier front is located about 3 km downvalley from the junction point of the two glaciers. (This junction point can be considered to correspond with the downvalley tip of Between Lake.) As the White Glacier was being pushed by the Thompson Glacier, the force exerted by the White Glacier upon the westernmost section of the Thompson Glacier front (by the action reaction principle) could have had the effect of offsetting a fraction of the vertical component of stress exerted by the Thompson Glacier to the point that the pressure field created by the weight of the Thompson Glacier would have been insufficient to induce the thrusting of slabs of material along its western front. The direction of the force exerted by the White Glacier would have been toward the northeast, a fact that tends to be supported by the manner in which the "S"-shaped supraglacial moraine of the Thompson Glacier (which was probably derived from the Crook Glacier, a tributary glacier joining the Thompson Glacier from the east some 15 km up from the present glacier terminus) was apparently distorted (cf figure 1.7).

The stress that was needed to deform what must have originally been a straight surficial moraine aligned parallel to glacier flow cannot be attributed to the presence of the Thompson Glacier moraine since the moraine was shown in the last chapter to have apparently opposed very little resistance to glacier front progression over the last 30 years. A logical alternative is that stress must have been induced by the resistance of the White Glacier to the forward movement of the Thompson Glacier.

The opposing White Glacier could have also acted as a dam, the effect of which would have been a redistribution of ice towards the zone of lesser resistance (the central and central-eastern portions of the Thompson Glacier). The Thompson Glacier moraine would then have began developing along the central and central-eastern front partly due to this ice (and consequently stress) redistribution. In fact the initiation of the thrusting process that is currently giving rise to the Thompson Glacier moraine may have coincided with such a redistribution of stresses along the glacier front. The present size of the moraine and its widening rate over the last 30 years suggest that the moraine could not have started forming much further upvalley than about 2 km from its current proximal position. This corresponds with a location slightly down from the present downvalley tip of Between Lake, where the collision between the two glaciers would have occurred.

In this context the western Thompson Glacier front would not have developed a moraine partly due to the direct contact with the White Glacier but also partly due to the offsetting of the vertical component of stress by the horizontal force exerted by the White Glacier and the ensuing redirection of stresses toward the central and central-eastern front of the Thompson Glacier. As the White Glacier was moved out of the way and the horizontal force along the westernmost Thompson Glacier front was decreasing, the increase of the vertical component could have induced a recent phase of moraine development in the west, thereby explaining the observed tendency for asymmetric development. Hence, the "missing" portion of the Thompson Glacier moraine would have been a temporal anomaly that is being "remedied" as the White Glacier is pushed out of the way.

Further investigations could shed more light on the recent glacial history of the Expedition Area and help explain current glacier dynamics and geomorphic evolution. Future work could namely be oriented towards determining morainic material provenance and evidence for past surge activity. Surges are believed to cause distortions in medial moraines (SHARP 1988, p.71) and they may also be linked to the initiation of moraine edification processes in the Expedition Valley sandur. More detailed work on ridge migration dynamics within the Thompson Glacier push moraine is also needed for a better understanding of push moraine formation. A full geodetic investigation, which was beyond the scope of this study, appears to be the only way to really account for such ridge migration dynamics.

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APPENDIX 1: LIST OF AERIAL PHOTOGRAPHS INCLUDING THE STUDY AREA

SUMMER 1959:	A16864 Nos 36 and 37; scale = 1: 60 000; monochrome
AUGUST 1972:	A23057 Nos 4 and 5; scale = 1: 20 000; monochrome.
JULY 1973:	A30860 Nos 140 and 141; scale = 1: 20 000; color negative.
AUGUST 1977	A24791 Nos 139 and 140; scale = 20 000; monochrome. A31165 Nos 17 and 18; scale = 1: 15 000; color negative
JULY 1978:	A31220 Nos 57, 58, 59 and 60; scale = 1: 7 500; color negative.
5 AUGUST 1990:	NO SERIAL NAME YET (temporary number identifiers are PCSP Nos 3, 4, 5 and 6; scale = 1: 20 000; color negative.

All photographs (except for the ones taken in August of 1990) are available at the Map and Air Photo Library in Ottawa.

Other photographs exist prior to 1959, but they are oblique shots

Canadian Armed Forces have a parallel coverage of aerial photographs, the extent of which is not known.

APPENDIX 2: SUMMARY OF IMPORTANT SURVEYING DATA

AT	SIGHT	DIRECT ANGLE deg	DIRECT ANGLE min	DIRECT ANGLE sec	VERTICAL ANGLE deg	VERTICAL ANGLE min	VERTICAL ANGLE sec	HOR. DISTANCE (meters)	ALTITUDE (meters)
Stn 3	Pt 1	0	0	0	89	54	15	1136 334	63.8 65 5
	Pt 2	1	54	35	90	2	35	1109 181	62 8
	Pt 3	4	20	15	90	12	40	1090 578	59 6
	Pt 4	7	17	20	89	57	20	1101.046	64 4
	Pt 5	11	17	0	89	56	55	1093.836	64 5
	Pt 6	17	0	50	90	2	30	1104.599	62 8
	Pt 7	19	1	40	90	4	40	1118.665	62
	Pt 8	21	43	30	90	8	20	1146 273	60 8
	Pt 9	25	39	10	90	17	30	1121.954	57.8
	Pt 10	25	10	25	90	12	25	1178 335	59.3
	Pt 11	30	22	55	90	14	20	1272.636	58 2
	Pt 12	53	33	35	91	12	30	1055.812	41 2
	Pt 13	61	5	15	91	10	40	1080.404	41 4
	Pt 14	65	40	45	91	29	10	1034 194	36 7
	Pt 15	74	34	35	92	9	45	804.555	33 2
	Pt 16	79	56	35	91	44	45	981 612	33 6
	Pt 17	82	17	5	91	54	15	957 077	31 8
	Pt 18	84	39	55	91	52	50	971 711	31 7
	Pt 19	89	15	45	92	7	20	917.646	29 6
	Pt 20	94	8	65	92	15	20	889.571	28 6
	Pt 21	99	31	40	92	9	5	951 324	27 8
	Pt 22	106	31	35	92	12	40	980 662	25 7
	Pt 23	111	47	20	92	2	5	1088 755	24 9
Stn 4	Pt 23	0	0	0	90	18	20	471 239	27.4 24 9
	Stn 6	16	36	20	90	24	30	883.987	21.1
	Stn 3	151	12	50	86	54	40		63 8
Stn 6	Pt 24	0	0	0	88	44	25	670.128	21.1 35 7
	Pt 25	2	45	10	88	49	50	587.844	33 1
	Pt 26	7	43	55	88	46	45	508.457	31 9
	Pt 27	15	30	25	88	40	55	431.425	30 9
	Pt 28	38	0	0	87	8	10	379 599	39 9
	Pt 29	48	9	25	87	10	20	371.05	39 4
	Pt 30	75	57	25	89	24	0	377.83	24 9
	Pt 23	83	9	0	89	31	10	452 802	24 9

The relative positions of station 4 and 6 (and hence surveyed points number 24 to 30) were tied in graphically with the measurements in the first set up (shown in the upper part of the above table). Stn = station where theodolite is located; Pt = surveyed point.

APPENDIX 3: TESTS WITH BRUNTON MAGNETIC COMPASS

FIRST TEST, JULY 4: COMPASS SET ON WORK BENCH

TIME	BEARING	TIME	BEARING	TIME	BEARING	TIME	BEARING
12:45	112	13:05	112.5	13:25	110	13:45	109.5
12:50	112.5	13.10	112.5	13:30	110	13:50	110.5
12:55	112.5	13:15	112	13:35	109		
13:00	112.5	13:20	111	13:40	109.5		

SECOND TEST, JULY 8: COMPASS SET ON TRIPOD IN SLEEPING QUARTERS

TIME	BEARING	TIME	BEARING	TIME	BEARING	TIME	BEARING
12:00	0	14:05	358.5	16:10	356.5	20:00	357.5
12:05	0	14:10	358.5	16:15	356.5		
12:10	359.5	14:15	358.5	16:20	356	22:00	356
12:15	359	14:20	358.5	16:25	355.5		
12:20	358	14.25	358.5	16:30	355	23:30	355
12:25	357.5	14.30	358.5	16:35	354.5	23:35	355
12:30	358	14:35	358.5	16:40	355	23:40	355
12:35	358.5	14:40	359	16:45	355.5	23:45	355
12:40	359	14.45	358.5	16:50	357	23:50	354.5
12:45	359	14.50	359.5	16:55	358	23:55	354.5
12.50	359.5	14:55	0	17.00	358.5	00:00	354.5
12:55	0	15:00	359.5	17:05	358.5	00:05	354.5
13:00	0	15:05	359.5	17:10	359	00:10	354.5
13:05	0	15:10	359.5	17:15	359	00:15	354.5
13:10	0	15.15	359.5	17.20	359	00:20	355
13:15	359.5	15:20	358.5	17:25	359	00:25	355
13:20	359.5	15:25	358.5	17:30	358.5	00:30	356
13:25	359.5	15:30	358.5	17:35	358.5		
13:30	358.5	15.35	358.5	17:40	358.5		
13.35	358.5	15:40	358.5	17:45	358.5		
13:40	358.5	15:45	359	17:50	358		
13:45	358.5	15:50	358	17:55	358		
13:50	358.5	15.55	357.5	18.00	358		
13:55	358.5	16:00	356.5				
14:00	358.5	16:0[illegible]	[illegible]56.5	19:00	358		

THIRD TEST, JULY 9: CC[illegible]S[illegible]T ON TRIPOD IN SLEEPING QUARTERS

TIME	BEARING	TIME	BEARING	TIME	BEARING	TIME	BEARING
08:45	0	09:05	359.5	09:25	0	09:45	359.5
08:50	0	09:10	359.5	09:30	0		
08.55	0	09:15	0	09:35	0.5		
09:00	0	09 20	0	09:40	0		

TIME is central daylight saving time (local time).
BEARING is in degrees

APPENDIX 4: HEADWALL RETREAT MEASUREMENTS USING TRANSECTS OF WHITE PAINTED STONES, WHITE GLACIER MORAINE

Figures underlined are reported on figure 4 8. All distances are in meters. Date of measurements expressed as (dd/mm/yy)

TRANSECT ORIGINATING FROM TS #8

TRAVERSE CENTER IDENTIFIER	DIST. WITH PREVIOUS IDENTIFIER	TRAVERSE LENGTH 18/6/90 FROM CENTER TO:		TRAVERSE LENGTH 10/7/90 FROM CENTER TO:		TRAVERSE LENGTH 20/7/90 FROM CENTER TO	
		EAST	WEST	EAST	WEST	EAST	WEST
Pt #8	0	0	0	0	0	0	0
X	39	22 4	28.15	22 4	25.95	22.4	2[illegible]
Y	39	14 2	23.5	14 2	19.65	14 2	18 5
OMEGA	58	27	20 5	27	17 2	27	16 [illegible]
ALPHA	58	28 4	24 5	28.4	19 8	28 4	18 [illegible]
GAMMA	58	19	37	18.2	32.6	17 55	30 [illegible]
Z	29	9	54 8	9	45 6	9	-----
GL FRONT	9 8 (18/6/90)						
	10.7 (20/7/90)						

TOTAL LENGTH OF TRANSECT 291 m (18/6/90).

TRANSECT ORIGINATING FROM TS #11

TRAVERSE CENTER IDENTIFIER	DIST. WITH PREVIOUS IDENTIFIER	TRAVERSE LENGTH FROM CENTER TO: WEST 21/6/90	WEST 20/7/90
Pt #11	0	0	0
PI 1	32		
PI 2	29	29.7	29.7
PI 3	45	29 35	29.35
PI 4	45		
PI 5	20		
PI 6	19		
GL FRONT	25 (Approx. distance from PI 6, 21/6/90)		
GL FRONT	15 (Approx distance from PI 6, 20/7/90)		

TS #10 4 meters from edge of channel (21/6/90)
3.85 meters from edge of channel (20/7/90)

TOTAL LENGTH OF TRANSECT: 215 m (21/6/90).

REMARKS: A lot of missing data because rocks falling off the glacier

TRANSECT ORIGINATING FROM TS #5

TRAVERSE CENTER IDENTIFIER	DIST. WITH PREVIOUS IDENTIFIER	TRAVERSE LENGTH FROM CENTER TO: EAST 21/6/90	EAST 23/6/90	EAST 28/6/90	EAST 29/6/90	EAST 5/7/90	EAST 9/7/90	EAST 20/7/90
Pt #5	0	0						
BETA 1	38		88 8		88		87.6	86 5
BETA 2	69		75.25			75.1		74 1
BETA 3	58							
BETA 4	46			60.4				54 4
BETA 5	72	5 5		4.6				2 8
GL FRONT	19							
TS #6				0 5		0	gone	
CAIRN						0.85	0 3	0 3

TOTAL LENGTH OF TRANSECT: 302 m (21/6/90)

Transect and traverse locations reported on map of study site in text
Abbreviations: Pt - point surveyed in 1989.

APPENDIX 5: FABRIC DATA, CENTRAL DISTAL MORAINE, WHITE GLACIER

Axis projection on lower hemisphere; azimuth and dip in degrees

STONE NUMBER	AXIS LENGTH (mm)			A-AXIS		B-AXIS		C-AXIS	
	A	B	C	AZIMUTH	DIP	AZIMUTH	DIP	AZIMUTH	DIP
1	145	70	66	50	17	140	30	293	57
2	35	22	17	0	26				
3	49	24	21	155	12	65	15	283	71
4	67	36	24	250	12	160	25	6	63
5	45	14	13	86	25				
6	44	31	22	275	3	185	20	7	70
7	28	16	13	70	10				
8	34	23	11	2	14	272	23	123	64
9	43	27	12	12	9	102	11	242	76
10	48	18	18	4	13				
11	47	21	21	337	19				
12	65	34	21	88	4	178	22	347	68
13	51	35	15	30	16	300	60	129	29
14	78	46	37	161	13	71	4	321	76
15	43	19	17	28	26				
16	46	23	18	305	1	215	26	37	64
17	44	19	16	350	15	260	6	155	75
18	50	33	19	100	26	190	15	309	71
19	37	18	12	294	6	24	20	189	69
20	41	2	11	242	33	332	2	65	57
21	63	35	26	5	16				
22	43	24	18	210	6	300	27	109	62
23	66	48	29	355	24	265	58	101	31
24	56	38	24	250	11	160	6	39	77
25	44	26	19	230	37	320	12	67	52
26	71	41	23	210	4	120	11	328	78
27	38	15	12	225	17	135	74	320	16
28	160	115	51	252	8	162	7	31	79
29	125	76	58	15	46	285	2	193	54
30	120	84	41	315	56		0	135	34

APPENDIX 6: DATA ON FRACTURES -- SANDUR AND DISTAL THOMPSON MORAINE

Angles between ledges are positive if their general tilt is towards the east when looking upglacier All angle measurements are in degrees and distances are in meters, unless otherwise specified. Dates at which some measurements expressed as dd/mm/yy Capital letters in quotation marks refer to transects along the fractures, with "A" being the most proximal transect Fracture numbers reported on map in text.

1) FRACTURE IN SANDUR, NEAR SURVEY MARKER #26

AZIMUTH· group of cracks trend 170, 175, 180, 185; one distal crack trended 215.
LENGTH: approximately 10 m.
WIDTH. 60-75 cm (19/6/90)
DEPTH: 55 cm (19/6/90)

TRAVERSE LOCATION	ANGLE BET LEDGES 25/6/90	ANGLE BET LEDGES 16/7/90	DIST. BET. LEDGES 19/6/90	DIST. BET. LEDGES 16/7/90
A			0.6	0.74

2) FRACTURE IN SANDUR, NEAR SURVEY MARKER #30

AZIMUTH: 185 before "A"; 205 between "A" and "B"; 200 between "B" and "C". LENGTH: 30 m (19/6/90, 16/7/90).
WIDTH: 60 cm (19/6/90).
DEPTH. 25 cm (19/6/90).

TRAVERSE LOCATION	ANGLE BET. LEDGES 25/6/90	ANGLE BET. LEDGES 16/7/90	DIST. BET. LEDGES 19/6/90	DIST. BET LEDGES 16/7/90
A	0	0	0.6	0.6
B			0.44	
C	1	1	0.14	0.125

3) FRACTURE IN SANDUR, NEAR SURVEY MARKER #31 (23)

AZIMUTH 235 before "A", 225 between "A" and "B", 240 between "B" and "C", 250 between "C" and "D"; 265 between "D" and "F"

LENGTH: approximately 70 m (25/6/90, 16/7/90)
WIDTH: 50 cm (19/6/90)
DEPTH. 20 cm (19/6/90).
DISTANCE FROM MAIN MORAINE 30 m (19/6/90).
COMMENTS: Distal bulging here is at "C" and not at the very distal end.

TRAVERSE LOCATION	ANGLE BET LEDGES 25/6/90	ANGLE BET. LEDGES 16/7/90	DIST BET LEDGES 19/6/90	DIST. BET LEDGES 16/7/90
A	-1	-7	0.17	0 17
B	-7	-6	0 26	0.26
C	3	4	0.6	0.6
D	-5	-6	0.22	0 21
E	2	1	0 06	0 06

4) FRACTURE IN SANDUR, NEAR SURVEY MARKER #31 (23)

AZIMUTH 245 before "A"; 325 between "A" and "B", 270 between "B" and "C"; 265 between "C" and "D", 250 between "D" and "E", 160-250 to "E". LENGTH approximately 70 m (25/6/90, 16/7/90)
WIDTH: on the order of the centimeter.
DEPTH: on the order of the centimeter
DISTANCE FROM MAIN MORAINE: 8,5 m (19/6/90)
COMMENTS: dense cracking zone

TRAVERSE LOCATION	ANGLE BET LEDGES 25/6/90	ANGLE BET LEDGES 16/7/90	DIST BET LEDGES 19/6/90	DIST BET LEDGES 16/7/90
A	-4	-4	0.29	0.29
B	-5	-5	0.2	0 2
C	5	-1	0.3	0 29
D	4	1	0.34	0 33
E	3	4	0 15	0 15
F	-2	-3	0.15	0 15

5) FRACTURE IN SANDUR, BETWEEN SURVEY MARKERS 23 AND 22

AZIMUTH: 210 ("A" to "B"); 225 ("B" to "C"); 200, 225 and 190 distally from "C"
LENGTH: 70 m (19/6/90, 16/7/90);
WIDTH AND DEPTH: a few cm.
DISTANCE FROM MAIN MORAINE:

TRAVERSE LOCATION	ANGLE BET. LEDGES 25/6/90	ANGLE BET. LEDGES 16/7/90	DIST. BET. LEDGES 19/6/90	DIST. BET. LEDGES 16/7/90
A	3	2	0.17	0 16
B	6	-6	0.58	0.58
C	11	-11	0.36	0.36

6) FRACTURE IN SANDUR, NEAR SURVEY MARKER 22

AZIMUTH: 265 degrees between "A" and "B"; 275 degrees between "B" and "C". LENGTH: 30 m (19/6/90).
WIDTH AND DEPTH: a few cm
DISTANCE FROM MAIN MORAINE. 4 m (19/6/90).

TRAVERSE LOCATION	ANGLE BET. LEDGES 25/6/90	ANGLE BET. LEDGES 16/7/90	DIST. BET LEDGES 19/6/90	DIST. BET. LEDGES 16/7/90
A	1	2	0.8	0.8
B	-2	-1	0.59	0.59
C	5	4	0.05	0.05

7) FRACTURE IN SANDUR, NEAR SURVEY MARKER 21

AZIMUTH: At "A" 235/280 (proximal/distal); At "B" 265/280, Between "A" and "B" 245/280 (16/7/90).
LENGTH. 30 m (25/6/90).
WIDTH AND DEPTH: a few cm.
DISTANCE FROM MAIN MORAINE: 4 m (25/6/90)
COMMENTS: Last measured fracture on the floodplain to the west

TRAVERSE LOCATION	ANGLE BET. LEDGES 25/6/90	ANGLE BET. LEDGES 16/7/90	DIST. BET. LEDGES 25/6/90	DIST. BET. LEDGES 16/7/90
A	5	10	0.11	0 11
B	-11	-10	0.14	0.14

APPENDIX 7: FABRIC DATA, CENTRAL-WEST PROXIMAL MORAINE, THOMPSON GLACIER

Axis projection on lower hemisphere; azimuth and dip in degrees

STONE NUMBER	AXIS LENGTH (mm)			A-AXIS		B-AXIS		C-AXIS	
	A	B	C	AZIMUTH	DIP	AZIMUTH	DIP	AZIMUTH	DIP
1	65	43	33	21	24	291	9	181	64
2	46	32	21	305	15	35	10	159	72
3	69	37	27	290	21	20	26	161	59
4	49	33	14	3	32	93	22	215	53
5	88	53	4	295	13	25	29	182	59
6	73	45	26	100	30	10	45	221	41
7	52	30	26	50	27	320	15	202	60
8	89	52	34	3	11	93	7	272	7
9	35	22	14	9	53	279	7	181	38
10	56	23	21	5	8				
11	26	17	14	81	12	351	5	234	78
12	48	29	19	56	9	326	3	215	80
13	34	18	14	178	19	88	34	295	53
14	33	2	13	45	56	135	3	229	52
15	43	29	15	153	10	243	32	57	32
16	47	21	14	67	17	157	12	333	12
17	43	25	12	47	27	317	23	150	13
18	55	29	24	68	25	158	1	252	65
19	94	53	46	338	32	68	15	238	15
20	35	18	14	18	34				
21	42	24	16	106	37	16	14	207	14
22	85	47	24	330	12	240	6	121	76
23	49	32	17	240	5	330	31	142	59
24	51	31	11	241	6	331	10	119	79
25	53	29	21	325	41	55	35	184	52
26	73	48	23	320	11	50	36	215	53
27	47	23	17	23	63	113	22	215	26
28	36	2	14	122	8	212	58	27	32
29	76	41	18	80	47	350	24	237	49
30	68	34	17	334	18	244	86	65	4