GLACIAL GEOMORPHOLOGY AND LATE QUATERNARY CHRONOLOGY OF INNER NACHVAK FIORD, NORTHERN LABRADOR

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BY

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B.Sc. (Hons)

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Frontispiece: Tasiuyak Arm, inner Nachvak Fiord. View looking north-east toward Mount Kutyaupak.

Abstract

Nachvak Fiord in the central Torngat Mountains has been the subject of several detailed studies, including some which deal with the horizontal and vertical extent of the Wisconsin ice sheet. This study examines the inner fiord to the head of the fiord proper, and draws on data from the entire fiord to provide an evaluation of previous reconstructions of glacial history.

Several stades or glaciations, involving ice of local and regional origin, are shown by the number and orientation of moraines in the inner fiord area. Examination of ice-flow indicators, including analysis of drift geochemistry, showed that regional ice was predominant during the last stade, while Kogarsok Brook valley was the main source of local ice. Glacial stades of different relative age were detected through morphologic mapping of moraines, measurement of solum development, and observation of weathering characteristics. However, absolute ages were difficult to determine. Soil pits dug on moraines of different altitude showed that time is rarely the only soil-forming factor influencing solum depth; solum depths on moraines of high altitude showed wide variability, while even at lower elevations a single moraine often showed considerable variation in solum depth.

Analysis of the lithostratigraphy of piston cores extracted from the centre of the fiord provided additional information on the late- and postglacial environment of the region. The cores were not deep enough to penetrate into late Pleistocene sedimentary units previously identified by acoustic survey, and therefore did not provide a correlation with terrestrially-identified glacial sediments. They do, however, show ice-distal and postglacial sedimentation, the most recent facies being dominated by fluvial deposits. Radiocarbon dated shells from the cores indicate that this major facies change occurred 7300- 5200 years BP, thus providing a minimum date for the final influence of pro-glacial deposition in the area. Pollen spectra of two cores correspond well with those from other parts of Labrador, showing a postglacial tundra vegetation, followed by an early increase in shrub pollen (7300 years BP), and a subsequent return to sedge-tundra.

Raised shorelines in the inner fiord may be indicators of individual stages of glacial retreat. Beach segments were levelled and correlated into thirteen shorelines, ranging in height from 73 to 8 metres above high tide (aht). Some of these were associated with moraines and submarine sills, suggesting that they were formed during glacial stillstands. This indicates that a stage-like retreat from the last ice maximum probably occurred. Very high, continuous shorelines with considerable

gradients were levelled in Tasiuyak Arm. Their elevation and tilt may be explained through fairly rapid ice retreat, which allowed them to experience as much uplift older shorelines of the same elevation, recorded in the outer fiord. Alternative possibilities for their tilt, such as postglacial faulting, were also considered.

At least three phases of glaciation were detected; the youngest *Nachvak phase* is correlated with the Late Wisconsin, and was the last regional glaciation. In the inner fiord, this phase is characterised by prominent moraines and numerous raised shorelines, suggesting that deglaciation occurred in stages, though overall retreat may have been quite rapid. A previously reported radiocarbon date has been used to show early deglaciation of the fiord, by 9000 BP. Although positive evidence of deglaciation by this time was found to extend only as far as central Tasiuyak Arm, the early date is corroborated by an 8000 BP inner fiord shoreline, and by dates from the piston cores.

Two inner fiord moraines may be associated with the Nachvak maximum. Moraine K2 indicates that the ice-sheet reached a minimum elevation of 180m aht, while moraine K1 suggests a maximum of about 220m aht. A local ice tongue emanating from Kogarsok Brook appears to have coalesced with the regional ice-sheet at this time. These elevations concur with evidence supporting a restricted Late Wisconsin glaciation by suggesting that the Nachvak ice-sheet was not vertically extensive. Association with the Nachvak moraines dated by Evans and Rogerson (1986) and Bell (1987) implies an 'early' glacial maximum, with retreat beginning by approximately 20 ka BP. The restricted vertical extent of ice implies a restricted horizontal extent; there is no support in the inner fiord for the hypothesis that the Late Wisconsin ice sheet extended beyond the Labrador shelf.

Older glacial phases are indicated by higher moraines, with a greater degree of weathering. An *Adams Lake phase* equivalent appears to be evident in moraines west of Kogarsok Brook; ice-flow indicators suggest that moraines M1 and M3 are of local origin, though M3 may be the result of coalescing local and regional ice. If these moraines are of the same age as the Adams Lake phase in the outer fiord, they suggest that local ice activity at this time was more extensive than previously thought. A much earlier glaciation is indicated by fragments of a moraine at approximately 500m aht. This is considered equivalent to the *Ivitak phase* observed in the Selamiut Mountains, and may be over 70 ka BP.

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1.1. Introduction

During the summer of 1986 a survey was made of the inner section of Nachvak Fiord, a glacial trough in the Torngat Mountains of northern Labrador. Labrador is known to have been affected by a number of glaciations during the Quaternary period, the latest of which has caused much controversy as regards its timing and extent. The Wisconsin glaciation is thought to have advanced in two or three major phases between 120 ka BP and 9 ka BP, from an ice dispersal centre in Labrador-Ungava. It strongly affected Saglek, Nachvak and Kangalaksiorvik Fiords, leaving geomorphological evidence of various stages of advance and retreat, yet eroding parts of this evidence with each readvance. The erosive character of glaciers makes any reconstruction of events difficult; chronologies in this area are tentative, the evidence often piecemeal and sometimes ambiguous.

A chronology of Wisconsinan events has been proposed for the eastern section of Nachvak Fiord on the basis of geomorphological, marine, soils and lichenometric data. This is probably the most detailed reconstruction for glacial activity of that time in north-east Labrador, and as such contributes greatly to knowledge of the Late Wisconsin ice-sheet. The vertical influence of Late Wisconsin ice and of ice that previously affected northern Labrador has been debated throughout the 20th Century. Of current importance is the horizontal extent of the Late Wisconsin sheet; whether or not it covered much of the Labrador continental shelf at its maximum is the subject of an argument centred around the fiords of the Torngat Mountains. Chronologies for Kangalaksiorvik and Saglek Fiords also exist, and support for both extensive and limited ice has been found from these, from Nachvak Fiord data, and from offshore marine studies.

In an attempt to solve some of the conflicts in interpretation, and to assess the Wisconsin chronology already devised for Nachvak Fiord, this study focused upon the innermost, western section of the fiord trough. This extended detailed research on the fiord itself, and added to knowledge of late and postglacial conditions here and in the Torngat Mountains as a whole. The study has also served to evaluate the chronologies and reconstructions previously hypothesised, from the perspective of the entire fiord.

1.2. Objectives

The aim of this study was to complete a comprehensive examination of Nachvak fiord, concentrating on a study area west of Eskimo Cove, to the head of Tasiuyak Arm. Objectives can be itemised as follows:

1. Examination of the morphological characteristics of the study area, to include:

- mapping moraine locations and elevations
- mapping ice-flow indicators
- geochemical analysis of sediments
- establishing a relative chronology through pedological analyses
- observation and analysis of relative rates of weathering
- identification and correlation of raised shorelines.

2. Evaluation of other chronologies proposed for the outer fiord: to test the correlation of moraine systems in this area with those to the east, and to evaluate a model of relative sea level change hypothesised from outer fiord data.

3. Lithostratigraphic and chronostratigraphic analysis of submarine cores, including examination of x-radiographs and pollen assemblages.

4. To evaluate the pro- and post-glacial history of sedimentation, as suggested by interpretations of acoustic data, with respect to core lithostratigraphies and chronologies. To correlate pollen spectra with others from northern Labrador.

5. To develop a chronology of Late Quaternary events, including origins and limits of ice sheets within this study area and a history of recession from the last glacial maximum.

1.3. Logistics

Field work was carried out between July 17^{th} and September 4^{th}, 1986. A party of five, plus equipment and supplies, was transported from St.John's to Nachvak Fiord on the *CCGS Sir John Franklin*; the ship's helicopter was used to establish a base camp at the mouth of Kogarsok Brook. Transportation within the fiord was by inflatable Zodiac and motor, which allowed access to Eskimo Cove, Tallek Arm and Tasiuyak Arm. A 5-day fly camp in Tasiuyak Arm was used to facilitate the survey of raised marine benches and the examination of Kutyaupak valley. Two members of the party were flown south by floatplane on August 3^{rd}; the remaining three flew out on September 4^{th}, when a floatplane removed equipment and samples to Goose Bay.

1.4. The Field Area

1.4.1. Physiography

The study area is located in the inner section of Nachvak Fiord, a glaciated trough in the Torngat Mountains of northern Labrador (Figure 1-1). It covers an area from Eskimo Cove, approximately 25km inland, to the head of Tasiuyak Arm, at the western end of the fiord proper (43km from Nachvak Bay along the fiord trough). The area is a highly dissected plateau, with rock walls bordering the fiord and land rising steeply from the valleys. Highland areas are generally difficult to access. Although official placenames are used wherever possible, unofficial names are included throughout this thesis for ease of reference.

Fieldwork centred around Kogarsok Brook valley, a wide gorge-like valley containing a misfit stream considerably smaller than the available valley. Several raised terraces and a large raised spit towards the river mouth testify to higher sea levels of the past. Kogarsok Brook originates in the north, occupying a broad trough which runs approximately north-south between the eastward-flowing Komaktorvik River and Nachvak Fiord. The wide river bed may have been formed during a major fluvial or meltwater event, perhaps involving water from the Komaktorvik Lakes and/or Chasm Lake valleys.

To the east of Kogarsok Brook is Kipsimarvik Head, a rock knob which has been sculpted by ice. An undulating sandy area to the north features numerous kettle holes and much hummocky till, suggesting that ice stagnated here. In Bay Cove, to the west of the headland, a Hudson's Bay Company Post was located, at a site locally named Kipsimarvik (Daly, 1902).

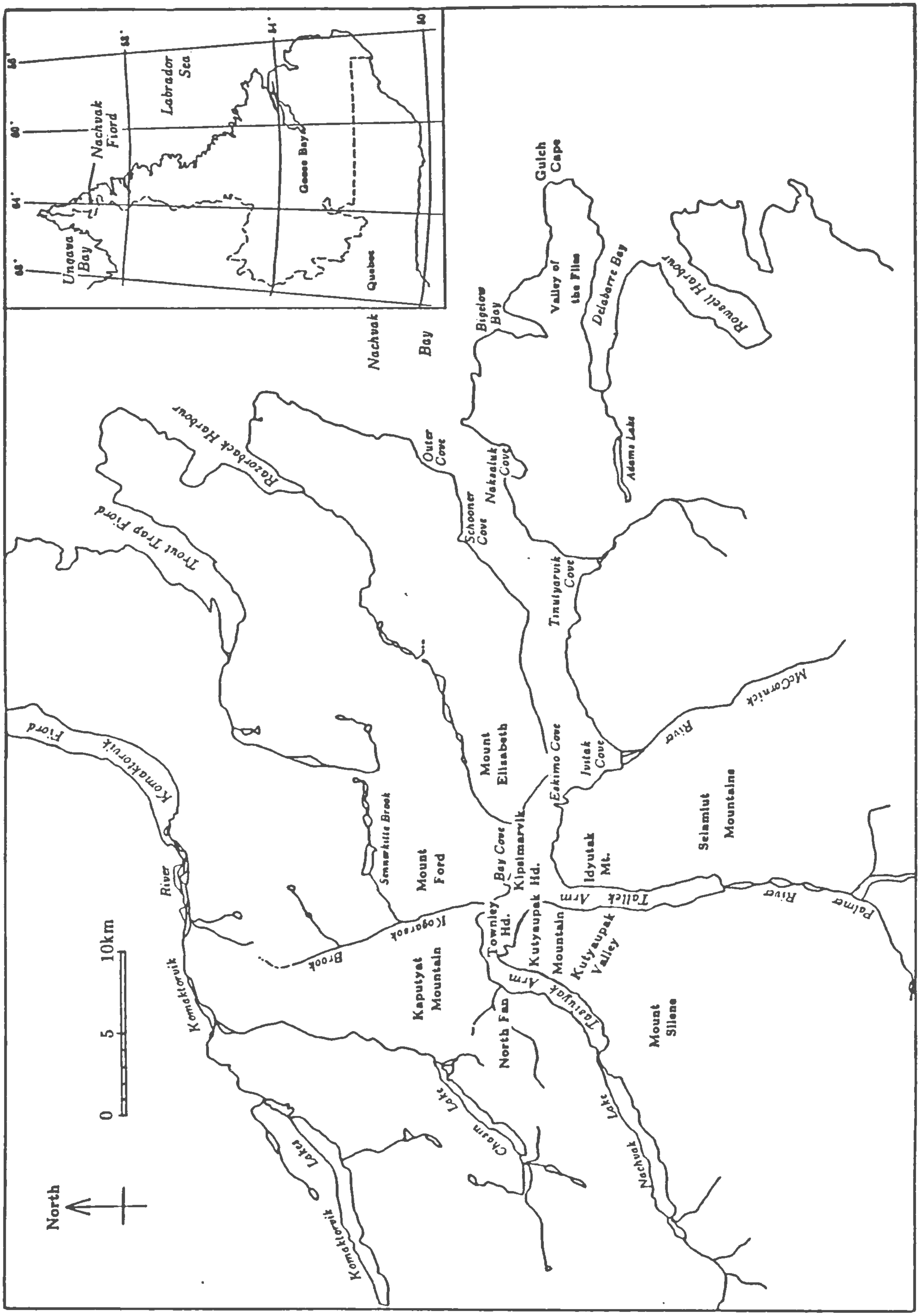

Figure 1-1: The study area: Nachvak Fiord, northern Labrador.

On either side of Kogarsok Brook valley evidence of glacial activity is visible; to the east a series of kame terraces rises to about 240m elevation. On the west, a more gradual upland area was surveyed in detail; several individual moraines, at elevations between approximately 200-500m above high tide (aht), are interspersed with hummocky till and meltwater channels. This area was originally described by Daly (1902). North of these ice-marginal features, graded terraces and a continuous plain of sediments were seen, possibly indicative of a former ice-contact lake.

Mountains surrounding Kogarsok Brook rise to over 1100m (eg. Mount Kaputyat, Mount Elizabeth, Mount Ford). Tors and well weathered blockfields are present on the higher slopes and summits of these peaks.

Tallek Arm, opposite Kipsimarvik Head, is a 9km trough running due north from the Palmer River into Nachvak Fiord. Its eastern side is bordered by very steep continuous rock walls which form the western edge of the Selamiut Range. Breaking the steep walls of the western side of this trough are two valleys, which feature wide deltas and raised terraces. The northernmost of these was named Kutyaupak valley after the mountain between Tallek Arm and Tasiuyak Arm; it connects these two bodies of water, and was examined from both entrances for evidence of glaciation.

Tasiuyak Arm represents the most westerly part of the fiord trough, running for 8km between Townley Head and Nachvak Lake, with a maximum width of 1.5km. It has a south-westerly orientation from Townley Head, and is largely surrounded by very steep slopes which rise to over 900m on both sides. Raised terraces have been preserved only at the entrance to Kutyaupak valley, on the south-eastern side of the arm.

Nachvak Lake is a 10km long finger lake, about 1km wide and of unknown depth. It runs west south-west from the head of Tasiuyak Arm, and is similarly bordered by steep high slopes. A 3km wide alluvial fan divides the two waterbodies, and prevented access to Nachvak Lake by Zodiac. The precipitous walls, scree slopes and talus cones of Nachvak Lake and Tasiuyak Arm made them unsuitable for detailed study on land. North Fan, a narrow valley which opens from the north shore of Tasiuyak Arm close to Townley Head, was examined for signs of glacial activity and preservation of raised marine shorelines.

Townley Head is a prominent, glacially-moulded rock knob from which a moraine extends to a point over halfway across the fiord. Visible at low tide, this moraine is thought to be similar to submarine sills identified down-fiord at Kogarsok (between Kipsimarvik Head and Kogarsok moraine on the south side of the fiord), Ivitak, Tinutyarvik and the fiord threshold. The fiord itself is divided into individual basins by these sills; this study area includes Koktortoaluk Basin and Townley Basin, plus one or more basins in each of Tallek Arm and Tasiuyak Arm. East of Townley Head is another, more subdued and unnamed headland.

1.4.2. Geology

The bedrock geology of the Nachvak Fiord area has been studied in some detail by Wardle (1983). Combining his own and earlier surveys (particularly that of Taylor, 1979), he concluded that the region can be divided into three structural sectors, which contain the boundary between the Nain and Churchill structural provinces (Figure 1-2). The entire fiord is predominantly underlain by Nachvak Gneiss, a granulite gneiss of plutonic origin which is thought to have been formed in the Archean period and stabilised about 2.5 Ga. Nain Province, on the outermost eastern edge of Nachvak Fiord, is dominated by Nachvak Gneiss. The Churchill Border Zone also contains a set of Lower Proterozoic super crustal sediments known as the Ramah Group. These are very distinctive, and were deformed during the Hudsonian Orogeny. In the Churchill Inner Zone, Nachvak Gneiss continues until it reaches a leucocratic band of uncertain age, the Tasiuyak Gneiss. West of this, granulite gneisses thought to be related to the Nachvak Gneiss continue. The fiord area was subjected to alteration and reworking during the Late Archean and Hudsonian periods, by metamorphic events which increased in intensity from east to west.

This study area lies entirely within the Inner Churchill Zone. Nachvak Lake, which marks the westerly extent of Wardle's survey, is underlain by granulite granitoid gneisses thought to be a continuation of the Nachvak Gneiss. They are separated from it by a 6-10km wide band of 'Tasiuyak Gneiss', a leucocratic gneiss composed mainly of quartz, plagioclase and garnet. It is thought to have formed by the metamorphism of Aphebian sedimentary rocks (Taylor, 1979), though this is not obvious from its composition (Wardle, 1983). It is reported as having a characteristic appearance on washed surfaces, with "mauve, garnet-rich bands alternating on a 2-10cm scale with white, quartz-plagioclase bands containing scattered 1-3cm garnet

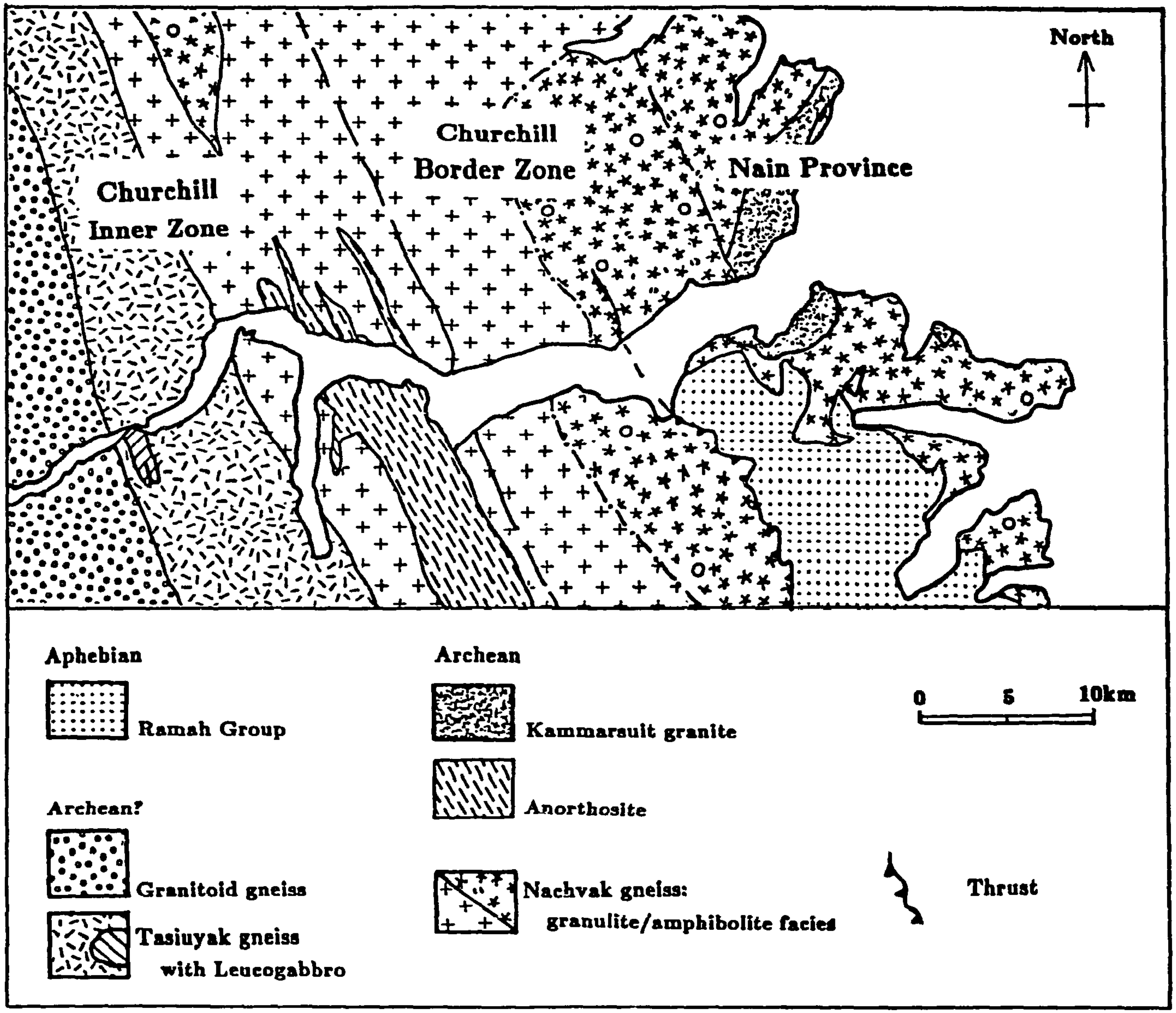

Figure 1-2: Bedrock geology, Nachvak Fiord (*after* Wardle, 1983).

porphyroblasts" (Wardle, 1983, p.83). In the fiord, weathered surfaces can be seen to have a rusty-brown appearance similar to that of Nachvak Gneiss, though the rock walls surrounding Tasiuyak Arm itself have a rich orange-brown colouring. Veins and mylonitic inclusions occur throughout the gneiss.

Within the Tasiuyak Gneiss, at the threshold of Nachvak Lake, is a narrow intrusion of "sheets of pale grey garnet + orthopyroxene + diopside + plagioclase rock with granoblastic texture" (Wardle, 1983, p.84). This is considered to be a leucogabbro, but its significance is unknown.

In the Churchill Inner Zone, Nachvak Gneiss was severely mylonitized and otherwise deformed by the Hudsonian Orogeny of c. 1.8 Ga. Immediately east of Tasiuyak Gneiss, most of the Nachvak Gneiss is thought to have been converted to mylonite and ultramylonitic gneiss; intense shearing during the Hudsonian appears to have removed all evidence of pre-existing Archean mylonitic fabrics. A band of anorthosite south of the fiord separates this intensely mylonitized gneiss from its eastward extension; the band stretches from the mouth of Tallek Arm to Ivitak Cove, a distance of approximately 5km. It continues in the north (notably in Kogarsok Valley) as several small 'fingers' of rock.

The anorthosite contains no quartz and thus appears to show none of the mylonitic foliations of the surrounding gneisses. It is probably Archean in origin, intruded post-tectonically by late dikes. Its relationship to Nachvak Gneiss is uncertain, though Wardle suggests that it is older. Such anorthosite intrusions are common to the Archean period of West Greenland, where they have been dated c. 3.3 - 2.8 Ga.

Chapter 2
Previous Research

2.1. Introduction

The aim of this chapter is to set the stage for the research carried out in Nachvak Fiord in 1986. The differing conclusions of previous researchers demonstrate how difficult it is to interpret some of the data from the Torngat Mountains, and highlight the varied opinions on the extent of the last glaciation. Recent debates are closely linked to the studies of the 1950-60-70's, hence it is felt that a thorough understanding of those studies, and the reasons for them, are necessary to this thesis. It is hoped that detailed examination of this area of the fiord will contribute, with the other small-scale studies previously carried out to the east and south-east, to a better understanding of the overall Quaternary history of Nachvak Fiord and of the central Torngat Mountains. Figure 2-1 shows the places referred to in this section.

The history of glacial and Quaternary research in the Torngat Mountains and in Nachvak Fiord is outlined in chronological order. Although studies in the islands of the high Arctic were integral to later interpretations of glacial evidence in the Torngat, they will only be referred to where direct parallels need to be drawn. Research in Nachvak Fiord has become increasingly localised, hence the final part of this chapter will deal with local evidence and proposed chronologies.

2.2. Early Studies

Early work in the Torngat Mountains was of a reconnaissance nature; Labrador was remote and inaccessible, particularly its northern coast and mountains, and the physiography of Labrador-Ungava was poorly understood. The study of glacial processes was in its infancy, and techniques were almost entirely descriptive. Nevertheless, literature about the northeast coast of

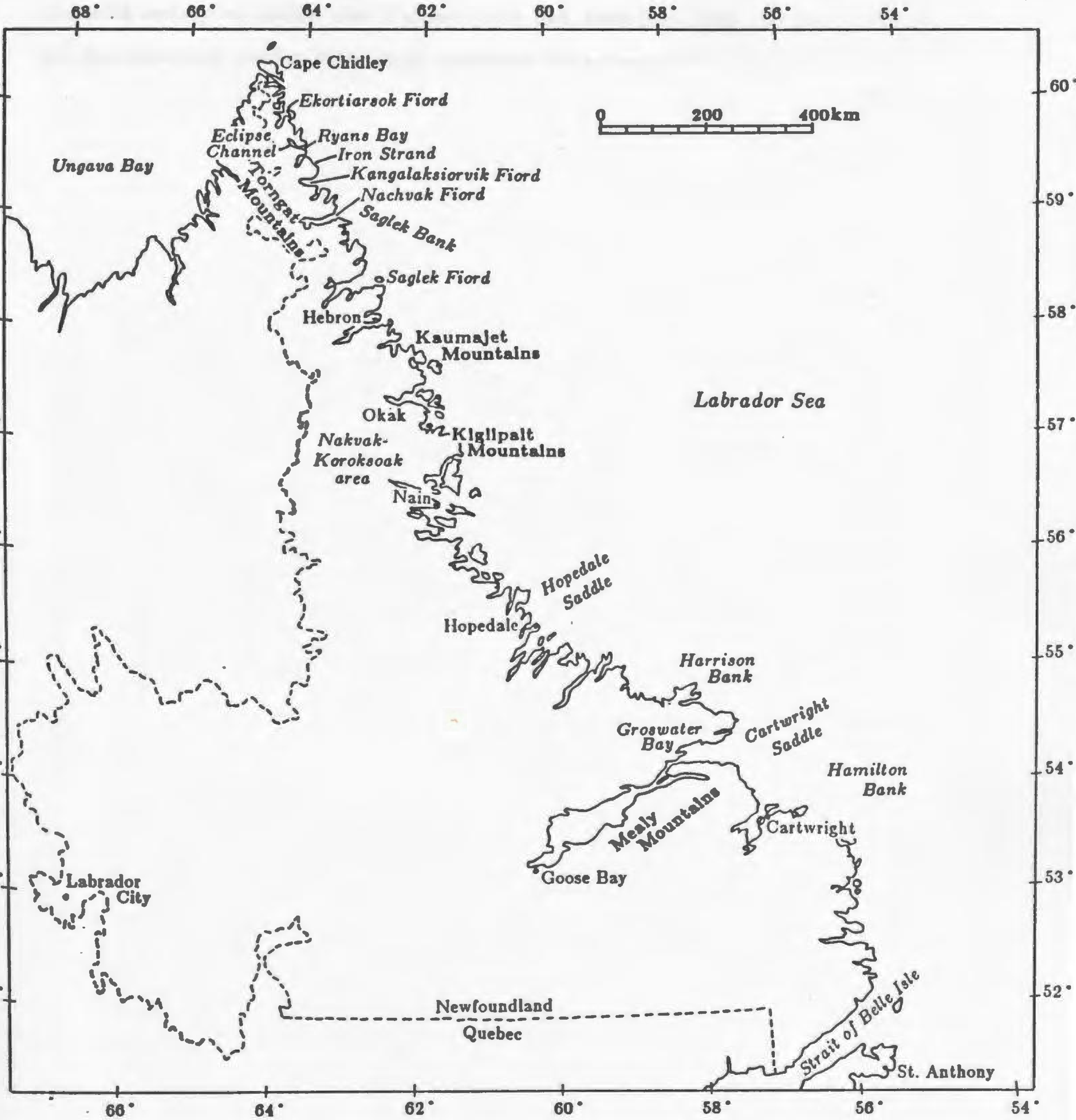

Figure 2-1: Location map of northern Labrador, showing places referred to in the text.

Labrador is considerable and expeditions to this area occurred periodically from the late nineteenth century (eg. Lieber, 1860; Packard, 1891; Bell, 1885; Daly, 1902; Coleman, 1921). The fact that these early workers did not fully understand the nature of the 'glacial epoch' caused many later misunderstandings about their interpretations. In the late nineteenth century, a single 'ice-age' was assumed to have occurred, and initially the division between glaciated and unglaciated areas was absolute. Daly (1902) was uncertain whether the Torngat Mountains had remained ice-covered throughout this epoch, or whether an interglacial had existed in northern Canada. The length of an interglacial, and the power of a second ice advance to destroy the earlier landscape, was unknown. Thus, while the influences of continental and local glaciation were understood, and sea level changes could be recognised, they were all thought to have been caused by the single advance of the last glaciation.

Daly (1902) reported that Lieber, Bell and Koch concluded that the higher peaks of the Torngat Mountains were not glaciated. Their steep craggy appearance was markedly different from the rounded peaks or 'domes' of lower elevation, and the generally flat-topped tableland of the shield inland. Furthermore, they were cut through by the smoothed u-shaped valleys and fiords, suggesting glaciation from the west. Although objective in his acceptance of these conclusions, and in his interpretation of his own observations of the 'alpine' character of mountain peaks, Daly agreed that the last inland ice advance did not reach summits over 2100 feet (640m) above sea level. By climbing several summits in the area of the Hudson's Bay Company Post at Kipsimarvik, he observed a change in the character of rocks with increased elevation. At low altitudes, he described polished, moulded and striated rocks, abundant glacial erratics and little evidence of weathering or erosion. Above 1600 feet (488m) there appeared to be no erratics and no moulded or striated bedrock. Felsenmeer began at that elevation, although Daly was uncertain whether it had developed *in situ* or had been carried down from higher altitudes in postglacial times. Weathered bedrock and deep felsenmeer above 2100 feet convinced Daly that peaks above that elevation had not been glaciated. Similar conditions were found in three separate locations, on Mounts Ford and Elizabeth, and on Kaputyat Mountain on the western slopes of Kogarsok valley.

Daly (1902) concluded that the Torngat Mountains acted as a barrier to the last advance of ice, allowing glaciers to pass eastward only through the deeply trenched fiords. High peaks stood as nunataks above the ice, although some were occupied by local glaciers which coalesced with the regional ice-sheet at certain times. Weathering on these high peaks left them as steep serrated 'horns', covered with angular felsenmeer.

Advances in the understanding of the glacial periods of north America progressed rapidly, so that by the time Coleman (1921, 1926) published results of his work in eastern Canada it was recognised that there had been several glacial periods; the latest of these was termed the Wisconsin. Coleman believed that the thickness of ice during the maximum of the Wisconsin period was not great enough to overtop the mountains of northern Labrador. He was a supporter of the Scandinavian nunatak hypothesis (Fernald, 1925), and believed that the presence of felsenmeer indicated prolonged weathering; thus he agreed with Bell (1885), Low (1985) and Daly (1902). His conclusions can be interpreted to suggest that the summits of the Torngat Mountains remained unglaciated throughout the Wisconsin glaciation.

Although Coleman recognised that local valley glaciers had occupied the Torngat Mountains, he proposed that regional 'Labradorean' ice had not passed into the fiords. This opinion was possibly caused by confusion over the origin and naming of the continental ice-sheet, and lack of knowledge about the physiography and role played by interior Labrador-Ungava in the build-up of ice (Coleman, 1926). Coleman also used degree of weathering as an indicator of the extent of glaciations that occurred at different times in Newfoundland (1921). While deeply weathered felsenmeer at high elevations was taken to indicate areas glaciated during some very early maximum extent of ice, intermediate areas of partially weathered rock still showing ice moulding and striations were thought to have been glaciated before the Wisconsin. Unweathered areas were taken to indicate local ice caps covering limited areas during a phase late in the Wisconsin.

In 1931, Alexander Forbes led the Grenfell-Forbes Northern Labrador Survey Expedition, which did much to establish a correct physiography of the region through aerial photography. N.E. Odell, a much-respected geologist and mountaineer, accompanied the expedition, providing detailed descriptions of the solid geology and physiography of the mountain ranges in the far north. He also made observations on the glacial geomorphology of the area; in two publications his ideas became more definite and eventually led to widespread acceptance of the idea of an extensive Wisconsin glaciation. At this time, at least four ice-advances were recognised in central north America, emanating from what would later become known as the Keewatin/Laurentide ice-sheets. The Wisconsin glaciation was known to be the most recent advance, occurring as a 'sub-epoch' in the 'glacial period', about 25,000 years ago. Odell did not divide the Wisconsin into phases, but did recognise a build-up to, and decline from, its maximum extent.

Odell (1933) believed that regional 'Labradorean' ice did reach the Atlantic via the fiords and troughs of the Torngat Mountains, thus disputing the conclusions of Coleman (1921, 1926). He realised that these mountains lie east of the continental watershed, and that they probably had little bearing on the drainage of a central ice-sheet. Local glaciation was also recognised. Studies of felsenmeer and glacial features on numerous mountains in the Kaumajet and Torngat ranges led Odell to conclude that the highest summits of both ranges, and presumably the Kiglipait as well, had been inundated by ice. Although extensive felsenmeer was clearly visible, Odell also described glacial erratics, *roches moutonnées*, and polished bedrock at altitudes up to 4700 feet (1433m) above sea level. He concluded that ice exceeded this elevation during the Wisconsin Maximum, reaching elevations well above the 2100 feet (640m) proposed by Daly to be its maximum extent.

Odell was able to explain the presence of felsenmeer by his firm belief that weathering processes in the Arctic are particularly severe. Parallels with Norway and Spitzbergen were drawn, citing high humidity, low temperature and ensuing rapid freeze-thaw frost activity; Odell and his supporters were convinced that climatic conditions allowed the formation of deeply weathered felsenmeer in postglacial times. In his 1933 paper, Odell makes reference to high mountain peaks standing as nunataks for a considerable period of time after the maximum of the Wisconsin period. In the 1938 report, the importance of those ideas diminished as the theory that felsenmeer developed postglacially became accepted. Fernald's nunatak/refugia theory (1925) was directly opposed by Odell, in 1933 and 1938.

Tanner (1944) accepted Odell's conclusions; again, felsenmeer development was based on the severe climatic conditions in the locality, and the arguments of Daly and Coleman were completely refuted. He too was opposed to the nunatak hypothesis and presumed that Wisconsin regional ice flowed out over the high peaks of the Torngat to the continental shelf. R.F. Flint was the next and possibly the greatest proponent of the 'maximum Wisconsin viewpoint'[1]. Working along the eastern seaboard, he observed glacial erratics amongst felsenmeer blockfields at high elevations; he opposed the nunatak theory, and interpreted felsenmeer as a product of postglacial processes. Despite a lack of direct evidence in certain locations, a comprehensive and easily understood model of glaciation was devised (Flint, 1944, 1971; Flint, Demorest and Washburn, 1942). It was proposed that the Laurentide ice-sheet covered all of eastern Canada during all of its maximum phases, such that it extended onto the continental shelf off north-east Labrador, and was continuous with the Baffin Island/Ellesmere Island ice-sheets, and with those of the island of Newfoundland. While the suggested extent of glaciation was 'intellectually attractive' (Ives, 1978), easy to teach and to integrate into climate models (eg. CLIMAP, 1976), it reflected many of Flint's biases. As previously stated, he was opposed to the nunatak hypothesis. He also admitted that evidence of glacial inundation was scarce or non-existent in some places (Flint, Demorest and Washburn, 1942), and he assumed that felsenmeer developed postglacially without consideration of other hypotheses. His 1971 book glossed over many of the details of glaciation, implying a Late Wisconsin origin for erratics and polished rock at high altitudes, and yet giving no examples and no other possible theories. By this time it was realised that the Wisconsin glaciation occurred in two or three phases; Flint suggested that the Late Wisconsin was less extensive than its predecessors, with a maximum areal extent 10% less than their maxima. While he implied that Late Wisconsin ice overtopped all summits of the east coast, he also conceded that some summits may have been glaciated only by pre-Late Wisconsin ice (1971, p.486). Again, no examples or other comments were provided, and the possibility of this explaining the strong development of felsenmeer was not considered.

Flint and his followers also assumed that the relatively recent work of Odell was more detailed than that of Daly and Coleman. While all of these authors climbed mountain summits in the Torngats, observing abundant felsenmeer above a certain elevation, Daly provided the most detailed accounts of his methods and appears to have been particularly thorough in determining that the felsenmeer had indeed developed locally and had not been carried into lower areas from

[1]A term coined by Ives (1978) in his attempt to summarise, clearly and concisely, this debate. The 'maximum viewpoint' holds that during the last glaciation, Laurentide Ice advanced over the high mountain peaks along the coast of eastern North America and extended out onto the continental shelf. The 'minimalists' ' argue that summits were not overtopped by ice during this period.

above. While Odell provided accounts of the mountains he ascended and the results he found, his descriptions were not detailed and his methods do not appear to have been rigorous. As Ives (1978) has observed, any dubious or equivocal evidence noted by Odell or Flint was interpreted as evidence *for* complete glacial inundation.

The idea that the Laurentide ice-sheet was very extensive during its last expansion dominated theories of glaciation until very recently. Ives' (1978) review of these interpretations emphasises how attractive and 'useable' Flint's model was, and how committed he was to his own theories. Flint appears to have been oblivious to alternative interpretations of the evidence, and because he was so well-respected his ideas dominated over conflicting evidence until the mid-1970's. They can still be seen in the works of Mayewski, Denton and Hughes (1981) and Hughes *et al.* (1981), for example.

Support for a more restricted Wisconsin glaciation returned after a series of highly localised studies in the late 1950's and early 1960's, largely by members of the McGill Sub-Arctic Research Laboratory. These did little to alter the opinions of Flint and his followers, and were not generally accepted until more detailed work had been carried out in Baffin Island, the high Arctic and Atlantic Canada. However, detailed examination of the Torngat, Kaumajet and Kiglipait Mountain ranges of northern Labrador, and of the moraines, trimlines and strandlines found in their valleys and fiords, convinced workers such as Andrews (1963, 1970), Ives (1957, 1958*a,b*, 1960), Loken (1962*a,b* and Tomlinson (1958, 1963), that more than one phase of glaciation was visible in this area, the last phase being least extensive.

Summaries of the sequential discoveries made by workers in northern Labrador and Baffin Island can be found in Andrews (1974) and Ives (1974, 1978). Conclusions hinged around increased understanding of the bi- or tri-modal Wisconsin glaciation, of the processes causing development of felsenmeer, and of the thickness, temperature, and strength of glaciers. Studies of relative sea level change provided more information on the extent of glaciation. Techniques of study have improved enormously in the last decade, allowing absolute and relative dates to be applied to landscape features.

2.3. The Weathering Zone Concept

The return to local support for a less extensive Wisconsin glaciation was prompted by Ives (1957, 1958*a*, *b*, 1960) who separated three vertically distinct areas on the basis of their morphology and degree of weathering. He traced these for a considerable distance in the Nakvak-Koroksoak watershed area. Zones with similar morphologies and altitudinal boundaries were identified by Loken (1962*a*; Ekortiarsok - Kangalaksiorvik Fiords) and Andrews (1963; Nain - Okak Bay region). These were correlated because of their similar appearance, and termed 'weathering zones' because it was unclear whether they related to separate periods of glaciation or to the individual effects of one or more glaciations. The oldest and highest zone, termed the Torngat (Ives, 1958*a*), represents the highly weathered felsenmeer of Daly (1902) and Coleman (1921). It is characterised by deeply weathered bedrock, tor formations and its high altitude ($>$ 2700 feet, 823m). This zone remains controversial, as workers dispute the presence of glacially-emplaced erratics. Ives maintained that erratics are visible on the peaks of the Torngats, and correlated them with boulders identified on the Kaumajet and Kiglipait Mountain ranges. Loken (1962*a*, *b*) argued strongly against this, believing those 'erratics' to be weathered-out inclusions of the local bedrock and stating that there is no unequivocal evidence to show that the mountain peaks were ever glaciated. It was generally recognised that whether the summits were glaciated or not, the felsenmeer blockfields and tors required a considerable period of time in which to form; the zone was therefore not thought to have been glaciated during the Wisconsin.

The issue was further debated with reference to Dahl's theory (1946) on the maximum slope of an ice sheet bordering a deep ocean (Tomlinson, 1963). If ice was thick on top of the mountain summits, it must have extended out onto the continental shelf, and possibly beyond as an ice-shelf, assuming the gradient of 1:100 to be correct. Sugden also prompted discussion with his theory on the effects of different basal thermal regimes within glaciers (1974; 1976*a*, *b*; 1977). He suggested that a cold-based ice carapace might have covered the upper Torngat mountains, causing little or no erosion and yet carrying erratic boulders into their present locations (Sugden and Watts, 1977). Although considered possible, the fact that a large, subaerially-formed moraine system exists at an intermediate level indicated that such a carapace was unlikely to have existed at the time that the lower level was glaciated.

In an attempt to resolve some of the controversy over the presence of glacial erratics, Ives (1978) suggested that the uppermost Torngat zone be divided in two. Areas north of Kangalaksiorvik Fiord in the Torngat Mountains, and on parts of Baffin Island, were assigned the three-zone altitudinal division on the surmise that no erratics have been found on their high summits; areas south of Kangalaksiorvik Fiord, possibly including the Kaumajet and Kiglipait ranges, the Mealy Mountains, Shickshocks (Quebec) and Long Range Mountains (Newfoundland), may be assigned a fourth division. This was termed the Komaktorvik Zone, and occurs immediately below the Torngat Zone. Ives suggested that an early 'Komaktorvik' glaciation may have emplaced glacial erratics, but that subsequent ice had not reached that altitude. An upper, unglaciated Torngat Zone may rise above the Komaktorvik Zone on high peaks.

The intermediate weathering zone is termed the Koroksoak (Ives, 1957, 1958*a*). No strong boundary defines it from the Torngat (or Komaktorvik) Zone, only the difference in the degree of weathering of bedrock, and the obvious presence of glacially-moulded and striated bedrock forms. The area has been described as one of 'incipient felsenmeer' and was thus thought to have remained unglaciated for some considerable period of time. That it was once inundated by ice is not in doubt.

The lowest, or Saglek Zone, is named after its type-site in Saglek Fiord, where large lateral moraines can be clearly seen at the upper boundary. Up to ~700m, bedrock showing little weathering and with fresh marks of glaciation is described (Andrews, 1963). Striations and polishes are considered abundant, and kame terraces, meltwater channels and both lateral and end moraines are visible in places (eg. Nain-Okak region, Andrews, 1963; Nakvak-Koroksoak area, Ives, 1957, 1958*a*, *b*; Ekortiarsok-Kangalaksiorvik Fiords, Loken, 1962*a*, *b*; Kangalaksiorvik Fiord, Clark, 1982, 1984). Although the bordering moraines are not present in all localities (eg. Loken, 1962*a*), the difference in appearance between this freshly glaciated terrain and the somewhat weathered Koroksoak Zone is considered obvious enough for identification of the Saglek Zone. Clark (1988) has recently defined the term 'Saglek Alloformation' to indicate those deposits laid down within the Saglek zone, below and including segments of Saglek moraine. His Shoal Cove Alloformation might be considered equivalent to the Koroksoak zone.

Figure 2-2 identifies each of the zones diagrammatically, and outlines their characteristics. The Torngat weathering zone occupied high coastal peaks north of Kangalaksiorvik Fiord.

Altitudes of each zone decline toward the coast, implying that successive glaciations were progressively less extensive, both vertically and horizontally.

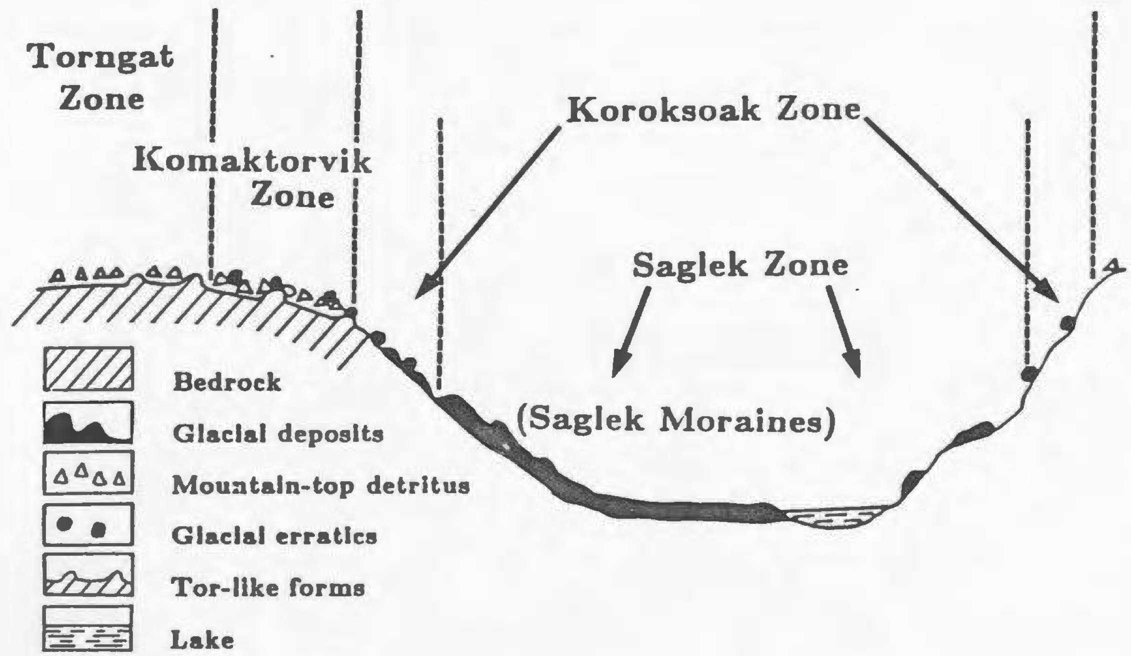

Figure 2-2: Weathering zones, as proposed for the eastern Canadian arctic (*after* Ives, 1978).

Dating of these zones proceeded after similar zones had been identified on Baffin Island. Boyer and Pheasant (1974) identified three weathering zones in the Maktak-Narpaing Fiord area of the Cumberland Peninsula; Zones I, II, and III were correlated with the Torngat, Koroksoak and Saglek weathering zones respectively. Pheasant and Andrews (1973) were able to date moraine systems associated with those zones. They concluded that the lowest Alikdjuak (Saglek equivalent) moraines were older than the date assigned to the Late Wisconsin Maximum glaciation, and thus that they probably formed during the Maximum of the Wisconsin glaciation. This implies that both Koroksoak and Torngat weathering zones are older than the Wisconsin, the Koroksoak being pre-Sangamon. Complementing this, and emphasising that ancient weathered surfaces can be preserved, is the fact that raised marine rock benches observed in Newfoundland have been assigned a pre-Late Wisconsin age (Grant, 1977*b*), as were features in parts of Baffin Island (Loken, 1966).

None of the weathering zones have been dated satisfactorily in northern Labrador. Relative dating methods, devised by Boyer and Pheasant (1974), may be applied to northern Labrador in an attempt to date and to stratigraphically correlate the three zones with those of Baffin Island. This is possibly the most realistic method of dating in areas where there are few organic deposits or artifacts, although different rates of weathering in different climates must be allowed for, and absolute controls are desirable. Pheasant and Andrews (1973) stress the likely time-transgressive nature of the weathering zones. Baffin Island probably experienced glaciation prior to northern Labrador, as did both areas prior to Newfoundland. Thus the Saglek Zone is likely to be equivalent in all three areas only in that it relates to the Maximum of the Wisconsin or last glaciation, for example (Ives, 1976). Debate over the exact age of the Saglek Moraines continues: Baffin Island deposits related to the Koroksoak Zone suggest that they are of Wisconsin age, but it has yet to be proven conclusively that they were formed in the Late Wisconsin. Andrews (1963) suggested that they were less than 25,000 years old. Radiocarbon dating of sediments from the bottom of Square Lake (Short, 1981), which is dammed by a segment of the Saglek Moraines, suggests an age of 18,200 years BP. This date may be erroneous, however, as it was obtained from a very small sample of carbon which might have been contaminated by 'old' or 'young' ^{14}C. Ives considered it to be a minimum age (1981).

Other dates from northern Labrador support the limited Wisconsin Maximum theory developed for Baffin Island. Ives (1977) dated marine shells from Iron Strand on the coast north of Kangalaksiorvik Fiord at $>$ 42,700 BP. Clark (1982, 1984) obtained similar dates from Iron Strand and within Kangalaksiorvik Fiord, and concluded that a narrow coastal strip remained unglaciated while the Saglek Moraines and their equivalents were being formed. By implication, the Saglek glaciation, and thus the Wisconsin Maximum, occurred during a Middle or Late Wisconsin advance. Other coastal areas probably remained unglaciated, shown for example by glaciomarine deposits at Delabarre Bay, Nachvak Fiord, which date to $\sim$30,000 years BP (Bell, 1987). Shells found in raised beaches at Ryans Bay and Nachvak Fiord (Loken, 1962*a*; Bell, 1987) suggest that final deglaciation of the fiords was completed by about 9000 years BP.

Ives (1978) suggested four hypotheses for the development of the weathering zones, and offers cross-sections in each of the areas in which they may be found. His favoured hypothesis is that the Saglek Zone represents the Wisconsin Maximum, the Koroksoak the pre-Saugamon glacial maximum, and the Komaktorvik Zone an earlier glaciation. The Torngat Zone, if it exists at all, would have remained unglaciated during those times. Other considerations are that all glaciations occurred within the Wisconsin stade, the Komaktorvik and Koroksoak zones being representative of Early or Middle Wisconsin maxima; the Saglek Zone would thus be accounted for by a Late Wisconsin Maximum. This hypothesis cannot be proven in northern Labrador until the Saglek Moraines and higher zones are dated; Baffin Island dates suggest that deposits related to the Saglek Moraine equivalents are older than the Late Wisconsin Maximum. A further hypothesis might be that all three zones were caused by variations in the basal thermal regime of ice during the Late Wisconsin Maximum, as theorised by Sugden (1977). This was discounted by Ives, on the assumption that the Saglek Moraines and their equivalents must have formed subaerially.

Ives' cross-sections attempt to account for the presence or absence of each of the zones at different localities. In the Nachvak Fiord area (Figure 2-3), the Komaktorvik glacial maximum is envisaged as overtopping all summits, the penultimate glacial maximum left high coastal peaks unglaciated (producing the Komaktorvik weathering zone on those peaks), while the maximum of the last (Saglek) glaciation was less extensive still, leaving an unglaciated area which became the Koroksoak Zone. All the literature stresses the seaward slope of these zones; this is also demonstrated in the cross-sections, as is the fact that earlier, vertically extensive ice-sheets probably extended onto the Labrador Shelf. Ives is of the opinion that local areas close to sea level remained ice-free during the Last Glaciation, stressing that this includes areas above and below present sea level.

Ives' 1978 paper almost draws the debate over the extent of glaciations in northern Labrador to a close, although his conclusions are tentative and ask to be proven. A 'minimum' Wisconsin view is preferred, however, and the idea that the Saglek Zone represents the Wisconsin Maximum (which may have occurred in the Late Wisconsin) appears to correspond with available absolute dates. More recent publications show that this opinion is far from universally accepted, however. Hughes *et al.* (1981) conclude that the Late Wisconsin saw an extensive ice-sheet in northern Labrador, both vertically and horizontally. Gangloff (1983) argues against the existence of nunataks in the Torngat Mountains. However, there appears to be a general consensus, particularly amongst authors who have worked in the area, that certain peaks remained ice-free

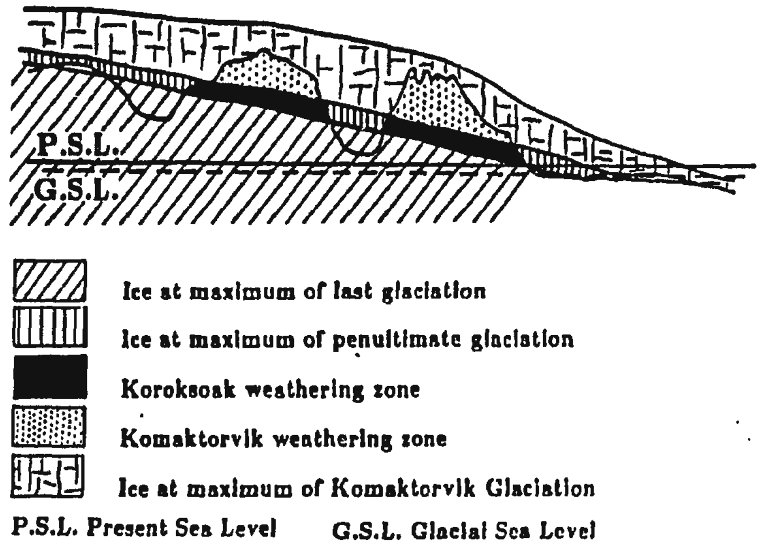

Figure 2-3: Nachvak Fiord type area; cross-section to show chronological development of four weathering zones (*after* Ives, 1978).

during the last glaciation (eg. Andrews, 1974; Ives, 1974, 1978; Loken, 1962*a*, *b*; Johnson, 1969, 1985; Dyke and Prest, 1987). Most recently, marine evidence from the continental shelf has been incorporated into the debate; the question of vertical ice extent has largely been left behind as conflicting onshore/offshore evidence presents a new argument.

2.4. Extent of Ice on the Labrador Shelf

Seismic, acoustic and coring operations have been carried out along the coast of Labrador, as well as in Baffin Bay and off the Newfoundland coast. Studies include oceanographic stratigraphies from grain-size, textural, lithological and geotechnical analyses, and paleontological interpretations from marine fauna and flora, as well as pollen analyses. Deep sea cores have been used to reconstruct past oceanic and climatic conditions relevant to glacial periods, while evidence from the continental shelf is of most importance to the reconstruction of ice-sheets and their extent of influence.

Josenhans (1983, 1984) and Josenhans, Zevenhuizen and Klassen (1986) attempted to describe the regional stratigraphy and topography of the shelf. It is composed of a number of banks and saddles, separated from the Labrador coast by the marginal trough. A shallow inner shelf with varied topography occurs on the coastal side of this trough, while a deeper outer shelf extends toward the sea. At least three till-like units (TLU) have been identified on the shelf using acoustic methods, the lowest TLU (Unit 3a) never having been sampled. This unit is most extensive, spreading up to 150km away from the coast and covering both banks and saddles alike. The sharp, smooth contact between units 3a and 3b suggests that the top of 3a was glacially eroded. Unit 3b is interpreted as occurring from Hamilton Bank to north Saglek Bank, discontinuously covering the inner shelf and extending across the outer shelf only in saddles. A Hudson Strait TLU (Unit 3c) is recognised in the north, extending south to approximately 60° latitude. Above these units, postglacial stratified sediments occur (Units 4 and 5a, 5b and 5c).

Early workers were able to distinguish layers of till-like material on the banks of the Labrador Shelf, overlain by stratified sediments of pro- and postglacial derivation. Van der Linden, Fillon and Monahan (1976; Hamilton Bank) and Fillon and Harmes (1982; north Saglek Bank) interpreted the upper TLU as being Late Wisconsin, assigning a date of 9-10,000 BP for the beginning of deglaciation on the shelf. A detailed and precisely dated Late Wisconsin - Holocene ice history was devised by Fillon and Harmes, based on radiocarbon dates obtained from organic matter in cores at different locations along the shelf.

An interpretation by Josenhans (1983) used data obtained from the Cartwright Saddle by Vilks and Mudie (1978) and Vilks (1980). Josenhans (1983) outlined a regional view of glaciation on the continental shelf, identifying three TLUs. Each TLU extended over a lesser area so that the upper (Unit 3b of later publications) occupied only the low saddles up to 120km offshore from Groswater Bay. The homogeneous unstratified appearance of the units led to the conclusion that each had been deposited by grounded ice. Vilks and Mudie (1978) analysed cores taken from pro- and postglacial stratified deposits, which were identified above the TLUs. Analysis of pollen and marine fauna suggested limited sea ice conditions off Hamilton Inlet, with a sedge-shrub tundra on land. Radiocarbon dates obtained from total organic matter indicated that these conditions began approximately 21,000 years BP. On the basis of this, Late Wisconsin ice was not thought to have extended onto the continental shelf, and the interpretation was correlated with the 'minimum Wisconsin viewpoint' of Ives (1978). If a constant rate of sedimentation could be assumed, an age of 40 - 80,000 years BP was placed on the uppermost glacial till.

Further support for this interpretation came from Vilks, Hardy and Josenhans (1984), from Clark and Josenhans (1984) and Clark, Josenhans and McCoy (1985), who attempted correlations of onshore and offshore data. Shell dates from Ives (1977) and Clark (1982, 1984) yielded pre-Late Wisconsin ages; suggesting that a stretch of the coastline had been left unglaciated during the Late Wisconsin. Further dating by pedogenesis and relative weathering studies led Clark to suggest that an older ($\gg$70 Ka BP) glaciation deposited moraines 650m asl within 1 km of the coast, and probably extended out onto the shelf. A submarine moraine system located 25-30 km off the coast between Noodleook and Saglek Fiords was correlated with the terrestrial 650m moraines, and attributed to an Early Wisconsin Glaciation. Deglaciation and glaciomarine deposition followed at about 40,000 BP, and the Late Wisconsin Maximum deposited the terrestrial Two Loon drift along with lower moraines which are clearly visible today. It was not thought to have extended onto the shelf, nor to the edge of the coast in all localities. Final deglaciation was assumed to have started by at least 9,000 BP.

While the interpretation of a restricted Late Wisconsin ice sheet appears to correlate well with terrestrial evidence, marine geologists began to reinterpret data as dating methods were suspected of being unreliable. Fillon *et al.* (1981), working on the Labrador Shelf, showed that dates from organic matter were frequently older than those from shells, even when both were collected from the same sediment types and depths. It was argued that shell samples are more reliable, since well-preserved shells deposited *in situ* at depths in which such creatures were likely to have lived can be chosen for dating. Organic matter is very open to contamination from older or younger ^{14}C, and to general reworking which may not be easily detected in the core. Dates from organic matter and total carbon have since been treated with skepticism (eg. Andrews *et al.*, 1985; Clark *et al.*, *in press*). In addition, McCoy (1984) stressed the uncertainty of amino acid dating on shells from the Labrador Shelf, noting the problems of iceberg scouring and sediment reworking. Many trenches were observed by Josenhans and Zevenhuizen (1984), all attributable to iceberg scours of different ages.

These results placed some doubt on the dates Vilks and Mudie (1978) and Josenhans (1983) assigned to the stratified units overlying glacial tills; they were considered to be too old, and are treated as maximum possible ages. Later ^{14}C dates on sediments in Hopedale Saddle suggested that the uppermost till-like unit was deposited $\sim$25 ka BP, while pro- and postglacial conditions began $\sim$22 ka BP (Josenhans, 1984; Josenhans and Zevenhuizen, 1984). Unit 3b, the most recent submarine till, was therefore reinterpreted as evidence that Late Wisconsin ice was grounded on the continental shelf off the coast of Labrador.

Josenhans, Zevenhuizen and Klassen (1986) carried out a survey of available radiocarbon dates from marine sediments on the Labrador coast (Fig.20, p.1208), concluding that deglaciation and deposition of the uppermost TLU (Unit 3b) began approximately 20,000 years BP. This unit is thought to have been deposited during ice retreat, when the glacier was not fully grounded (some hydrostatic support is suggested, though a floating ice-shelf is ruled out), since it is not overly consolidated and appears to have had a low loading pressure. A fourth unit, Qeovik Silt, is interpreted as having been deposited after ice retreat but before 8000 BP. It contains numerous limestone clasts, assumed to have been transported in icebergs from the Hudson Strait or other northerly source areas. Ice rafting is considered to have been an important process at this time, indicating that the shelf was clear of glacial ice during the deposition of Unit 4.

Onshore-offshore correlations using these more extensive interpretations of the Late Wisconsin ice-sheet have caused a renewal of the 'maximum - minimum Wisconsin' debate. Clark, Josenhans and McCoy (1985), Josenhans (1986), Josenhans, Zevenhuizen and Klassen (1986), and Clark and Josenhans (1986) correlated the till-like unit 3b with TLUs visible in acoustic records of the fiord basins, and with the Saglek Moraines and their equivalents. At the same time Unit 3a (lower TLUs) was correlated with 'pre-Wisconsin' glacial sediments on land (Clark and Josenhans, 1986). Thus the 18,200 BP date from Square Lake was correlated with the ~20,000 BP date from Unit 3b; the terrestrial moraines appear to be composed of local bedrock materials, as does the submarine glacial TLU. Postglacial stratified sediments overlying Unit 3b were correlated with postglacial raised marine deposits on land, as the terrestrial deposits also contain quantities of the limestone which is characteristic of Unit 3b.

Arguments against this interpretation are based upon terrestrial evidence, including raised marine shorelines, some of which are dated, moraine locations and elevations, and evidence of local ice activity. As already stated, glaciomarine deposits dated by Clark and Ives suggested that some coastal areas remained ice free in the Late Wisconsin. Rogerson and Bell (1986) noted large changes in relative sea level and high raised shorelines in eastern Nachvak Fiord and south of Nachvak Bay. The major changes in elevation between shorelines were interpreted as evidence of stage-like recession from the last glacial maximum, while the high shorelines on the outer coast suggested that an older glacial advance extended onto the continental shelf. Acoustic survey of Nachvak Fiord showed at least two major ridges crossing the fiord, both of which were likened to moraines by their shape and till-like covering (Rogerson, Josenhans and Bell, 1986). These were interpreted as recessional moraines formed during glacial stillstands, or as the grounding lines for floating ice shelves further east (Bell, 1987).

In Nachvak Fiord a glaciomarine diamicton dated at ~38,000 BP, and a 9,000 BP raised beach can be interpreted in the same way that Clark (1984) interpreted units of similar age from Iron Strand, Kangalaksiorvik Fiord and Ryans Bay. Thus a more extensive Early or Middle Wisconsin glaciation may have reached the continental shelf. Evans and Rogerson (1986) provide evidence of local ice activity in Nachvak Fiord; regional ice appears to have been extensive during the Early and Late Wisconsin periods, though a restricted Late Wisconsin ice-sheet was suggested. Bell (1987) considers the fiord threshold to mark the maximum extent of the latter phase. Evidence for these reconstructions is based around the elevations of moraines at Ivitak and Naksaluk Coves, which indicate maximum ice thicknesses of 400m (Evans and Rogerson, 1986) and 350m (Bell, 1987) respectively. It was considered unlikely that an ice-sheet with these thicknesses 25-10 km inland would extend onto the Labrador Shelf. The well-preserved glaciomarine diamicton and an overlying marine sand unit led Bell to conclude that ice had not entered Valley of the Flies after their formation; he also provided evidence for the eastern section of Adams Lake valley remaining ice-free in the Late Wisconsin. A date of 9,000 years BP was applied to a shoreline considered to extend through most of the fiord. It implied advanced deglaciation by that time, which suggests that the glacial maximum was relatively early and that the ice was not so extensive as to preclude retreat by this date.

Clark and Josenhans (1984) and Tomlinson (1963) considered the horizontal extent of the Late Wisconsin ice-sheet with regard to equations for maximum slope and stability of the ice-sheet (eg. Dahl, 1946; Schilling and Hollin, 1981). Clark and Josenhans (1986) drew profiles of the Late Wisconsin ice-sheet at Saglek and Nachvak Fiords on the basis of moraine elevations and the submarine glacial till observed on the shelf; in Nachvak Fiord, moraines varied between 200m and 600m above sea level (asl). Bell, however, reports that the highest moraines east of Tinutyarvik Cove reached elevations of only 180m above high tide (aht), in Adams Lake valley and Naksaluk Cove. He disputed the measurement of one moraine in particular, which he reported to be ~130m aht, while it was represented as being 280m asl by Clark and Josenhans (1986). Bell considered the high moraines Clark and Josenhans observed on the northern side of the fiord (in Schooner

Cove and Outer Cove) to belong to a much earlier glacial phase. Clark (1988) produced similar profile diagrams, using the same north-shore moraines and those assigned a Late Ivitak age (Evans, 1984), to show an extensive Late Wisconsin ice surface in Nachvak Fiord.

While Bell, Evans and Rogerson argue for restricted Late Wisconsin ice within Nachvak Fiord, they do consider it possible that ice in the fiords north and south of Nachvak Fiord was more extensive at that time. Clark and Josenhans (1986) concluded that the Torngat Mountains would reduce the flow of ice onto the Labrador Shelf for their entire length. Evans and Rogerson suggested that the higher mountain ranges around Nachvak Fiord in particular might have caused a divergent flow of ice to the north and south of it, allowing considerably less ice to enter Nachvak Fiord. This would explain tills of Late Wisconsin age on the Labrador Shelf, and Clark's interpretation of a high marine limit, and thus a fairly extensive ice-sheet, in Kangalaksiorvik Fiord (1984).

Although Clark and Josenhans (1986) and Josenhans, Zevenhuizen and Klassen (1986) implied that acoustic units observed within fiord basins correlated with those recognised on the continental shelf, they provided no evidence. This, together with the inaccurate mapping and plotting of elevation of Nachvak Fiord moraines in Clark and Josenhans (1986), led Bell to the conclusion that offshore evidence for an extensive Late Wisconsin glaciation is not unequivocal. He suggests that until the acoustic units of the fiord and shelf can be accurately sampled, glacial models based on terrestrial surveys should be preferred. His argument is that down-core extrapolation of lithological and paleontological data introduces uncertain information and may be very problematic.

It appears that an impasse has been reached; marine evidence, in the form of seismic and acoustic stratigraphies supported by palaeontological, lithostratigraphic and compositional analysis of cores, which are usually shallow, appears to indicate that ice was grounded along the Labrador Shelf approximately 20,000 years BP. Correlations with terrestrial data cause much debate, since, in certain locations, a restricted Late Wisconsin ice-sheet is suggested by moraines of fairly low altitude, by dated coastal glaciomarine deposits, and by coastal raised marine shorelines preserved at high elevations. The attempted *regional* identification of offshore glacial influences (Josenhans, 1983; Josenhans, Zevenhuizen and Klassen, 1986) may be too ambitious at the present time; concentration on individual fiords and accurate correlation of offshore and onshore evidence appears to be necessary if these arguments are to be resolved.

Dyke and Prest (1987), in their most recent reconstruction of Late Wisconsin ice margins, place the ice sheet on the continental shelf until at least 18,000 BP. They also leave nunataks in the Torngat Mountains, indicating restricted vertical extent. It is obvious that their interpretation is far from conclusive, as Rogerson, Evans and Bell maintain that Late Wisconsin ice did not extend onto the Labrador Shelf through Nachvak Fiord.

2.5. Nachvak Fiord Chronologies

Chronologies for Wisconsin and Holocene glacial events in Nachvak Fiord were proposed after localised studies by Evans (1984) and Bell (1987). They are described here in some detail, so as to provide a background to research in the inner fiord. Their suggested correlations with chronologies from other parts of northern Labrador are also given. Figure 2-4 shows locations of places in the fiord mentioned in this section.

Evans (1984) studied the surficial sediments, moraines and shorelines of the fiord at and south of Ivitak Cove, extending into the Selamiut Mountains. Relative and absolute chronologies were proposed, based on lichenometry and depth of soil development on moraine surfaces. These are summarised in Evans and Rogerson, 1986. Three major phases of glaciation were suggested, each including some local ice activity by the Selamiut glaciers.

The Ivitak glaciation was earliest, marked by extensive till sheets, above which felsenmeer-covered peaks occur. These peaks were presumed to have been left as nunataks during that period (eg. Mesa-Top mountain). Moraines formed below these summits allowed Evans to map the extent of regional and local ice-sheets; regional ice appears to have occupied Ivitak Cove, while local ice extended throughout Ivitak Valley. Local ice occupied the major part of McCornick Valley, which was not influenced by regional glaciation. An 80m aht raised shoreline in McCornick Valley was taken to indicate that the valley held a pro-glacial lake for at least part of this period. The Ivitak glaciation was divided into two phases on the strength of two separate moraines seen in Ivitak Valley; the pro-glacial lake appears to have formed during the Late Ivitak, after local McCornick Valley ice retreated. Early and Late Ivitak phases were not separated into individual glaciations as their respective moraines have similar soil profile depths.

The subsequent Nachvak glaciation was also marked by local and regional ice activity, regional ice again occupying Ivitak Cove. Bell (1987) suggested that Nachvak ice extended to the

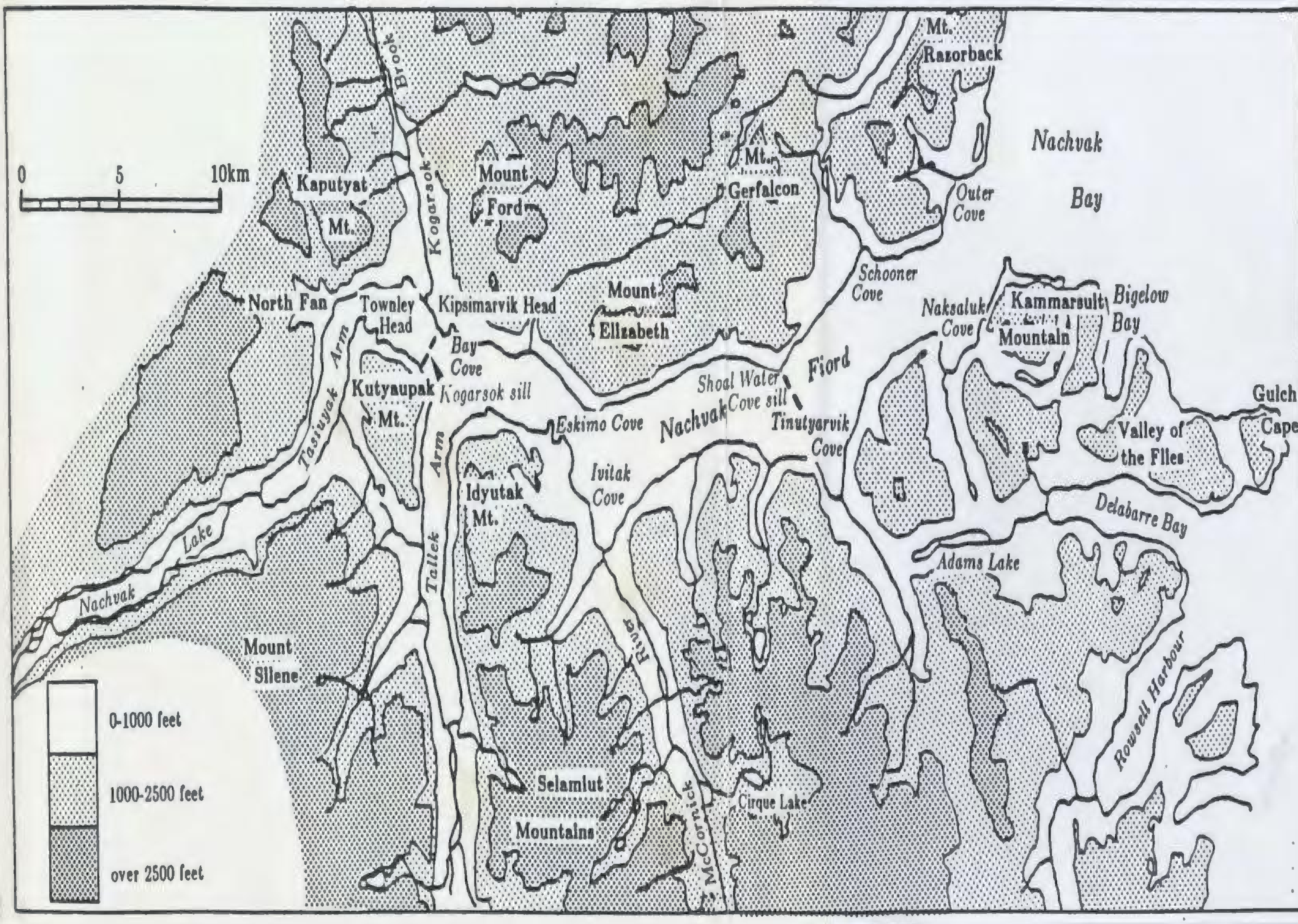

Figure 2-4: Locations of previous field study in Nachvak Fiord.

fiord threshold, and into Adams Lake valley. Local glacier activity formed more restricted lateral and end moraines within both Ivitak and McCornick Valleys, though another ice-dammed lake appears to have occupied the lower McCornick Valley. Two shorelines were observed here, at 67m and 53m aht, though again soil depths indicate that they are of similar age.

The third major glaciation was termed the Superguksoak I; neoglacial subphases were named Superguksoak II and III. Evans detected considerable ice advances through moraines extending from cirques. The amount of ice almost reached the proportions suggested by the Nachvak glaciation. However, regional ice activity was not apparent, and it was concluded that if ice had extended downfiord, it did not reach the Ivitak Cove area. A 33m shoreline in Ivitak Cove was interpreted as the marine limit in this area, from which it was calculated that the post-Nachvak ice load must have been small, or that there had been a late final deglaciation. Cirque Lake end moraines mapped by McCoy (1983) were considered to be correlative to Superguksoak I moraines; these were dated at $\gg$ 4 ka BP and were associated with the Late Wisconsin glaciation.

These glaciations were dated according to the degree of soil development on their moraines. An absolute chronology was suggested by Evans (1984) and reconsidered in Evans and Rogerson (1986). A development rate of 1.5cm ka^{-1} was initially adopted for the Torngat, using soil depth to the base of the Cox horizon; thus, a maximum age for the Superguksoak I glaciation was 12 ka BP, the Nachvak was dated at ~23 ka BP, and the Late Ivitak at $\gg$ 40 ka BP. It was suggested that the Early Ivitak may be > 70 ka BP, similar to the situation postulated by Clark (1984), who drew comparisons between Kangalaksiorvik Fiord deposits and the Kogalu glaciation of Baffin Island. An alternative chronology, using depth of soil to the base of the B horizon and a development rate of 1cm ka^{-1}, was put forward in Evans and Rogerson (1986). This placed the Late Ivitak at ~40 ka BP, the Nachvak at 17 ka BP and the Superguksoak I at a much younger 5 ka BP. Using this chronology, the Superguksoak I glaciation might still be correlative with the Cirque Lake basin moraines of McCoy (1983), though both events may have occurred in the Holocene (5 ka BP) or the Late Wisconsin (12 ka BP). A tentative correlation with Loken's 9 ka BP Kangalaksiorvik glaciation (1962*b*) was also suggested.

Two neoglacial subphases were identified through different sets of cirque moraines in the Selamiut; these were termed the Superguksoak II and III. Lichenometric and pedologic dating was attempted, though a lack of synchroneity between the results from each set of moraines led Evans to conclude that an absolute chronological sequence could not be devised for the moraines in these two phases.

A paper by Rogerson, Evans and McCoy (1986) queried the chronology suggested by Evans (1984) and Evans and Rogerson (1986) for Nachvak Fiord glaciations, and had important repercussions for soil development studies in the Torngat. After a 5 year assessment of lichen growth, the authors found that lichen were growing at much faster rates than previously suspected. McCoy (1983) had adopted growth rates from Baffin Island; however, the Torngat rates appeared to be 3 to 20 times faster. It had to be concluded that either the moraines assigned to the Superguksoak I glaciation were all of neoglacial age ($\leq$ 1300 years BP), or that an accurate curve of lichen growth rates cannot be drawn after only 5 years of study. Given the first condition, soil development rates must also be much faster than was originally suspected: in the order of 18cm ka^{-1}. Although such a rate is unrealistic, more rapid soil development might be expected in the Torngat Mountains region compared with Baffin Island or more exposed coastal areas of Labrador.

Bell (1987) conducted a study of relative sea level change and Quaternary glaciation in outer Nachvak Fiord. His study included acoustic surveys of the fiord (summarised in Rogerson, Josenhans and Bell, 1986) and of Adams Lake valley (Bell *et al.*, 1987). Local and regional glaciations of various ages were detected; absolute dating was carried out using radiocarbon and amino acid methods on shells and organic deposits, and pedogenesis on some moraine surfaces.

The highest moraines in the outer fiord were taken to indicate the oldest glacial phase, termed the MI phase. Moraines and trimlines reaching a maximum of 180m aht were measured, above which felsenmeer and bedrock outcrops were recorded. Regional fiord ice is believed to have deposited these moraines and occupied Tinutyarvik and Adams Lake valleys; Bell suggested that moraines observed by Clark and Josenhans (1986), on the north side of the fiord, may be correlative. No raised shoreline was directly related to this phase, though numerous beaches at high elevations were observed.

Lower moraines and a more restricted drift sheet were attributed to the Adams Lake glacial phase. It was interpreted as a local ice advance, as moraines bordering Adams Lake valley and extending into Valley of the Flies and the Kammarsuit Valley system indicate an origin from highland cirques. A recessional stage was also recognised, during which an ice-dammed lake formed within Adams Lake valley. A 60-70m aht marine shoreline was associated with this phase, incorporating a diamicton and a sand unit described in Valley of the Flies.

Moraines bordering regional drift sheets showed that fiord ice entered Naksaluk Cove and the western end of Adams Lake valley after the Adams Lake glacial phase. Cross-cutting relationships confirmed that this regional ice advance was younger; the moraines are interpreted as the easterly limit of Evans' Nachvak glacial phase. Ice-dammed lakes appear to have formed in Naksaluk and Tinutyarvik valleys at this time.

Using a variety of methods, Bell suggested a tentative chronology for each of the phases recognised. The age of the MI phase is unknown. The maximum of the Adams Lake glacial phase occurred between 34-50 ka BP, based on radiocarbon dates obtained from shells in the glaciomarine diamicton (mean $\geq$ 38 ka BP), on amino acid ratios from shells in the overlying marine sand (38-39 ka BP), and on soil development on Kammarsuit Valley East moraine ($\leq$ 50 ka BP). The recessional phase occurred between 29-32 ka BP, according to similar dating methods. This phase was tentatively correlated with Clark's Iron Strand drift (1984; 33-50 ka BP) on the strength of these dates.

Tentative correlations were drawn between the MI phase and the early Ivitak phase of the Selamiut Range (Evans and Rogerson, 1986). The latter was considered to be Early Wisconsin in age, and implies that Early Wisconsin glaciation was extensive and involved considerable regional ice-flow. A date of $\geq$ 75 ka BP was given after consideration of consistent dates from other north-eastern areas (Bell, 1987, p.222). Moraines measured at 940m and 750m asl in Kangalaksiorvik Fiord and Ryans Bay by Clark (1984) may be MI equivalents.

Soil development data suggested that the maximum of the Nachvak phase in the outer fiord occurred approximately 22±2 ka BP. This corresponds well with other dates suggested for the Late Wisconsin glacial maximum, and allows correlation with the Saglek phase (for example Andrews, 1963: < 25 ka BP; Short, 1981: 18 ka BP; Josenhans, Zevenhuizen and Klassen, 1986: 20 ka BP).

An acoustic survey of the fiord was interpreted as showing glacial-deglacial sequences, with the major till-like unit (Unit C) being associated with the last (Late Wisconsin) glaciation. Unit C extends to the fiord threshold; this was proposed as the easterly extension of Late Wisconsin fiord ice according to terrestrial evidence, though an ice shelf east of Tinutyarvik Cove was suggested on the basis of acoustic evidence. Moraine-like ridges at Tinutyarvik (the Shoal Water Cove sill) and Kogarsok were interpreted as grounding points of the ice margin, suggesting a retreat in stages from the glacial maximum. A similar survey of Adams Lake showed that the Tinutyarvik Moraine extends underwater, marking a definite boundary which was assigned a Late Wisconsin age. A radiocarbon date on marine organic deposits collected from the base of an Adams Lake core indicated that the lake was open to the sea 22,000 years ago; ie. that Late Wisconsin ice did not occupy the eastern part of this valley. However, this date might be inaccurate as organic matter is easily contaminated.

A somewhat complicated system of ice retreat and relative sea level change was proposed for the period after the last or Nachvak glacial maximum. A partially-grounded ice shelf was suggested for areas beyond the Tinutyarvik sill, up to the fiord threshold and Tinutyarvik Moraine. Retreat to Ivitak sill and/or Kogarsok sill, and a readvance phase, were suggested to explain the formation of several sets of shorelines. Bell associated his Shoal Water Cove readvance with Loken's (1962*b*) Noodleook phase, and suggested that a stillstand at either Kogarsok or Townley Head may correspond with Loken's Two Loon phase. A major stillstand or readvance, the Tessersoak, was identified on the basis of a shoreline (SI-D) thought to extend throughout the fiord, and dated in Adams Lake Valley at 9170 BP (radiocarbon date on marine shells found 4m below SI-D). This gives a minimum date for deglaciation, which corresponds well with Loken's 9,000 BP Kangalaksiorvik readvance phase. Tentative correlations were made between the Tessersoak readvance and the Superguksoak I phase of the Selamiut; both were related to the Two Loon and Coleman phases of Clark (1984; 9 ka BP). Shorelines below SI-D were almost horizontal, interpreted as indicating minor readjustments of isostatic/eustatic equilibrium. A 15m shoreline was tentatively correlated with the Scandinavian Tapes transgression, and more positively correlated with Loken's 15.5m shoreline in northern Labrador (1962*b*).

2.6. Summary

Recent studies indicate that, at the latitude of the Torngat, at least two glaciations reached the Labrador Shelf during the Wisconsin. The Early Wisconsin appears to have supported extensive regional ice-sheets, as did the Late Wisconsin. Terrestrial evidence from Nachvak Fiord suggests that Early Wisconsin, or Ivitak, ice reached the continental shelf, but that Late

Wisconsin, or Nachvak, ice did not. It is suggested that ice from other fiords was grounded on the Labrador shelf at that time. The Middle Wisconsin in Nachvak Fiord appears to have supported only local ice activity, from cirque glaciers in highland areas. Sea levels appear to have been well above those of today. Marine evidence has been interpreted as showing that Late Wisconsin ice extended onto the Labrador Shelf from *all* fiords of the Torngat, to a distance of 25-30km offshore.

Although new evidence for the horizontal extent of Wisconsin glaciations will not be directly provided by this study of the inner fiord, the vertical thickness of ice at particular times should evaluate the two Late Wisconsin interpretations. Examination of cores from the central fiord, of the elevation, morphology and origin of moraines, and accurate measurement of raised shorelines observed well within the fiord should add more detailed information to the reconstruction of late Quaternary history in Nachvak Fiord.

Chapter 3
Glacial Activity in Inner Nachvak Fiord

3.1. Introduction

This chapter deals with ice-flow directions and the provenance of moraines and tills in the study area. Two types of glacial activity are described: **local glaciation**, referring to ice which derived from the mountains and valleys in the immediate vicinity of the fiord, and **regional glaciation**, referring to the widespread Laurentide ice-sheet which flowed eastward from central Labrador-Ungava. Moraines believed to have been formed by both local and regional ice sheets are found in this area, an hypothesis supported by ice-flow indicators (striations, fractures, moulded bedrock and similar features) and geochemical analysis. The morphological appearance and associations between moraines gives an impression of their relative age, though pedological dating and some weathering studies were attempted in order to establish a more reliable relative chronology.

3.2. Morphology of Moraines

Figure 3-1 shows the locations of moraines found within the study area. In general, there is an increase in age with increased elevation, so that higher moraines show characteristics typical of older features (ie. degree of weathering, development of soil and vegetation). The moraines can be assigned to two categories: (i) those that were obviously formed by regional ice occupying the fiord trough, which are parallel and perpendicular to the fiord, and (ii) those that occur inland, which are higher and less clearly related to regional glaciation. Moraines in category (i) appear to be recessional lateral and end moraines, resulting from the last retreat of the Laurentide ice-sheet out of Nachvak Fiord. They suggest a stage-like retreat, and are likely to be associated with specific distal marine limits and raised marine shorelines.

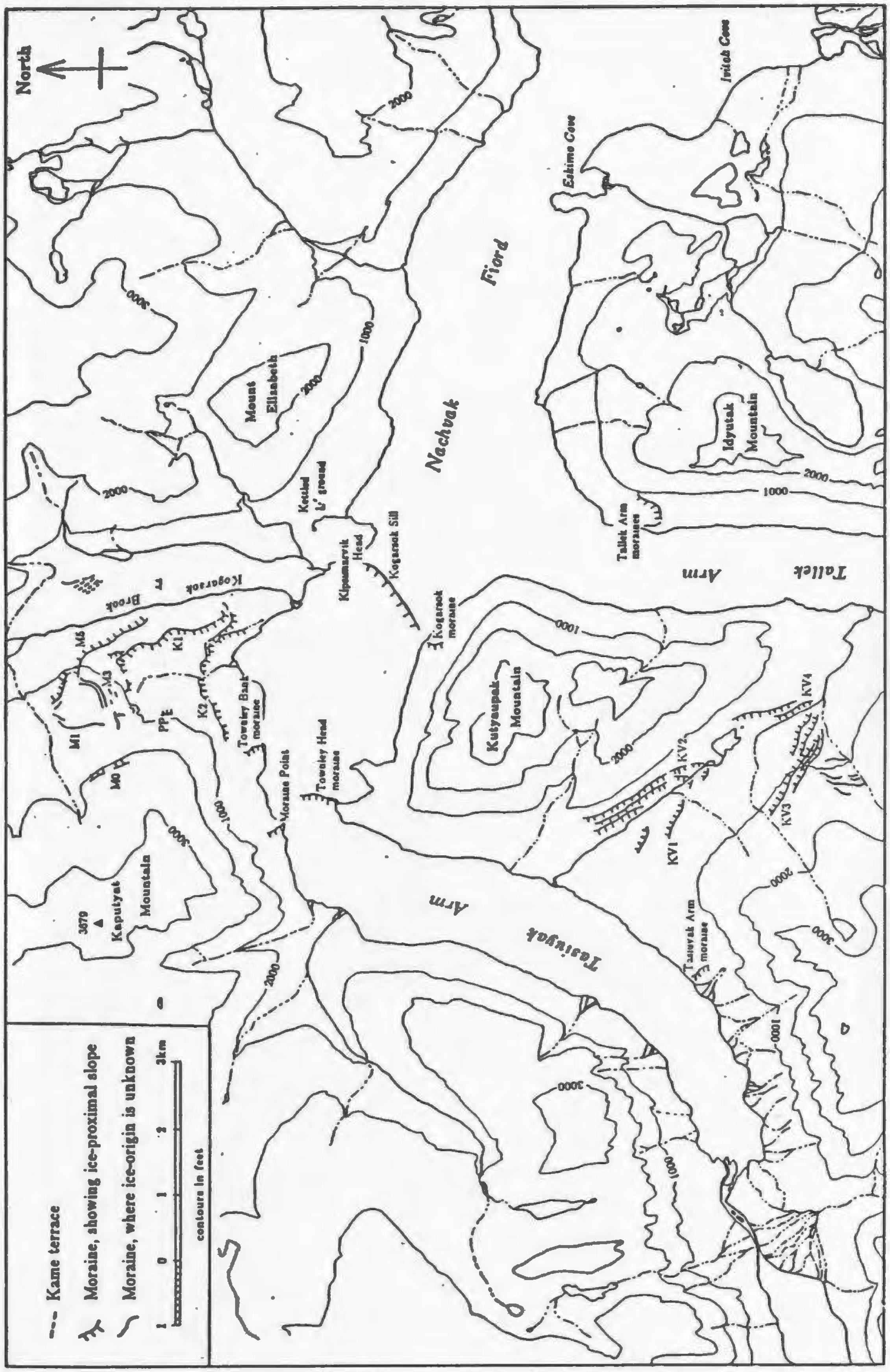

Figure 3-1: Locations of moraines mapped within Inner Nachvak Fiord.

Two moraines were identified on the eastern shore of Tallek Arm near its junction with the main fiord. The ice-proximal slope of the higher one (at 300-500m above high tide (aht)) appears to face north-west into the fiord, indicating that regional ice backfilled into Tallek Arm at considerable elevation. The lower moraine (50-100m aht) has less clear origins, though it seems likely that it too is a product of fiord ice backfilling into the arm.

The Kogarsok sill was identified by acoustic survey as a submarine moraine-like ridge crossing the fiord between Kipsimarvik Head and a fragment of terminal moraine on the south side of the fiord (Rogerson, Josenhans and Bell, 1986; Bell, 1987. See section 5.2). The sill was thought to be an end moraine, marking the ice-margin of a recessional phase after the last glacial maximum. Its landward manifestation is termed the Kogarsok moraine (KM), which has a steep ice-proximal side facing up-fiord (Figure 3-2). KM has no obvious continuation on the northern side of the fiord, suggesting that evidence of it may have been removed by a major meltwater or fluvial event that took place within Kogarsok Brook valley.

Figure 3-2: Kogarsok Moraine (KM), south-shore of inner Nachvak Fiord.

To the north-west of Kogarsok Brook, a continuous and fairly long lateral moraine extends above Townley Bank (Figure 3-3). This has been called Kogarsok moraine 2 (K2), and it may be related to the Kogarsok sill and KM. It drops from 189m to 124m aht from west to east, then divides into two ridges. One crest extends towards sea level, but is indistinct below 60m aht. The other can be traced as a definite ridge at approximately 124m aht until it curves in toward Kogarsok Brook valley at ~116m; it is most easily identified by the boulders and erratics occurring on its surface. A steep-crested ridge located on a marine or fluvial terrace at 73m aht (Figure 3-4) may be a recurrence of this upper crest; it is within the valley, reaching a maximum elevation of 76m. A series of boulders, some of them erratics from up-fiord, was tentatively traced over the rock shoulder toward moraine K2. Moraine K2 appears to be relatively fresh, with a well-preserved crest easily traced over a considerable distance. It shows no signs of severe weathering.

Figure 3-3: Kogarsok moraine 2 (K2, with arrows), north-shore of inner Nachvak Fiord.

Figure 3-4: Crested ridge on 73m aht terrace, west bank of Kogarsok Brook valley; a potential continuation of moraine K2.

Other moraines formed within the fiord are almost perpendicular to the shore. Townley Bank moraine (Figure 3-5) appears to be structurally influenced as it merges with a bedrock crest at ~120m, and outcrops occur above ~35m. Townley Head moraine is very clearly visible, extending over halfway across the fiord as a bouldery-clay ridge which may be walked on at low tide (Figures 3-6 and 3-7). A north shore continuation of it, called Moraine Point, can also be seen. Tasiuyak Arm moraine (Figure 3-8) does not reach sea level, and is less distinct as it has been subject to erosion (solifluction, surface water runoff); it occurs at the south-western end of two long and continuous benches, partway down Tasiuyak Arm (Figure 4-2).

The majority of category (ii) moraines, those that are inland of the fiord trough which are not obviously related to regional glaciation, occur on the highland west of Kogarsok Brook valley. The area is covered by drift sheets, has numerous moraines, and is further confused by ridges and hummocky ground apparently left by stagnating ice (Figure 3-9). Moraines were identified as definite crests and have been mapped in as much detail as possible.

Figure 3-5: Townley Bank moraine (arrows), north-shore of inner Nachvak Fiord.

Figure 3-6: Townley Head Moraine, extending from Townley Head into the fiord.

Figure 3-7: Townley Head Moraine, facing northward to Moraine Point, its north-shore extension.

Figure 3-8: Tasiuyak Arm moraine (arrows), south-east shore of Tasiuyak Arm.

Figure 3-9: The highland area west of Kogarsok Brook valley, showing numerous ridges and moraine crests.

The highest moraine, M0, occurs at an approximate elevation of 500m aht as a crested ridge. It extends for several metres in a general north-south direction. The ridge is almost entirely made up of weathered rocks of varied size, having very little fine material and almost no vegetation. Most rocks are covered with black crustose lichen species, the only other vegetation being a few mosses and grasses. Ice depositing this moraine must have occupied the lower area to the east. Above and below M0 are rubble terraces with outcropping bedrock (Figure 3-10). The higher terraces are characterised by dark lichen and a high degree of weathering. Hill tors occur on the hillside above and to the north of the highland study site, rising up to Mount Kaputyat. Although they were not visited, a similar tor near the summit of Mount Elizabeth was (Figure 3-11). Below M0 terracing is more pronounced, there being wide areas of wetland and bedrock between rises. Benches close to 500m aht contain less fine material and are poorly consolidated, the lower ones possessing soils and moss-grass-lichen vegetation, and containing snowpatches in late July. M0 appears to be the oldest moraine fragment in the field area.

Figure 3-10: Terraces above and below moraine M0 (A), with hill tors (B) on the sides of Kaputyat Mountain.

Figure 3-11: Tor at approximately 790m aht, near the summit of Mount Elizabeth.

Below M0 and the terraces rising to it is an area where ice appears to have stagnated, leaving hummocks and ridges of drift interspersed with meltwater channels. The channels have no particular orientation, though the ridge crests do follow a north-south pattern. A sorted till 'polygon field' occurs to the north, bounded roughly by meltwater channels. Moraine M1 rises as a lobe of crested till from the northern end of this field, curving around it to the south and east. The west-facing slope of this moraine is the steepest, though it does not appear to be the only ice-proximal face. It is possible that regional and local ice coalesced here, leaving M1 as an interlobate moraine. Meltwater channels may have flowed around it, steepening the west slope. Sorted stone polygons are abundant in the area east of M1, reaching diameters of up to 1.5m.

Moraine M3 is to the south of M1. It remains as two crests curving around the southern side of the summit, and appears to continue across the valley to the west where it might have once connected to moraine fragment PP. The crests of M3 are vegetated and well-consolidated, displaying little bare rock except where bedrock outcrops. In the western valley there are many ridges and cones of drift at various orientations, separated by meltwater channels. The large amount of drift material here makes it difficult to associate ridges with the major moraines.

Moraine M5 is long and sinuous, easily visible and characterised by a subdued boulder-gravel crest with little vegetation. It curves northward from Kogarsok Brook, extending to the west and reaching the polygon field north-east of M1 (Fig. 4-2). A crest was also noted on the eastern side of the valley, approximately opposite that on the western side. The mapped location of M5 suggests that it was formed by ice flowing out of Kogarsok Brook valley; where steep ice-proximal slopes could be identified, they supported this interpretation.

Moraine K1 was less easily detected; it winds about the flattest part of the highland, on an area of exposed bedrock alongside Kogarsok Brook valley (Figure 3-12). The moraine is visible chiefly by its boulders and erratics; it has very little fine material or soil, and is sparsely vegetated. It disappears into bedrock-controlled ridges below moraine M3, and is thus not thought to be related to that moraine. Most of the boulders along K1 showed considerable amounts of weathering. It was almost impossible to identify ice-proximal or ice-distal sides as the moraine contains so little material.

Figure 3-12: Moraine K1 (arrows), looking south onto bedrock plateau west of Kogarsok Brook valley.

Figure 3-13: Kame terraces on the eastern side of Kogarsok Brook valley, approximately 200-240m aht.

Figure 3-14: Example of large moraines at the south-eastern end of Kutyaupak valley.

Figure 3-15: Cirque valley with moraines (examples are arrowed), south-west Kutyaupak valley.

On the eastern side of Kogarsok Brook, at elevations of approximately 200-240m abt, were a series of terraces (Figure 3-13). These are tentatively identified as kame terraces, though site KE6 has a crest of gravel and till which might be related to moraine M5.

Another set of moraines occurs within Kutyaupak valley. The moraines form 'V' shapes across the valley floor, ponding water bodies toward the centre of the valley and helping to create a wetland area to the north-west. Those in the south-east are considerably larger than those further north (Figure 3-14), being clearly visible on aerial photographs. The shapes and locations of these moraines indicate that they were created by ice flowing into the valley from Tasiuyak Arm, though the type of material found in them suggests that tills have been deposited and reworked more than once. The moraines are poorly vegetated but well consolidated, formed mainly of clays and rubble with numerous large boulders.

A smaller set of moraines was mapped toward the cirque in the south-western section of the valley (Figure 3-15). These moraines probably derive from local ice, though they are greatly modified by kettle holes, frost-heaved ground and stone stripes and polygons. Their crests are poorly consolidated, formed largely of gravels, and support little vegetation.

3.3. Ice-flow Indicators

In order to confirm or establish the directions of ice movement within the fiord, striations, gouges, and plastically-moulded bedrock forms were sought within the study area. It was hoped that these would reveal the dominant directions of ice flow, as well as any more minor or older directions. Ice-flow indicators were looked for on any areas of exposed bedrock; striations were most frequently found underneath coverings of loose rubble or below moss/herb vegetation, and along the sea shore where little weathering has taken place. *Roches moutonnées* are common in highland areas, for example on the high area west of Kogarsok Brook valley, and on top of Kipsimarvik Head where other P-forms were also found. Gouges and fractures were found at a variety of sites, though they are best preserved near sea level.

Information obtained from these indicators is summarised in Figure 3-16. Most of the data derive from striae, the other indicators being marked in their locations. The arrow-heads show the direction of ice-movements as determined from striations; lines not marked with an arrow are those of dubious directional origin. Dominant ice-flow is seen to be regional, with indicators suggesting that ice pushed up onto the rocks along the shore of the fiord and into the mouths of valleys. A large number of striations was found around the western shoulder leading into Kutyaupak valley, showing the progressive movement of ice into that valley and confirming evidence shown by the moraines. Ice must have crossed over the top of Townley Head. It completely inundated Kipsimarvik Head, as shown by the *roche moutonnée* forms existing at about 50m aht (Figure 3-17). Plastically-moulded bedrock north-east of Kipsimarvik Head indicates that ice also flowed around the rock knob, polishing bedrock and creating striated channels.

Figure 3-16: 'Whalesback' *roche moutonée* feature near top of Kipsimarvik Head.

Striae and chattermarks at the mouth of Tallek Arm indicate that ice flowed from the fiord proper into the arm. This implies that ice did not flow out of Tallek Arm, at least during the last phase of the last glacial period.

Striations and gouges within Kogarsok Brook valley and along Townley Bank indicate regional ice-flow into these areas; they confirm that moraine K2 was formed by ice derived from the fiord, and suggest that ice did enter into the valley. To the east of the brook, most striae below 150m have a northerly orientation. However, there are some which have no clear directional

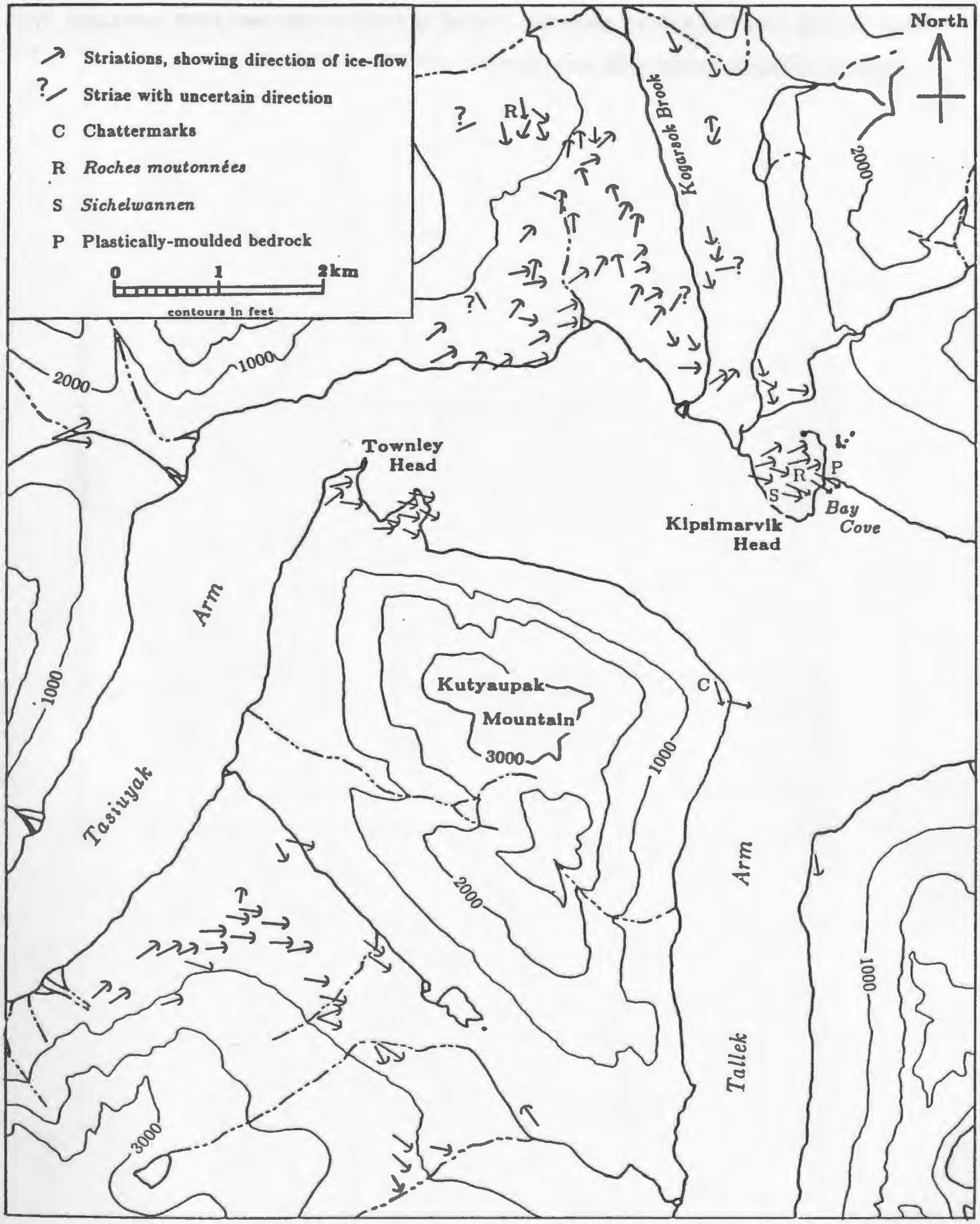

Figure 3-17: Ice-flow indicators identified in inner Nachvak Fiord.

origin, and above 150m two sets of striae can be seen, indicating ice flow both into and out of the valley. These suggest that local glacier activity occurred at the time when regional ice occupied the fiord, and that the ice-sheets coalesced.

Striae were found in abundance to the south-west of moraine K1, and on the bedrock underlying it. Most of them suggest a push from the direction of the fiord (average orientation 240° TN). Above K1, close to the summit and moraine M3, the ice-flow indicators were less conclusive; some poorly preserved examples thought to be of regional origin were found, but the badly weathered bedrock and thick drift cover made directions difficult to determine. *Roche moutonnée* features in bedrock on the summit above M3 provided evidence for local ice-flow southward toward the fiord. The origins of M3 could not therefore be determined in this way.

No striae were found below the level of moraine M5 on the western side of Kogarsok Brook valley; those on the eastern side suggest that regional ice entered the mouth of the valley but that local southward flows were responsible for movement north of the mouth.

3.4. Drift Geochemistry

3.4.1. Background Information

Geochemical analysis of sediments is frequently carried out in remote areas with the aim of assessing the economic value and distribution of minerals found there. The Geological Survey of Canada has performed large-scale systematic sampling in areas such as the Cordillera, northern Labrador-Quebec, and the central arctic. In glaciated areas, drift prospecting may provide evidence of ice-flow directions, as well as indicating the provenance and distribution of economic minerals.

Most geochemical mapping projects are done on a regional scale, with samples being taken at regular intervals from broad geographic areas. In Nachvak Fiord, however, samples have been collected on a more local scale by workers concentrating in very specific areas. Evans (1984) began sampling in 1983, collecting till samples from locations in the Selamiut Mountains south of Ivitak Cove. Bell (1987) collected samples from the outer fiord south of Nachvak Bay in 1984, and made a more detailed survey of the outer fiord area in 1985. In 1986, 54 samples were collected from the inner fiord, between Eskimo Cove and Tasiuyak Arm; five samples were also taken from consideration are discussed in this section, though the geochemistry of the entire fiord is also considered using the earlier data.

Aside from mapping any minerals of potential exploratory value, the aim of this analysis was to see if minerals acted as ice-flow indicators within the fiord, in which case they might be visible as trains of material not local to the area. Such indications are likely to be seen in regional studies of large areas, and in areas which include distinctive bedrock types. Nachvak Fiord divides into three geological zones, the Nain Province on the outer coast being most diverse. The Churchill Border Zone separates the Nain Province from the Inner Churchill Province in the inner fiord (see section 1.4.2). Since the inner fiord area is largely homogeneous, being composed of granulite gneisses, the variety and distribution of minerals found there might be expected to be low. Toward the outer fiord, the dispersal of distinctive local rock types suggests local ice activity and a division between regional and local drift deposits (Bell, 1987).

The success of previous analyses has been variable; Evans (1984) was unable to make any conclusions regarding ice-flow directions or the provenance of drift material, probably because the samples were from a limited area of similar rock type. Bell identified regional and local drift sheets in the outer fiord, defining the limits of each, and showing that the geochemical composition of their sediments is related to their clast lithology.

Direct comparison of results from the 1985 survey with those of other years is not possible. The textural composition of sediments is such that analyses of different particle-size classes cannot be compared; each class has a different mineralogical and chemical composition, and the components of each may vary greatly within a study area. As a result, it is recommended that only one particle-size class be used in an analysis (Shilts, 1971). Since geochemical analyses of the 1983, 1984 and 1986 data were carried out on the clay size fraction (less than 2 microns: $< 2\mu$), and those of the 1985 data were on the silt and clay size fraction (less than 63 microns: $< 63\mu$), Bell's detailed survey of outer fiord drifts cannot be directly compared with the other data.

3.4.2. Methods

Sediment samples were collected from till sections and pits in the inner fiord area, at locations marked on Figure 3-18. Five additional samples were collected from Schooner and Outer Coves, close to Nachvak Bay. A total of 59 samples was analysed by Chemex Labs Ltd., North Vancouver, after preparation by the G.S.C. in Ottawa. The clay size fraction ($< 2\mu$) was processed using ICP analysis to find 32 elements; of these, eleven metals were selected for consideration here, on the basis of other studies. These were: Ag, Co, Cr, Cu, Fe, Mo, Mn, Ni, Pb, U and Zn.

Rose, Hawkes and Webb (1979) outline the principles and methods of geochemical analysis and interpretation. A background value of concentration should be identified for each element in the samples; samples containing elements at concentrations higher than the background value may then be identified as anomalous and can be accorded further study. The background value is more accurately a range of values, within which the mean might be identified as typical. The range can be seen by plotting a frequency histogram of each element's concentration. Frequency histograms sometimes show anomalously high values, or a secondary peak separate from the main body of data, indicating two populations; however, Rose, Hawkes and Webb stress that other methods of background delimitation should be considered. The identification of a 'threshold' concentration to accurately define anomalously high values is important to the effectiveness of such definitions. A threshold set at too low a concentration will show some background concentrations to be anomalous; too high a threshold will not recognise significant metals. In mineral exploration this is of great importance, as uneconomic quantities of minerals may be researched, or potentially valuable minerals may be overlooked. A threshold should therefore be set using the background information for each element within the individual population, while also considering the purpose of the survey.

In this study the threshold was calculated for each metal by adding two standard deviations to the mean concentration of the metal, worked out using a population of 54 samples for the inner fiord data set. This is the method suggested by Rose, Hawkes and Webb (1979) for use in initial and general surveys. Figure 3-19 shows frequency histograms for the 1986 data, on which the range of background values can be seen, and where the threshold values are marked. Threshold concentrations and mean 'background' values are listed for each metal in Table 3-1. They are

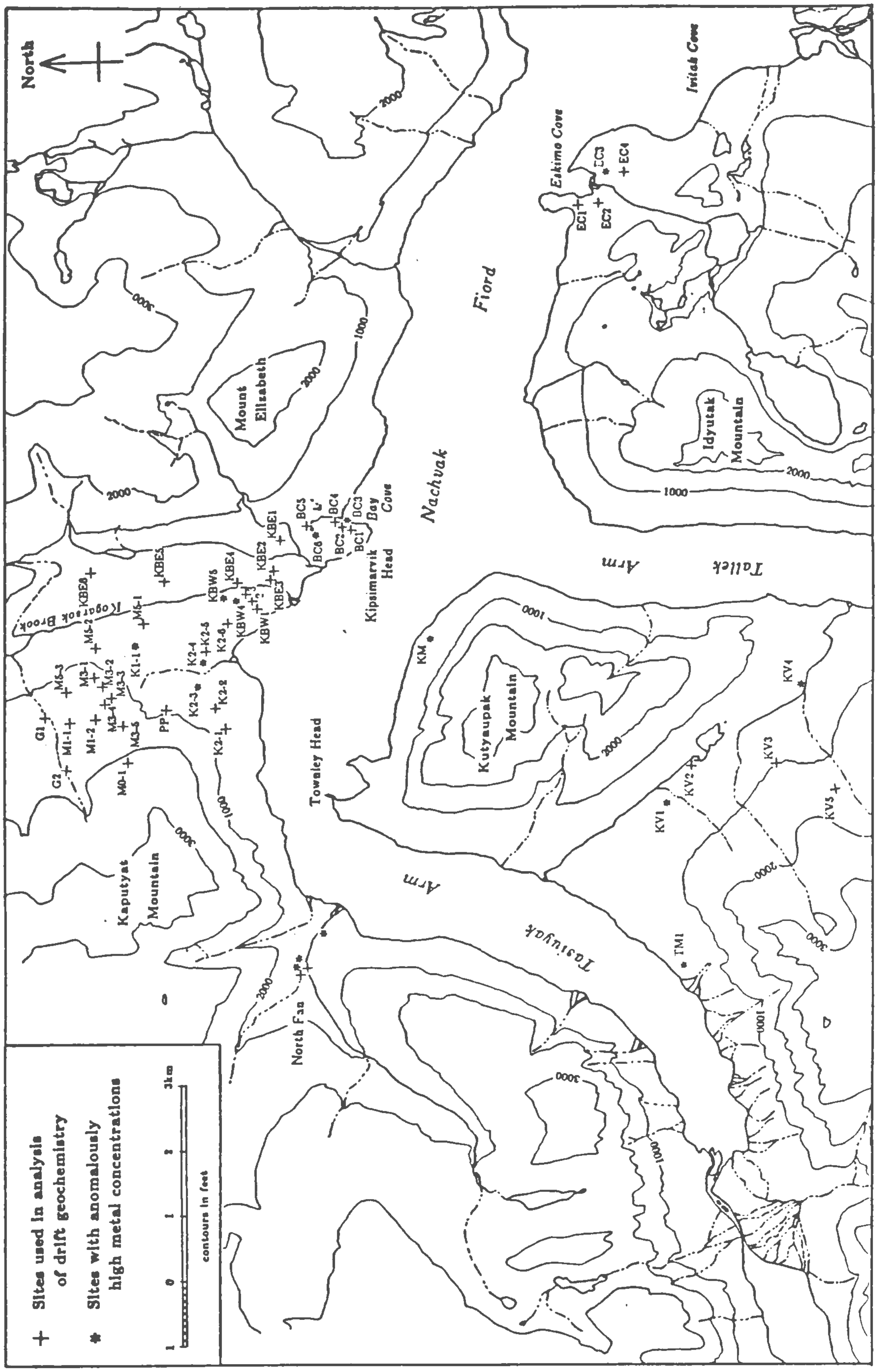

Figure 3-18: Locations of sample sites used in geochemical analysis; sites with anomalous heavy metal concentrations are shown.

compared with the threshold values used by Evans (1984; obtained directly from Dyke, 1983) and Bell (1987).

Bell calculated threshold values by taking 2.5% of the total number of observations of each metal, excluding erratically high values. Dyke's thresholds were based on the clay size fraction of Somerset Island samples, though he gives no details of how the values were decided upon. It is considered unwise to transfer threshold values between data sets, since they should be based on the background and anomalies within the working data set alone. Comparison with threshold values used by Bell in the outer fiord, as calculated from the silt and clay size fraction, shows the 1986 concentrations to be much higher; this was expected given the difference in particle-size class. Bell showed that concentrations of metals in the $< 2\mu$ fraction were almost twice those of the $< 63\mu$ fraction for the same sample sites analysed in 1984 and 1985 respectively (1987, Table 3-10). The 1986 threshold concentrations are also higher than Dyke's values.

Table 3-1: Table of Background and Threshold Values, with anomalous samples (all values are in ppm unless otherwise indicated).

Metal	Background value	Threshold value	Threshold (Bell,1987)	Threshold (Dyke,1983)	Anomalous Samples
Ag	0.29	0.602		>100	KM1 K2-3,K2-5
Co	62.46	121.02	42	>100	K2-4
Cr	111.81	186.77	85	>100	SC1 BC6,KV1
Cu	240.00	457.80	187	>100	KM1 KV1,K1-1
Fe	6.26%	9.82%	8.5%	>10%	KV1,TM1
Mn	837.90	1574.70	950	>1000	K2-4
Mo	2.70	9.45			KW5 KV1,TM1
Ni	182.60	385.60	100	>100	K2-4 NF1,NF5
Pb	4.81	12.00	25	>100	EC3 BC3,KW4
U	< 10.00	10.00	1.6	0 - 1.6	
Zn	143.93	280.97	150	>150	K2-4,NF4 NF5,KV4

3.4.3. Results

The concentrations of metals at all sample sites are given in Table A-1, Appendix A. Fifteen sites gave anomalously high concentrations of one or more metals, as listed in Table 1 and Table A-1; anomalous sites are also indicated on Figure 3-18. Using the threshold calculation method of Bell similar results would have been obtained, though there would have been a lower number of anomalies in most cases. The only anomalously high sites identified by Bell's method, but not by the method used here, were at site K1-1 (high Co) and site KV-5 (high Mo).

All of the anomalous sites occur along the fiord coast, extending throughout Kutyaupak valley and into North Fan. Three of the six sample sites on moraine K2 show high metal concentrations, as does the 'terrace moraine' (site KW-5) and the 73m terrace at the mouth of

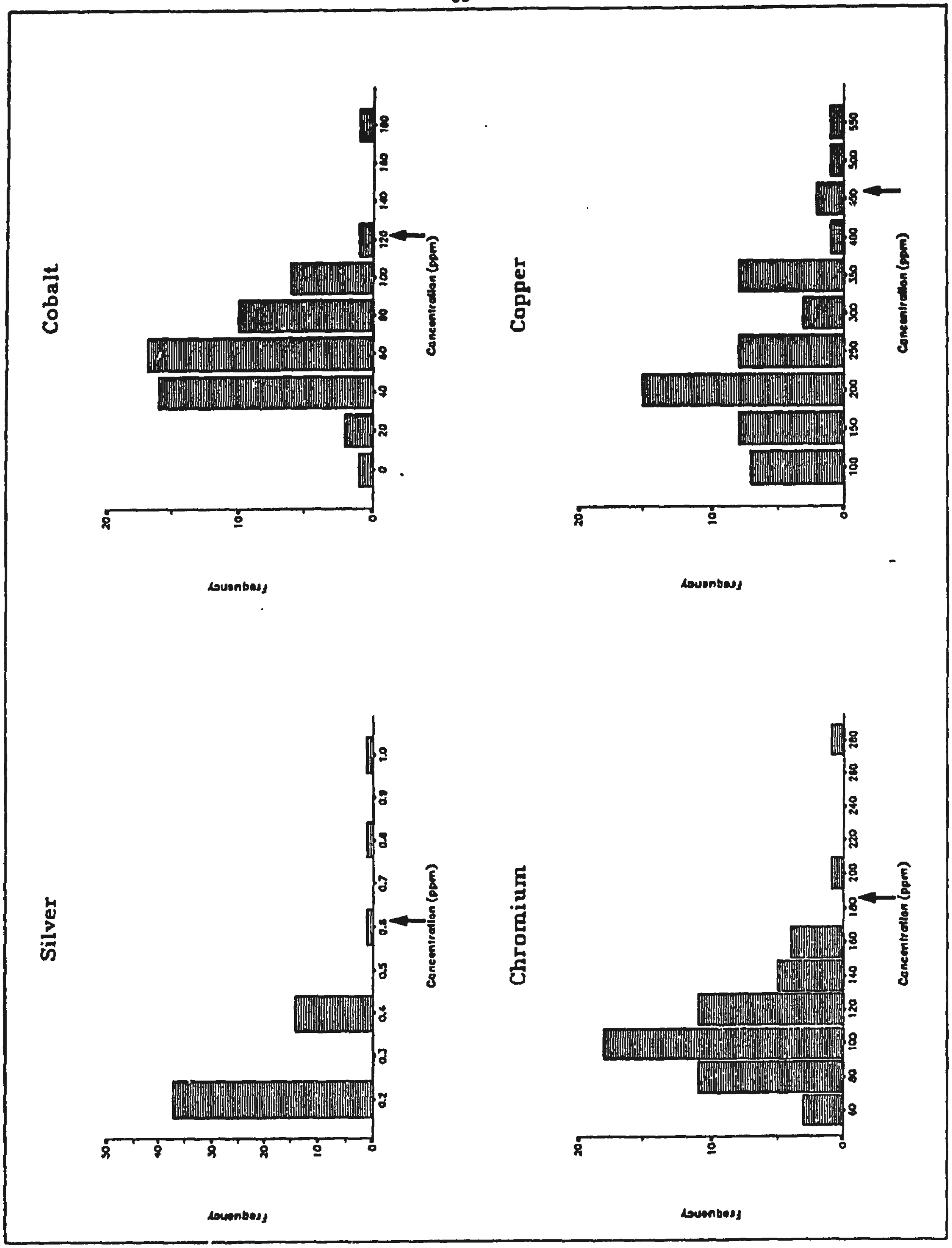

Figure 3-19: Frequency histograms of metal concentrations in inner Nachvak Fiord. Arrow denotes threshold value for anomalous concentrations.

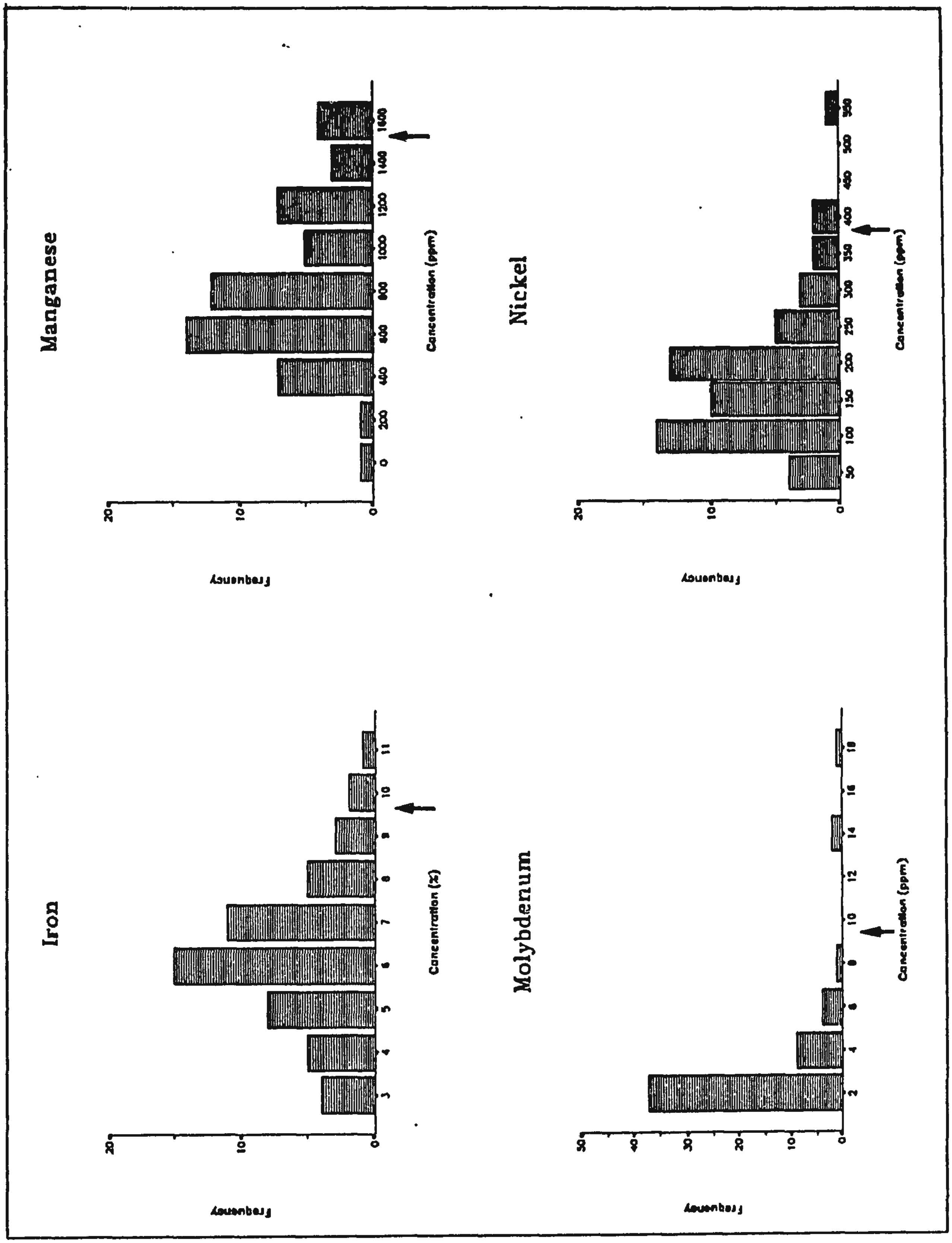

Figure 3-19: Frequency histograms of metal concentrations in inner Nachvak Fiord. Arrow denotes threshold value for anomalous concentrations.

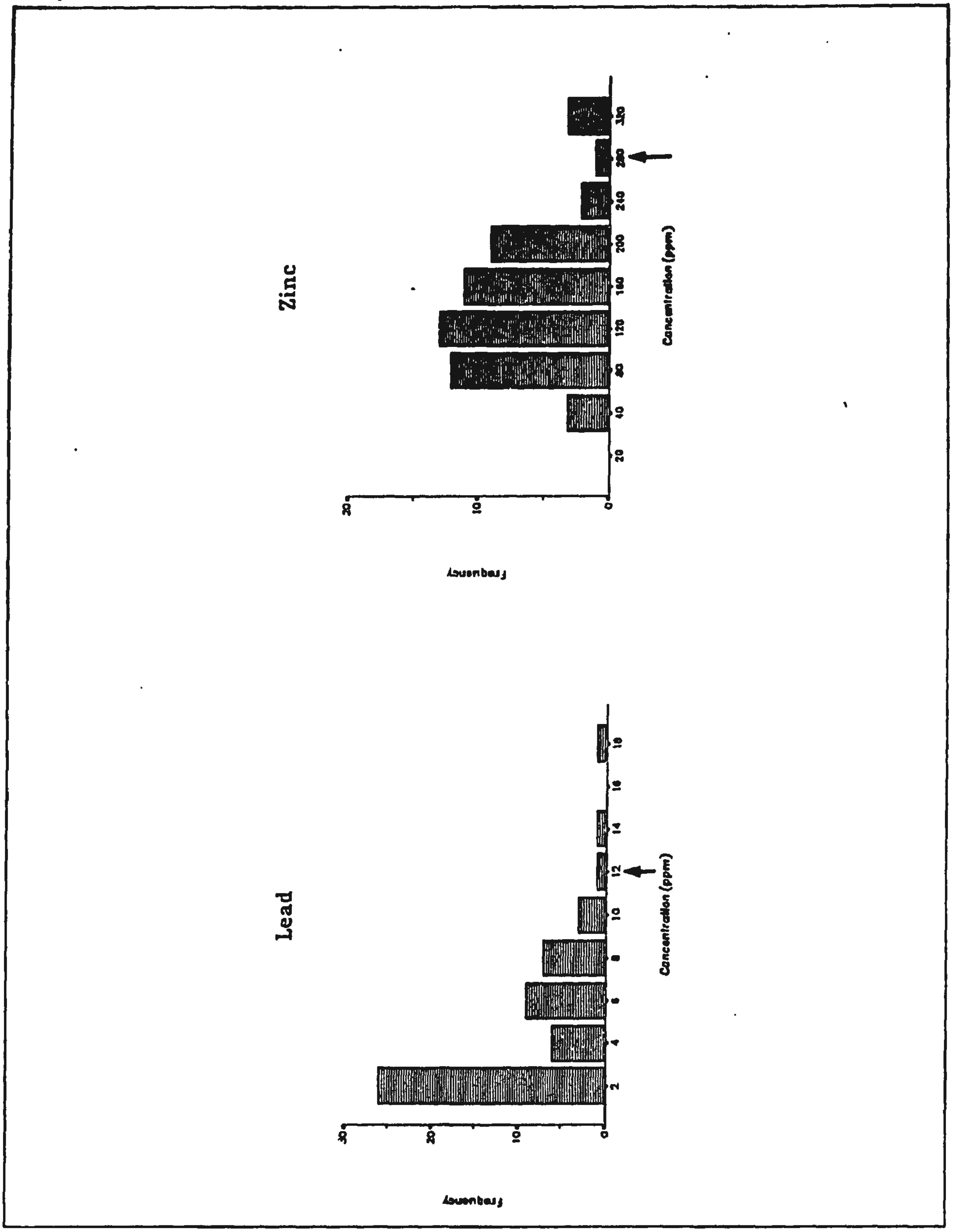

Figure 3-19: Frequency histograms of metal concentrations in inner Nachvak Fiord. Arrow denotes threshold value for anomalous concentrations.

Kogarsok Brook. The single site on moraine K1 contains anomalous concentrations of copper. Other moraine sites around Kogarsok Brook noticeably show no anomalous metal concentrations. There do not appear to be any particular metals that are abnormally high; silver and uranium have the most uniform range of values.

3.4.4. Discussion

These results have been analysed by examining the distributions of the anomalous metal concentrations, and by comparing the 1986 data with those collected down-fiord. In the inner fiord study area, little difference was expected between the lithologies of local and regional drift composition; the entire area is composed of Nachvak and Tasiuyak gneiss, and the geological area beyond Nachvak Lake is also thought to be composed of a similar granulite gneiss (Wardle, 1983). As lithology was not examined in this study, differences between the gneisses and the possible provenance of drift material travelling over similar rock types cannot be suggested; however, major differences allowing detailed reconstruction of ice-flow directions were not expected.

The background metal concentrations calculated from the entire data set appear to be fairly uniform, giving normal or slightly skewed histograms and indicating a single set of populations. Despite this, a number of anomalously high metal concentrations occur in tills along the fiord trough. High concentrations suggest an additional source of metals and thus a somewhat different supply of sediments; in a glacial environment they are usually related to drift sheets of different provenance to the background, presumably local, sediments. It might therefore be suggested that some of the materials in the fiord trough were carried into it by a regional ice-sheet from further inland. The location of anomalies mapped on Figure 3-18 shows that only sediments thought to have been influenced by regional ice contain metals in high concentration. The Kogarsok highland tills appear to be of local provenance, deposited by local ice, and thus displaying more uniform 'background' metal concentrations.

Since the 1986 data cannot be compared directly with Bell's survey of 1985, a relative comparison was attempted. The percentage composition of key metals used in the definition of clusters in the outer fiord was calculated for all the 1985 data ($< 63\mu$). Average percentages were then found for each cluster. The compositions of the clusters were compared to see if clusters could be identified using their relative concentrations only, in which case similar relative compositions might indicate clusters of similar origin in the inner fiord. The 1985 cluster averages did not, however, show any distinct patterns or groups using their relative concentrations, the percentages of each metal being almost identical in each cluster. The silt and clay size fraction could not, therefore, be easily compared with the clay size fraction.

Other attempts to compare the data obtained from the entire fiord were made:

1. The $< 2\mu$ fraction data from samples collected in 1983, 1984 and 1986 (including those from Outer Cove and Schooner Cove) were treated as a single population; background and threshold values were calculated as previously described, and anomalous values were mapped. Histograms of the metal concentrations show that background values produce normal or only slightly skewed populations, thus indicating that the sediment data belong to one population (Appendix A, Figure A-1).

Figure 3-20 shows the sediment sample sites and the anomalous metal concentrations throughout the fiord, as analysed in 1983, 1984 and 1986. Abnormally high concentrations occur in Outer and Schooner Coves, in Ivitak, McCornick and Kutyaupak valleys, on the Kogarsok highlands, in the Adams Lake and Tinutyarvik Valleys and on the northern shore of Delabarre Bay. The latter outer fiord examples have few sample sites and thus might be less representative.

These results show no clear patterns of distribution. They do not correspond with the 1986 high concentration data, nor with proposed patterns of drift sheet provenance as inferred from moraine and striae information. Anomalous concentrations occur within the fiord trough and in upland areas, almost irregularly. It is possible that they have been influenced by post-depositional processes, and thus that they give metal concentrations unrelated to their original metal content. This is suggested on the basis of these concentrations being derived from the clay size fraction of the sediment; the clay fraction is very active, having a high capacity for ion exchange with groundwater (Shilts, 1971; Rose, Hawkes and Webb, 1979). It is thus most likely to be altered in the process of soil formation, or by groundwater exchange, which may lead to ion concentration or depletion. Since there is no pattern displayed by the anomalous samples seen in this total population, it is suggested that they reflect post-depositional changes in composition.

2. A comparison of the concentrations of certain metals found at selected sites throughout the fiord was made to see if there were any visible patterns of concentration increase or decrease. Sites along the edge of the fiord were chosen where possible, in a transect from west to east. If

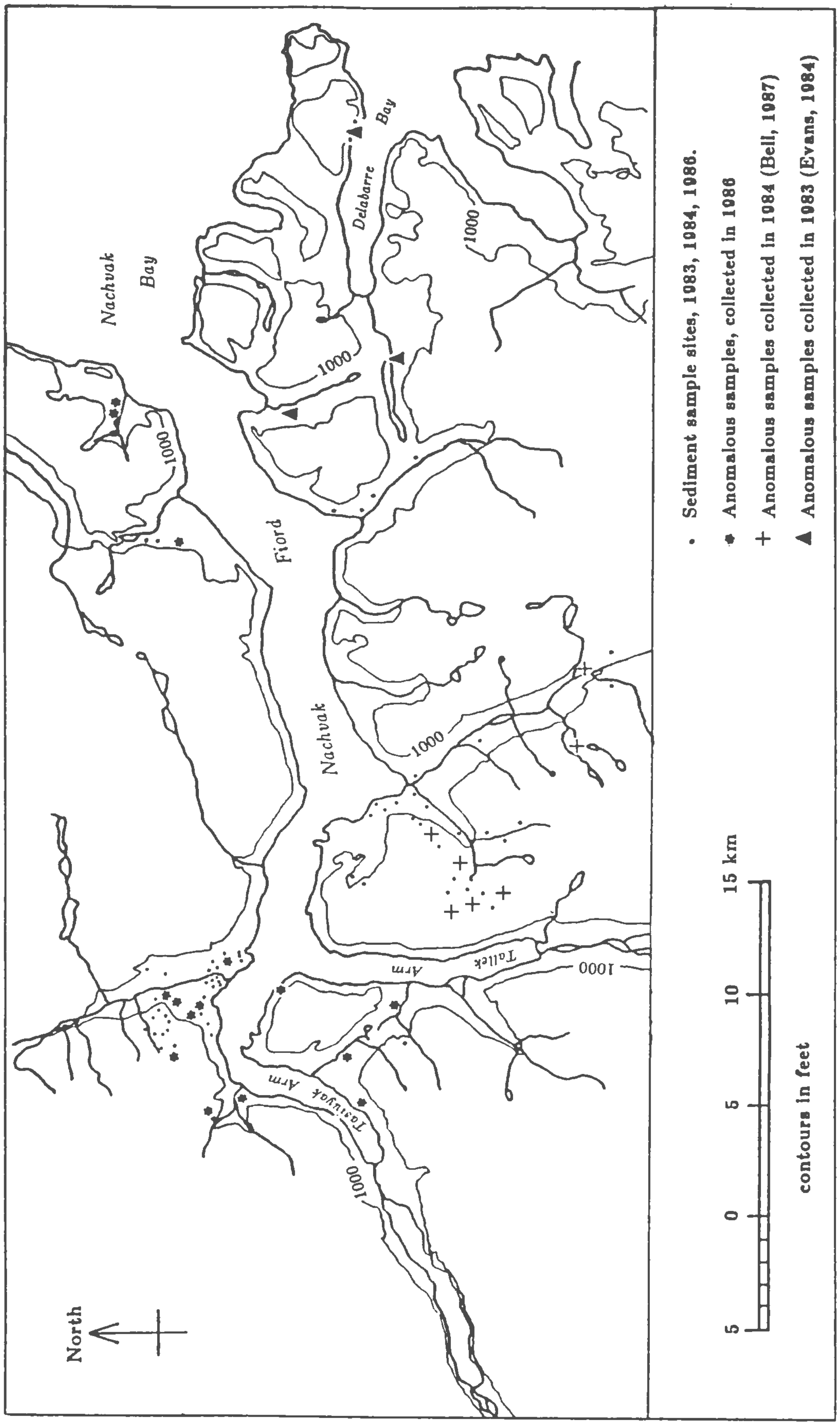

Figure 3-20: Sites sampled for geochemical analysis in 1983, 1984 and 1986 throughout Nachvak Fiord; anomalous metal concentrations, found by considering the data to be one population, are shown.

regional ice flow did account for some of the concentrations, a dilution or decrease in relative concentrations of some metals might be expected downfiord. Visual inspection of the concentrations showed no distinct patterns; Figure A-2 in Appendix A shows the relative concentrations of metals common to each study in histogram form, the baseline being a west-east transect. There do not appear to be any patterns in any of the metals used. This is probably a reflection of the bedrock geology of the area, which alters greatly from the inner to the outer fiord; it is not taken to indicate that regional ice did not once occupy the fiord.

3.5. Weathering Observations

Dating of events in northern Labrador is hampered by a lack of organic materials for which absolute radiocarbon ages can be obtained. Relative techniques such as lichenometry, weathering studies and pedogenesis have been used instead. Observations of weathering characteristics were made on the Kogarsok highland moraines, with the intent of establishing a quantified estimate of their relative ages. Pedological analyses are discussed in the next section.

Weathering zones were identified in northern Labrador during the late 1950s and early 1960s by Ives, Loken, Andrews and others. Similar zones were recognised and dated on Baffin Island (eg. Pheasant and Andrews, 1973; section 2.3), and relative dating methods were devised by Boyer and Pheasant (1974). It is difficult to quantify the degree of weathering on a rock surface, and it is particularly difficult to compare surfaces which are at different elevations and have different bedrock material. The methods of Boyer and Pheasant involved counting and measuring certain types of features, and some qualitative observations. Through statistical analysis they found five characteristics which were most useful in identifying weathering zones I, II and III; the older boundary (I/II) was more difficult to identify than the younger boundary (II/III).

A combination of the criteria used in Maktak and Narpaing Fiords was used in this study. Observations were carried out only on the highland west of Kogarsok Brook, an area which appears to display several phases of glaciation. Potential division into the weathering zones identified by Ives (1978) and others would greatly facilitate correlation of the moraines in this area with dated features elsewhere in northern Labrador.

Table 3-2: Analyses and results of weathering studies (*after* Boyer and Pheasant, 1974).

Weathering Criteria	585m aht	568m aht	381m aht	236m aht
1. Occurrence of large pits (>25cm) in bedrock boulders	Abundant	Few; none very large.	Infrequent	Infrequent
2. Percent of surficial boulders, cobbles, pebbles with small pits (<3mm)	∼100%	100%	∼100%	∼80%
3. Percent of a boulder, cobble or pebble surface covered with small pits	∼70%	∼70%	∼50%	50%
4. Soil development	None, except in nivation hollows	Shallow; in bog areas only	None	Poor
5. Percent of oxidised rocks & cobbles that disintegrate with light blow from hammer	∼85%	65 - 70%	∼85%	∼85%
6. Edge modification of *in situ* split rocks	Considerable on all rocks	Considerable, though few split rocks	Great modification; more than higher rocks	Some; less obvious
7. Occurrence of tors	Several	Only above this elevation	None	None
8. Felsenmeer development	Good; abundant	Good; abundant	None	None
9. Occurrence of macroweathering	Present on all rocks	Less apparent than on higher rocks	Obvious on large clasts, along inclusions & fractures	Obvious on large clasts but inclusions more subdued
10. Occurrence of microweathering	Present on all rocks	Very obvious	Present on most rocks	Present on all rocks

Table 3-2 shows the criteria used to describe weathering, and the results found at four sites on the highland. Sites were chosen at locations where different degrees of weathering were apparent. A thick till-like cover and standing water made observations in the area between the terraces below crest M0 and moraine M3 unrealistic. Sites 1 and 2 were well above the M0 crest, on very well weathered terraces, at 585m and 568m respectively. At site 3, approximately 381m aht and close to the M3 crest, bedrock modification appeared to be much greater than at lower elevations, though it was obviously less than at the first two sites. The fourth site, at 236m, again showed less weathering. Soil, vegetation and till cover prevented observations of bedrock weathering on or around moraine K2; below it, weathering appeared to be highly dependant on the type of bedrock and boulders present: Tasiuyak gneisses showed a greater severity of weathering than did Nachvak gneisses.

The data in Table 3-2 provide little real information that could be analysed statistically; as only four sites were described, any character analysis programme is unlikely to be significant. They are therefore not compared with the data of Boyer and Pheasant (1974). There is a pattern of increased weathering at higher elevations, with tors visible only on slopes above 585m, felsenmeer development being complete at that elevation but intermittent below. Soils were poorly developed at all sites, perhaps because of the considerable elevation and harsh climatic conditions in this area. Microweathering was fairly uniform at all sites; macroweathering was less common at the lower two sites, but similar between sites 1 and 2, and sites 3 and 4. The occurrence and frequency of pitting on rock surfaces also varied considerably between the two upper and the two lower sites. The test on rock strength was found to be highly subjective, dependent on the strength of each blow and the observation of disintegration; although all tests were performed by the author, their reliability is questioned. Results of an angularity study are provided although they show no significant patterns; greater angularity was expected at lower sites, though analysis of frequency histograms drawn for each roundness class showed that this did not occur.

3.6. Pedological Analysis

3.6.1. Introduction

Pedogenesis is the study of soil development. Soil studies show that five factors influence the formation of a soil: nature of bedrock or parent material, climate, vegetation, topographic location and time (Jenny, 1941). If all other factors can be assumed to remain constant in a given area, time is the only variable. Thus the depth of weathered horizons on a particular landform may be taken as an indication of its age, or the time that it first became exposed to subaerial weathering (Birkeland, 1974, 1978). Soil depths of features within a limited area may be compared and a relative chronology applied to them, deeper soils indicating greater age.

This method has been used on Baffin Island by Birkeland (1978) and L.J. Evans and Cameron (1979). McCoy (1983) used soil development in conjunction with lichenometry to study Holocene glacier fluctuations in the Torngat Mountains; Clark (1984) developed a chronology for the Kangalaksiorvik Fiord area of northern Labrador using soils depths. Pedology also formed the basis of chronologies proposed by Evans (1984) and Evans and Rogerson (1986) for glacial events in the Selamiut Range of the Torngat Mountains, and was used by Bell in outer Nachvak Fiord.

Although it is assumed that the physical parameters influencing soil development are held constant in a limited area, surficial drift deposits that act as parent materials for developing soils may be very varied. Altitudinal variations may also produce major differences in moisture supply and vegetative cover. Such factors must be considered when locating soil pits, and when the soil depths are compared for the production of a relative chronology. Ideally, only soils forming on similar landforms should be compared in relative dating.

3.6.2. Methods

Soil pits were dug on a variety of landforms in order to get an unbiased opinion of relative development rates. These included moraines, marine and fluvial terraces, and a kame terrace. Sites were chosen in well-drained, stable areas where soils were not obviously exposed to erosion or gelifluction; they were always on the crests of moraines, and toward the centre of terraces. Pits were generally dug until a marked colour change was observed, exceptions to this being in sites where boulders prevented digging, or where no colour change occurred before about 1m depth.

The intensity and depth of oxidation are recognised as the most important criteria for geomorphological studies relating to the time of soil development (Birkeland, 1974); measurements of the depths of the oxidized cambic B and Cox horizons are therefore taken as a relative measurement of the time taken since soil development began. Ideally, digging would continue into the unoxidised subsurface Cn horizon, which excludes bedrock, though this was not always possible because of the nature of the soil-forming parent material (abundant boulders, soils forming on top of tills with no solid bedrock, buried soils). Measurements given for the depth of Cox horizons are therefore minimum depths in most cases, and solum depth[2], to the base of the B horizon, is used as an indication of soil development in this study. These measurements are comparable with those of Clark (1984) and Evans (1984).

No chemical analyses were carried out, as Birkeland (1978) and L.J. Evans and Cameron (1979) found that properties such as pH, content of organic matter, clay mineralogy and other mineral composition values did not vary consistently with age. Depth and colour were the main parameters used by Clark (1984) and Evans (1984).

Soil colour is expected to show degree of oxidation; colour is not easily quantified, though Buntley and Westin (1965) calculated a colour development equivalent (CDE) using the numeric notation of the Munsell Soil Colour Chart. CDE values are expected to increase with the preconceived age of a soil, and with soil depth. Clark (1984) adopted this method and found that CDE values from his cambic B horizons did increase with the presumed age of landforms. Evans (1984), however, found that CDEs showed no regular pattern with either depth or expected age. In this study, the colour of wetted soil horizons was found using a Munsell colour chart. CDE values were calculated by multiplying the soil's hue by its chroma, where a scale from 1 to 7 is applied to hue values from 5Y to 10R in ascending order. Since the B horizon is considered to be most critical in the assessment of oxidation, CDEs for that horizon only are provided in the tables of results.

[2]'Solum' is defined as the true soil, including the weathered A and B horizons only. The C horizon is regarded as the partially-weathered parent material or subsoil (Whittow, 1984).

3.6.3. Results and Discussion

Soil pit locations and their solum depths are shown on Figure 3-21. Table B-2 in Appendix B provides details of the depths, colours and site characteristics of each pit. Table 3-3 lists the site characteristics used in relative dating, giving depth *to* the Cox horizon and CDEs of the B horizon, which is thought to be the most important indicator of oxidation (Birkeland, 1974).

Table 3-3: Major site characteristics of soil pit locations, inner Nachvak Fiord.

Site	Alti-tude (m)	Depth to Cox (cm)	Total depth (cm)	CDE of B horizon
EC1	27.6	7	61	3
EC2	46.5	27	76	3
EC3	33.0	6	93	3
EC4	49.4	21	92	3
BC1	38.4	59	94	4
BC2	32.0	-	92	3
BC3	23.8	62	100	3
BC5	18.7	7	52	3
BC6	19.4	46	71	3
KE1	35.5	42	67	3
KE2	18	12	59	3
KE3	34	32	62	3
KE4	43.9	32	63	3
KE5	131	24	61	3
KE6	237	28	51	
KW1	38.9	23	56	3
KW2	43	19	57	3
KW3	50	35	63	3
KW4	73	35	63	3
KW5	76	23	69	3
K2-1	181	27	61	3
K2-2	156	26	90	3
K2-3	124	17	60	3
K2-4	122	44	69	3
K2-5	124	26	79	3

Site	Altitude (m)	Depth to Cox (cm)	Total depth (cm)	CDE of B horizon
K2-6	124	47	58	4
M1-1	405	38	67	2
M1-2	398	27	62	2
M3-1	383	46	87	3
M3-2	387	16	78	3
M3-3	370	24	63	3
M3-4	379	18	79	3
M3-5	371	44	57	3
PP	269	44	54	4
M5-1	148	26	52	3
M5-2	228	50	79	4
M5-3	380	41	62	2
K1-1	211	37	66	3
TM1	69	18	64	3
KV1	219	23	71	3
KV2	217	35	94	3
KV3	305	41	67	3
KV5	363	37	66	3

Results of solum depth are discussed in two categories because of the very different nature of landforms on which pits were dug. Table 3-4 compares soil depths at moraine sites only, showing the mean soil depth on each moraine and the preconceived relative ages of the moraines. All moraine crests are considered comparable as they are dry, poorly-vegetated, have a substrate of till and are likely to be windswept. While their rates of soil development were expected to be similar, they were thought to be very different from the rates of the lower terraces on which other pits were located. Most terrace sites are flat and fairly well vegetated, with subsoils varying from coarse gravels to very fine sands and silts.

The mean solum depths of moraines found on the highland west of Kogarsok Brook are very similar, ranging from 30-44cm (this excludes moraine M0, which supported no soil at all). This suggests that the moraines formed within a relatively short period of time; however, the fact that a variable number of soil pits was dug on each moraine (due to length of moraines, presence of

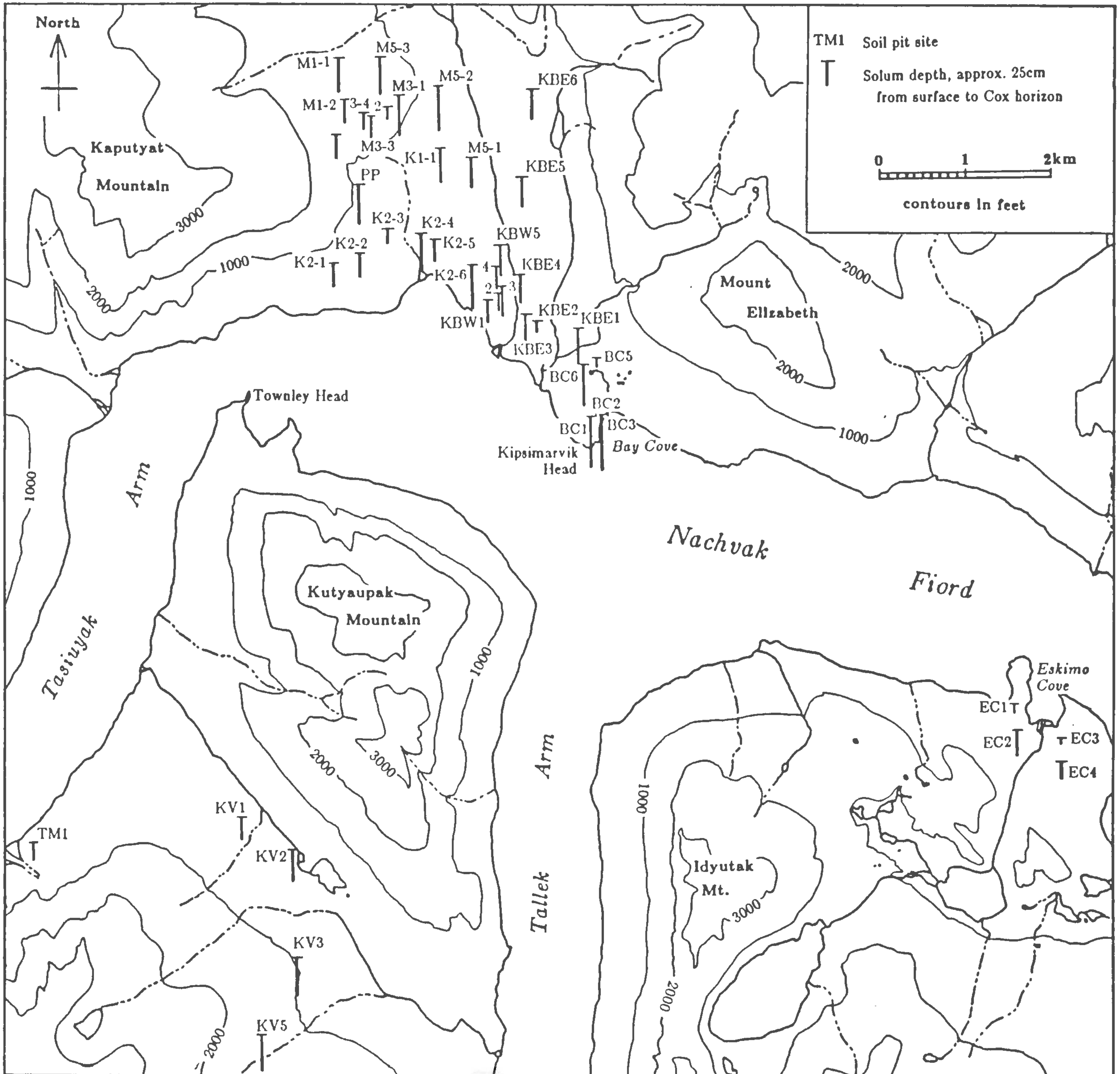

Figure 3-21: Location of soil pit sites in inner Nachvak Fiord, showing depth of solum.

soil cover, and time limitations) makes the mean values difficult to compare. In addition, standard deviations about the means are considerable in some cases, indicating a wide variety of solum depths on those moraines. Given this background, comparisons and correlations between moraines must be made very carefully. Moraine K2 is definitely the youngest, with a mean of 30cm to the Cox horizon and a fairly low standard deviation. The data from site KW-5 are included in these calculations, as the depth and colours of the solum are similar to those of the rest of moraine K2 and morphological evidence suggests that the moraine continues into Kogarsok Brook valley. The depths of pits K2-4 and K2-6 are considerably greater than those of other pits on this moraine (44cm and 46cm respectively). If they were excluded from the calculation of the mean, solum depth range would be 17-27cm, with a mean of 23.8cm (s.d. = 4.09). This would suggest that K2 is considerably younger than its counterparts.

Table 3-4: Mean solum depths on inner Nachvak Fiord moraines.

Moraine	Mean alt. (m)	Mean depth to Cox	s.d.	Range	Number of sites	Age
TM1	69.0	18.0			1	young
K2	129.6	30.0	11.14	17-47	7	
M5	221.8	35.25	12.42	24-50	4	
K1	211.0	37.0			1	
PP	269.0	44.0			1	
M3	378.0	29.6	14.38	16-46	5	
M1	401.5	32.5	7.78	27-38	2	old

The single pit on moraine K1 has a solum depth anomalous with its age as interpreted from morphological data. It is believed to be younger than moraines M1 and M3, though it may be older than M5.

Pits from moraines M1, M3 and M5 indicate a confused relative chronology. While their mean solum depths suggest that M5 is older than both M1 and M3 (mean depths of 35.25cm, 32.5cm and 32.0cm respectively), wide standard deviations indicate that the means alone are not reliable. Morphological evidence shows that M5 is in fact younger than M3, and probably younger than M1. Moraine M5 is taken to include site KE-5 on the eastern side of Kogarsok Brook, approximately opposite site M5-1; both of these pits have similar solum depths (24cm and 26cm respectively). Moraines M1 and M3 may have been formed within a short period of time, particularly if the ice-contact area immediately north of the highland summit does indicate coalescing local and regional ice. These moraines are therefore considered likely to be of similar age, greater than that of M5.

Moraine segment PP is tentatively associated with M3, on the basis of solum depth (54cm to the Cox horizon; site M3-5 has a solum depth of 57cm) and its location and orientation. However, this requires that M3 was deposited by a regional ice sheet, a fact not clearly shown by ice-flow indicators.

The Tasiuyak Arm moraine without doubt has the most shallow soil profile. This agrees with its geographic location as the most westerly moraine in the fiord, and thus with the assumption that it is younger than all other moraines formed by the regional ice-sheet. However, only one soil pit was dug; on the basis of soil profiles on other moraines, which yield very variable depths in some cases (eg. moraine M3), this single pit is not necessarily reliable.

Figure 3-22 shows each soil pit site on every moraine, with elevation above high tide plotted against depth of solum. Up to approximately 250m asl there is a general pattern of depth increasing with altitude, as expected given that older moraines occur at high elevations and have been subject to longer periods of weathering. Moraine K2 is the exception to this, with pits K2-4 and K2-6 displaying very deep solum depths at less than 150m altitude. Above approximately 250m aht, however, solum depths range between 16 and 46cm. The wide scatter makes relative age difficult to determine, and suggests that above a certain altitude, weathering and solum development is unpredictable and of little use as an indicator of age. These observations are similar to those made by Evans (1984), who also found that high altitude sites displayed widely differing solum depths.

As a result, these depths are not considered to be representative of age. Single moraines that were sampled several times show that rates of solum development are not equal in all places along a crest. Factors other than time are shown to be influential in soil development by the wide standard deviations about the means of moraines such as K2, M3 and M5. Single soil pits are thus considered to be poor indicators of age; the work of L.J. Evans and Cameron (1979), who based an absolute chronology spanning 107,000 years on development in four pits, might also be

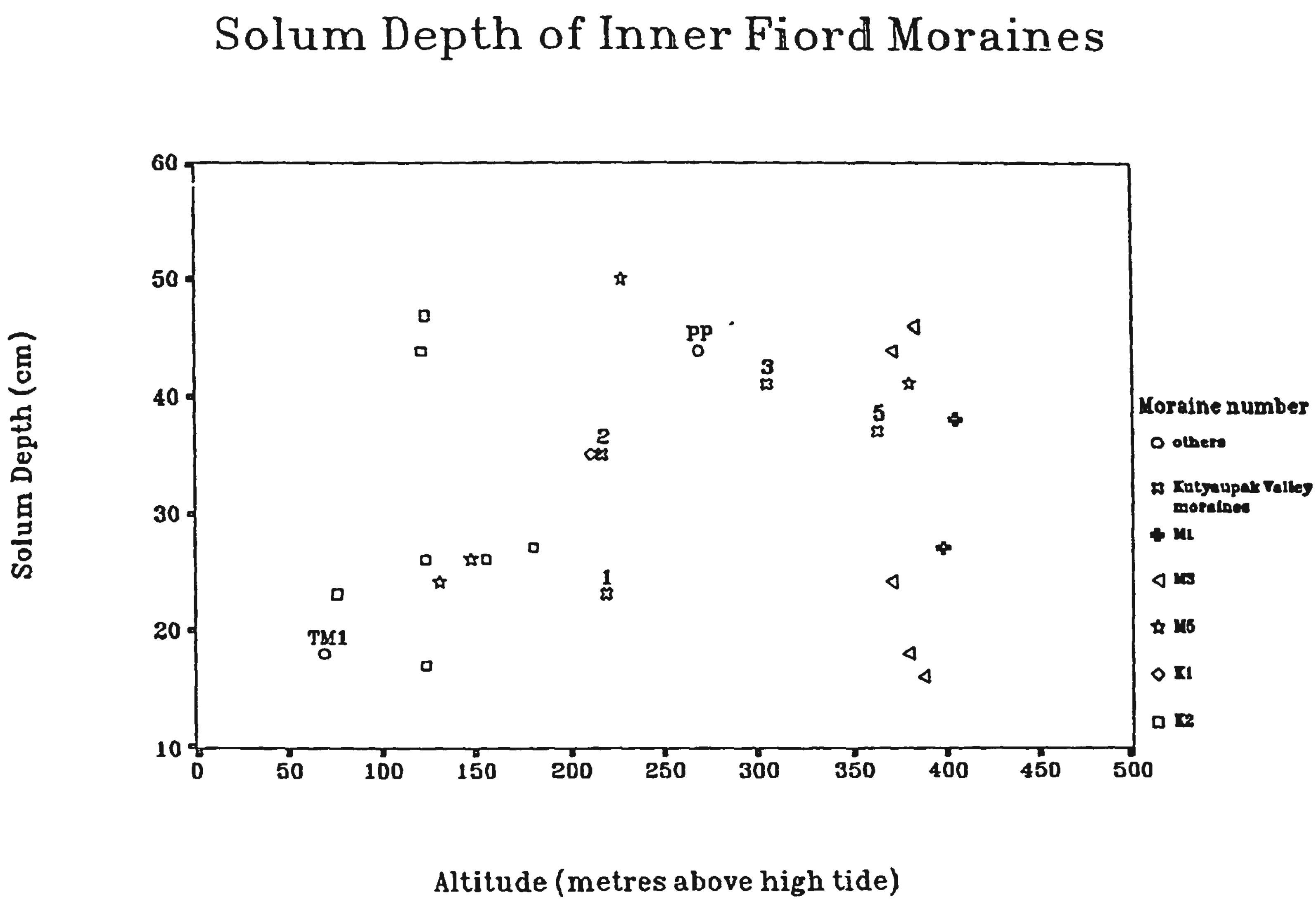

Figure 3-22: Scatterplot showing elevation of soil pits on each moraine against solum depth.

considered unreliable. Clark (1988) used only 15 soil profiles, between Eclipse Channel and Saglek Fiord, to describe a number of moraines which comprise the Saglek Alloformation. Many of these were at high elevations (245m and 396m in Nachvak Fiord), thus factors other than time may have influenced their rate of solum development.

Mean colour development equivalents for each of the moraines are given in Table 3-5. CDE is expected to increase with the age of a soil and with soil depth. As can be seen from Table 3-4, the pattern of CDE's is very irregular, moraine K2 having the highest value while it is the youngest of the highland moraines. M3 is more oxidised than M5, though M1 is less oxidised than them both. Reasons for this irregularity are unknown. Certainly the calculation cannot be used as an indicator of relative age. Further calculations showed that CDE values did not regularly increase with depth in all pits.

Table 3-5: Mean CDE values for inner Nachvak Fiord moraines.

Moraine	Mean CDE	s.d.	Range	Number of sites	Age
TM1	9.0			1	young
K2	19.29	5.44	9-24	7	
M5	9.75	4.35	6-16	4	
K1	6.0			1	
PP	16.0				
M3	14.17	3.71	9-18	6	
M1	4.0				old

Site KE-6 was located on top of a kame terrace at ~237m aht. It is on the highest terrace in a series, and has a crest of gravel and large boulders which suggest till deposition and possibly an association with moraine M5. The solum has a depth of 28cm, within the range of cambic B horizon depths at other M5 sites. The kame therefore appears to have been formed at approximately the same time as the moraines on the western highland. No colour identifications were made at this site.

Moraines in Kutyaupak valley show a regular sequence of soil depths. The innermost moraine (KV3) has the deepest solum, at 41cm. To the north-west, site KV2 has a cambic B horizon 35cm deep, while that of site KV1 is relatively shallow at 23cm. Solum depths decrease to the north-west indicating that moraines become younger in that direction. This reflects the hairpin-shaped pattern of moraines and the logical expectation that ice retreated out of the valley in a gradual sequence over time. Pit KV5, located within the cirque valley to the south of Kutyaupak valley, has a B horizon depth of 37cm. This suggests that it is of intermediate age between KV2 and KV3. It was probably formed by local ice during a minor glacial advance, or perhaps during retreat from the main valley where local and regional ice coalesced. The moraine is thought to be as young as or younger than KV2, on morphological evidence only; at 363m asl it appears to be above the altitude where solum depth reflects age, making the depth of solum development meaningless as an age parameter.

CDE values in Kutyaupak valley may be taken to indicate that all the moraines are of similar age; they each have an oxidation measure of 3. However, the similarity in soil colouring may also reflect the small areal extent of this valley and the uniformity of till material making up the soil substrate.

Pits dug on fluvial and marine terraces show soil development since subaerial weathering began; they are therefore an indication of the relative age of raised beaches and river terraces. These sites were originally chosen in order to establish a regional rate of soil development for all surfaces. They also served to confirm the origin of certain benches. Table 3-6 shows the expected

Table 3-6: Mean solum depths on inner Nachvak Fiord terraces.

Site	Alt. (m)	Site	Alt. (m)	Site	Alt. (m)	Depth to Cox (cm)	Individual means	Age
		K-2	18.0	BC-5	18.7	9.5	12+7	young
				BC-6	19.4	46.0		
				BC-3	23.8	62.0		
		KE-3	34.0	BC-2	32.0	32.0	32+?	
KW-1	38.9	KE-1	35.5			32.5	23+42	
KW-2	~43	KE-4	43.9	BC-1	38.4	36.7	19+32+59	
KW-3	~50					35.0		
KW-4	~73					35.0		old

ages of the terraces in which pits were dug, and the depth to their Cox horizon. Benches which are of similar elevation and which are likely to have formed during a single sea level stand are correlated. In these cases, depths are given as mean values.

It is apparent that depth to the Cox horizon does not correspond with expected age. Although the lowest pits are most shallow, the pattern becomes very erratic at higher altitudes even though elevations are far below those of the moraine soil pit sites. This can be partially explained by the nature of the substrate forming particular terraces, and by the soil-forming processes influencing them. Although pits were dug in the centre of terraces as far as possible, flat surfaces are prone to changes in drainage and sediment input within short distances. Poor drainage, rapid through-flow, overflow or aeration are likely to have contributed to the differences in development. For example, three sequential benches on the north-east face of Kipsimarvik Head provided very deep pits (sites BC-1, BC-2, BC-3), each displaying evidence of water saturation and gleying. It was impossible to identify normal soil horizons, as the pits contained fine sands and silts in alternating yellowish-brown and dark-brown layers (Figure 3-23). Similar results were found at site BC-6, which was characterised by banded muds and silts in gleyed and oxidised layers. Soil depths are not regarded as representative of relative age.

The soil pit at site KE-1 was distinctive because it included a buried soil. At 31cm depth a dark orange-brown soil was encountered, below a coarse grit and sand B-C horizon. This bench is located north of Kipsimarvik Head, below a steep vegetated cliff slope. It is open to debris falling from above, an event that probably caused burial of an earlier soil and provided new substrate for more recent soil development. The depth of the weathered horizons here is not representative of the age of this bench, and the bench itself must have been modified by processes occurring after its formation.

Other soil pits were dug in the coarser material of terraces on either side of the Kogarsok Brook valley. The highest benches have maximum depths, though at 50m and 73m aht pits KW-3 and KW-4 have identical B horizon development (35cm); their difference in altitude suggests that they are of very different ages. Again, different soil substrates and thus drainage characteristics are thought to have caused these variations. Site KW-3 shows few large clasts but an extremely gritty subsoil. Frost action has disrupted the latter terrace, and may have influenced soil development at the site of KW-3 although it was located in an area with little indication of disturbance.

Other pits show no patterns in their rates of soil development. Correlated terraces have soils of different depths, out of sequence with their expected age, despite their similar substrates and vegetation.

Figure 3-23: Soil profile at site BC-2, showing irregular oxidation and gleization.

Colour development equivalents for the B horizons of terrace pits are very varied, as seen in Table 3-7. There appears to be no pattern of increase with age, and the highest, oldest terrace (site KW-4) has the lowest CDE value. Even within the Kipsimarvik Head benches there is no pattern, suggesting that degree of oxidation in these soils cannot be used as an indication of age.

Sites EC-1 to EC-4 were dug in terraces on either side of Eskimo Cove at the eastern end of the study area. The lower benches, at 27.6m and 33m aht, have very similar soil depths. They are likely to have been formed at the same time, or within a short period of time. The western bench shows effects of frost heaving and poor drainage in its central area; the eastern bench is undisturbed, being extremely sandy with no coarse particles.

Table 3-7: CDE values for inner Nachvak Fiord terraces.

Terrace	CDE	Terrace	CDE	Terrace	CDE	Age
		KE-2	6	BC-5	6	young
				BC-6	12	
				BC-3	6	
		KE-3	12	BC-2	3-12	
KW-1	6	KE-1	12			
KW-2	6	KE-4	6	BC-1	8	
KW-3	6					
KW-4	3					old

Bench EC-4 is at an elevation of 49.4m aht and has a soil profile extending 49cm to the Cox horizon. As it is higher, it is thought to be older than the 46.5m bench which shows considerably less soil development (27cm to base of B horizon). The large differences in these soil depths suggests that there was a long time period between their formation. This seems unlikely given their similarity in elevation, unless the western bench was freshly formed by fluvial deposits after the relative fall of sea level. Differences are more realistically explained by the very different characteristics of eastern and western benches: sites EC-3 and EC-4 show very sandy substrates with little coarse material and no boulders, while sites EC-1 and EC-2 have many rocks and boulders and relatively little fine-grained material. Colour development equivalents are equal on all benches.

The Eskimo Cove terraces appear to have a rate of soil development not comparable to the rates on benches in the Kogarsok Brook area, and with those of the moraines. Eskimo Cove is likely to have become ice-free before other terrace sites to the west of it, and the higher benches are probably older than all but the highest terraces within the Kogarsok valley system. They do not, however, show a greater degree of soil development. Soil depths on the lower benches suggest that they were formed relatively recently, although it is probable that they are older than, for example, the low ridges and the kettled ground area at the mouth of Kogarsok Brook.

3.6.4. An Absolute Chronology

Soil depths can provide an absolute dating method if the rate of soil development over time is known. In eastern Canada, rates have been decided upon by independent dating of landforms either through radiocarbon dating (eg. Clark, 1984; Kangalaksiorvik Fiord) or correlation with other dated features (eg. L.J. Evans and Cameron, 1979; Baffin Island), and by modifying a rate used in a similar location (eg. Evans, 1984; Bell, 1987; Nachvak Fiord). Consideration of environmental and climatic conditions changing over time has led to non-linear rates of development: for example, in Clark (1984), more recent soil development is considered to have been faster than that taking place 10 ka ago. Evans and Rogerson (1986) did not expect sediments to be greater than 10,000 years old, thus they used a linear rate. The accuracy of dating is dependent on knowing the *rate* of soil development, and also on time being the only variable factor in the soil formation process. Realistic dating must therefore be carried out using soils from surfaces similar in their location, altitude, vegetative cover and parent material. In this study, analysis of soil depth alone suggests that these other factors are not equal on all of the moraines (particularly above a certain elevation), and indicates that an absolute chronology cannot be firmly established. However, in order to obtain some indication of age, and to allow tentative correlations with other Nachvak Fiord studies, approximate rates of development will be applied to these depths.

L.J. Evans and Cameron (1979) calculated a rate of 1cm ka^{-1} for soils in Baffin Island, which were expected to develop slowly because of harsh environmental conditions. Clark (1984) based his rate of 1.25cm ka^{-1} on two radiocarbon dates, and used pedogenesis in part of his chronology for Kangalaksiorvik Fiord. Bell (1987) adopted Clark's rate for a chronology using solum depths at sites in outer Nachvak Fiord. Evans (1984) used a rate of 1.5cm ka^{-1} for soils in central Nachvak Fiord; this was 0.25cm ka^{-1} faster than the Kangalaksiorvik Fiord rate as his depths included the Cox horizon (Clark measured to the base of the B horizon). There is some doubt over the measured depths of soils used by L.J. Evans and Cameron (Clark, 1987; Rogerson and Evans, 1987), and the results of this study suggest that age of a single moraine cannot be determined from the depth of one soil pit alone. However, the rates used by Evans and Clark appeared to give realistic results. Soil development rates in Nachvak Fiord are expected to be much faster than those of Baffin Island.

The use of soil development rates in Nachvak Fiord formed the basis of a three-phase chronology proposed by Evans (1984), and Evans and Rogerson (1986). Ages of related landforms were estimated according to the mean of their soil depths; thus the Ivitak phase is considered to have occurred more than 40 ka BP, the Nachvak phase 17-23 ka BP and the Superguksoak I approximately 5-12 ka BP. Evans (1984), and Evans and Rogerson (1986), made direct comparisons with Clark's work by excluding the Cox from their measurements and recalculating the mean ages according to a rate of 1.0cm ka^{-1}. Bell's chronology utilised more than soil dates alone, but the soil-based chronology corresponded well with other absolute dates and with morphostratigraphic observations. A fourth phase was added to Evans' glacial sequence: the Adams Lake phase, occurring 29-50 ka BP (Bell, 1987).

As soil depths on moraines in inner Nachvak Fiord show at least two rates of development (in Kutyaupak valley and on the Kogarsok highland), the rates suggested by both Evans and Clark are used to tentatively outline the ages of these moraines. Kutyaupak valley soils are considerably deeper than those on the highland, though their location in the fiord and their morphology suggest that they are recent features. They have therefore been dated using Evans' rate of 1.5cm ka^{-1}, assuming a rapid rate of development. A rate of 1.25cm ka^{-1} is preferred for the Kogarsok moraines, though morphostratigraphic interpretations are still considered more reliable than the dates so obtained, particularly at high elevations. Table 3-8 shows the mean soil depths of each moraine expressed as an absolute age according to these rates; Tasiuyak Arm has age limits provided by both rates.

These data suggest that the highland moraines formed within a short period of time, although given the wide range of soil depths on certain moraines, a broader time span is considered possible. M5 is known to be younger than M1 and M3, contradicting the soils data; K1 is likely to be older than M5, though it is certainly younger than M1 and M3. Site PP is thought to be associated with M3. Morphologically, K2 is younger than M1 and M3, its suggested age perhaps providing a minimum date for their formation. However, the larger number of soil pits dug on K2 make it difficult to accurately correlate mean solum depth with the depths of other moraines.

Table 3-8: Estimated absolute ages of moraines in inner Nachvak Fiord.

Moraine	Depth to Cox (cm)	Age (ka BP)
Kogarsok highland; rate 1.25cm ka^{-1}		
TM1	18.0	14.4
K2	30.0	24.0
M5	35.25	28.2
K1	37.0	<29.6
M3	29.6	23.7
PP	44.0	35.2
M1	32.5	26.0
Kutyaupak valley; rate 1.5cm ka^{-1}		
TM1	18.0	12.0
KV1	23.0	15.3
KV2	35.0	23.3
KV5	37.0	24.67
KV3	41.0	< 27.3

A date of 12-14 ka BP for the Tasiuyak Arm moraine may be a maximum for complete deglaciation of the fiord, it being within the framework suggested by other workers. The soil development rates in Kutyaupak valley are not synchronous with those on the Kogarsok highland, making it difficult to date moraines found there. Moraines are expected to have been formed at about the time of K2 deposition, with final retreat of ice from the valley shortly before the deposition of the Tasiuyak Arm moraine.

3.7. Conclusions

Inner Nachvak Fiord shows evidence of several periods of glaciation. Figure 3-24 summarises information obtained through examination of various aspects of the landscape, showing relative ages of moraines and the sources of ice which formed them.

The highland west of Kogarsok Brook includes the oldest moraines in this area. The Kogarsok moraine and moraine K2 mark the most easterly location of recent glacial activity in

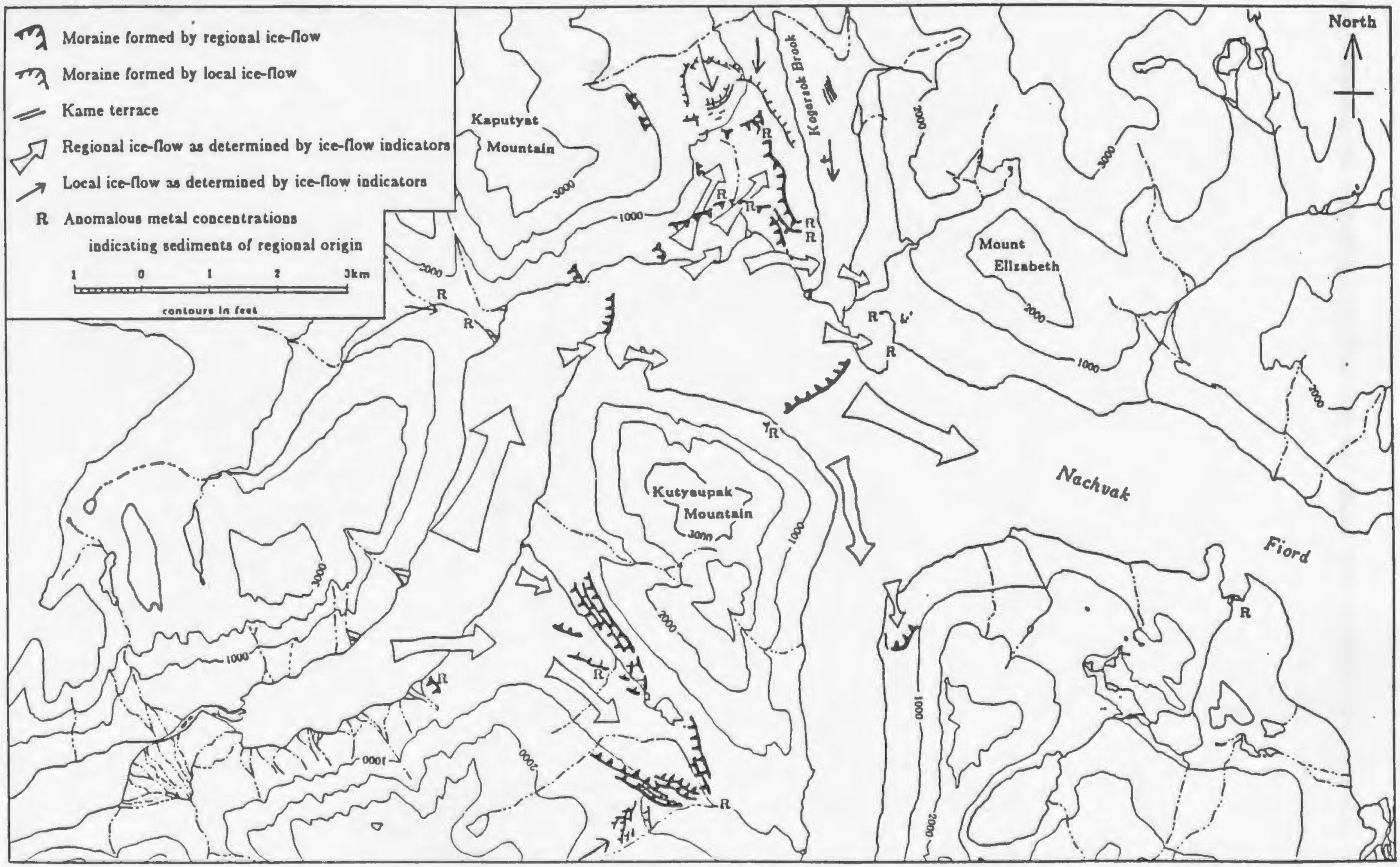

Figure 3-24: Summary map to show evidence of regional and local glaciation within inner Nachvak Fiord.

this area; they may be representative of a readvance phase, or a stillstand from a greater maximum. Moraines west of K2, at lower elevations, are thought to represent stillstands, such that they decrease in age to the west. The presence of at least one recessional moraine at the mouth of Tallek Arm suggests either that ice did not enter the fiord from the arm during the last glacial period, or that after recession there was a readvance from the west which backfilled the mouth of the arm. Moraines extending to the south-eastern end of Kutyaupak valley tend to support the first interpretation, as they indicate no resistance to ice occupying the whole valley, and perhaps part of Tallek Arm. Regional ice entered Kutyaupak valley from Tasiuyak Arm. The location of the valley, west of moraine K2, and its low elevation, suggests that ice retreat proceeded during and after retreat from K2.

Ice-flow directions marked on Figure 3-24 were provided by the morphology and location of moraines and by the directional measurement of striations, grooves, gouges and moulded bedrock. The last glacial phase was characterised by regional fiord ice extending to at least moraine K2 and the Kogarsok sill, and occupying the mouth of Kutyaupak valley. Moraine K1 appears to have been formed by a more extensive phase of regional glaciation, and it too may be related to the Kogarsok sill. Striations were identified on the bedrock alongside K1, though none were seen further east; those above K1, close to M3, were not easily detected. This might be taken as evidence for K1 marking the limit of the last glacial maximum in this study area.

M3 was initially interpreted as evidence of an older regional glacial advance which occupied the entire highland plateau, and continued into moraine segment PP. However, *roches moutonnées* and striae on the summit indicate that ice from the north overrode the rock in this area, while the polygon field or ice-contact area between M1 and M3 suggests that ice of northern origin stagnated here. Drift geochemistry data indicate that M3 contains no anomalous metals, hence it may not be of regional provenance. The origin of M3 is therefore unclear. Moraine M5, which truncates M3 to the east, is a remnant of a local ice advance, probably dating from the last glaciation. It may have removed evidence of a larger ice lobe occupying Kogarsok Brook valley from the south by truncating moraine K1.

Although geochemical analysis of sediments did not provide any new evidence, it does not contradict the results of other ice-flow indicators. Heavy metal concentrations show a background value for sediments throughout the area, with anomalously high concentrations occurring only along the fiord trough. It is suggested that the high concentrations result from a regional input of drift material derived from the inland Laurentide ice-sheet; local drift accounts for the majority background material, and explains why the moraines within and west of the Kogarsok Brook valley do not contain high concentrations of metals. Attempts to correlate the 1986 data with those of other geochemical analyses within the fiord were hampered by the fact that the particle-size fractions analysed were not the same in each study; different particle size classes are not comparable. Treatment of all the $< 2\mu$ fraction data as one population showed no conclusive patterns, but the distribution of anomalies suggested that they were a result of post-depositional metal concentration. Regionally, metal concentrations do not appear to change in any consistent patterns throughout the fiord.

Relative ages of moraines were suggested after pedological analysis and qualitative weathering observations had been carried out. At least two separate zones of weathering were detected after examination of four sites on the Kogarsok highland. Weathering characteristics of the upper sites differed considerably from the lower sites, indicating a boundary at crest M0. The characteristics of the two lower sites may suggest another division above and below the level of moraines M1, M3, and M5. It is logical to assume that another major boundary occurs at the elevation of moraine K2. Although these boundaries cannot be proven from the data gathered here, the descriptions do support such a basic boundary division, with sites 1 and 2 being in the topmost weathering zone, and sites 3 and 4 in the intermediate zone.

Soil development was measured on a number of surfaces. No single rate of development is adopted, however, and soil depths cannot be relied upon to show the ages of moraines. Mean solum depth for each moraine was calculated, the results generally corresponding to preconceived ages except in the case of certain highland moraines. However, morphological evidence is preferred over that of solum depth alone. Moraines M1 and M3 thus appear to have been formed within a short time period; moraine M0 is interpreted as being considerably older, though its exposed location has resulted in no soil development at all. Moraines K2 and M5 are thought to be the youngest of the highland moraines, probably forming after the maximum of the last glaciation; K1 is likely to be older than M5, and is certainly older than K2. It may represent the Late Wisconsin maximum. Soil development rates in Kutyaupak valley appear to have been faster than on the highland, giving the moraines a deeper, 'older' solum depth. They are assumed to have been formed at about the same time as, or later than, moraine K2, with their age decreasing to the north-west. Tasiuyak Arm moraine is the youngest in the study area, and has the shallowest soil profile though only one pit was dug in it.

Relative ages of moraines are provided using solum depth in conjunction with other morphologic characteristics. Absolute ages are very difficult to estimate given the lack of a dating control for the inner fiord, the irregular rates of soil development, and the inequal number of sample pits dug on each moraine. The 'dates' provided on Table 3-8 for each of the highland moraines are therefore not regarded as reliable age-indicators. Comparison of the topographic locations and elevations of these moraines with others found in the central and outer fiord is preferred as a method of dating.

On a relative timescale only, moraine M0 is most certainly the oldest moraine mapped in the inner fiord. It was formed by a regional ice-sheet. A second glacial period appears to have caused moraines M1 and M3 to be deposited within a short time period; M3 may have been formed by coalescing local and regional ice-sheets. Moraine K1 may represent the maximum extent of the last glacial period in this study area, and may be associated with the Kogarsok sill. K2 was deposited during a recessional phase from that maximum, and is more definitely linked to the Kogarsok sill. Local ice appears to have been active at the same time, withdrawing to the north to deposit moraine M5 in Kogarsok Brook valley. Moraines in Kutyaupak valley are considered to be of similar age to moraine K2. Other moraines west of K2 are interpreted as representing recessional phases from the last glacial maximum, becoming younger toward the head of the fiord.

Chapter 4
Relative Sea Level Change

4.1. Introduction

Raised shorelines are common features of glaciated coastal landscapes, representing relative sea level change which results from glacial isostatic and associated gravitational processes. Many short fragments of raised shorelines are visible within inner Nachvak Fiord, providing some indication of the nature and timing of glacial retreat and marine inundation. Their elevation above present sea level was measured, and they were correlated into synchronously formed shorelines. The existence of several different sea level stands is demonstrated in this chapter; these provide information about the nature of deglaciation, its timing and its effects on the earth's crust and geoid.

4.2. Methodology

Altitudes of raised beach fragments were initially measured by altimeter during field traverses. These preliminary surveys allowed benches to be identified as particular shorelines, and continuous benches to be marked for subsequent detailed survey. An optical surveyor's level was then used to measure the elevation of significant marine and fluvial features, since it is considered to be more accurate than the altimeter. In certain cases the altimeter readings are used in shoreline analysis, as it was not practical to level all benches, nor those in areas difficult to reach. These elevations are marked [A] to distinguish them.

All measurements were made in metres above present high tide (aht). The elevation of high tide was established using surrogate water level indicators: in this case, the upper limit of sea drifted debris, such as seaweed, driftwood, etc.. This approximation of a datum line was necessary since there is no established datum in northern Labrador. A temporary datum plane was therefore created for the field season, using bench marks at measured elevations above the high tide line. This method assumes that the water body is horizontal, and therefore that it forms a surface of equal elevation all around its edge. The errors involved with such an assumption are considered in the next section. Bench marks were established slightly above the datum line so as to avoid the possibility of storms or higher tides destroying the original datum.

Traverses were made across and along raised shoreline segments, which often occurred one above another in discontinuous steps. When the altimeter was used, closure to the datum line was made at the beginning and end of each traverse, and as many times as possible during it. Levelled traverses opened and closed at major bench marks, although closure directly to high tide level (the surrogate water level of drifted material) was made in order to reduce traverse length when it was known that no further traverses would be made from that point. Minor bench marks were set up during traverses which included several beach segments; these made it easier to ensure that traverses were closed, and reduced potential errors. Figure 4-1 shows the levelled shorelines on each traverse, plus major bench mark locations and elevation points measured by altimeter alone.

Consistency in the relative height of measured points on different raised features was maintained by taking elevations at or within 1m (horizontal) of the break of slope on their landward side. Care was taken to avoid post-formational modifications such as sediment slumps rockfalls or erosional gullies, wherever possible. Benches were examined for evidence of their marine origin; pits were dug in some to investigate their composition and soil (see section 3.6.3) Structural features and bedrock outcrops were noted. This helped in the interpretation and correlation of raised shoreline segments.

Identification of the highest raised marine feature in all locations is also important to interpretation. Marine limits represent the maximum height of a particular sea level stand above present high tide. While it was often apparently easy to determine which benches did represent the marine limit on a particular traverse, certain anomalously high terraces introduced a degree of uncertainty. In these situations it was particularly important to evaluate whether some process other than a marine shorezone process could have formed the terrace. For instance, fluvial terraces, far above a contemporaneous sea level, may on first sight appear similar to beaches. Steep inland gradients and proximity to major drainage allow some recognition of fluvial origin, and such characteristics were carefully examined and assessed in the field.

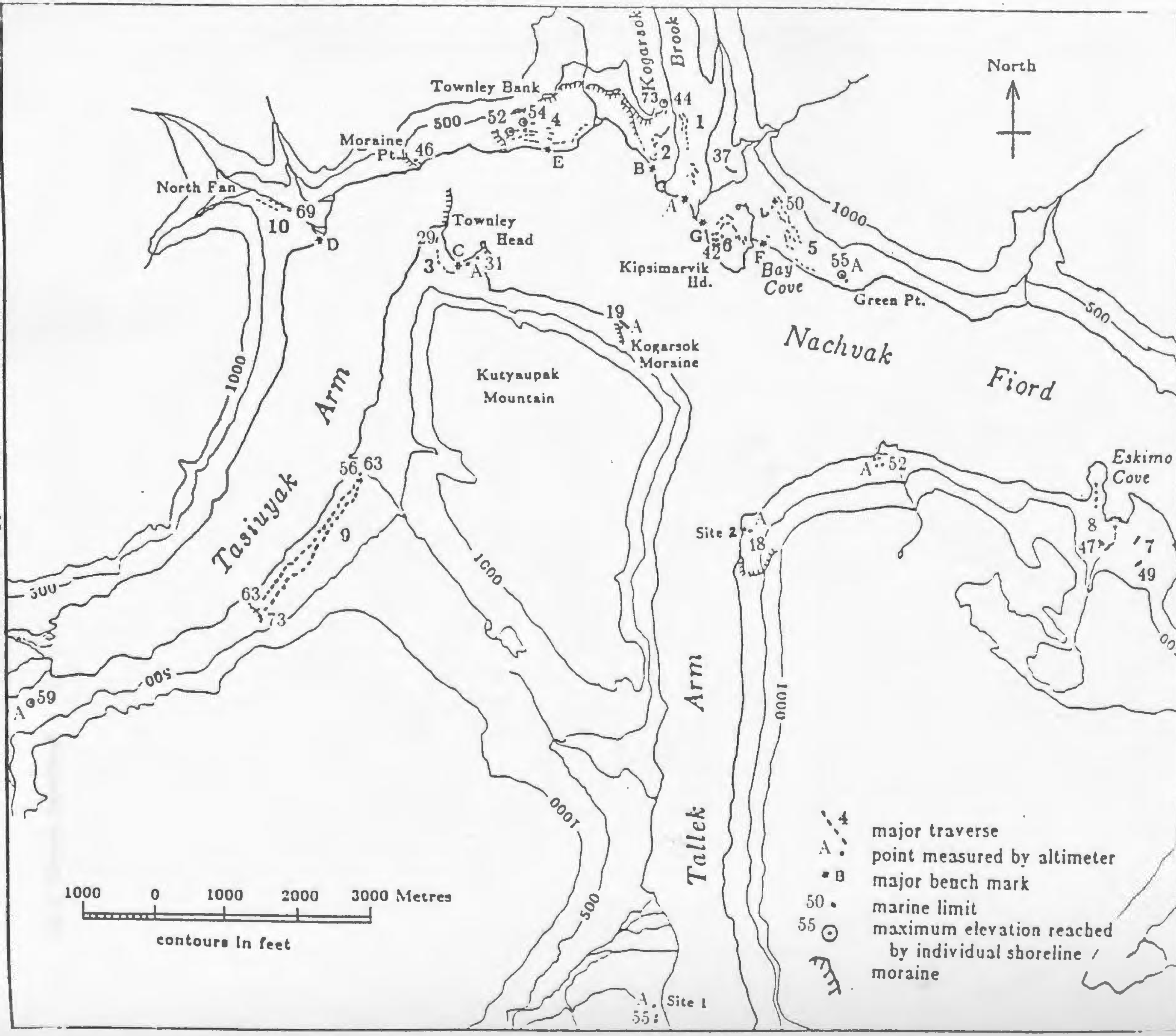

Figure 4-1: Levelled shorelines, major bench mark locations, and marine limit data within the study area.

4.2.1. Errors Involved

There are a number of errors involved with the measurement of shoreline elevation. It is important to make precise measurements to ensure accurate correlation of discontinuous shoreline segments. In an ideal situation, it would be possible to trace shorelines continuously throughout a field area; this is very unusual however, and in Nachvak Fiord preserved fragments tend to be short and are clustered on gentle slopes. A systematic method of elevation measurement was used here, as outlined by Gray (1983). This reduced the probability of errors, although there are a number of sources of error which remain. These are associated with the datum line, instrumentation, field techniques and final correlation of shoreline data.

i. The datum line

Surrogate water level indicators provided an approximation of the high tide plane around the fiord. This method of datum line representation was chosen because northern Labrador is not linked to a national datum; there are no bench marks, and tidal observations are scarce. By assuming that the surface of a waterbody is horizontal, a convenient plane may be established (Rose, 1981; Gray, 1983). In the case of the sea, however, this assumption is violated; local differences in tidal range and the effects of storms introduce irregularity and a potentially uneven surface. Johnson (1985) points out that the irregular shape and depth of a fiord coastline make for large differences in the timing and range of local tides, even between individual bays. These variations are likely to be enhanced by the passage of weather systems and by changes in atmospheric pressure. As a result, errors may increase if bench marks are not established in the same meterological period.

In outer Nachvak Fiord, Delabarre Bay and on the shores of Adams Lake, Bell (1987) established a temporary datum plane using surrogate water level indicators. Through construction of multiple bench marks, he was able to reassess its height some time after it was formed. Over a 22-day period, a maximum error of 0.093m was attributed to changes in the datum plane; Bell concluded that surrogate water levels make reliable datum lines where there is no official datum. He also noted that the difference in error between coves within the fiord and in Delabarre Bay was minimal, suggesting that the irregular shape and depth of these areas did not greatly affect the tidal range, at least within the area of study.

While it is assumed that inner Nachvak Fiord has a different tidal range from that at the mouth of the fiord, it is thought that the range is likely to vary little within the field area itself. Bench marks were constructed over a period of 35 days. The error margin associated with the datum plane is therefore assumed to be larger than that calculated for the outer fiord. Although error depends on meterological as well as tidal changes throughout a period, an approximation of error should probably incorporate the 28-day lunar month. An error of 0.12m will therefore be allowed for the 35-day survey period.

II. Instrument error

The altimeter is an easy and convenient instrument for one person to carry and operate over any terrain. It is an aneroid barometer, which works on the basis of pressure change with altitude, and is therefore most accurate when conditions of atmospheric pressure are stable or are changing at a linear rate. Since optimum conditions could not be guaranteed in the field, and time was not plentiful, the altimeter was used despite changing meterological conditions. Frequent checks to the datum line help to improve accuracy, though these were not always possible. Gray (1983) and Johnson (1985) summarise the inadequacies of the altimeter and give possible solutions; correctional methods were not introduced here as the optical level was used for most traverses. Løken (1962*b*), working north of Nachvak Fiord, allowed an altimeter error of ±0.7m; Bell (1987) calculated the error to be ±0.838m. On the basis of these studies, an error margin of ±0.8m will be allowed for this study.

Detailed discussions on the advantages and disadvantages of the altimeter versus the optical level (eg. Rose, 1981; Gray, 1983) have demonstrated that the level is a more accurate instrument provided that it is properly used and conditions of operation are favourable. Proper use includes the correct alignment of cross-hairs within the instrument; failure to do this produces a collimation error. Poor field conditions such as high winds, rain and steep or uneven terrain increase the magnitude of this error.

Collimation errors are evident when the reading taken at the closing point of a traverse does not equal the known elevation of the closing point (a bench mark or the datum line). Johnson (1985) suggests that short traverses keep errors to a minimum, though Bell (1987) found that collimation error did not increase with length of traverse. Instead, large errors were associated with surveys of high relief. Although the occurrence of error was not examined in this study, it was apparent that poor weather, uneven ground and steep gradients caused the most difficulty in accurate levelling.

The collimation errors of individual traverses are listed in Tables 4-1 and 4-2. These were not distributed throughout each traverse as has been done in previous studies (Gray, 1983), since that tends to give a false impression of the accuracy of results. Instead, an error deviation is given for each traverse and thus for each altitude. Major traverses are those opening from and closing to a 'major' bench mark located close to the datum line. Minor traverses centred around bench marks created during longer surveys. Table 4-2 includes a cumulative error, found by adding the errors associated with major traverses to the minor traverse error.

Table 4-1: Collimation errors associated with major traverses.

Traverse location	Collimation error	Height of bench marks created	Additional bench marks
1 E. Kogarsok	0.235	A - 0.618	1-1
2 W. Kogarsok	0.294	B - 1.373	
3 Townley Head	0.407	C - 0.555	
4 Townley Bank	0.129	E - 1.707	4-1,4-2,4-3,4-4
5 Bay Cove	0.390	F - 2.010	5-1,5-2,5-3,5-4,5-5
6 Kipsimarvik Hd.	0.207	G - 0.688	6-1,6-2
7 Eskimo Cove E.	0.154		
8 Eskimo Cove W.	0.598		
9 Tasiuyak Arm	0.324		9-1,9-2,9-3,9-4
10 North Fan	0.332		
Mean:	0.307		

The mean closing error for major traverses is 0.307m; that for the minor traverses is 0.438m, while the cumulative error increases to 0.793m. All of these values are larger than the closing error quoted by Gray (1983) as being too large to be acceptable in Scottish studies. There, traverses were repeated or checked if they were found to have an error greater than 0.15m. However, the conditions in Labrador are thought to warrant a higher error margin than allowed for Scotland, when the short field season, unavoidable weather conditions and poorly accessible beaches are considered. Bell (1987) had a mean closing error of 0.184m per traverse, considerably less than the mean error for this field area. This may be attributed to the comparatively more gentle terrain in the outer fiord, where longer stretches of gently sloping shorelines are visible. The Kogarsok area is characterised by short fragmented benches, not always obviously identifiable as raised beaches, and reached for the most part by steep slopes (for example, on Kipsimarvik Head or in Tasiuyak Arm).

Table 4-2: Collimation errors associated with minor traverses.

Traverse number	Collimation error	Cumulative error	Bench marks created
1a	0.213	0.448	
1b	0.165	0.557	
4a	0.283	0.412	
4b	0.099	0.228	4b-a
4b-i	0.302	0.530	
4c	0.464	0.593	
5a	0.023	0.413	
5b	1.032	1.422	
5c	0.104	0.494	
5d	0.590	0.980	
6a	0.157	0.364	6a-i,6a-ii
6b	0.108	0.315	
6c	0.136	0.707	6c-i
6c-i	1.924	2.631	6c-ia
9a	1.351	1.675	
9b	0.060	0.924	
Mean:	0.4382	0.7933	

Although the mean closing errors from the optical level are less than the 0.8m error allowed for the altimeter, several bench marks can be seen to have considerably higher cumulative errors (eg. traverses 5b, 6c-i, 9a and b). This shows that there is likely to be little difference between an altimeter reading and an optical level reading of this accuracy, and is considered as evidence for the usefulness of the altimeter as a reasonably accurate instrument.

III. Measurement Procedures

Errors may also be introduced through inconsistency in measuring techniques. Elevation is likely to vary considerably between different points on a single feature, so a representative elevation should be measured. Points at the inner break of slope at the back of each shoreline were measured so as to avoid any natural slope toward the sea. There were still variations in elevation measurement, however, especially where post-formational modifications had affected a shoreline (for example, the benches in Tasiuyak Arm). Some benches showed structural control, having frequent bedrock outcrops or considerable gradient; these were noted, as they could be inconsistent with the interpretation of raised shorelines throughout the area. An error margin of ±0.5m has been allowed for the variety of measurements that might be made on a single landform. This was the figure used by Johnson (1985) in northern Labrador, and adopted by Bell (1987).

It is also important to make some interpretation of the origin of a feature at the time of survey. Raised features of different origin are likely to have distinct relationships to the tidal regimes that created them; for example a delta will form both above and below the tidal level, while a weathered water-level or drift platform usually forms well above it (Rose, 1981). Since the elevation of a feature need not represent the high tide level of its time of formation, a correctional factor may be associated with it to bring it to a more appropriate level. To determine the magnitude of this factor, studies estimating the relationship of modern coastal features to high tide levels have been carried out. Since it cannot be assumed that past conditions of tidal range, storm frequency, topography and so on were the same as they are today, such studies may not be significant, but they can provide some guide to the amount of correction required.

Studies of modern coastal landforms in Nachvak Fiord were not carried out, as they would have been time-consuming; instead, error values from other areas have been incorporated. Relevant figures have been taken from studies carried out in northern Norway (Rose, 1978), western Scotland (Dawson, 1979, and Sutherland, 1981, *in* Gray, 1983), and Baffin Island (Andrews, 1970). Most levelled platforms in inner Nachvak Fiord were identified as shorelines, so have a correctional factor of ±1.0m. The spit and terrace features of the wide delta at Kogarsok Brook probably require a fairly large correction to bring them to mean sea level; on the basis of work in Norway and Scotland, an error margin of +2.0-3.0m has been applied. The varied elevations of the kettled ground areas north and east of Kipsimarvik Head suggest that sea washed over them, probably at several different levels. A correction of $\pm$1-2m had thus been allowed, based on estimations for platforms made by Rose (1981) and Sutherland (*in* Gray, 1983).

4.2.2. Interpretation of Data

Correlation is carried out using both surveyed elevations and field evidence, with the aim of establishing links between discontinuous segments formed at the same time by a single sea level stand. A number of difficulties may be encountered, depending on the nature of data distribution, the accuracy of individual data points, and the events of deglaciation and relative sea level change.

Relative sea level change occurs on glacial unloading, when uplift of land and geoidal adjustment causes shorelines to emerge from the sea. Uplift is expected to be greatest at the centre of ice dispersal, although the highest raised beaches are often found around the former ice margin where the length of the total period of emergence is greatest. In a fiord situation such as this, ice is likely to retreat in stages. Provided that the earth's crust is elastic enough to respond to individual stages of glacial retreat, several shorelines of different elevation might be found in a fiord, which actually represent stillstand conditions. The shorelines may be successively more extensive upfiord, as age and elevation decrease. In northern Labrador, marine limits toward the outer part of a fiord are expected to be at higher elevations than those further within it, since they are older and have undergone more uplift than their younger counterparts. Johnson (1985) used Nachvak Fiord as an example to illustrate this phenomenon, although he had no hard data to support his statement.

Ice margins, positions where the ice stood still or readvanced during overall deglaciation, are usually marked by the presence of moraines. Such locations are often the site of an obvious up-fiord drop in the height of the marine limit on the proximal side of the moraine. Moraines are not always present, however, so the patterns of marine limits represented by the maximum elevation of raised marine features must be carefully observed. A marine limit, as referred to in this study, is defined as the highest shoreline in a particular locality. All marine limits in inner Nachvak Fiord are likely to be Late Wisconsin or Holocene, as the fiord was glaciated until that time and those of previous glacial periods are unlikely to have survived. This contrasts with the outer fiord, where Bell (1987) considered the highest marine limits to be of pre-Late Wisconsinan age.

Depending on local conditions of crustal elasticity and glacial retreat, shorelines may exhibit a concave profile, increasing in height and gradient toward the position of an ice margin or the centre of uplift. The elevation of a single strandline is therefore expected to increase exponentially up-fiord. Continuous shoreline segments can provide valuable information about the gradient of a shoreline, and so about the elevations of segments expected to belong to that shoreline further up- or down-fiord. The gradients of the oldest (and highest) shorelines are expected to be the greatest; those below should become progressively less steep until almost horizontal beaches are attained.

These factors were considered in the correlation and interpretation of shoreline data. By describing raised benches as they were levelled, an indication of their origin and relationship to both tidal regime and other shorelines was gained. Once data analysis began, other field constraints were considered. These restrict the correlation of shoreline segments, basically relating to the logical pattern of shoreline development on glacial retreat. They have been formalised by Cullingford (1977), as follows:

1. The staircase constraint. Where raised beaches occur above one another on a 'staircase' they cannot have been formed at the same time; thus their elevations must not be correlated on a diagram, even if they are statistically similar.

2. The continuity constraint. If two or more measurements are made on the same beach fragment, they *must* correlate, even if they show a considerable degree of slope on that beach. It is, of course, important to determine that a bench is in fact marine, and not a structurally-controlled terrace.

3. The ice margin (or marine limit) constraint. Shorelines formed at a time when an adjacent area is known to have been ice-covered cannot be correlated with raised features observed in that area.

Each of these constraints reduces the number of possible correlations, and thus makes drawing shoreline diagrams slightly easier. It can still be difficult, however, especially when many different shorelines exist at only short distances below one another. Shoreline gradients and marine limits at locations successively closer to the ice centre then become vital to interpretation.

Clustered data points also cause difficulty. Gray (1983) recommends that several elevation points taken from the same segment be represented by a single point for purposes of correlation. The single point would be at a mean geographic location and mean elevation. This would remove some of the effects of spatial clustering and prevents autocorrelation between points when shoreline diagrams are drawn. It also removes the visible gradient of shorelines, and places equivalent weight on raised fragments of differing length and reliability (Cullingford, 1977). In this study, when two elevations were measured on a short shoreline segment, a mean height and position was used for correlation purposes. However, where a longer beach was measured, two or more points were included so that the gradient of the feature could be incorporated into the overall interpretation.

One of the problems in this study area was the clustered 'staircase' nature of many of the raised beaches. Due to the linearity of the fiord, shorelines tend to remain only in the wide bays and on gentle slopes. Where they are found, for example at the mouth of Kogarsok Brook valley, they are often at many levels (Figure 4-2). An area such as Townley Bank was difficult to interpret because of frequent bedrock outcrops and numerous benches with different gradients.

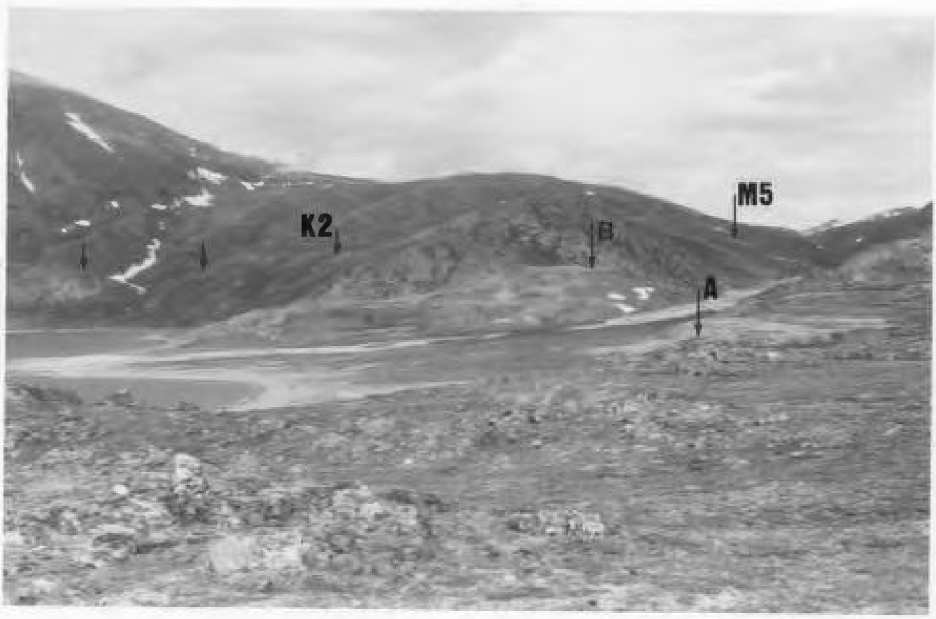

Figure 4-2: The mouth of Kogarsok Brook valley; a small misfit stream runs through this wide valley, which has several prominent raised shorelines and fluvial terraces at different levels on either side. A raised spit and terrace is shown at point A; the 73m aht terrace, with moraine, is shown at point B. Also marked are moraines K2 and M5.

4.2.3. Shoreline Representation

Results of this study are presented in a series of shoreline diagrams, where elevation points are plotted into a projection plane drawn at azimuths running parallel to different sections of the fiord trough. These are approximations of the conventional equidistant or height-distance diagrams preferred for use in Scotland and North America; other types attempt to show a rate of sea level change over time. The baseline of an equidistant diagram is drawn normal to the isobase trends of a particular shoreline. An isobase is defined as "a line joining points of equal postglacial emergence" (Andrews, 1970, p.7). By convention, it is taken to refer to simultaneously-formed features (Loken, 1962*b*). If the earth's crust is sufficiently flexible to respond to local glacial unloading, local isobase direction is likely to change over time as an ice centre shrinks and shifts its position. Thus each shoreline might have an individual isobase trend. Where response to unloading is not rapid, or the topography of an area controls the direction of ice retreat, changes in isobase direction are likely to be less pronounced.

Two assumptions are made in the normal construction of an equidistant shoreline diagram, violation of either of which results in error (Gray, 1983). Isobases should not be curved; if they are, individual points will plot in the wrong position relative to each other. The likelihood of this increases in large field areas and close to the centre of uplift. In this study, it is thought that the area covered is small enough and sufficiently distant from the probable centre of the Laurentide ice sheet to minimise the danger of isobase curvature. Secondly, the isobases of shorelines plotted on the same diagram should be parallel to one another; if they are not, points from one shoreline will plot in the wrong position relative to those of other shorelines. This means that several shorelines cannot be plotted on one diagram. The problem has been overcome by using a projection plane normal to the *mean* isobase trend (eg. Bell, 1987), although points may still be plotted in the wrong position and gradients are not accurate.

Correlation for this study was carried out by plotting shoreline elevation points into a number of projection planes roughly parallel to the orientation of the fiord. An arbitrary origin at grid reference 443000 6542000, to the south-west of the study area, was used for all projections. They are measured in degrees from True North. The 'Surface II' digitizing programme (Sampson, 1978) was used for accurate results. It may be assumed that isobase lines run across the fiord, since ice retreat must have taken place along the fiord trough. Marine limits were marked as potential indicators of an ice margin, and thus the termination of a shoreline. These helped to identify the number of shorelines present in the area, which was made more difficult by the small differences in elevation between successive raised beach levels. Particular attention was paid to the gradient of continuous shorelines and those which were noted for having frequent outcrops of bedrock along them. The latter were suspected of being structural features, perhaps enhanced by marine action.

The resulting interpretation includes marine features from the delta at the far end of Tasiuyak Arm to Eskimo Cove in the east. The orientation of the fiord is very different between these areas, being at a bearing of approximately 036°30' in Tasiuyak Arm and 118°30' in the main trough (bearings are from True North). No single projection plane could therefore be used for the entire data set, without having elevation points plotted in the wrong positions relative to each other. Instead, plots were made along the orientations mentioned for initial interpretation, following which they were transposed into planes more likely to be normal to a *regional* isobase trend. Where more than one interpretation is possible, alternatives are suggested.

4.2.4. Summary of Errors

Correctional errors associated with the datum line, instrumentation and measurement procedures are summarised in Table 4-3. An attempt to quantify these errors is made in response to Gray's criticism of authors who do not specify their methods nor the accuracy placed upon their results (1983). Although the data have weaknesses, these are indicated and some attempt has been made to quantify them.

An overall error margin for each elevation may be found by adding the relevant sections from each of the error types 1), 2), 3) and 4). By following a systematic approach to data collection, it is assumed that there have been no major errors in measurement or in landform recognition. Johnson (1985) argues that no elevation in northern Labrador will be accurate to within a metre, due to the lack of a datum and the poor preservation of raised features. The greatest error is associated with relationship to tidal regime, a factor attributed to the variety of landform types seen in this part of the fiord. The degree of error associated with data interpretation cannot be quantified, and it must be assumed that careful consideration of bench descriptions and field conditions resulted in an accurate correlation.

Table 4-3: Table of Errors.

Type of Error	Error Margin (metres)
1) Datum error	±0.12
2) Instrument error	
a) surveyor's level -	
i. major traverses	±0.307
ii. minor traverses	±0.793
b) altimeter	±0.8
3) Landform error	±0.5
4) Relationship to tidal regime	
4i) raised terrace	±1.0
4ii) delta features	+ 2.0 - 3.0
4iii) kettled ground	±1.0 - 2.0

4.3. Results

The final interpretation and correlation of shoreline data is presented in a series of height-distance shoreline diagrams. Correlation relied upon the identification of an upper altitudinal limit for each of the higher shorelines, and the gradients suggested by continuous shoreline segments for lower ones.

4.3.1. Identification of Marine Limits

The marine limits observed in this area indicate several sea level stands, formed during stepwise glacial retreat up the fiord with differential changes in relative sea level accompanying each stage of deglaciation (all named locations are shown on Figure 4-1). There are many moraines in the area, supporting this interpretation of shoreline formation, though there appear to be more changes in the marine limit than there are surviving moraines. This may be due to incomplete preservation of marine limit features or failures in identification.

The marine limit at Green Point, where a short 52-55m bench was measured by altimeter, may be the oldest in the field area. Although there is no corresponding indication of glacial stillstand at this point, neither are there any shorelines above the bench to represent a higher marine limit. This bench appears to correlate with others of high elevation down-fiord.

A 48-50m terrace within Bay Cove (traverse 5v) may represent the marine limit of a slightly lower shoreline. Again, there are no obvious moraines in the vicinity, though this shoreline could be associated with the Kogarsok sill, a moraine-like ridge crossing the fiord between Kogarsok moraine and Kipsimarvik Head. It is possible, however, that this is not the marine limit, as there is a terrace on the western side of Kogarsok Brook valley, at an elevation of 73.09m aht. This terrace may be marine or fluvial in origin. Although the gradient between it and the Bay Cove beach is considerable, that is expected of a fairly old and high shoreline. It is possible that the two were connected and represent a contemporaneous water level.

On Townley Brook a marine limit was identified at 53-54m aht, a short distance east of an obvious moraine which runs down to sea level from approximately 100m aht [A]. While many benches are visible on Townley Bank, the higher ones are short and very fragmentary, with frequent bedrock outcrops. Certain lower benches exhibit some structural control, made more apparent by their length and gradient (eg. traverse 4i). Some bedrock influence to the upper benches is also possible.

Moraine Point is believed to be the northerly extension of the Townley Head moraine. Two benches are cut into it, the highest at 16m aht [A]. This is not considered to be associated with the Townley Head stillstand because it actually exists in the moraine, and because higher shorelines were levelled on Townley Bank. No shorelines at Townley Head reach as high as 40m aht. It is possible that a shoreline segment of 51-52m aht on Townley Bank is a remnant of a sea level stand that once extended from Townley Head moraine. This might explain its similarity in elevation to the 53-54m bench previously described.

North Fan is a wide valley system displaying well-developed raised fluvial terraces. Two terraces on the south-western side of the valley were levelled from an area in which the valley mouth opened out, to a point of stream divergence in the north-west. The lower end of each terrace is therefore approximately at the level where the stream once met the sea. Based on these terraces, sea levels here are suggested to have been at 41.3m and 68.8m aht.

Two long, continuous benches were levelled in Tasiuyak Arm (Figure 4-3). Bench A, the highest, is identified as the marine limit for this area, reaching a maximum elevation of 73.9m aht. The Tasiuyak Arm moraine runs down beside both benches to their south-west, indicating that ice halted partway down Tasiuyak Arm, at least during the formation of Bench A.

Figure 4-3: Continuous shoreline benches A and B, south shore of Tasiuyak Arm.

At the far end of Tasiuyak Arm a landslide fan or alluvial fan divides Nachvak Lake from the fiord proper. Although the lake area was not examined, a bench on the Tasiuyak Arm side of the fan provided a marine limit of 59m aht [A]. Ice may have halted at the fan, or beyond the lake. Other shorelines, visible as lower segments within the main fiord, may occur beyond the head of the lake.

It should be noted that the 33m shoreline in Eskimo Cove, which was identified as the marine limit by Evans (1984) and Evans and Rogerson (1986), is actually below the marine limit. Two higher beaches were levelled in this study, at 49m on the eastern side of the cove, and 47m on the west. The 49m beach is correlated with a 51-52m bench at Small Fan and the 52-55m marine limit at Green Point. A sea level probably existed above 33m in Eskimo Cove although there is no evidence of it in the field. This may require a reexamination and reinterpretation of the lower lake shorelines in the McCornick valley (Evans, 1984; Evans and Rogerson, 1986), as suggested by Bell (1987), and of their proposed 33m marine limit in Ivitak Cove.

4.3.2. Correlation of Shorelines

Once marine limits had been identified, correlation of certain shoreline segments was straightforward. Thus Shoreline 13 consists of the highest marine features measured in Eskimo Cove, Small Fan and Green Point. Shoreline 12 includes the 47m terrace at Eskimo Cove, a 48m [A] bench at the mouth of Tallek Arm (Site 2) and the 48-50m beach in Bay Cove, with the possible inclusion of the high terrace to the west of Kogarsok Brook valley. Shoreline 11 is first visible at ~44m aht in Bay Cove, continuing to a 50m level west of Kogarsok Brook and the 53-54m marine limit on Townley Bank. The highest terraces observed on Kipsimarvik Head, at 42m aht, are associated with Shoreline 10, which continues as a 48m bench west of Kogarsok Brook, and the 51-52m segment on Townley Bank, considered to be its marine limit. The 33m raised beach in Eskimo Cove might possibly relate to Shoreline 10, or to Shoreline 9.

Correlation of lower shorelines relied upon the elevation and gradient of the continuous benches in Tasiuyak Arm. Shorelines of this altitude were not expected so far inside the fiord, as areas towards the centre of ice dispersal do not usually have a record of as much emergence as those further down-fiord, and the maximum elevation of shorelines in the outer fiord was 73m (Bell, 1987; SI-K). The high elevation and steep gradients of these shorelines implies that they are quite old and that differential uplift has been considerable since their formation. However, they fit the sequential pattern of shoreline development indicated by marine limits in the main fiord trough, and provide a control for the gradients of shorelines found below them.

Elevation points from Benches A and B were plotted into an azimuth running parallel to Tasiuyak Arm at 36°30'. Scatterplots showing height against distance from the origin display very variable elevation data, which are thought to be due to the large number of erosional gullies and meltwater streams running across both benches. Gradients were drawn on each bench using least squares regression analysis; these show the overall slope of the shorelines without considering the minor variations in elevation (Figure 4-4).

Bench A drops by 4.55m km^{-1} to the north-east, from a height of about 73m aht. Shorelines found below Bench A are expected to have proportionally decreasing gradients, since they will have experienced less relative uplift. However, Bench B has a gradient of 2.05m km^{-1}, less than half that of Bench A. This places an even greater control on lower shorelines, which must become close to horizontal relatively quickly.

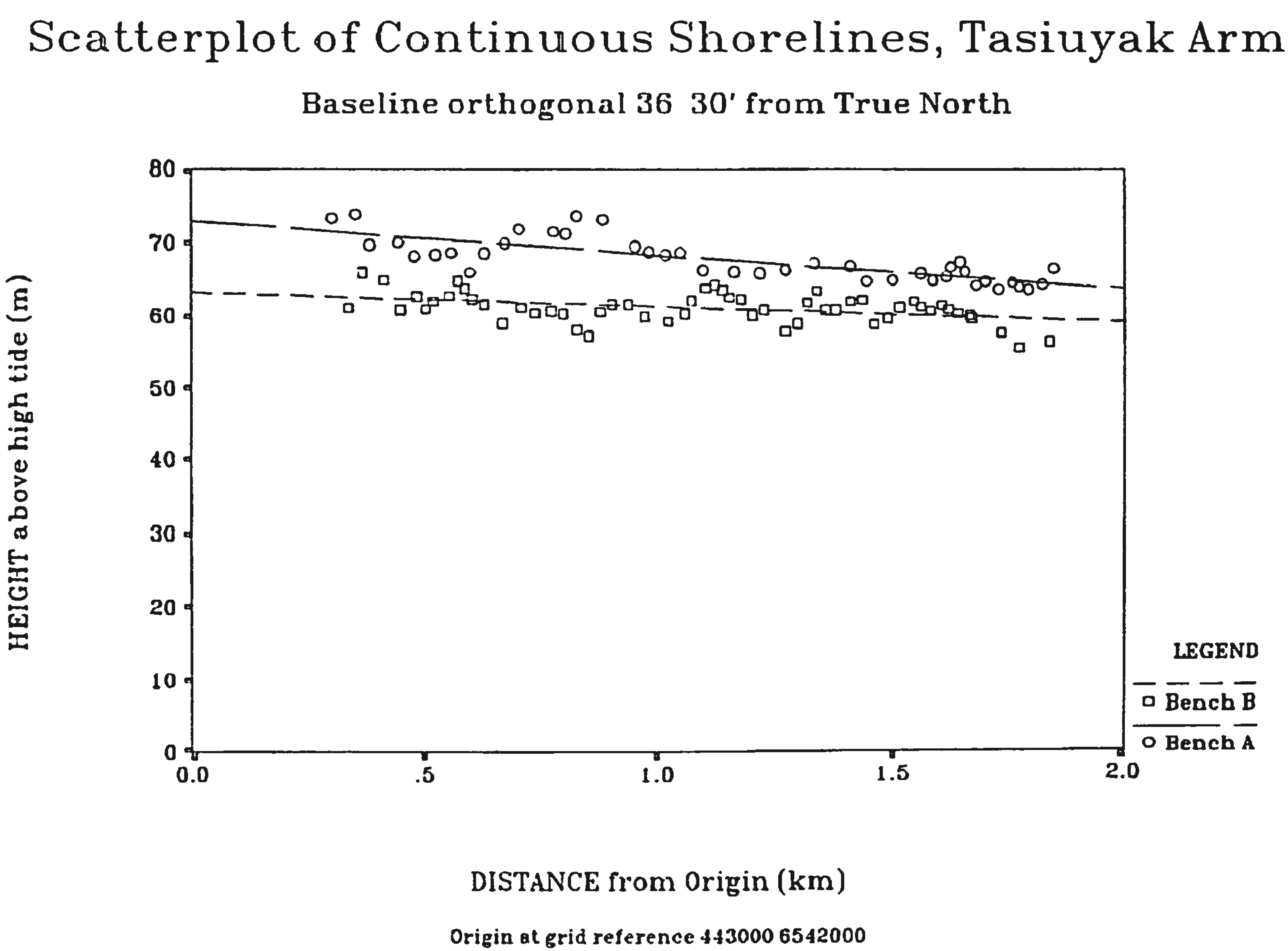

Figure 4-4: Scatterplot to show elevations and gradients of Tasiuyak Arm benches A and B.

It is assumed that the gradient of Shoreline 9, which is marked by Bench A, becomes progressively less steep down-fiord. Extrapolation of the Bench A gradient provided elevations too low for the shoreline segments observed in the main fiord; it is therefore assumed that the gradient decreased in a relatively short distance. The upper terrace levelled in North Fan is included in this shoreline, as it is above the elevation of Bench B. Shoreline 9 then drops fairly rapidly, to include 36-38m benches on Kipsimarvik Head and possibly the 33m beach at Eskimo Cove.

Tasiuyak Arm Bench B was similarly extrapolated down-fiord, where it intersected Moraine Point at 48m aht. A bench of 46m was measured here; it is considered sufficiently close to be included in Shoreline 8. Lower terraces in the main fiord correlated fairly well as far as Kipsimarvik Head, where beaches of 33-35m aht were included.

The 2.05m km^{-1} gradient of Bench B was applied to the shoreline commencing at Nachvak Lake delta, Shoreline 7. It intersected North Fan at 42m, Townley Head at 40m, and Townley Bank at 37m aht. Using these approximations as a guide, North Fan's 41m fluvial terrace is related to this sea level, as are a range of segments varying between 36-38m on Townley Bank. The shoreline is thought to extend to a ~28m platform in Bay Cove.

Beaches below this were more difficult to correlate into shorelines, though a number of benches at about 20m aht suggested that shorelines had become horizontal at that elevation. Correlation was carried out by considering the gradient between points and the quality of data where more than one interpretation was possible. The end result does leave a few disconnected bench levels, and some shorelines consist of very few data points. The lowest shoreline is composed of a multitude of points ranging between 7-12m aht, the one above of points predominantly at 14m aht. Extremely shallow gradients are exhibited by the two shorelines immediately above them.

4.3.3. Data Presentation

Figure 4-5 is a composite height-distance diagram for the study area, joining raised beaches from Tasiuyak Arm, which are plotted in a projection plane of 36° 30', to those of the main fiord, plotted at 118° 30'. Elevation points related to the same shoreline are connected to give an impression of the concave profile of each, and the decrease in gradient occurring with successively lower shorelines. This scatterplot cannot be referred to as an equidistant shoreline diagram since it gives no consideration to the isobase trends of each shoreline. In previous studies, several diagrams have been drawn for each shoreline, the angle of each projection plane varying over 5° to 15° (Gray, 1983). The aim of this was to find the baseline most obviously normal to a shoreline's isobase direction. In Nachvak Fiord, deglaciation has clearly taken place along the fiord trough, with the glacier altering direction according to the fiord's orientation. The technique of drawing multiple shoreline diagrams in order to find a single isobase trend for each shoreline would therefore produce baselines running parallel to the fiord at each orientation; no trend would be continuous throughout the length of the fiord.

Given these conditions, a regional interpretation of isobase trends might be more realistic, since, although the centre of ice dispersal might have shifted over time, the whole of the Nachvak Fiord area is likely to have undergone a relatively slight change in its dominant direction of uplift. This is especially likely given the apparently rapid relative sea level changes which took place between the outer fiord and Tasiuyak Arm.

Bell (1987) identified isobase trends for thirteen raised shorelines in the outer fiord; he plotted the shorelines into a single equidistant shoreline diagram using the *mean* of the isobase trends, 237° from True North. This orthogonal has been adopted here so that direct comparisons may be made with Bell's shorelines, and so as to provide a regional orientation for the fiord. Figure 4-6 shows inner fiord shorelines plotted into this azimuth. Elevation points are not plotted in their correct positions relative to one another because the shoreline isobases are not parallel

4.3.4. Interpretation of Shoreline Diagrams

These diagrams show thirteen different raised shorelines within inner Nachvak Fiord. The lowest were probably caused by emergence after complete deglaciation, but shorelines 6 to 13 almost certainly accompanied temporary halts in ice retreat. Glacial stillstands are indicated by moraines visible on the fiord walls in several locations. It seems likely that some form of the Kogarsok moraine and sill was associated with Shoreline 12. Part of a moraine remains on the 73m terrace, rising to approximately 76m aht; moraines are also visible on top of and to the west of the rock knoll bordering this side of the brook (K1 and K2 respectively).

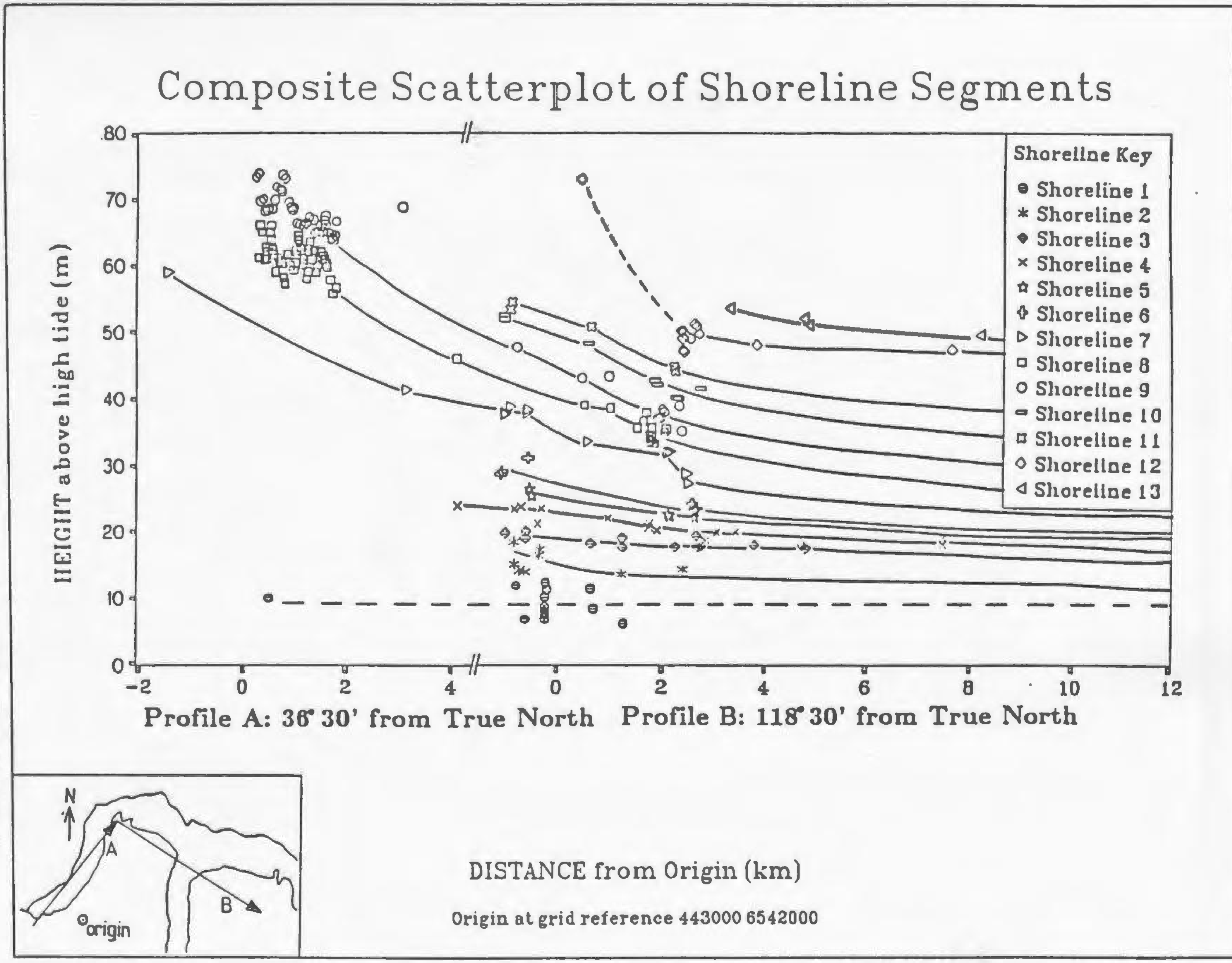

Figure 4-5: Composite height-distance diagram showing shorelines identified in the inner fiord study area. A projection plane of 36°30' TN is used for Tasiuyak Arm shorelines, and of 118°30' TN for shorelines in the main fiord (see inset).

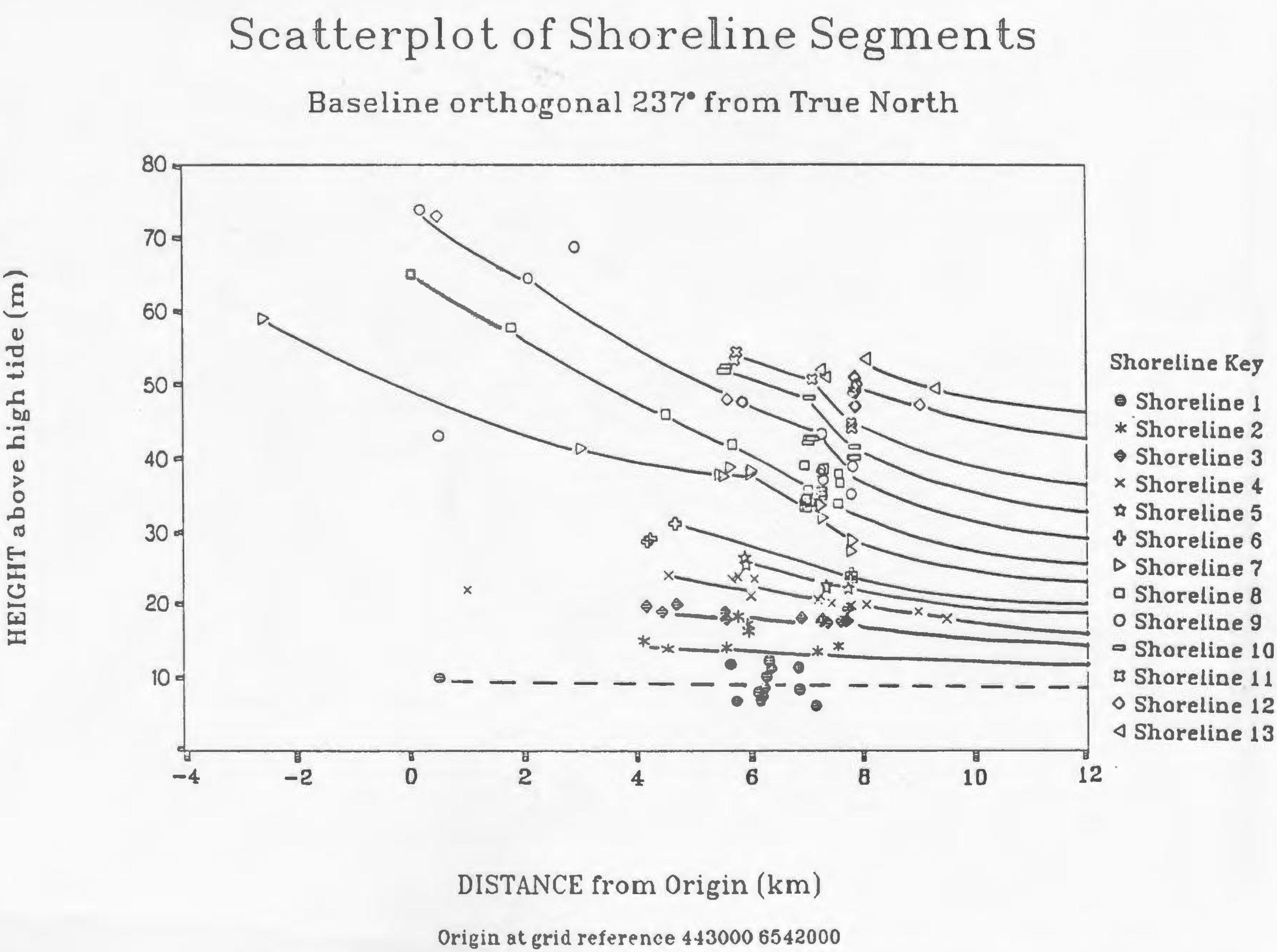

Figure 4-6: Height-distance diagram showing shorelines identified in the inner fiord, using a projection plane of 237° TN.

The highest bench on Townley Bank occurs to the east of Townley Bank moraine, which may have continued across to Townley Head, or to the lesser headland to the east. A north shore continuation of Townley Head moraine can be seen west of Townley Bank; it is a ridge rising from bedrock at about 15m aht, and passing into much higher rock walls above. The marine limit associated with the latter moraine is on Townley Bank at 51-52m aht.

A crested ridge partway down Tasiuyak Arm was identified as a moraine. It represents a stillstand during the formation of Bench A. Bench B must have been formed at a later date as its gradient is considerably less than that of A. This proximity to an ice margin might explain the large difference in gradient between benches A and B, which is anomalous because of their close elevation. Clark (1976), and Farrell and Clark (1976) showed how the surface of a water body, the ocean, may be deformed by gravitational attraction to a large ice mass. Very steep instantaneous curves of relative sea level change were expected in areas which had had large ice bodies retreating at sea level. In this case, Bench A might represent an earlier shoreline severely distorted by the gravitational attraction of ice resting at the position of the Tasiuyak Arm moraine. On ice retreat, a lower sea level would be attained almost instantly as the gravitational distortion was removed. Bench B, formed at a later period by ice further up-fiord, would show no distortion at this location, its gradient reflecting emergence that took place over a longer period of time. Figure 4-7 demonstrates this model, showing how bench A and B elevations might have remained similar while their gradients varied considerably.

It is possible that Bench B formed during another stillstand in Tasiuyak Arm, though the cliff-like nature of the fiord walls that prevented preservation of other shoreline segments has not favoured the preservation of moraines either. Alternatively, a stillstand between Nachvak Lake and Tasiuyak Arm might have accompanied the formation of Bench B; this could also be related to the 59m raised beach seen at the Nachvak Lake fan. Aerial photographs show moraines in the valley beyond the head of Nachvak Lake. These might relate to Shorelines 5 and 6, and possibly to Shoreline 7.

The fact that so many shorelines are present in the study area might suggest that Nachvak Fiord experienced several major phases of ice retreat. Stillstands, followed by periods of ice melt, may have stimulated formation of proximal beaches and platforms during the Holocene. Similarly, periods of retreat may have been marked by relative sea level change, so that older

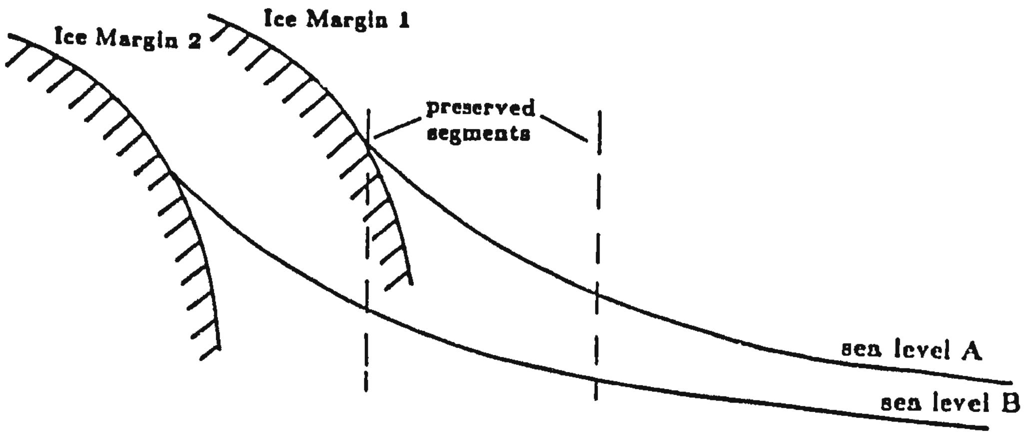

Figure 4-7: Model to show how differing shoreline gradients might be caused by the gravitational attraction of water to ice. Shoreline A forms against ice margin 1; in a subsequent period, shoreline B forms against ice margin 2. The segments between the dashed lines represent the preserved shorelines remaining in Tasiuyak Arm.

shorelines have been continuously uplifted. This would imply that the earth's crust responded rapidly to changing ice and ocean loads.

The high elevations and steep gradients of the raised beaches in Tasiuyak Arm are typical of old shorelines located close to an ice margin. The fact that such high benches exist so far inland indicates that deglaciation must have been rapid; the extreme tilt of the shorelines suggests that the earth's crust was fairly flexible at this time.

4.4. Comparison with Shorelines in the Outer Fiord

Raised shorelines and relative sea level changes have been studied in outer Nachvak Fiord, Delabarre Bay and Adams Lake valley by Bell (1987). Eleven individual shorelines were identified, ranging in height between 9m and 73m aht, although the highest (Sl-K) was recognised as being pre-Late Wisconsin. A complex system of glacial retreat was hypothesised for the creation of these shorelines and a number of moraines seen in the area. Bell made tentative correlations with shorelines observed by Loken in the Eclipse Channel - Ekortiarsok Fiord area of northern Labrador (1962*b*); he also used the gradients of shorelines in the outer fiord to predict elevations of raised beaches at certain locations in the inner fiord. As mentioned previously, marine limits at Eskimo Cove and Ivitak Cove, as identified by Evans (1984) and Evans and Rogerson (1986), are considered to be in error; other raised benches in the McCornick valley may be more controversial. Although there have been earlier observations of shorelines within Nachvak Fiord (eg. Daly, 1902), the later studies are the most detailed and will be discussed in full.

Some correlation is expected between shorelines of this study area and those of the outer fiord. Although Bell made estimations of shoreline elevations expected to be found within the fiord, these are probably wrong because gradients appear to increase so rapidly inland. His interpretation included six shorelines that continue into this study area, Sl-A to Sl-F. There are obviously many more than six, however, which suggests that raised beach preservation in the outer fiord was poor, and that segments observed there might have belonged to more than the eleven sea level stands that they were thought to represent. Attempts to correlate shorelines by extrapolating the decreasing gradients of inner shorelines 1 to 13 down-fiord produced uncertain results without additional elevation data from the central part of the fiord. Shorelines are depicted as lines rapidly increasing in linearity down-fiord, while they decrease in gradient. They may be more steep than this in reality, and the higher ones are expected to be slightly curvilinear.

The lowest shorelines almost certainly run throughout the fiord as horizontal benches, thus Bell's Sl-A and Sl-B are related to Shorelines 1 and 3 . In the outer fiord, they are found at elevations of 9m and 15.5m respectively. A third horizontal set of shoreline segments measuring ~13m aht is tentatively correlated with Shoreline 2. These segments were not classified as a shoreline by Bell because they consisted of so few data points. Shoreline C, at 17-20m in the outer fiord, might be a continuation of Sl-4, which has a very slight gradient in the inner fiord. Alternatively, it might relate to Sl-3, if it can be assumed that that bench remains horizontal. Shoreline D appears to be contemporaneous with one of the Tasiuyak Arm benches, Sl-8 or Sl-9. Some relationship to both benches might explain the variation in height shown by Sl-D in the outer fiord. If Sl-D does relate to Sl-8 or Sl-9, its date of formation, 9170±100 BP (GSC-4161; Bell, 1987), must be applied to the Tasiuyak Arm benches. Other comparisons are equally difficult to make: outer fiord Sl-E might continue from either Shoreline 10 or 11; Sl-F from Shoreline 12 or 13.

While little comment can be made about the older shorelines in the outer fiord, some doubt is placed on the hypothesis that readvance phases account for Shorelines I, H and D. Bell argues that the glacio-isostatic process of recovery was reversed twice during general deglaciation, when glacial readvances caused renewed downwarping of the crust (1987, p.159); this was demonstrated by the 'backward' tilt (ie. *toward* the ice dispersal centre) of Shorelines H and E. Further evidence for these phases was provided by the Shoal Water Cove moraine and two raised benches observed in Ivitak Cove (Evans, 1984; Evans and Rogerson, 1986), which were associated with Shorelines I and H; and by a moraine system observed by Rogerson beyond the head of Nachvak Lake, associated with Sl-D, the Tessersoak Readvance. As pointed out above, Sl-D is unlikely to have extended as far as Nachvak Lake, and the moraines mentioned are not considered to be related to Sl-D at all. The higher benches in McCornick Valley were originally interpreted by Evans and Rogerson to be lacustrine features. Whether the earth's crust is flexible enough to respond almost instantaneously to glacial loading is open to debate; it seems unlikely that renewed downwarping occurred here, as deglaciation and isostatic rebound occurred rapidly, producing many different sea levels.

Shoreline J in the outer fiord provides some evidence that deglaciation did take place rapidly. It consists of a number of raised beach fragments in Bigelow Bay, Delabarre Bay, Adams Lake valley and Valley of the Flies, and represents the highest Late Wisconsin shoreline in the outer fiord (height range 47 to 68m aht). One would normally expect inner fiord shorelines to be of lower elevation than those in the outer fiord, since the older outer shorelines would have normally undergone more relative uplift than their younger counterparts (eg. Johnson, 1985). In Nachvak Fiord, however, shorelines 8 and 9, and possibly shoreline 12, have elevations equal to, or greater than, those of Sl-J. This suggests that deglaciation and relative sea level change has taken place quite rapidly; the amount of emergence experienced by the inner shorelines is about equal to that of the outer shorelines. The period of relative sea level change between the time of formation of Sl-J and Sl-8 appears to have been very short.

Bell made tentative correlations between his Sl-D and Loken's Sl-3 (1962*b*), suggesting that they resulted from synchronous readvance phases. Dates obtained from shells associated with each shoreline were similar, indicating formation about 9000 years ago. This correlation might still be valid, although in this study it is based on elevation data and the ages of the shorelines alone, excluding readvance hypotheses and comparison of moraine sequences.

The lowest horizontal benches visible throughout the fiord may correlate with others in northern Labrador. Loken measured one at 15.5m aht, which he related to the Tapes transgression of western Norway. The latter was given an age of 4700 years BP (Faegri, *in* Holtedahl, 1960). Bell correlated Sl-B, 15.5m aht, with Loken's shoreline, and tentatively applied the same date. A radiocarbon date of 8260 ±60 years BP (TO-1084) was recently obtained by the author from shells found at 14m aht, in a beach to the west of Bay Cove. Fragments of *Astarte spp., Acmaea spp., Balanus balanus, Chlamys islandica, Hiatella arctica* and other cold-water species were found in a heavy marine clay. These are full-salinity subtidal filter-feeders, found living today on rocky or gravelly substrates rather than deep water or soft sediments. They are likely to have lived at a time when sea level was above 14m aht, and thus their date is not thought to be representative of the age of Shoreline 2. However, the date does correlate with that proposed for deglaciation of the fiord, 9170 years BP (Bell, 1987).

Very marked horizontal benches 8-10m aht are reported by R.J. Rogerson from the Porcupine Strand area (1977), where they were formed during a significant Holocene transgression, and from Ivitak Cove (personal communication, 1988). Other transgressive beaches of this elevation have been reported from the St. Lawrence area by Dionne (1988). Figure 4-8 shows the modern coast and an 8m aht bench in Tasiuyak Arm.

Figure 4-8: Modern coast in Tasiuyak Arm, with raised bench at 8m aht.

4.4.1. Postglacial Faulting

The high degree of tilt displayed by shoreline benches A and B in Tasiuyak Arm led to an investigation of mechanisms other than relative sea level change which could have influenced them. The possibility of postglacial faulting was considered, particularly since there is growing evidence that such faults occurred in eastern Canada (Adams, 1981; Gale *et al.*, 1986). A local fault in the area of Tasiuyak Arm might have caused the benches to be uplifted, thus increasing their elevation, at the same time tilting them and exaggerating their gradient. While the difference in gradient between the benches may have existed prior to faulting, both gradients might have been quite low.

Postglacial faulting has been investigated in Fennoscandia, where the stability of the Baltic Shield has become an important question with regard to the disposal of nuclear waste. It has been proposed that glacio-isostatic rebound was accompanied by faulting, usually along structural boundaries, and often rejuvenating old faults (Mörner, 1982). Lundqvist and Lagerbäck (1976) documented several early observations (from the 1930s) of possible seismic or tectonic movements, and recorded their own observations of the Pärve Fault. The Pärve Fault is continuous for over 50km in northern Sweden, it has an angular scarp and consistent downthrow to the west and north-west. Although it appears to have been influenced by much earlier geological events, its angularity and the fact that it breaks a till cover blanketing the area suggests that it is postglacial. The authors describe a number of sites where glacial and late-glacial formations (eskers, drumlins and the like) have been altered by the fault. No very recent activity has been recorded; it was suggested that the fault was activated by isostatic rebound on deglaciation.

After the Pärve Fault had been discovered, several other 'late-glacial' faults were found in northern Sweden. They have been described as having conspicuous morphologic form, often being very long, and frequently offsetting glacial phenomena. Investigations were generally initiated by interpretation of aerial photographs, ground reconnaissance taking place after potential faults had been identified. Lagerbäck and Witschard (1983) report several prominent faults; Henkel *et al.* (1983) compared a number of these 'late-glacial' phenomena with older fault zones using aeromagnetic maps. Lagerlund (1977) reports tills of 13,400 years BP which are cut by later faults.

Since late and postglacial faulting in Fennoscandia has been proposed, the implications similar events might have for the stability of shield areas in North America have prompted investigations here. In a literature survey, Adams (1981) documented bedrock faults of approximately 10,000 years of age, occurring in eastern Canada and parts of the United States. Most have been observed between western Ontario and southern Newfoundland. They appear to be mainly small thrust and reverse faults which have displaced glacial features, most frequently striations and polished surfaces, but sometimes depositional features. It is assumed that glaciation, the smoothing of bedrock surfaces and deposition of debris, would remove or subdue the most noticeable effects of previous fault lines. Grant (1980) and Neale (1963*a,b*, *in* Adams, 1981), for example, observed postglacial faulting along raised shorelines, which appears to have made the shorelines higher and, in some cases, increased their gradient. Gale *et al.* (1986) note that observations of postglacial faulting have occurred predominantly in the populated areas of north America. Few such phenomena have been observed in Labrador, although Lee (1965) and Mörner (1979, *in* Gale *et al.*, 1986) recorded possible postglacial faults around Hudson Bay and Poste-de-la-Baleine, respectively. A post-depositional fault was also observed in the sediments recorded by acoustic survey below Adams Lake, just south of Nachvak Fiord (Bell *et al.*, 1987). While independent evidence from a variety of sources and areas suggest that postglacial faulting *has* occurred, it may have been caused by tectonic rather than glacio-isostatic activity. Gale *et al.* (1986) left this question open, suggesting that further investigation was necessary, particularly in the north American shield areas.

Given this background, aerial photographs of Nachvak Fiord and those available for the surrounding areas were examined for any indication of faults. Certain very straight and very noticeable lineaments were seen, many in the Korok River valley, south of Nachvak Fiord; some stream offsets were noted, these indicating more clearly the size and nature of the faults. Occasional moraines were thought to be offset or divided by faults. Figure 4-9 shows a number of tentatively identified faults, as drawn from aerial photographs in the study area and the valley inland of Nachvak Lake. Their downthrow appears to be to the east or west; examination of stereo pairs suggests that elevation differences are in the order of 1-5m. Within the study area several offsets are suggested, for example along a north-westerly trend from Bay Cove into Kogarsok Brook valley, and from the east side of Tallek Arm to Kutyaupak valley and beyond.

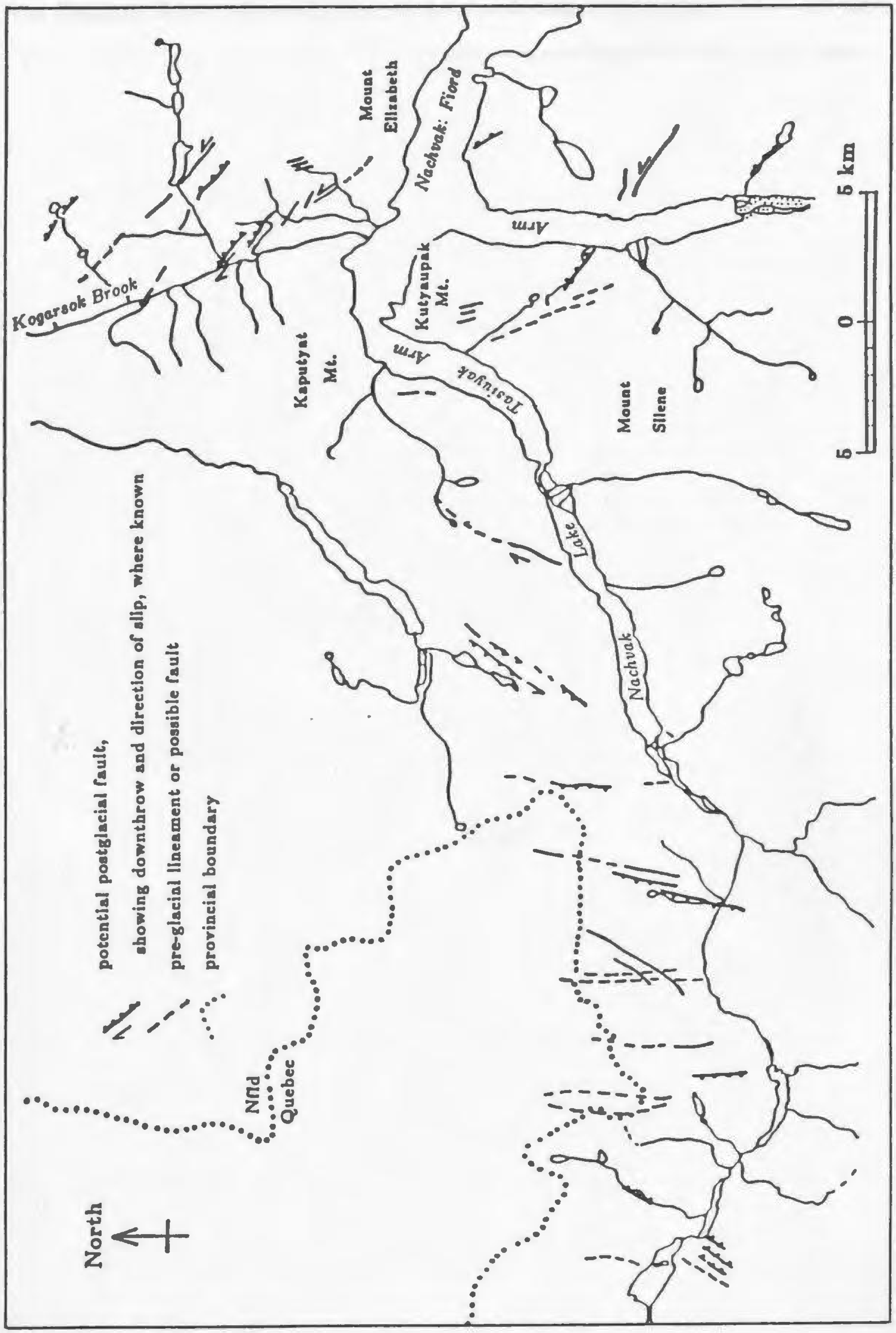

Figure 4-9: Locations of possible postglacial faults in inner Nachvak Fiord, as identified from aerial photographs at an approximate scale of 1:40,000.

The Kogarsok Brook valley examples are most noticeable, since stream offsets are visible, and a tributary stream appears to have been caused to run northward into the brook. These lineaments were not visited in the field, since their presence was not considered until after the field season. Their age cannot be estimated, but the fact that they are so apparent in an area that was glaciated during the Late Wisconsin suggests that they occurred on or soon after deglaciation. In the field, no evidence of faulting was seen. However, such features were not looked for, and natural slope processes may have hidden any prominent signs of crustal activity. This explanation for both the magnitude of tilt and the elevation of the benches is therefore considered possible, though it has not been incorporated into the interpretation of shorelines since it cannot be proven.

4.5. Summary

This chapter deals with the relative sea level change of inner Nachvak Fiord, from which suggestions concerning the deglaciation of the whole fiord can be made. There are thirteen shorelines visible in the inner fiord, several of which become marine limits in this area. All of them are expected to extend to the outer fiord, though the fact that only six observed there could possibly continue inland suggests that those benches belong to more than one shoreline, and possibly that shoreline preservation between Tinutyarvik Cove and Delabarre Bay is poor.

Correlation of shorelines throughout the fiord is not of primary importance except in terms of the chronology of events. It is suggested that deglaciation was rapid and that isostatic recovery began on or soon after initial ice retreat. Ice retreat must have taken place in several phases, since there are numerous moraines around the fiord; uplift may have occurred rapidly in response to each phase, producing many shorelines of different elevation. Despite this step-wise deglacial sequence, ice retreat was quite rapid, as indicated by the high elevation of shorelines within the fiord. Shorelines 8 and 9, and possibly Sl-12, are as high or higher than those observed in the outer fiord (Sl-J; Bell, 1987). Their degree of tilt implies that the earth's crust was very flexible at that time.

The lowest two shorelines are thought to occur in several parts of northern Labrador at approximately the same elevations, and probably relate to major transgressional events. Marine shells associated with Sl-D were found in Adams Lake valley; they provided a radiocarbon date of

9170±100 (GSC-4161; Bell, 1987) for the formation of SI-D, and thus indicate that the fiord was ice free at least as far as Tasiuyak Arm by that time. A new radiocarbon date of 8280±60 (TO-1084), associated with a sea level above 14m aht, appears to to support this interpretation. The formation of SI-D is not associated with a readvance phase as hypothesised by Bell, as there is no evidence of such; it may, however, be correlative with Loken's SI-3, also dated at approximately 9000 years BP (Loken, 1962*b*).

Assuming that the fiord was largely ice-free by 9000 BP and recognising that deglaciation took place very rapidly, initial ice retreat may have begun at a relatively late period. The many shorelines seen below Shorelines 7, 8 and 9 may represent a slower period of relative sea level change, possibly lasting from the mid-Holocene.

Chapter 5
Analysis of Sediment Cores

5.1. Introduction

Sediments of the continental shelves of eastern Canada have been examined extensively through acoustic and seismic surveys, and analysis of cores. These explorations have provided some information on the style and extent of glacial periods by showing deposits of glacial origin in sequential layers. More recently, the fiords of Baffin Island, western Greenland and northern Labrador have been subject to such scrutiny. Fiordic sediments are considered to be of great potential in the attempt to correlate terrestrial and marine evidence concerning the extent of glacial events, as they serve as a link between oceanic and continental environments (Andrews *et al.*, 1985). The glacial sediments of the Labrador shelf have been examined in detail through various surveys and coring operations (see section 2.4). An acoustic survey of Nachvak Fiord carried out in 1984 was followed by seismic and air-gun profile studies in the summer of 1985; sediment cores were also collected in 1985. Interpretations of the sedimentary units seen in the fiord are given in Rogerson, Josenhans and Bell (1986) and Bell (1987); this chapter concerns the lithologies and chronologies shown by four cores from the central part of the fiord, and their contribution to an understanding of the late- and postglacial history of the fiord.

Chapter 2 summarised the arguments for and against an extensive Late Wisconsin glaciation. Based mainly on terrestrial evidence, Rogerson, Evans and Bell (Evans, 1984; Evans and Rogerson, 1986; Rogerson, Josenhans and Bell, 1986; Bell, 1987; etc.) argue for a limited Late Wisconsin ice sheet, while Clark and Josenhans (Clark, 1984; Clark, Josenhans and McCoy, 1985; Clark and Josenhans, 1986; Josenhans, 1986) use mainly marine evidence to support their more extensive version. At the latitude of the Torngat Mountains, Clark and Josenhans (1986) attempted to correlate land and sea records for the Late Quaternary and postglacial periods; they drew models of Late Wisconsinan ice surfaces in Nachvak and Saglek Fiords, and proposed a deglacial chronology for northern Labrador. As pointed out by Bell (1987), however, they gave no evidence to support their claim that acoustic units have been traced from the Labrador Shelf into fiord basins; the interpretations of Nachvak Fiord sedimentary units do not match those of the continental shelf units as proposed by Clark and Josenhans (1986) nor Josenhans, Zevenhuizen and Klassen (1986). Analysis of fiord cores in this study may provide some ground-truthing for the sedimentary units interpreted by Rogerson, Josenhans and Bell, and Bell, and may help to evaluate the opposing models of glaciation proposed by Rogerson and Bell (1987) and Clark and Josenhans (1986).

5.2. Nachvak Fiord Sediments

A 3.5kHz acoustic survey of Nachvak Fiord was carried out in 1984 during a joint operation between the Canadian Hydrographic Survey and the Atlantic Geoscience Centre (A.G.C.). The main traverse, from Nachvak Bay to Kipsimarvik Head, shows four basins, each separated by a distinct sill. Five sedimentary units were identified by Rogerson, Josenhans and Bell (1986), who interpreted them as indicating a deglacial sequence ranging from basal tills to ice-distal and modern deposits.

In 1985 the A.G.C. took air-gun profiles and made a *Huntec* deep-tow seismic survey of the fiord during *CSS Hudson* cruise 85-027; at the same time, piston and gravity cores were collected from various locations. Bell's interpretation of Nachvak Fiord sediments (1987) includes this more recent information as well as the acoustic data, and thus utilizes the greater resolution provided by *Huntec* and air-gun systems. Again, sediments were interpreted as indicating a deglacial sequence, though a unit deposited before the last glaciation was recognised on top of the impenetrable basement unit. Four of the cores are analysed in this study.

Figures 5-1 and 5-2 show the locations of the four major sills that divide the fiord into basins, 5-2 depicting the sedimentary units identified by Bell. From the west, Kogarsok Sill separates Townley and Koktortoaluk Basins, Ivitak Sill divides Koktortoaluk and Ivitin Basins, and Tinutyarvik or Shoal Water Cove Sill divides Ivitin and Outer Basins. The fiord threshold separates Nachvak Bay from Outer Basin. The cores discussed were taken from the ice-proximal side of two of these ridges, both of which are thought to be moraines. Cores 85027-105 and 106

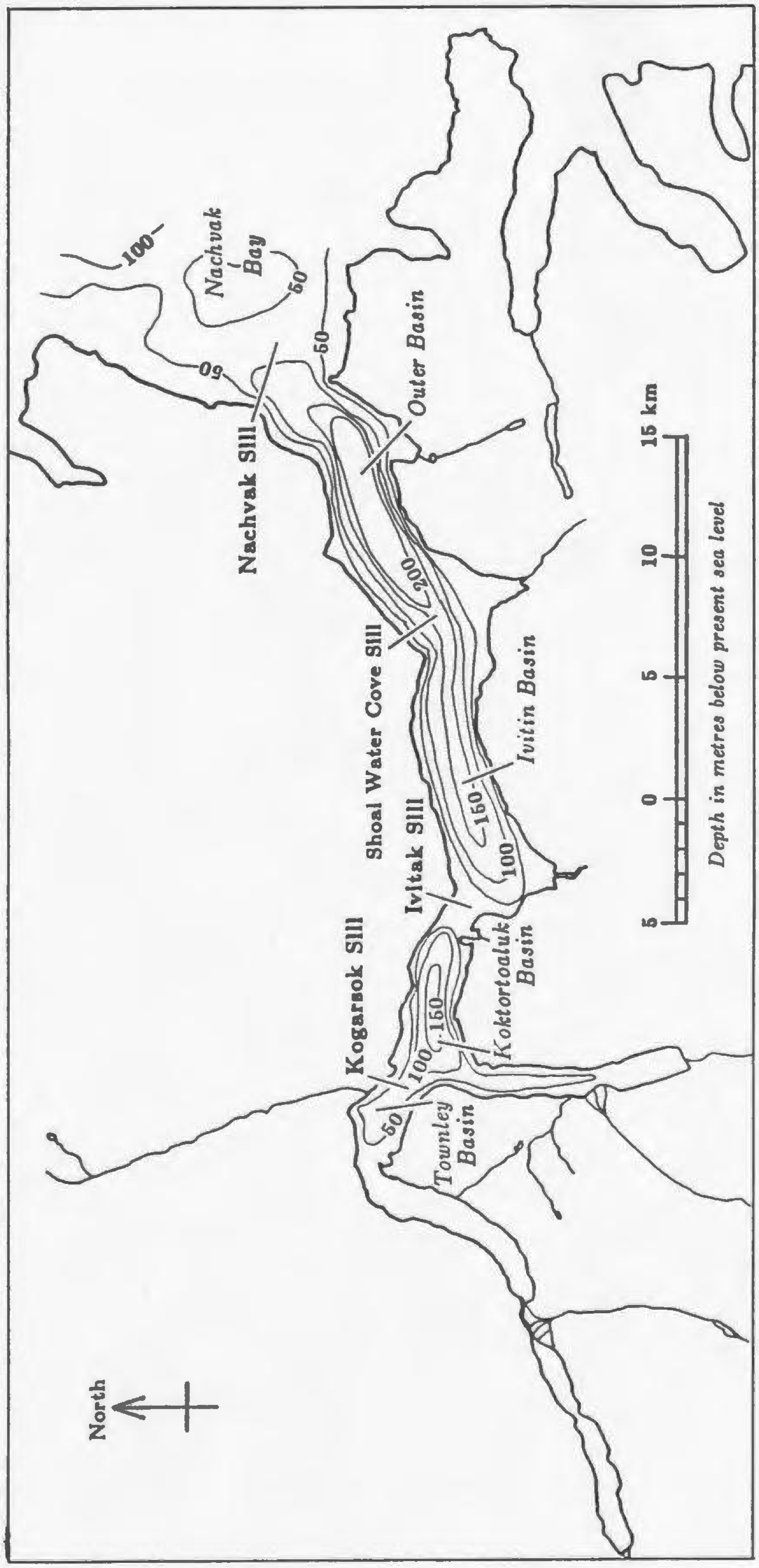

Figure 5-1: Bathymetry of Nachvak Fiord, showing positions of basins and sills (*after* Rogerson, Josenhans and Bell, 1986).

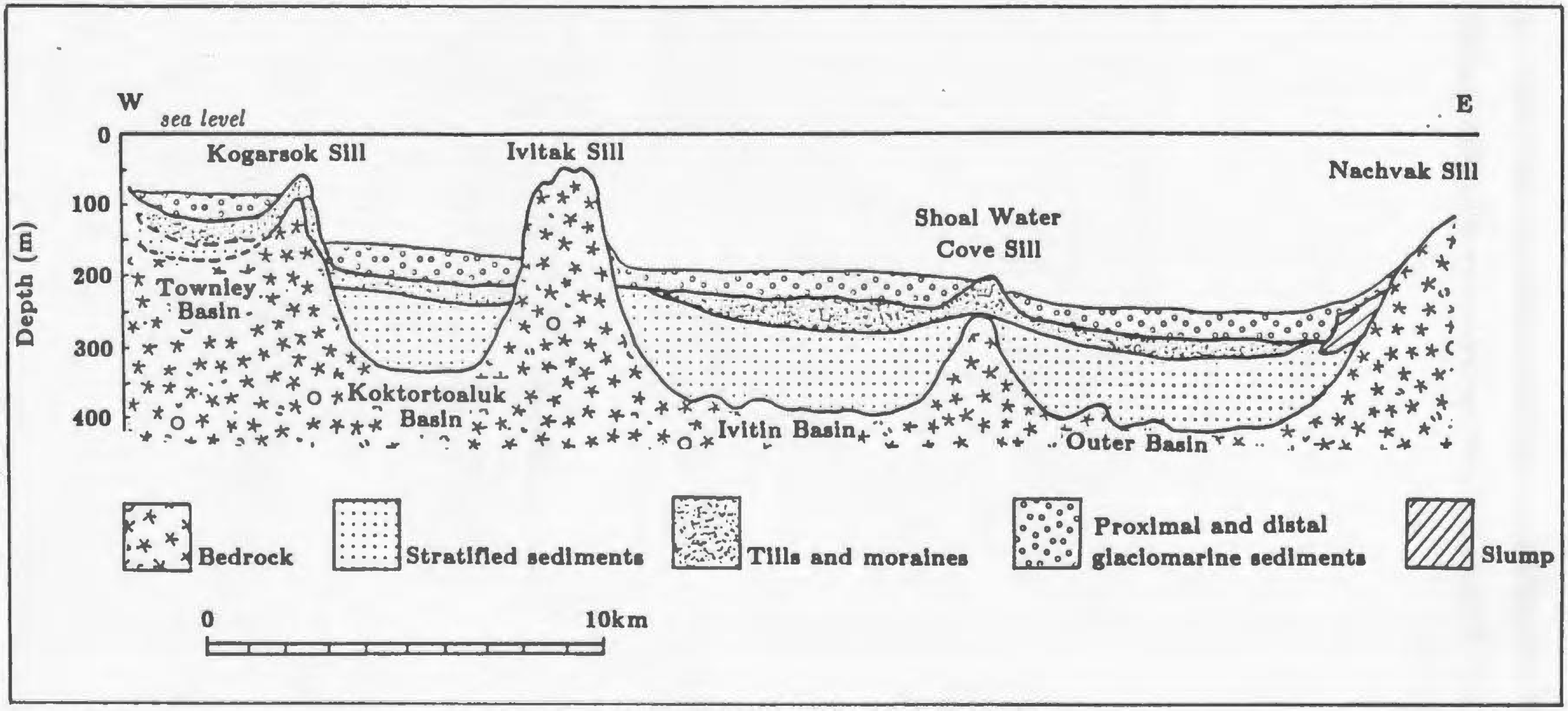

Figure 5-2: Longitudinal profile of Nachvak Fiord, showing sedimentary units as identified by Bell (1987).

were collected from the Shoal Water Cove Sill in Ivitin Basin, at position 59° 03' 12" N, 063° 34' 39" W; Cores 85027-107 and 85027-108 were extracted from Kogarsok Sill, Townley Basin, at positions 59° 03' 58" N, 063° 54' 37" W and 59° 03' 54" N, 063° 54' 22" W.

The interpretation of acoustic and seismic records by Bell and Rogerson, Josenhans and Bell includes a sequence of sedimentary deposits that represent a deglacial cycle; Bell, with the added resolution provided by seismic and air-gun surveys, identified a unit of glacial till (Unit C) and a unit of marine or lacustrine sediments that predate the last glacial period (Unit B). Table 5-1 simplifies the interpretations of both sets of authors, giving a short description and the proposed origin of each unit.

Unit B in Rogerson, Josenhans and Bell, and Unit C in Bell, are interpreted as basal till. At Kogarsok and Shoal Water Cove sills the units have the form of moraines, and are thought to have been deposited during still-stands in recession. A 1985 traverse in a *Pisces IV* submersible showed Tinutyarvik sill to be a "steep bouldery ridge" (Rogerson, Josenhans and Bell, 1986), resembling a moraine. Above the till and moraine complex are ice-contact sediments, thought to be coarse grained sands interspersed with fine grained sediments (Units C and D respectively). Bell suggested that they were laid down in open water ice-shelf conditions, the cyclic stratification being due to a freeze-thaw sequence which allowed suspended sediments to settle. The uniformity of this deposit was taken to indicate close proximity to an ice margin.

Ice-proximal and ice-distal glaciomarine deposits (Units D and E) are considered to overlay the ice-contact unit. These display acoustic variations thought to have been caused by a fluctuating ice margin, which would have produced changes in the quantity and type of sediment being laid down. There may have been complete disintegration of the ice shelf, leaving only a drifting ice cover. Using the facies model of Powell (1981), Bell suggested that a tidewater glacier with an actively calving ice-front may account for parts of his Unit E, particularly at the Kogarsok moraine and in Townley Basin.

Table 5-1: Lithological units interpreted from acoustic/seismic surveys

Rogerson *et al.*, 1986	Bell, 1987
Unit E: Well stratified fine grained sediments, uniform rain-out. Upper part continuous with modern deposits. Lower part ice-distal sediments.	Unit F: A sheet draped over all lower deposits, continuous with modern deposits above. Ice-distal sediments below, uniformly stratified fine grained sediments indicated by parallel reflectors. Dropstones present. F^1: Koktortoaluk Basin only. Stratified sediments, considerable input of material from Tallek Arm.
Unit D: Glaciomarine sediments. Discontinuous stratification, some ponding, gas pockets and lenses visible. Deposits variable due to changes in amount and type of sediments received from fluctuating ice margin.	Unit E: Ice-proximal to ice-distal glaciomarine sediments. Acoustically variable due to fluctuating ice-margin and changes in sediment input.
Unit C: Ice-contact sediments. Partially stratified, with some massive beds. Hummocks and layers of ponded deposits present, maybe due to disturbances caused by glacial processes or slumping. Coarse-grained sands with laterally extensive silt; perhaps deposited at immediate ice-margin.	Unit D: Ice-proximal deposit showing cyclic sedimentation of fine-grained sediments. Has two subunits: D^1 ponded sediments, D^2 finely stratified sediments.
Unit B: Poorly-stratified bedded sediments forming moraine-like ridges between basins; interpreted as basal tills and frontal moraine complexes deposited during still-stands in recession.	Unit C: A thick unit not penetrated completely by 3.5kHz survey. Glacial till and moraine complexes indicated by distinctive morphologies, lens and wedge shaped units, hummocks and lenticular configurations.
	Unit B: Stratified basin deposits, unconformities at both upper and lower boundaries, eroded by ground ice. May be marine/lacustri deposits of terrigenous sediments, or proglacial deltaic unit.
Unit A: Impenetrable base of fiord, rarely exposed. Composed of crystalline gneisses, anorthosites and metasediments. May include coarse blocks of talus, fanglomerates and tills.	Unit A: Impenetrable base of fiord, exposed rarely. Bedrock sills occurring between basins are overlain by upper units.

The topmost unit shows well stratified sediments conformable with the underlying deposits; it is taken to indicate a uniform rain-out of fine grained sediments. An ice-distal environment is suggested, with little influence from the ice front. Bell interprets point source reflectors as indicating dropstones from icebergs or floating ice; since these decrease in frequency toward the upper part of his Unit F, the influence of icebergs is considered to have declined steadily during the deposition of this unit. In the interpretations of both Bell, and Rogerson, Josenhans and Bell, the upper part of the topmost unit is considered to be continuous with modern sediments.

The thickness of each sedimentary unit was observed to increase toward the east. This, and the existence of steeply dipping strata at the western ends of the three easterly basins, was taken to indicate an upfiord source for the sediments. Such an interpretation correlates with the time-transgressive nature of the sedimentary units; it follows that Outer Basin became ice-free before Ivitin Basin, Ivitin before Koktortoaluk Basin, and so on, as ice retreated to the west. There is, however, some indication that a large quantity of sediment emitted from Tallek Arm to form a wedge-like subunit within the Koktortoaluk Basin sediments; a subunit is recognised by Rogerson, Josenhans and Bell in Unit D, and by Bell in Unit F.

Subunit F^1 was interpreted as an acoustically stratified deposit, overlain by slumped material. Bell proposed that it was related to either lacustrine deposition from Tallek Arm, carried in while ice occupied Koktortoaluk Basin, or to a catastrophic input of lake sediments after their drainage through the Palmer River into Tallek Arm (Bell, 1987, p.105).

The latter hypothesis was initiated by R.A. Klassen, who in a recent presentation (1988) proposed that vast quantities of water and sediment was emitted from the Palmer River into Nachvak Fiord toward the end of the last glacial period. His hypothesis was based upon lake levels during the deterioration of the Laurentide ice sheet, and the fact that ice appears to have deflated without decreasing its areal size, remaining thickest at Cape Chidley in east Ungava Bay. Evidence was obtained mainly from air-photograph interpretation, but included analysis of eskers and measurement of lake and river levels at their points of outflow. Klassen concluded that the ice sheet stagnated *in situ*, leaving relatively high lake levels along the Labrador-Quebec border and allowing their waters to drain to the north following that watershed. Lakes examined in the study included the Naskaupi sequence, all of which were thought to have drained northward into an outlet at the Palmer River, and thence into Tallek Arm. This hypothesis appears to support the notion of non-glacial sediments in the basins east of Kogarsok sill, and might explain the thickness of deposits in those basins as compared to the deposits in Townley Basin.

Bell offers two tentative suggestions for the presence of his Unit B, for which there is no equivalent in the interpretation of Rogerson, Josenhans and Bell. The sediments are interpreted as basin-fill deposits which occur in the three outer basins. Bell suggests that the deposits originated from the rivers draining into the fiord, as they show steeply dipping reflectors which are taken to indicate major drainage input to the fiord. They may have been laid down in a marine or lacustrine environment, possibly during a low sea level stand, and were subsequently eroded by ice and/or ice-contact sediments. An alternative hypothesis suggests that these sediments are a proglacial deltaic unit, deposited at the close of the penultimate glaciation of the fiord. Either way, they appear to predate the last glacial advance, represented by the deposition of Unit C.

The cores considered in this study were extracted from the ice-proximal sides of Shoal Water Cove and Kogarsok sills. These locations were chosen so that the largest possible number of sedimentary units could be penetrated, the aim being to sample postglacial ice-contact and upper till deposits. In this way, the cores provide a method for ground-truthing the acoustic and seismic interpretations, and add to the information on the late and postglacial history of the fiord. Knowledge of the sedimentary history of the fiord allows comparisons to be made with observations on the continental shelf and in other high latitude fiords. The paucity of datable materials in northern Labrador makes any information on the timing of ice retreat valuable, and the cores provide additional dating techniques with radiocarbon dates and pollen analysis. The cores, and the dating controls used on their sediments, provide a good basis for a late- and postglacial chronology of events.

5.3. Lithological Analysis of Sediments

5.3.1. Methods

The Nachvak Fiord cores were raised using a *Pingo* winch and the forward crane on the *CSS Hudson*. Cores 85027-105 and 85027-107 were extracted using a Benthos piston corer; cores 85027-106 and 85027-108 were collected using a Lehigh gravity corer. The gravity corer is able to retain the uppermost water-saturated layers of mud which cannot be preserved by the piston corer, thus cores 106 and 108 are likely to represent recent deposits, while the upper centimetres of cores 105 and 107 are not likely to be recent.

Table 5-2 summarises the locations, water depths and lengths of each of the cores. The longer cores are considered to represent continuous deposition within their respective basins, and have been subject to most analyses. X-radiographs of all the cores were taken at the Bedford Institute of Oceanography (B.I.O.), where subsamples for grain size and pollen analyses were also taken from the piston cores. A number of shell fragments were collected, and total organic carbon was assessed in part of core 107.

Table 5-2: Core locations and statistics

Core Number	Core Type	Location	Water Depth	Core Length
85027-105	piston	59°03'12"N, 63°34'39"W	170 m	5.9 m
85027-106	gravity	59°03'12"N, 63°34'39"W	170 m	0.7 m
85027-107	piston	59°03'58"N, 63°54'37"W	84.5 m	4.5 m
85027-108	gravity	59°03'54"N, 63°54'22"W	84.5 m	0.6 m

Lithostratigraphic analysis was carried out using the core x-radiographs; the cores themselves were not seen by the author, a fact which introduces potential error to their interpretation. Radiocarbon dates from shell fragments found within the piston cores were obtained by the A.G.C.; these provided a chronostratigraphy. Pollen analysis was carried out on one set of cores at Memorial University, so providing a supporting chronology.

5.3.2. Lithology of Cores

Townley Basin cores

Figure 5-3 is drawn from the x-radiographs of cores 107 and 108 (A and B respectively). It shows the major lithological features of the cores, in which two facies can be seen. The lower facies, below 80cm depth in core 107, is distinctive for its lack of coarse material and its abundance of organic debris. Most of the deposits appear to be graded sands and silts; a few large clasts are seen. Solid dark lines within the x-rays are indicative of iron sulphide strands or organic debris. These, and the bioturbation tubes seen in places throughout the core, indicate faunal presence and organic activity.

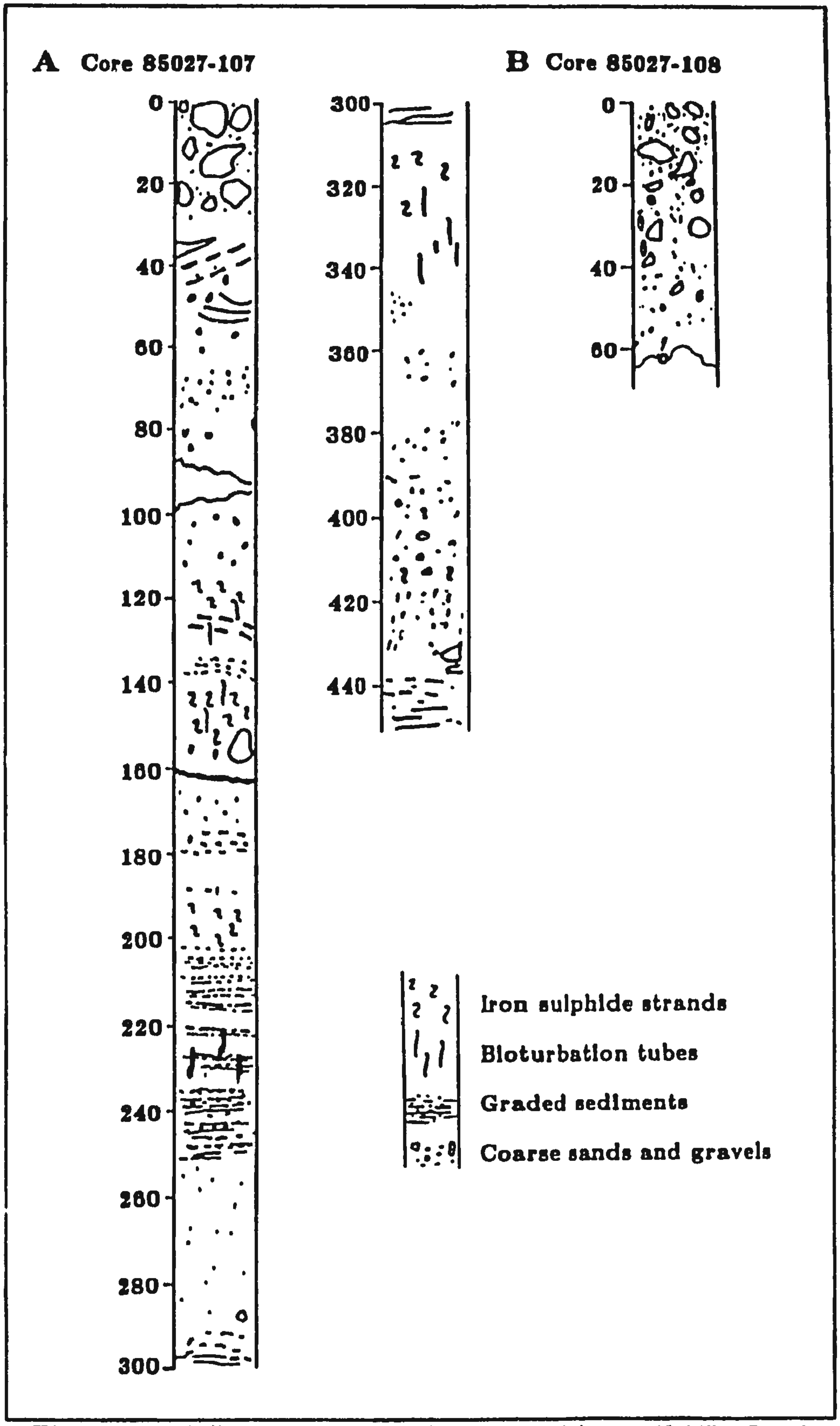

Figure 5-3: Sedimentary textures and structures of A: core 85-027-107, and B: core 85-027-108, drawn from x-radiographs.

The fine nature of these deposits, their regularity, and the fact that the bioturbation tubes are not disturbed suggest a consistent sedimentary environment, with little or no influence from slumping or reworking. Graded sands may result from flow deposits, similar to turbidity currents, indicating fairly quiet waters. Normally-graded couplets seen between 200-240cm depth resemble Bouma sequences[3]; they may be a result of regular fluctuations in basal current flow, perhaps in response to thermal turnover, spring melt, or summer rainfall events, but they are not considered to be annual varves. Large clasts seen scattered throughout the core may be evidence of ice-rafting.

Between 0 and ~80cm depth there are numerous outsized clasts, increasing in frequency toward the top of core 107. Sediments become more coarse above 50cm depth; a matrix of muds and sands is present, displaying bioturbation in places. There is little regular structuring and few layers of fine-grained sediments above 30cm. Core 108 resembles the uppermost centimetres of core 107, confirming the assumption that it represents more recent deposition on top of the piston core. It consists of large clasts up to 4.5cm in length, with a matrix of coarse sandy material and no evidence of bioturbation or organic debris. Shell fragments were noted at ~18cm depth. The upper section of core 107 and all of core 108 will be treated as one facies.

The outsized clasts and lack of fine material in this facies suggests a high-energy environment with rapid deposition of large particles, and/or winnowing of fine sediments. This environment appears to have been variable in core 107, where faunal activity and some fine-grained sediments are evident; outsized clasts in the lower part of the facies might be the result of ice-rafting, from icebergs or floating sea-ice. In core 108, however, coarse materials are dominant. Strong currents may have both eroded fine-grained sediments already deposited, and brought in the larger material seen in the core.

Ivitin Basin Cores

Figure 5-4 shows the sedimentary textures and structures of cores 105 and 106 (A and B respectively). Two facies are identified, combining core 106 with the top 90cm of core 105. The lower part of core 105 (90-590cm) displays an assortment of finely-grained sands and muds with sections of coarser unstructured gravels but few very large clasts. The coarser materials generally

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[3]Regular fining-upward deposits ranging from granular to sandy silts and into muds (Blatt, Middleton and Murray, 1980).

form layers or lenses across the core, for example at 275-285cm; fine sediments are generally unbedded, although there is a notable exception in two laminations at 400-425cm depth. Bioturbation tubes and iron sulphide strands are seen in the fine-grained deposits, particularly between 210-260 and 285-320cm respectively.

The lower section of core 105 appears to have been laid down in quiet waters, as it contains generally fine deposits. Fluctuations in basal current flows may have caused some of the bedding, with high energy input or ice-rafting depositing coarse layers. The presence of bioturbation tubes and iron sulphide strands at certain depths shows infrequent organic activity; sediments appear to be undisturbed, suggesting that slumping and reworking did not occur. The environment was, however, more variable than that indicated by the lower facies of core 107; sediments are generally coarser in 105 and show less consistent structuring.

The top 90cm of core 105 contains more coarse material, including gravels, sands and several outsized clasts. Lens-shaped sand and gravel layers are interspersed with laminated muds and sands, which act as a matrix for larger clasts. Core 106 also has coarse lens-shaped layers and scattered gravel-sized particles, set in a matrix of finer sands or muds. Between 0-40cm there are laminated fine-grained deposits layered with coarse material. Large clasts reach a maximum length of 1.5cm. There are no iron sulphide strands, although bioturbation tubes occur from 10-20cm. Individual clasts are not as large, nor as abundant, as they are in the equivalent facies of cores 107 and 108.

In core 105 coarse materials and large clasts are interspersed with fine-grained sediments, suggesting that the environment fluctuated. Fine-grained sediments were likely to have been suspended, while coarse material may have been ice-rafted or deposited after variations in the strength of current flows. In core 106 coarse materials are consistently dominant, though the presence of fine deposits suggests that there was some fluctuation in current strength. Fluvial input is thought to account for the sediments here, though the smaller clast size indicates a different fluvial source than that providing sediments to Townley Basin. The bioturbation in the top 20cm of core 106 indicates organic activity and thus suggests a relatively calm environment.

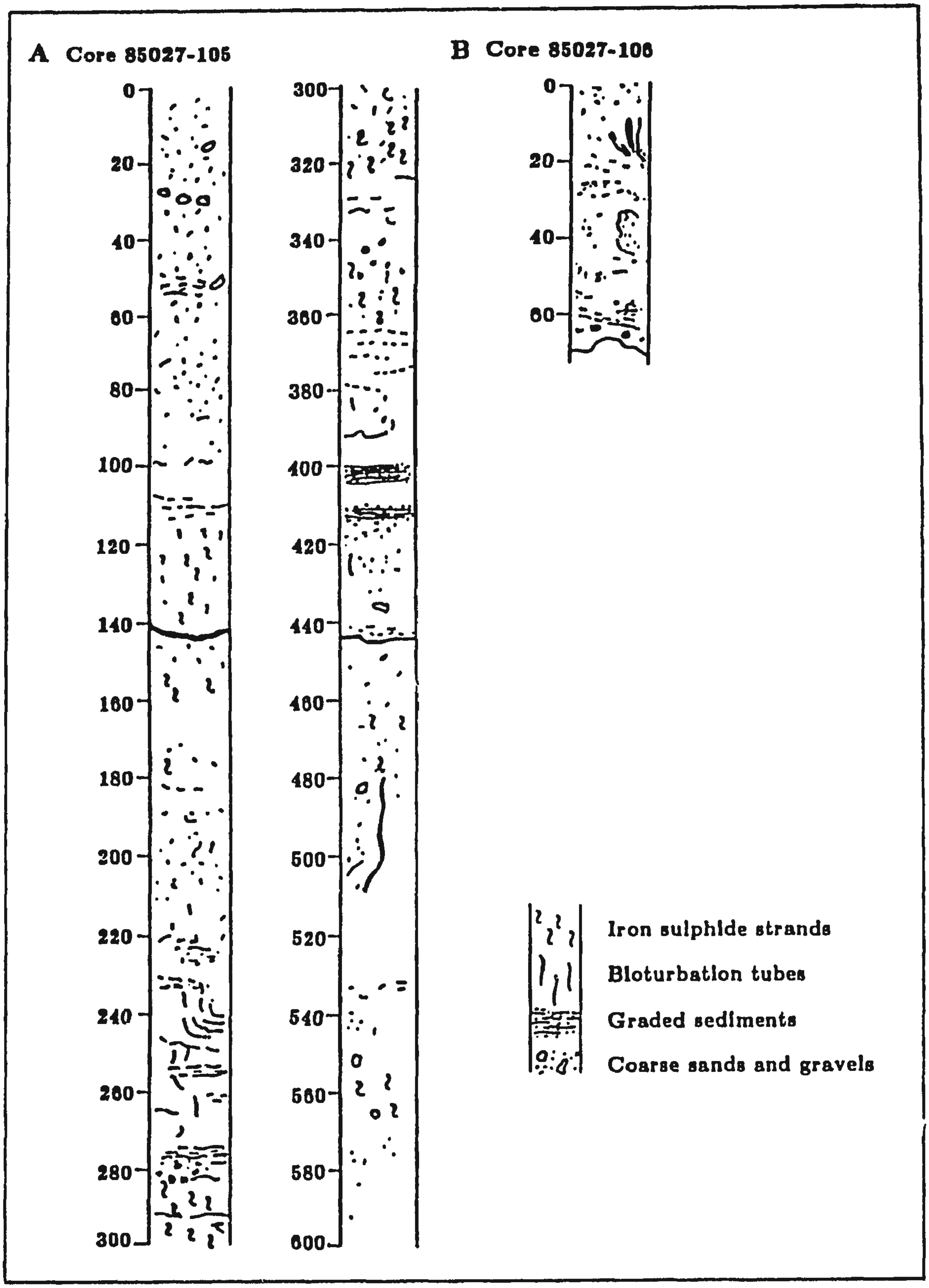

Figure 5-4: Sedimentary textures and structures of A: core 85-027-105, and B: core 85-027-106, drawn from x-radiographs.

5.3.3. Comparison with Acoustic Record

The above sections describe the lithology of the cores under consideration. Two major facies can be identified in each set of cores, with perhaps a zone of sediments strongly influenced by ice-rafted debris between those two facies. An interpretation of the sediments described is attempted here, using the acoustic information and lithofacies analysis from other glaciomarine environments. The likely conditions within the fiord during and after deglaciation, the shape and dimensions of the fiord basins, and the influence of terrestrial input should also be taken into account.

The locations of the coring sites were chosen with the aim of penetrating a maximum number of acoustic units; units were expected to be thin on the steeply sloping sills. Rogerson, Josenhans and Bell (1986) gave maximum depths of acoustic units D and E in the four fiord basins. Bell (1987) gave maximum depths of all five units above solid bedrock. These suggest that Townley Basin core 107 should penetrate at least through units F and E, while Ivitin Basin core 105 might penetrate only into Unit F. If the lithofacies appearance can be taken as an indication of acoustic boundaries, two units were sampled in each case; however, the upper coarse sediment facies of all four cores was not described in either interpretation of acoustic and seismic data. Both Bell and Rogerson, Josenhans and Bell indicate that the topmost unit consists of fine-grained sediments, deposited uniformly over the fiord bottom; it is considered to be ice-distal and is continuous with modern sediments. Bell suggests that ice-carried dropstones are present in the lower part of Unit F, but he notes that they decrease in frequency toward the top

This description best matches the lower facies identified in cores 105 and 107; fairly fine sediments with regular laminations and occasional outsize clasts are seen below 90cm and 80cm respectively. They are not, however, continuous with modern sediments; there is a change to a more coarse facies which is also visible in the recent sediment cores. This upper coarse facies appears not to be visible on the acoustic record, or it has not been interpreted correctly in the location of these cores. It is also possible that the breaks in facies noted in the lithostratigraphy do not represent the acoustic boundaries, in which case the lower facies of both cores 105 and 107 might be divided into Units F and E.

The cores analysed therefore appear to include the topmost unit identified by acoustic and seismic interpretation, that being the ice-distal fine-grained sediment unit, plus an upper, younger unit dominated by coarse deposits. Alternatively, the boundaries between acoustic units may not be visible, and the lowest parts of cores 105 and 107 might represent ice-proximal deposits.

5.3.4. Explanation of Depositional Environments

There is a considerable amount of literature relating to glaciomarine sedimentation and the analysis of lithofacies. Facies models for particular glacial and marine conditions are sometimes given, to which examples can easily be compared.

Townley Basin is the smallest basin as yet identified in Nachvak Fiord. It has an area of approximately $7km^2$, with a maximum recorded depth of 90m. It is bounded to the east by Kogarsok Sill, a steep submerged ridge believed to be a moraine, and to the west by Townley Head moraine, which is visible at low tide. Kogarsok Brook is the largest stream entering the basin; there are few large streams upfiord, beyond Townley Head. Raised marine features around the fiord walls indicate a maximum sea level 54m above present high tide, believed to have occurred while ice stood at Townley Head moraine. This means that the maximum possible water depth in Townley Basin was 144m. The basin is presumed to have become progressively more shallow with ice retreat, as relative sea level altered.

Ivitin Basin is larger and deeper than Townley Basin. It has an area of approximately $60km^2$ and a maximum recorded water depth of 170m. Although raised shorelines in this area have not been studied by the author, raised features appear to indicate a maximum water depth of approximately 210m. Ivitin Basin receives sediments from Tallek Arm (via Koktortoaluk Basin), from Ivitak River and McCornick River, as well as from the fiord.

Cores 105 and 107 show a transition from a low-energy depositional environment, with fine-grained interlaminated muds and sands, to a high-energy environment of coarse particles and numerous outsized clasts. The lower facies has been referred to as an 'ice-distal deposit' in interpretations of acoustic and seismic records. Laminations are caused by variations in the discharge and amount of sediment carried by subaqueous streams (possibly due to seasonal changes in meltwater output), or by altered current activity caused by temperature changes, basin morphology or tidal events (Powell, 1981; 1984; Molnia, 1983; Eyles, 1984; Elverhoi, 1984; Eyles, Eyles and Miall, 1985). These factors have been used to explain fine-grained, stratified ice-proximal and ice-distal sediments, for example Elverhoi (1984) notes that finely stratified sediments in the Weddell Sea are associated with current activity on the sea floor, and that interbedded deposits occurring close to the Kongsvegen glacier are probably due to variations in the rate of overflow meltwater input.

A facies model put forward by Powell (1981) may be analogous to the core 107 facies in Townley Basin. Powell describes a tidewater glacier slowly retreating or readvancing into a shallow, fairly constricted basin. Deposition under these conditions was observed in Glacier Bay, Alaska; it lead to the proposal of Powell's 'Facies Association III' (1981; 1983). In this example, sedimentation is influenced by numerous lateral streams close to the ice-margin, which produce large fan deltas of sand and gravel deposits; interlaminated sands and muds occur near subaqueous stream outlets and distal to delta formations. Where such streams do not exist, an 'iceberg zone mud'[4] may be deposited, perhaps with intercalating tongues of gravel and sand in more distant areas. More occasional laminations in finely grained materials occur in areas distal to the ice front. Glacier retreat is thought to be due primarily to ice-melt, rather than calving.

Away from the ice-front, Powell reports x-radiographs displaying "interflow deposits of thin laminae of very fine-grained sand and silt" (1981, p.133); normally-graded thicker sand units also occur, resembling Bouma sequences. The iceberg zone mud generally contains few large clasts (less than 10% pebble-sized clasts), and little coarse ice-rafted debris reaches more distal areas of a basin. Since core 107 is at the ice-distal end of the basin, it is more likely to resemble the iceberg-zone mud, where sand and gravel deposits, with fine turbidite-like sequences, are present. This description corresponds with the x-radiographs as they are interpreted here.

An alternative explanation for some of the layered coarse- and fine-grained deposits in the lower facies of core 107 might be slumping and subsequent settling, as occurs on steeply-sloping side walls. Kogarsok sill is very steep and high sedimentation rates or overloading might cause local collapse. Slumps can influence a considerable area around and below the location of the collapse as coarse (fining-upward) flow deposits and suspended sediments are deposited. The sedimentary record in a core might be distorted by this process, as deposits are likely to become thicker and out of chronological sequence. Although the strong bioturbation tubes and presence of iron sulphide strands in the core indicate faunal activity and thus a fairly stable environment, the possibility of slumps cannot be overlooked.

[4]A diamicton composed of silt and clay from meltwater streams, plus ice-rafted debris from icebergs that contain a relatively low proportion of coarse-grained materials (Powell, 1981).

Many of the models describing ice-proximal sedimentation also refer to the effects of prograding deltas, which advance across the floor of a basin as sediment is added to them. Depending on the location of a core site, the sedimentary record might cut through the lower foresets of such a delta, suddenly showing coarser material with perhaps some upward fining. Core 107 is not considered to be in a position likely to be affected by such progradation, since it is on the ice-proximal side of Kogarsok sill, and not close to any major stream inflows.

The occasional outsized clasts seen in the lower facies of core 107 are likely to have been dropped from icebergs or floating sea-ice. This might also be the origin of thin layers of coarse sediments. The importance of ice-rafted sediments is stressed in the literature, it being described as "the unique depositional agent for glaciomarine sediments" (Elverhoi, 1984, p.59); however, its importance varies in different locations and for different regimes. In the lower section of core 107, ice-rafting probably accounts for the large clasts; they are considered to be genuinely ice-rafted as they occur in the middle of the core (outsized clasts seen toward the edge of the core might have been placed there during extrusion).

The upper facies of core 107 represents a much more active environment, with few quiet depositional periods and little fine material. From 50-90cm there are some pebble-sized clasts and sand layers in a sand and mud matrix. Above that (0-50cm), clasts become larger and the matrix composition is reduced; very large clasts (maximum 4.5cm) are evident near the top of the core and in core 108.

While some of the coarse material visible throughout this facies may be attributed to ice-rafting, perhaps due to an increase in calving and floating sea-ice, it seems unlikely that this origin could account for the whole facies. A change to a high-energy environment and a change in the origin of sediments is a more probable explanation. Consideration should be given to the increased amounts of material available around the fiord walls, relative sea level change, and the changing climate and environment of the time. Stronger currents may have been caused by increased stream inputs, altered tidal conditions or basin morphology, or a change in the temperature of the water body (Molnia, 1983; Eyles, Eyles and Miall, 1984). These factors, separately or combined, could cause an increase in the size and amount of bedloads. Fine materials, possibly even fines eroded from the bed, would be carried seaward in high energy regimes, to be deposited beyond the core location. Alterations in current strength would allow fine-grained sediments to be deposited in quiet periods. As local and regional glacial retreat continued, new sources of sediment must have become available, contributing to the change in depositional environment.

Relative sea level change is likely to have altered basin morphology and thus the influence of tides and waves. As already stated, the maximum water depth in Townley Basin can be calculated as 144m; it has since dropped to 90m, making the basin smaller and shallower. Wave and tide activity might influence the fiord bottom at these relatively shallow depths, causing a coarsening-upward facies; Eyles (1987) mentions a critical 'wave base' threshold, above which sediments are subject to disturbance. Powell (1983) suggests that the wave base might occur between 30-60m depth, thus making only the fiord walls and sills directly susceptible to such disturbance; they may, however, be the precursers of disturbance at greater depth through slumping. Wave activity may not be particularly strong this far within the fiord, though it may become influential during severe storms.

A more important aspect of relative sea level change in this environment is likely to be the incision of streams into their beds, and the subsequent availability of loose debris at and above sea level. Shore-fast ice, meltwater streams and storm tides were almost certainly able to carry some of this debris into the fiord, providing new, coarse layers of sediment.

A change in the source of sediments, occurring as ice retreated out of the fiord, is, however, thought to be the main reason for the upper facies. While ice remained in the fiord, sediments would have been dominated by fine-grained glacial flour and occasional ice-transported sands and gravels. During and after retreat, deposits would have gradually become dominated by fluvial input, particularly with many meltwater streams running into the fiord and the exposure of loose debris after ice and snow melt and relative sea level changes. Streams such as Kogarsok Brook show evidence of considerably greater amounts of discharge, as they are now misfit streams in larger valleys. Fluvial sediments and concentrated currents probably account for the consistent presence of coarse material in this facies. Modern sedimentation is similarly dominated by fluvial deposits, and, as can be seen from cores 106 and 107, it produces a coarse sand and pebble facies.

Cores 105 and 106 show similar facies to those of the Townley Basin cores; there is a transition at 90cm depth from sediments dominated by fine materials to a more clastic upper facies. Here, however, the lower section appears to contain more coarse sand and gravel layers, with few fine-grained deposits and less structuring than was evident in core 107. The upper facies in cores 105 and 106 does not contain as many large clasts, nor are their sizes as great as in the Townley Basin cores. These differences are sufficiently small that they may not indicate significantly different sediment sources or environments.

Sediments at the bottom of core 105 are mainly fine-grained, perhaps representing ice-proximal or predominantly ice-distal deposits. Occasional outsized clasts may have been ice-rafted or carried in on a stronger current. Above this the facies becomes more coarse and shows less stratification. It is possible that glacial sediments were no longer dominant, and that terrestrial input from Tallek Arm, via Koktortoaluk Basin, was contributing to the fluvial influence of the McCornick and Ivitak Rivers. The number of streams entering Ivitin Basin, and the Tallek Arm deposits, may account for the thicker sediment units seen here. Ice-rafted debris is also likely to have supplemented the supply of coarse material. Deltaic progradation, relative sea level change and wave activity should again be considered, particularly since they would disturb stratification.

5.3.5. Summary

Cores 107 and 108 show two major sedimentary environments. The lower facies, in core 107, appears to have been laid down in increasingly ice-distal conditions, probably while the glacier was at or west of Townley Head. It is characterised by fine-grained sediments, which are likely to have been deposited from suspension in quiet waters, and interlaminated sands and muds, a result of subaqueous stream flow and flow currents. Organic indicators suggest that there was little disturbance during or after deposition. Occasional outsized clasts and gravel lenses are likely to be the result of ice-rafting.

The upper facies, which continues into modern sediments, shows a change in the dominant processes within the fiord. There is a gradual change to more coarse debris, probably indicating the declining influence of glacial sediments and an increase in fluvial input. Relative sea level changes may have allowed loose debris around the fiord walls and in valleys to become more available, and an increase in seasonal sea-ice might have allowed that debris to be transported into the centre of the fiord. Sediment entering the fiord with streams appears to have become dominant; coarse deposits indicate large debris loads, and the lack of fine material suggests selective erosion (winnowing). It is also possible that a changing climate caused temperature and tidal conditions to alter, or that the fall in relative sea level emphasised the coarsening upward effect by subjecting the fiord bottom to storm conditions. Modern sedimentation is almost certainly dominated by fluvial sediments and current action; core 108 is probably strongly influenced by Kogarsok Brook.

Cores 105 and 106 show the same overall patterns, though the variety of sediments in the lower facies of core 105 suggest a more variable environment. This maybe a result of Ivitin Basin's different sediment sources, for example the Tallek Arm input, or because this basin was further from the ice-margin during deposition of this section. The facies is still considered to be ice-distal. Core 106 and the upper part of core 105 are interpreted as fluvial deposits, although they are less coarse than those of the Townley Basin cores.

5.4. Radiocarbon Dating

Radiocarbon dates were obtained from shell fragments and samples of organic matter in cores 105 and 107 allowing the development of a chronology which can be related to the core's lithology. This can be used to estimate the age of depositional units and their rates of sedimentation; the position of the ice-front at a certain time might also be estimated. Comparison with sedimentation rates, litho- and chronostratigraphies in other cores from similar environments might help validate the Nachvak Fiord facies and their ages.

Table 5-3: Radiocarbon dates from Nachvak Fiord cores 85-027-105 and 85-027-107

Core	Depth(cm)	Material	Date	Reference
105	100	shell frags.	5170±80	TO-424
105	422	*H.arctica* valve	6810±70	TO-422
105	422	*H.arctica* valve	7870±130	Beta 17870
107	100	shell frags.	7328±110	TO-423
107	423	organic matter	19,730±400	Beta 17875-2577

Table 5-3 summarises the radiocarbon dates obtained by the A.G.C., which were made available for use in this thesis by H. Josenhans. Two halves of a single *Hiatella arctica* valve were dated separately using conventional and accelerator methods. There is a 1000 year difference between the two dates, the reason for which is unknown. The example shows that ^{14}C dating of shells is not always reliable. The total organic matter date was obtained from a 218g sample between 423-449cm depth (core 107). A sample from 445cm contained 0.6% carbon.

Possible errors and sources of contamination must be considered when any radiocarbon dates are used. Contamination with 'old' radiocarbon appears to be the major problem since it can so easily become incorporated into more recent organic material. 'Old' carbon may be derived from bedrock (particularly glacially-scoured bedrock), from glacial meltwater, from reworked older sediments containing organic materials, or perhaps from particular chemical reactions taking place in photosynthesising plants (Sutherland, 1980; King, 1985; MacDonald *et al.*, 1987; Clark *et al.*, *in press*).

There is evidence that shells or shell fragments provide more reliable dates than does total organic material. Studies from areas with good independent dating controls have shown that when compared, total organic dates are frequently considerably older than shell dates from similar core levels (Fillon *et al.*, 1981; Andrews *et al.*, 1985; MacDonald *et al.*, 1987). Shells appear to be less prone to contamination than total organic material, particularly those found in or near growth position; thus the shell dates, while they may be considered maximum ages, are normally thought to be fairly reliable. The *Hiatella arctica* sample from core 105 perhaps challenges this.

The degree of error associated with organic sediment dates appears to increase with the increasing age of sediment (ie. the error is not linearly distributed throughout a core), with increasing northerly latitude, and when there is only a small amount of organic carbon present in a sample. Sediment with a low carbon content (< 5%) may contain a relatively large amount of 'old' carbon, which would give it a disproportionately old 'age' (Sutherland, 1980; King, 1985). Thus samples with greater than 2% organic carbon are recommended for accurate routine analyses (King, 1985; Fowler, Gillespie and Hedges, 1986), although smaller percentages (0.5 - 1.5%) are regularly used (eg. Vilks and Mudie, 1978; Andrews *et al.*, 1985). The low percentage carbon content of core 107 at 445cm depth suggests that even a very small amount of 'old' carbon would produce an erroneous age, and implies that the 19,730 BP date is unreliable.

Most authors show an increase in age-error with the actual age of the sample, or with depth into a core (eg. Nambudiri, Teller and Last, 1980; Fillon *et al.*, 1981; Andrews *et al.*, 1985; MacDonald *et al.*, 1987). Andrews *et al.* (1985) suggest that, where the major source of contamination is reworked older sediments, this non-linear increase in contamination is associated with deglaciation and the rate of sedimentation. They found that high sedimentation rates were related to reworking, and hypothesised that reworking would be reduced after deglaciation, partly due to increased marine and terrestrial productivity in the interglacial period. In the fiords of Baffin Island and in Baffin Bay, peak rates of sedimentation occurred between 9500 and 6500 years BP; deglaciation occurred at approximately 8000 BP. The effects of glacial scouring and the release of meltwater and older sediments from the ice may also have contributed to contamination. It was suggested that 'old' carbon contamination may be highest on the continental shelf, decreasing with distance into fiords, although this has not been proven. Although the Nachvak Fiord cores contain evidence of organic activity that suggests minimal reworking, the possibility cannot be discounted.

Fillon *et al.* (1981) noted that organic dates from sites on the continental shelves of south-east Baffin Island and northern Labrador were highly contaminated, while samples from southerly locations were more accurate. This is thought to be due to the difference in temperature with latitude, warm southerly waters encouraging more marine life and a higher productivity, with faster rates of decay and recycling than those occurring in the north. The amount of organic carbon produced and deposited, and the rates at which any older carbon is incorporated into modern sediments, is therefore faster in the south.

This information suggests that the organic matter date from core 107 is likely to be anomalously 'old', largely because it has such a low carbon content. It is possible that contamination took place through 'old' ^{14}C infiltration after deglaciation, and/or through reworking of sediments. The date is thus treated as an absolute maximum.

Some authors have attempted to quantify the degree of error associated with organic dates. Nambudiri, Teller and Last (1980) used the frequency of pre-Quaternary microfossils, as did Mudie and Guilbault (1982). It was argued that the reworking of fossils indicated reworking of 'old' ^{14}C, and thus possible contamination of younger sediments. Fossils of earlier Quaternary periods are equally likely to have been reworked, however, though this might not be easily detected. In this study, there was no obvious evidence of older or reworked pollen grains in any of the pollen sample levels, suggesting no older or reworked carbonate fossils.

King (1985) used sedimentation rates from cores with some radiocarbon dating control to calculate a 'correct' age for organic dates; pollen concentrations and rates of influx were used in the equation. Andrews *et al.* (1985) attempted to correct total organic matter dates by statistical means, using a number of core dates from their own studies and from the literature, and comparing abnormally 'old' organic dates with shell dates considered to be more accurate. Where these dates came from similar levels in a core, direct comparisons could be made. The result was an equation, in which O represents a date from organic material, and S represents an organic date corrected to a shell equivalent:

$$S = 706 + 0.65O$$

Using this equation, the 19,730 BP date from core 107 is 'corrected' to 13,530 BP. The error margin calculated by Andrews *et al.* is ±1700 years. While this figure might be suggested as a guide for the actual date of the sample, it must be recognised as an estimate; the equation was calculated from a limited data set derived mainly from Baffin Bay, and takes no consideration of local conditions of sedimentation. All references will be to the original date.

5.5. Rates of Sedimentation

Radiocarbon dating of cores 105 and 107 allows sedimentation rates to be calculated, and provides the date at which sedimentary environments changed. If it is assumed that rates were regular throughout deposition, the top 100cm of core 107 (shell date 7328 years BP) must have been laid down at a rate of 0.014cm yr^{-1} (73.3 yrs cm^{-1} or 0.14m ka^{-1}). Using the organic date (19,730 years BP) from 423cm depth, the rest of the core was deposited at a rate of 0.026 cm yr^{-1} (38.4yrs cm^{-1}, or 0.26m ka^{-1}). Deposition in the lower part of the core was therefore almost twice as fast as that in the upper part. These rates are presented in graphic form in Figure 5-5.

Nachvak Fiord core 85027-105 has a rate of 0.019cm yr^{-1} (51.7yr m^{-1}, or 0.19m ka^{-1}) in its top 100cm, and of either 0.20cm yr^{-1} (5.09yrs cm^{-1}, or 2.0m ka^{-1}) or 0.12cm yr^{-1} (8.4yr cm^{-1}, or 1.2m ka^{-1}) below, depending on which radiocarbon date is used from 422cm depth. Again, the lower part of the core was deposited much more quickly than the upper part, overall rates of sedimentation being faster in core 105 than they are in core 107. Rates presented in Figure 5-4; rates of both cores 105 and 107 are summarised in Table 5-5.

It should be remembered that these are piston cores and that they are unlikely to contain very recent sediments. Therefore, they do not date from the present day and some allowance

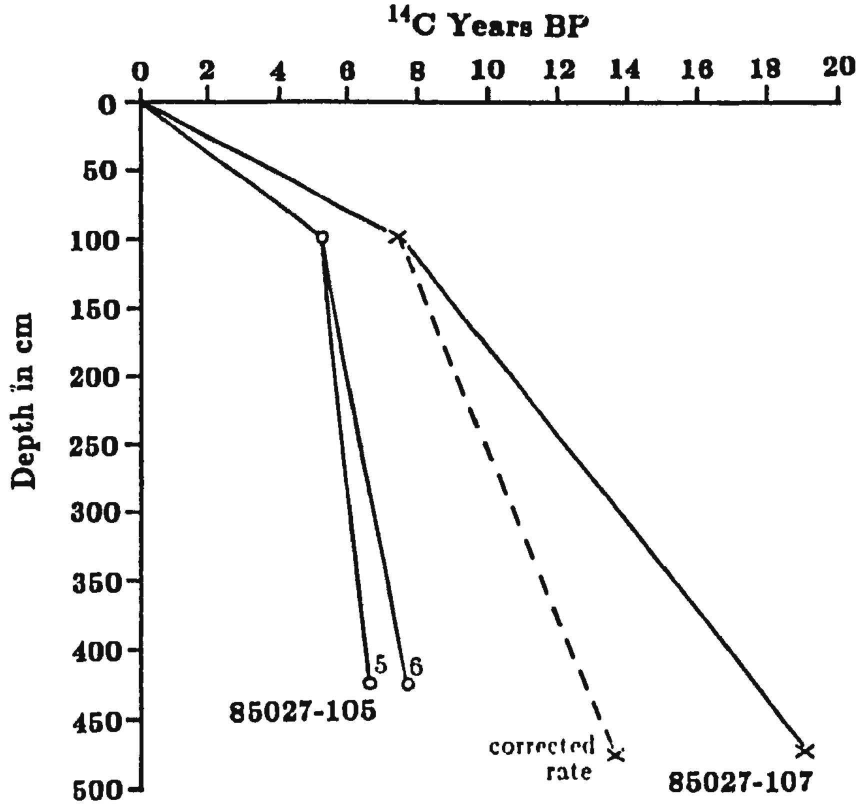

Figure 5-5: Rates of sedimentation in cores 85-027-105 and 85-027-107, determined from radiocarbon dates on shells; 'corrected' rate uses the equation devised by Andrews *et al.* (1985) for the age of total organic matter.

should probably be made for their age. Andrews (1987*b*) assumes that the 0cm level in a piston core represents 300 years BP, and calculates rates of sedimentation accordingly. For this example, the alternative rates do not differ greatly from those already given (see Table 5-4). The assumption is not made by all authors, so calculations are based on the original rates.

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[5]TO-422

[6]Beta 17870

Table 5-4: Rates of sedimentation in cores 85027-105 and 85027-107.

Depth (cm)	yrs cm^{-1}	cm yr^{-1}	m ka^{-1}
Core 85027-105	Rate of sedimentation		
0-100	51.70	0.019	0.19
100-422	5.09	0.200	2.00[5]
100-422	8.40	0.120	1.20[6]
Core 85027-107	Rate of sedimentation		
0-100	73.30	0.014	0.14
100-423	38.40	0.026	0.26
Where 0cm = 300 years BP			
Core 85027-105	Rate of sedimentation		
0-100	48.70	0.021	0.21
100-422	6.02	0.166	1.66[5]
100-422	9.32	0.107	1.07[6]
Core 85027-107	Rate of sedimentation		
0-100	70.30	0.014	0.14
100-423	39.30	0.025	0.25

Rates of sedimentation depend on (i) the amount of material available for deposition, (ii) the forces within the fiord influencing which particles will be deposited and which carried away, (iii) the distance of the coring site from the source of sediment, and (iv) any erosion taking place after initial deposition.

The amount of material available for deposition is influenced by a wide variety of factors: the areal size and thermal regime of the glacier; its state of advance or retreat, and how it might be retreating (rate of melting and of calving) and the nature of the fiord itself (presence of talus slopes, abundance of loose fluvial or glaciofluvial material, the angle of slopes above and below the water line, the morphology of the fiord bed). Factor (ii) is also affected by the nature of the fiord and the glacier: meltwater streams produce overflow and underflow currents which may be

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[5]TO-422

[6]Beta 17870

capable of carrying sediment of considerable size for long distances; steep slopes and loose debris add to the likelihood of high volumes of sediment and of slumping; differences in water temperature might produce traction currents; and the relief of the fiord bottom might promote density flows and resedimentation. Factor (iii) is included as depositional rates appear to decrease with distance from the position of an ice front: continental shelves receive very little sediment, whereas the amount increases with distance upfiord. This results from the existence of basins within a fiord, since basins act as sediment traps collecting both coarse and fine deposits before they can reach the ocean. Finally, erosion may occur as a result of strong current activity or iceberg scouring, so removing material that was already deposited, or causing selective deposition and leaving a lag deposit of coarse particles only.

The sedimentation rates seen in Nachvak Fiord can probably be explained through local conditions of sediment supply and deposition. A faster rate would be expected during deglaciation since a glacier carries large volumes of mostly fine material which must be deposited on ice melt. The volume of material carried fluvially is much less by comparison, so a smaller amount of sediment would be deposited in the upper 'non-glacial' section of a core in the same given period of time. Rates of sedimentation are expected to be faster down-core, as greater quantities of glacial debris would likely be deposited earlier in the deglacial sequence. Acoustic units D, E and F (Bell, 1987) and C, D, and E (Rogerson, Josenhans and Bell, 1986) represent the considerable depths of such material already laid down in these basins. Thus rates seen in the tops of cores 105 and 107 are likely to be much slower than those of the lower units, while rates in the upper section of both cores are slower than those of the lower parts. Andrews *et al.* (1985) found that sedimentation rates in a number of Baffin Bay fiords were much higher during deglaciation than they were afterwards (a peak was reached between 9500 and 6500 years BP). The same explanation might be offered for the extremely high rates being observed in Muir Inlet (2 to 9m yr^{-1} since 1960), where the Muir Glacier is actively retreating (Powell, 1981; Molnia, 1983).

Rates in core 105 are considerably faster than those of core 107 for both sections. This was unexpected since each basin in a fiord appears to act as a sediment trap, causing rates of sedimentation to decrease downfiord and leaving very little material to be deposited on the continental shelf. However, the nature of the basins in Nachvak Fiord does offer some explanation. Ivitin Basin may have been fed by Tallek Arm sediments as well as by those of the fiord. Townley Basin can have received sediments only from Tasiuyak Arm. The sediment output of rivers flowing into Ivitin Basin might have been greater than that of rivers flowing into Townley Basin. Also, the depth of Ivitin Basin (170m) probably promoted sedimentation, by providing quiet conditions removed from the influence of tides and waves. The shallower Townley Basin might be subject to greater wave and tidal influences, producing a more turbulent environment and perhaps preventing deposition of fine materials. Erosion might have taken place during deposition of the upper section of core 107 or core 108.

Rates of sedimentation in Nachvak Fiord were compared with rates from fiords and bays elsewhere in the Arctic. As expected, they are lower than most, particularly where currently retreating modern glaciers occupy fiords; rates are fastest where deglaciation is actively taking place (eg. Gulf of Alaska; Molnia and Carlson, 1978). Nachvak Fiord rates are most similar to the lower end of ranges given for fiords in Baffin Bay, as expected given generally similar conditions of climate and glaciation, and also considering the advanced state of deglaciation during which these cores were deposited.

The slow rates of sedimentation offer no insight to the rate of ice retreat or the thermal regime of the glacier tongue that occupied Nachvak Fiord. As mentioned previously, the rates are likely to be very strongly influenced by the local conditions of the basins themselves, and cannot be explained by broad regional factors without more information.

5.6. Pollen Analysis

Pollen analysis has been used as a stratigraphic tool in the evaluation of cores 107 and 108. Pollen spectra from the Townley Basin cores have been correlated with those of other cores from north-eastern Canada, using alterations in the frequencies of different taxa as stratigraphic markers. If it can be assumed that the same environmental conditions effected an entire region and produced similar changes in vegetation within that region, then those vegetative changes should be visible in the pollen records of most cores. It is possible to assign approximate dates to pollen spectra which have no absolute dates using this method. For this study, correlation of cores provided an alternative method of 'dating' the lithostratigraphy and offered tentative conclusions regarding changing environmental conditions within the fiord over time.

5.6.1. Use of Pollen Analysis as a Stratigraphic Tool

Cross-correlation of cores is based on the assumption that the pollen rain of a particular region reflects the vegetation of that region. In addition to local pollen grains from the immediate area, there is usually a certain amount of regional pollen in any sample; however, 'regional' grains may have travelled long distances, in which case they might be regarded as exotic to the vegetative region being studied. Study of modern pollen rain, its source areas, methods of transportation and relationship to the vegetation of the immediate area is the only way in which fossil pollen spectra can be interpreted. It is vital for both the correlation of stratigraphies and the reconstruction of environmental conditions.

Labrador has been divided into 4 or 5 climatic/vegetative regions (Short and Nichols, 1977; Lamb, 1984); Nachvak Fiord falls into the tundra zone in most descriptions. Studies of modern pollen spectra show that these regional vegetation assemblages are reflected in the pollen rain. Most studies give a broad impression of modern pollen fallout, presenting results in isopoll maps which enclose areas of approximately equal pollen frequency. Elliott-Fisk *et al.* (1982) used samples collected from 39 terrestrial sites in the central-eastern Canadian Arctic to draw percentage isopoll maps for eight taxa. The data were related to regional vegetation and climate characteristics, and, through factor analysis, it was shown that pollen assemblages are regional and do relate to particular vegetation zones. Nachvak Fiord is between the 'low Arctic mesic shrub community', characterised by Ericaceae, *Betula* and *Pinus*, and the 'low Arctic floristic zone' with *Salix*, Cyperaceae and Gramineae.

Lamb (1984) sampled seventy-four small lakes from the different vegetation zones of Labrador. He drew isopoll maps showing percentage frequencies of eight key taxa throughout Labrador, and summarised the spectral characteristics of each vegetation zone. Nachvak Fiord is in his tundra zone, and is characterised by $< 25\%$ *Picea*, at least 15% *Alnus* and *Betula*, 2% *Salix* and up to 4% Ericaceae. Cyperaceae were dominant at 30%; other herbs and spores of *Lycopodium, Filicales* and *Sphagnum* were also observed.

Given this information, it seems reasonable to assume that fossil pollen spectra also reflect a regional vegetation, and thus that a comparison of cores from the same vegetation community would show correlative features. However, factors such as long distance transportation of 'exotic' pollen grains, and the marine environment of a fiord situation should also be taken into account.

Aerial transportation is considered to be very important in more northerly locations such as Baffin Island and Baffin Bay (Short, Mode and Davis, 1985), and in offshore areas (Mudie, 1982). Although the actual number of wind-borne pollen grains may not be very high in these latitudes, a drop in the concentration of all pollen grains north of 52° N (Mudie, 1982) means that they are strongly represented.

The site of cores 106 and 107 is likely to have received pollen from both local and regional sources. Numerous streams entering Townley Basin carry in pollen, as do winds blowing east-west through the fiord trough and north-south through Tallek Arm and Kogarsok Brook valley. Pollen grains from the valleys and vegetated banks of the fiord would also be deposited. These sources, and perhaps others, would have existed throughout the deglacial period. Mudie notes that air-borne exotic pollen is usually deposited close to the coast, where warm and cold air mixes and fogbanks form; while such a source is unlikely to be important today, it may have been in the past, when different temperature regimes dominated in the fiord. There was, therefore, ample opportunity for regional and long-distance pollen to enter the fiord environment. For this reason, accurate reconstruction of the vegetation and environment of the fiord at particular periods of time is not possible; pollen spectra almost certainly represent regional vegetation.

Nachvak Fiord is a tidal, saltwater marine environment, therefore the pollen assemblages of cores might potentially resemble those from the continental shelf. This is considered unlikely, however, as the site of cores 107 and 108 is about 40km inland, surrounded by steep fiord walls, and probably has a depositional environment more like that of a lake. Fiord basins with dividing sills and considerable depths of sediments suggest that ocean current influences are minimal.

The depositional environment of the ocean is very different from that of terrestrial lake sites. Deposition is thought to be near-continuous in an oceanic environment, and thus long records of climatic events may be obtained, often covering hundreds of thousands of years. Dating controls are good, since shell fragments or organic layers are often common and relative chronologies may be applied through oxygen isotope analysis or the identification of volcanic ash horizons. Chronostratigraphic correlation of oxygen isotope stages (Shackleton and Opdyke, 1973) has probably been the most useful method of dating. Pollen grains and spores are the most common microfossils to be found in oceanic or continental shelf sediments (Mudie, 1982). They allow terrestrial and oceanic pollen spectra to be correlated, and provide a means of comparing climatic events and estimating past patterns of air and ocean current circulation.

Despite these advantages, marine cores are not very useful when short periods of deposition are to be correlated. Slow rates of sedimentation leave very short depositional records and thus condense pollen spectra. Each period of climate change might therefore be represented by only a thin section of sediment, leaving visible only major climatic events. Scott *et al.* (1984) note that less than 1m of sediment often represents all of the postglacial period in deep sea cores; a core from the south Labrador Sea was shown to cover 300,000 years in 9m (de Vernal and Hillaire-Marcel, 1987*a*); in Notre Dame Bay, Newfoundland, the entire Holocene sequence was found within 17cm of sediment (Macpherson, 1988). These examples demonstrate the difficulties of correlating a long and detailed lake core with a short marine core section.

Related to this is the fact that oceanic cores do not respond to changes in ice margins taking place either inland or on the continental shelves (Scott *et al.*, 1984); their record is therefore incomplete as regards minor climatic fluctuations which might be compared with the terrestrial fossil pollen record.

A further problem with the correlation of marine and terrestrial cores involves the origin of pollen deposited in the ocean environment. Pollen grains may travel long distances prior to deposition on land or in a water body; once in the sea they may travel further under the influence of fluvial or ocean currents, tides and prevailing winds. Pollen assemblages might therefore be seen to change due to changes in the origin and distribution mechanisms of the grains, rather than by climatic change alone.

Reworking of older sediments is also more frequent in marine cores. Disturbances may be caused by fluvial drainage, iceberg scouring, ocean currents and tides, slumping, bioturbation and the like. This disruption of chronological order makes pollen assemblages difficult to interpret. Pre-Quaternary pollen grains may be distinguishable from more recent grains because of their colouring and degree of corrosion; they may therefore be excluded from the pollen count (eg. de Vernal and Hillaire-Marcel, 1987*a*). However, Quaternary grains of different ages are often impossible to differentiate.

Marine and fiord environments have significant differences when compared. Much faster rates of sedimentation in fiords emphasise their similarity to lake sites and their suitability to studies of pollen assemblages. Given the difficulties of interpretation of marine core spectra, no attempts have been made to correlate them with the Nachvak Fiord cores. Recently, pollen analysis of cores taken from the continental shelf at the mouth of Nachvak Fiord began; this should provide an interesting comparison when the results become available.

Pollen analysis on cores taken from fiords appears to be rare. A few examples from Baffin Island fiords do provide some data which can be compared with the Nachvak Fiord data, although emphasis has been placed on sedimentation rates and the problems of radiocarbon dating (eg. Andrews *et al.*, 1985; Andrews, 1987*a*, *b*). These data have not been published as pollen spectra, however, making correlations impossible.

5.6.2. Fossil Pollen Analysis in Northern Labrador

Pollen diagrams from north-eastern Canada indicate that climate changes were broadly similar throughout the Holocene. Individual spectra from different vegetation zones vary in their representation of plant species frequency and dominance, as expected over such a broad area. The Holocene was characterised by periods of warming and cooling; most easily distinguishable in pollen spectra is an amelioration about 6000 BP, and a general cooling that occurred about 2500-3000 years BP (Bartley and Matthews, 1969; Short and Nichols, 1977; Short, 1978; Lamb, 1984). The vegetation and climate history of northern Labrador has been continuously refined, although there are problems with radiocarbon dates in some spectra.

Modern research north of the tree-line began relatively recently (Nichols, 1967; Bartley and Matthews, 1969). Several cores from lakes in and around the Torngat Mountains have been analysed, however, providing a number of spectra with which the Nachvak Fiord cores can be correlated. A sampling programme carried out by Ives, Nichols and Short (1976) led to a series of papers that discussed the results of cores taken from six lakes north of the tree-line but south of the Torngat Mountains in north-central Labrador (Short and Nichols, 1977; Short, 1978). Patterns of warming and cooling shown by these cores were broadly correlative for both the vegetation assemblages and their dates of arrival. Briefly, the data showed a dry, cold tundra episode after deglaciation at all sites, its duration depending on the time at which each site became ice-free. The earliest recorded deglaciation was at 10,300 BP (Ublik Pond); other sites experienced a tundra vegetation between 8600 and 5000 years BP. At approximately 6500 BP, a highly productive shrub-tundra became apparent, indicating a warm climate; prevailing southerly winds are thought to have carried alder and birch pollen northward from woodlands in the south. Between 4200-4500

BP a transition to open spruce woodland took place, possibly an indication of still warmer conditions since the spruce arrived almost simultaneously at several locations. This lasted for only a short time, however, as alder, birch and spruce frequencies declined about 2500-3000 BP, and a more open vegetation with lower rates of productivity became apparent in all six lake sites. This cooler and drier environment is thought to have continued, with minor fluctuations, into the present.

Lamb has investigated the vegetation history of Labrador, firstly in the south-eastern forested area (1980) and then in more central and northerly regions (1984, 1985). He has analysed both modern and fossil sediment samples, and has worked in areas close to Nachvak Fiord. Of particular interest to this study is Lamb's description (1984) of pollen frequencies from Hebron Lake (58° 12' N, 63° 02' W). The history of this site should be comparable to that of Nachvak Fiord, since, although it is approximately 100km to the south of the fiord, it is at an altitude of 170m. Hebron Lake appears to have followed a succession from a snowbed community (sparse sedges and herb species, mainly *Ranunculus* and Gramineae, plus a little birch) at 8350±85 BP (Q-2076) to a more stable sedge-willow community, with increasing birch. *Alnus crispa* immigrated about 6000 BP, just after a peak in birch frequencies and as *Ranunculus* and Cyperaceae declined. This birch-alder shrub cover was characterised by maximum pollen concentrations, and the presence of *Picea* about 4500 BP. Spruce pollen was probably blown into the area from low-lying woodland to the south. The birch-alder shrubland appears to have continued until 3000 BP, when Cyperaceae increased in importance and *Alnus* and *Betula* began a decline. It was followed by a more open tundra environment, with sedge-willow communities, characterised by high frequencies of various herb and moss species as well as Cyperaceae and *Salix*.

The pattern of climate deterioration after 3000 years BP is reiterated in Lamb (1985), where four lakes in central Labrador (between 55° N and 57° N) were analysed with regard to the tree-limit in their surrounding area. The tundra component of all sites increased after approximately 3000 BP, corresponding with above-mentioned indications of a cooler and drier climate at that time.

Cores extracted from four lakes in the Torngat Mountains represent the only lacustrine pollen analysis to have been carried out near Nachvak Fiord. One core from Square Lake was collected in 1978 and has recently been analysed by Clark *et al.* (*in press*). Three other lakes, plus Square Lake, were cored by T. Bell, A.K. Dyer, R.A. Klassen and R.J. Rogerson in August 1985. Adams Lake and Gurnot Lake are immediately south of Nachvak Fiord.

The cores collected in 1985 were described and subsampled at the GSC in Ottawa, then analysed for pollen at Memorial University by A.K. Dyer. Interpretation was by Elliot Burden of the Department of Earth Sciences at MUN. Pollen grains, spores and dinoflagellate cysts were included in the count. The CONSLINK computer programme (Gordon and Birks, 1972) was used to analyse the spectra, which displayed four local pollen assemblage zones[7] with only slight statistical differences between each. Although no results have yet been published, seven diagrams and a report were made available to the author.

The spectra are largely similar to those of other northern lake sites, as previously described. They follow a sequence from a sedge-herb tundra, to a shrub-tundra with dominant birch and alder, and then return to a herb tundra with more diverse species representation. The relative frequencies of species present are tabulated below (Table 5-5); four assemblage zones are seen in up to seven separate cores, and thus no single diagram exists to display all the zones. Only three cores from two sites (Adams Lake and Square Lake) showed all four zones.

Radiocarbon dates were obtained on cores from Adams Lake (AL3b), Brimful Lake (BL6b) and Square Lake (SL4). An organic layer at 191-192cm depth provided a date of 22,090±170 years BP (TO-640) in Zone I of the Adams lake core. The Brimful Lake date was obtained from moss stems found between 175.5-178.5cm depth. It gave sediments an age of 6,890±80 years BP (TO-639). This dates the base of Zone II, where Cyperaceae percentages rise rapidly and *Salix* and Ericaceae peaks at 10%. The Square Lake date is the second to be obtained from this site. It was initially cored in 1978 in an attempt to date the Saglek Moraines, a segment of which dams Square Lake. Short (1981) reports a date of 18,210±1900 years BP (GX-6362) from the base of a 97.5cm core. The 1985 core provided a date of 15,760±300 years BP (TO-641) from 64.5-66.5cm depth, at the base of Zone III. More radiocarbon dates have since been obtained from the 1978 core (Clark *et al.*, *in press*).

[7]An assemblage zone is defined by Hedburg (*in* Birks and Birks, 1980) as "a body of strata whose content of fossils, or of fossils of a certain kind... constitutes a natural assemblage or association which distinguishes it in biostratigraphic character from adjacent strata". A pollen zone is more specific biostratigraphic unit, defined as "a body of sediment with a consistent and homogenous fossil pollen and spore content that is distinguished from adjacent bodies in the kind and frequencies of its contained fossil pollen and spores" (Birks, *in* Gordon and Birks, 1972, p.962).

Table 5-5: Summary of pollen record in four lakes in the Torngat Mountains: Adams Lake, Brimful Lake, Gurnot Lake and Square Lake[8]

Zone	Discription
ZoneIV	decline in shrubs: *Alnus* 10-20%, *Betula* < 20% Cyperaceae consistent ~20% *Picea* ~20%, *Pinus* ~10% concentrations decline, < 5000 grn g^{-1}
Zone III	peak *Alnus*, 40% *Betula* 10-20% Cyperaceae < 20%; other herbs very low *Picea* rising, ~20% concentration maximum > 5000 grn g^{-1}
Zone II	peak Cyperaceae > 50% Gramineae declining, 10% to 0% *Alnus* < 30%, *Betula* < 20%, *Salix* < 10% *Picea* and *Pinus* < 10% - exotic concentrations 4000-5000 grn g^{-1}
Zone I	dominant herbs; shrub frequencies < 20% Gramineae 20% Cyperaceae 40-50% concentrations 1000-2000 grn g^{-1}

These dates ought to be considered with some caution; growing evidence indicates that organic matter within waterbodies is likely to contain 'old' ^{14}C-deficient carbon. Contamination of deposits can occur, apparently quite easily, leading to anomalously 'old' radiocarbon dates. This happens when it is incorporated into a sediment, which may take place in a number of ways (section 5.1.4). MacDonald *et al.* (1987), working in southern Alberta, found that an aquatic moss (*Drepanocladus crassicostus*) gave radiocarbon dates consistently older than those provided by terrestrial macrofossils and an independent dating control (Mazama ash). This is partly due to the fact that ^{14}C-deficient carbon is being incorporated into the moss through chemical processes in photosynthesis, such that even modern samples give an 'old' date. It was suggested that this throws dates from all aquatic mosses into some doubt, and, since mosses are likely to make up a considerable amount of the organic material in any northern lakes or ponds, all such dates might

[8]unpublished data, J.B.Macpherson, personal communication, 1988.

be considered dubious. Given these possibilities, all of the radiocarbon dates mentioned above might be considered to represent maximum ages for these sediments.

Reworking, the process by which older sediments become mixed with younger sediments, is thought to be common, especially where current activity is high or there is the danger of slumping. The 'hard water effect', occurring when photosynthesis takes place underwater in the presence of 'old' carbon (Deevey *et al.*, 1954), means that plants (and therefore sediments) incorporate ^{14}C-deficient carbon into their tissue. Sutherland (1980) found that 'old' carbon dioxide released by glacial meltwater may also be incorporated into waterbodies, soils and plants after deglaciation. Sutherland (1980) and King (1985) describe ways in which glacial scouring can make 'old' carbon available from bedrock, particularly carbonates but also granites and metamorphosed rocks. Recently deglaciated regions may therefore be more prone to contamination with ancient carbon. Clark *et al.* (*in press*) also consider redeposition of pollen grains transported by ice to be a potential contaminant.

Comparison of the dates and zones identified in the Torngat lakes suggests that the dates are erroneous. Assuming the Adams Lake date to be a maximum, Zone 1 must have begun prior to 22,000 BP. The dates from the *Br...ful* and Square Lake cores are not in sequential order, however, showing the base of Zone 2 to be 6890±80 years BP and the base of Zone 3 to be 15,760±300 BP. Most other northern lake sites show concentrations and percentage frequencies of alder and birch to increase at about 6000 BP, and decline around 2500-3000 years BP, significant dates which might be expected from zones 3 and 4. It is possible, though it seems unlikely, that the assemblage zones recognised here do not represent the accepted deglacial vegetation sequence.

The single Square Lake core described by Clark *et al.* (*in press*) displayed a pattern of vegetation change basically similar to that found in the Torngat Lakes (J.B. Macpherson, personal communication, 1988), although five pollen assemblage zones were recognised and dates are sequential throughout the core. The lowest deposits are thought to have been laid down close to an ice margin; there are a large number of crumpled and/or reworked pollen grains, concentrations are extremely low [200-600 grains per gram of sediment at dry weight (grn gdw^{-1})], and the percentage of organic matter is low. *Alnus* and *Betula* are dominant; small herbs and grasses are also important. Although the maximum age for deglaciation at this site is considered to be 8,000 years BP, Zone I is thought to be older than 8,500 BP.

Zone II dates between 8,500 and 7,800 years BP. It too is thought to have been deposited close to the ice margin, though pollen concentrations begin to rise slightly. Gramineae and Cyperaceae are dominant, reaching maximum frequencies at 70-80cm depth; a sparse vegetation of grasses and sedges is suggested.

An overall increase in concentration characterises Zone III. *Alnus* and *Betula* frequencies also rise considerably. An increase in organic matter and in pollen influx is interpreted as evidence of a rich shrub-tundra vegetation, with locally abundant alder and birch; spruce probably grew in central Labrador. The warming period represented by this zone appears to have started before similar warm periods observed in other pollen diagrams (eg. Short and Nichols, 1977; Short, 1978; Lamb, 1984, 1985), as it dates between 7800 and 4700 years BP.

Zone IV maintains this rich shrub-tundra, although *Alnus* begins to decline and Cyperaceae reaches a low peak here. Concentrations are again high. The frequency of *Picea* pollen grains peaks at 40%, though the conifer is not thought to be local.

A regional cooling appears to occur after 2000 years BP, in Zone V. Overall concentrations are lower, particularly of *Alnus* which also declines in frequency. Cyperaceae values increase again, in both concentration and frequency. Although *Betula* frequencies remain high, it is thought that there was an increase in the tundra component of the forest-tundra vegetation. This would correspond with the cooler and drier climate observed in other pollen diagrams after approximately 3000 BP.

There are relatively few correlations of oceanic pollen spectra from the Labrador Sea and those of terrestrial cores; where comparisons have been made the Holocene record of deep sea cores have been shown to reflect certain characteristics of the terrestrial cores described. De Vernal and Hillaire-Marcel (1987*a*) report a definite rise in *Picea* frequencies midway through the postglacial record, a result of the northward expansion of spruce woodland. *Betula* and *Lycopodium* species also rise. There is a decline in tree pollen accompanied by an increase in tundra pollen toward the top of the postglacial sequence. De Vernal and Hillaire-Marcel (1987*b*) compare stratigraphies from cores collected in the southern, eastern and western Labrador Sea. *Pinus* pollen grains dominate all three pollen spectra, indicating their capacity to be transported aerially for long distances. Otherwise, offshore pollen stratigraphies of the postglacial period (oxygen isotope stage 1) compare favourably with those of terrestrial lake cores. Core 84-030-021 was taken from the continental rise off north-central Labrador, south of the Torngat Mountains. It indicates a shrub-tundra rich in *Betula, Alnus* and *Lycopodium*, which occurred after 11,000 years BP, followed by a coniferous forest assemblage at about 4000 BP. *Picea* dominates this second assemblage.

Mudie and Aksu (1984) demonstrate a similar sequence from core 77-027-017 (from the Davis Strait, between Baffin Island and Greenland), although the importance of coniferous pollen is reduced. In oxygen isotope stage 1, the relative dominance of pollen species alters from high percentages of *Artemisia* and Gramineae, to *Betula* and then *Alnus*. Overall concentrations increase with time.

Cores from the Labrador continental shelf are more common than deep sea cores, probably because they are more accessible. Most were collected in order to verify acoustic interpretations of shelf sediments. Few have been analysed for pollen, however, leaving little data for comparison with the fiord cores. Vilks and Mudie (1978) report a sequence very similar to that of coastal lake sites in a core from the shelf off Hamilton Inlet. Pollen stratigraphies demonstrate an early postglacial sedge-shrub tundra vegetation, followed by an increase in shrubs such as *Alnus* and *Betula*, and then a dominant coniferous assemblage. A late decline (2000 BP) in the relative representation of *Picea*, accompanied by an increase in *Betula* and *Alnus*, indicates an expansion of forest-tundra vegetation. Radiocarbon dates on total organic matter suggest that the timings of these events are very similar to those onshore, although a date of 22,000 BP for the beginning of the sedge-shrub tundra episode is apparently inconsistent with other chronologies in that it is as much as 10,000 years too old.

Pollen analysis on Baffin Island and in Baffin Bay has progressed rapidly in recent years. Publications suggest that a vegetative sequence broadly similar to that described was experienced, with differences in the variety and relative representation of taxa (Short, Mode and Davis, 1985). Exotic coniferous pollen was abundant, a reflection of the low concentrations of naturally-occurring pollen and the capacity of these grains for long-distance transportation.

5.6.3. Nachvak Fiord Cores 107 and 108

Pollen samples were extracted at 25cm intervals from core 107, providing 18 sample levels. Three samples at 2cm, 25cm and 50cm depth were obtained from core 108. The samples were processed and the pollen grains counted at Memorial University; standard procedures were followed, as outlined in Appendix B. The POLSTA computer-graphics programme (Green, 1985) was used to manipulate raw data and construct the diagrams. Pollen from trees, shrubs and herbs was included in the pollen sum. A relatively low sum of 100 was considered acceptable as a representation of regional vegetation at this latitude, based on other work done in Labrador and Newfoundland (eg. Morrison, 1970; Macpherson and Anderson, 1985). In the case of core 108, a sum of 100 was easily reached in all three samples; however, despite counting multiple slides, it was reached in only three samples out of 18 in core 107. The sums for the other samples ranged between 35 and 99, as shown on the diagrams of pollen concentration. These low sums are assumed to be a result of very low plant concentrations, perhaps complimented by fast rates of sedimentation.

Figures 5-6 and 5-7 show the percentage frequencies and concentrations of pollen grains and spores at each level within core 107, Figures 5-8 and 5-9 showing the same information for core 108. No great reliance is placed on the differences in the representation of taxa between individual levels, due to the inexperience of the author at pollen grain recognition. However, general patterns within both cores are consistent, and allow core 107 to be divided into two pollen assemblage zones. The assemblage zone of core 108 is basically similar to the upper zone in core 107, though a separate zone is tentatively assigned to the top of core 108.

Core 107

This core is divided into two pollen assemblage zones, with a subzone in the lower assemblage. Zone I (100-425cm depth) is characterised by high herb pollen percentages and low relative frequencies of shrubs. Cyperaceae are dominant, with over 50% representation and maxima $> 70\%$. Gramineae are also important with consistent frequencies of 10-20%. *Artemisia* are common in the early part of the zone, with up to 10% abundance. Other herbs are consistently present in trace amounts, as are *Lycopodium* and *Filicales* spores (5-15% representation). *Alnus* and *Betula* have relative representations of 5-15% although *Betula* fluctuates widely; *Salix* is consistently present at $\sim 5\%$. Coniferous pollen is irregular, with trace amounts below 5%.

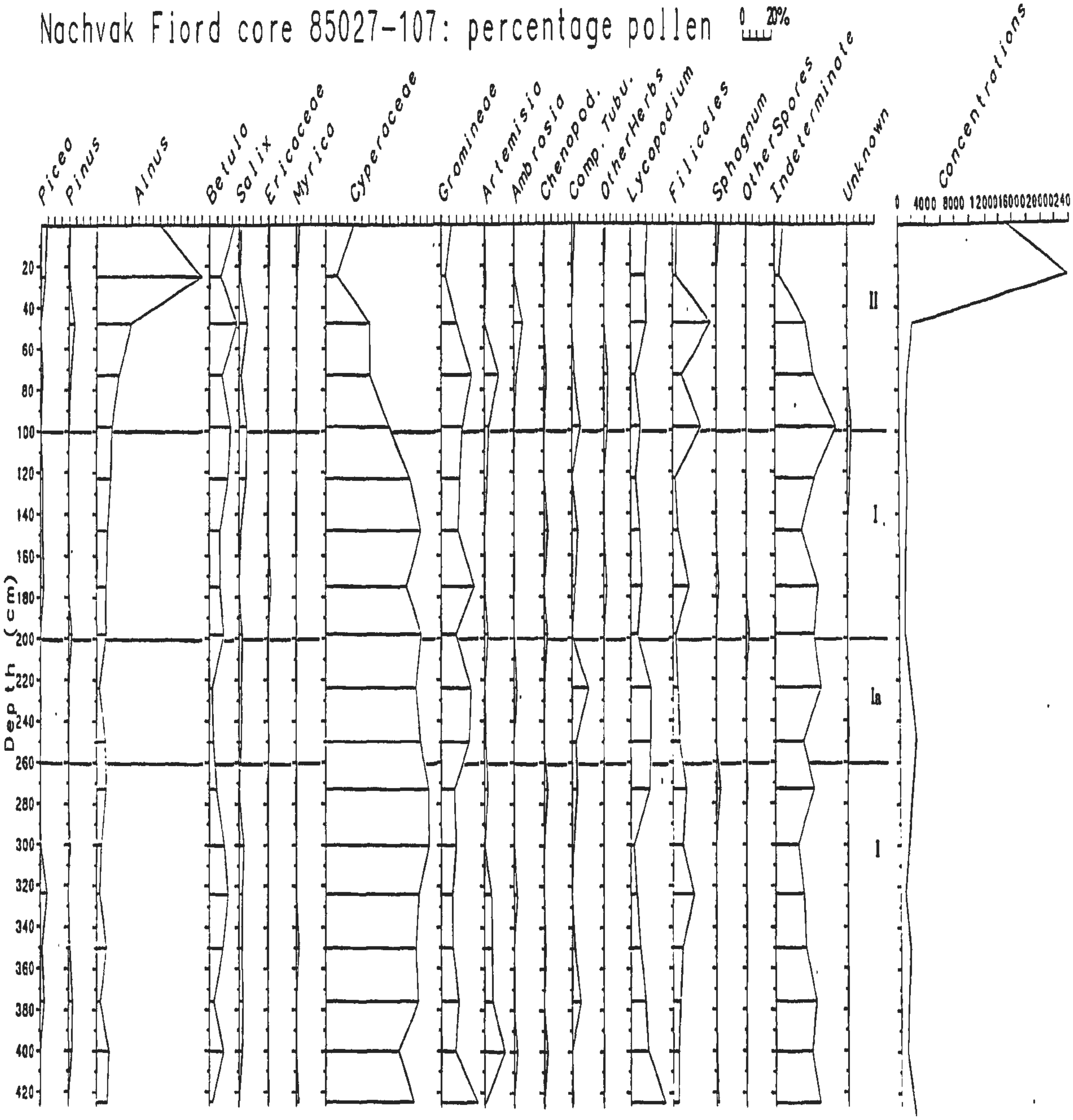


Figure 5-6: Diagram to show percentage frequency of key pollen and spore taxa in core 85-027-107.

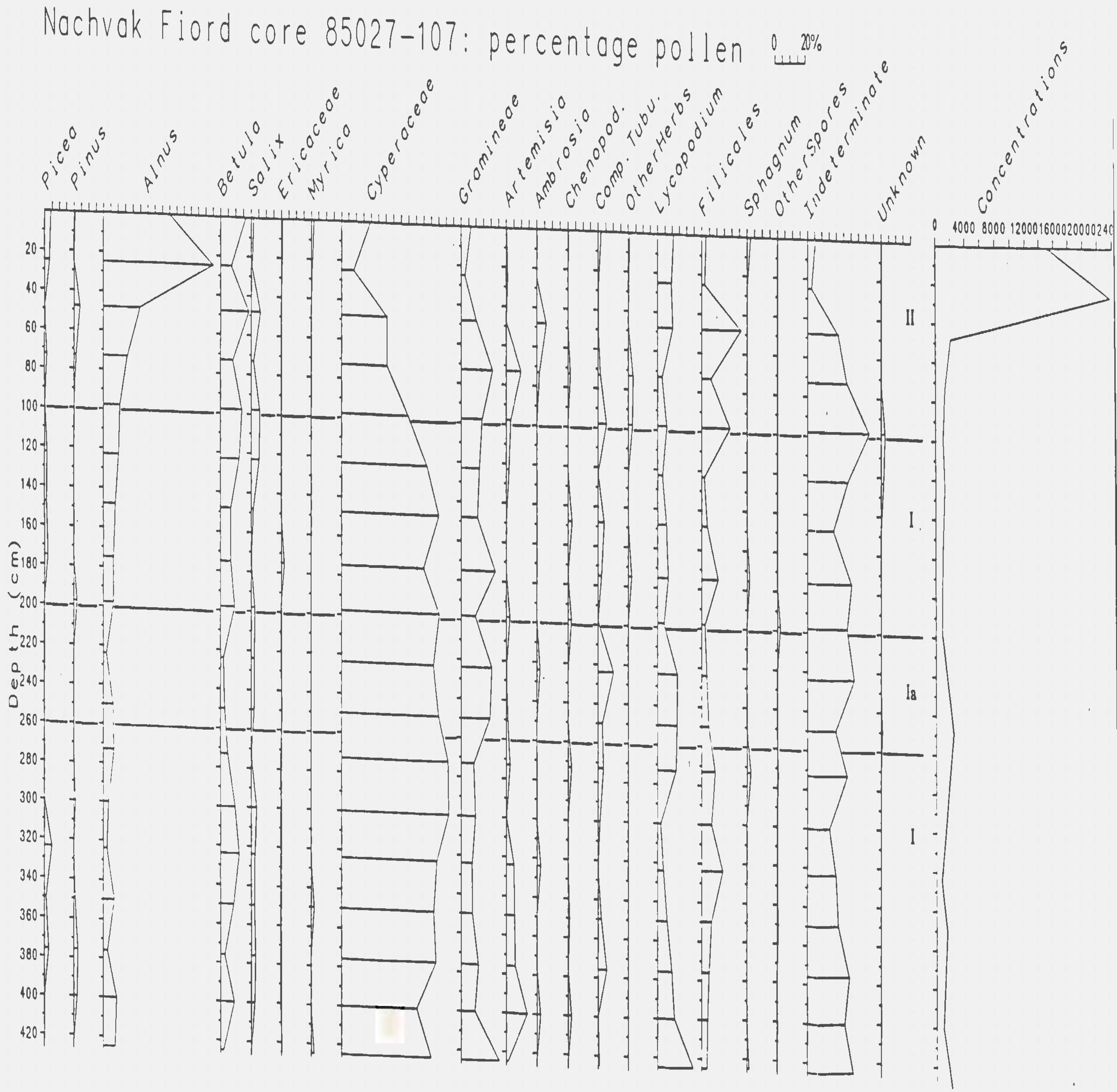


Figure 5-6: Diagram to show percentage frequency of key pollen and spore taxa in core 85-027-107.

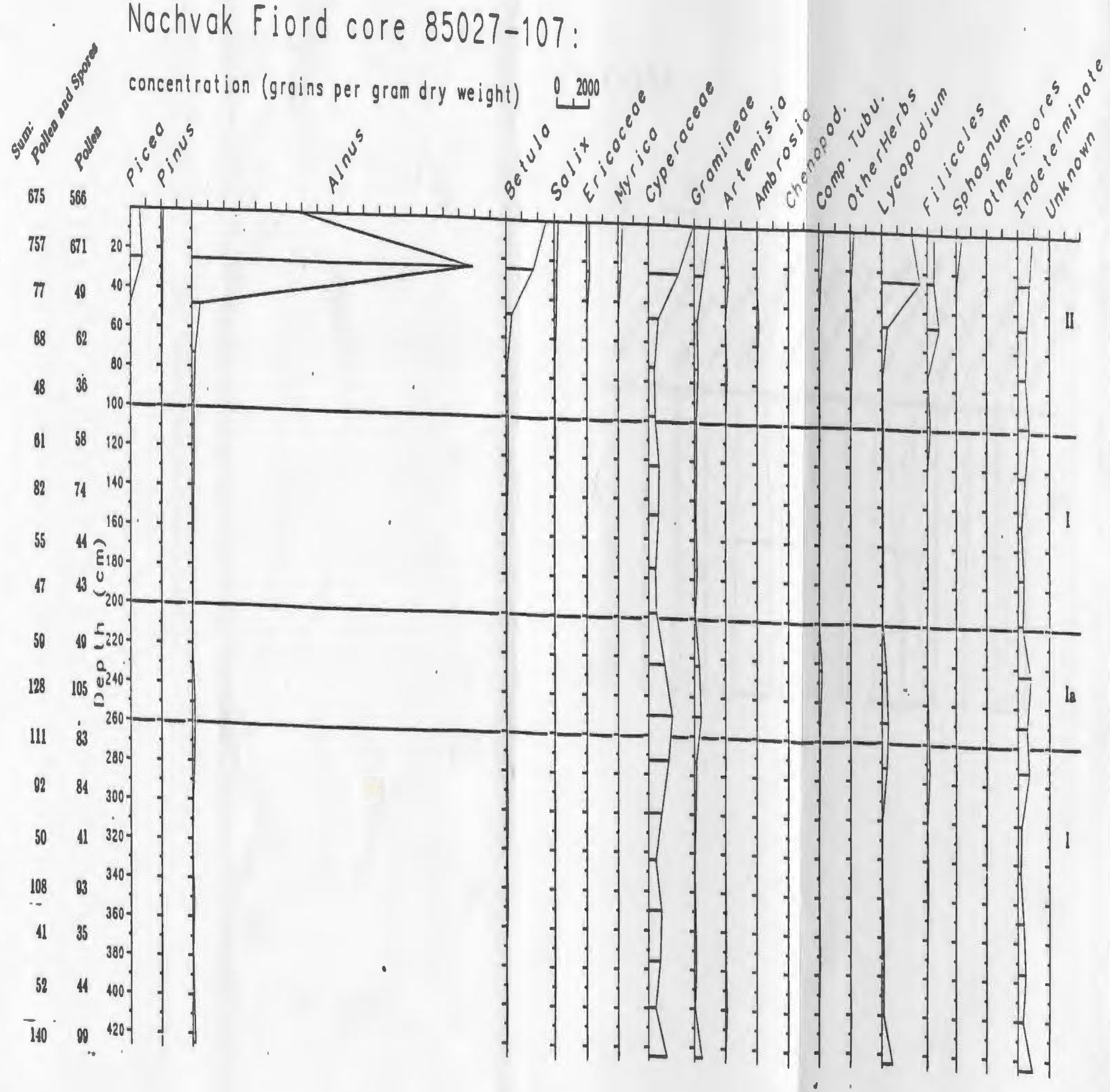


Figure 5-7: Diagram to show absolute concentrations of key pollen and spore taxa in core 85-027-107.

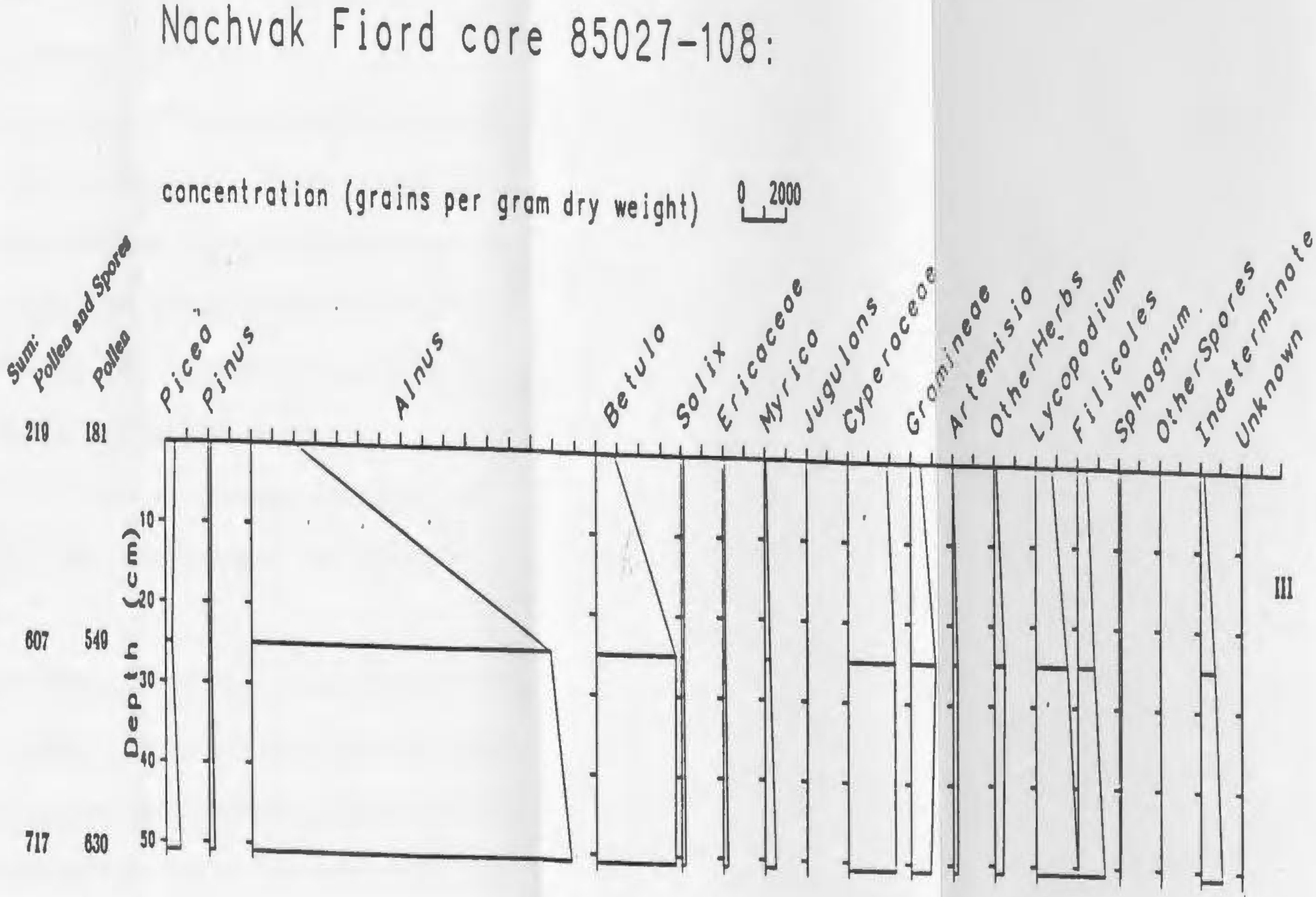
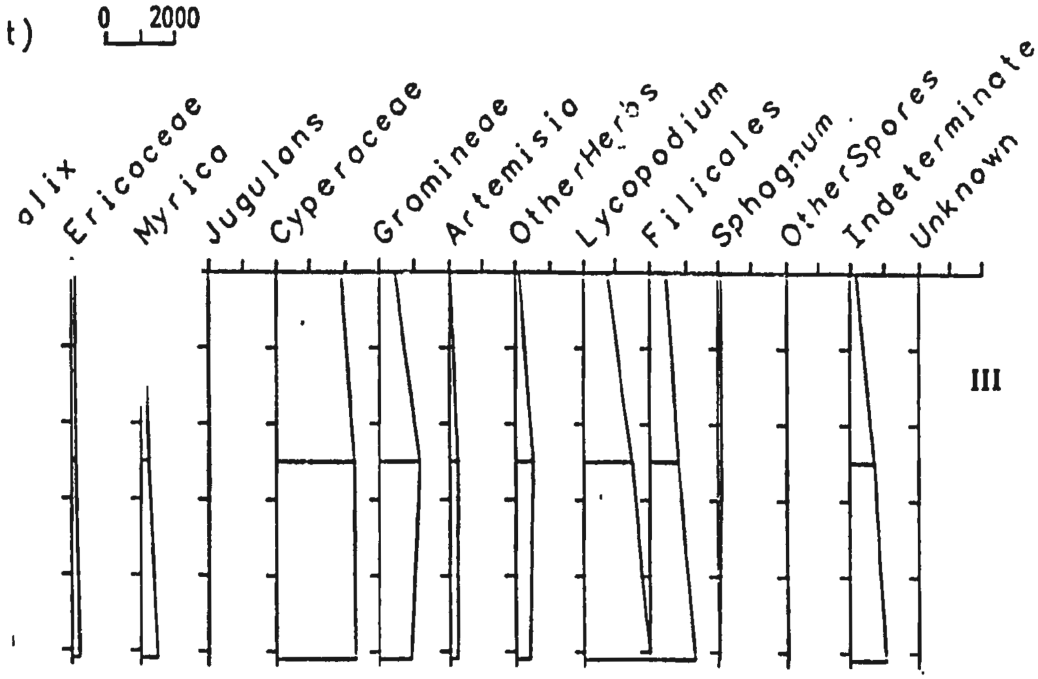


Figure 5-9: Diagram to show absolute concentrations of key pollen and spore taxa in core 85-027-108.

108:


t)
0 2000
alix
Ericaceae
Myrica
Jugulans
Cyperaceae
Gramineae
Artemisia
OtherHerbs
Lycopodium
Filicales
Sphagnum
OtherSpores
Indeterminate
Unknown
III

Pollen grain concentrations are very low throughout this zone. Total concentrations are between 1000-1500 grn gdw^{-1}, dropping to 7,480 grn gdw^{-1} at ~325cm depth. Concentrations of individual taxa rarely exceed 200 grn gdw^{-1}, excepting Cyperaceae, which has up to 1,560 grn gdw^{-1} in subzone Ia, and ranges between 460 and 1,325 grn gdw^{-1} otherwise. Gramineae concentrations are also relatively high, with a maximum of 460 grn gdw^{-1} in subzone Ia. Total concentrations reach a maximum of 2,400 grn gdw^{-1} in subzone Ia.

Subzone Ia is identified between 200-260cm depth. It has higher overall concentrations than the rest of Zone I, and herb taxa such as Compositae Tubuliflorae and *Ambrosia* reach peak abundances here. The relative frequencies of Cyperaceae, *Alnus* and *Betula* decline, while Gramineae reach a maximum of 20%, *Lycopodium* reach about 20%, and Compositae Tubuliflorae reach a maximum of over 10%. Concentrations of Gramineae, Cyperaceae, Compositae Tubuliflorae, *Lycopodium* and *Filicales* actually increase.

Another distinct rise in the concentration curve is seen at 380cm depth. This is not accompanied by rises in pollen percentage frequencies other than by Cyperaceae, so it is not defined as a subzone.

Zone II, from 0-100cm depth, is characterised by a dramatic rise in the relative abundance of *Alnus* pollen. A maximum of ~70% *Alnus* is reached at 25cm depth, this declining to 40% in the topmost sample. Cyperaceae percentages decline throughout the zone, dropping from over 40% to less than 10% at 25cm depth; an increase to 20% accompanies the fall in *Alnus* at 2-4cm. The relative representation of Gramineae also drops, to < 10%. *Betula* frequencies fluctuate, but have maxima of over 15%, greater than those in Zone I. *Lycopodium* representation is consistent at 10%; after a peak of 25% at 75cm depth, representation of *Filicales* drops to 5%. The conifers appear to be more consistent than in the lower zone, though they are never present at over 5% frequency.

Concentrations begin to rise immediately in Zone II (~1,200 grn gdw^{-1}), though a dramatic rise is seen at 50cm depth; total concentrations rise from ~2,000 grn gdw^{-1} to almost 24,000 grn gdw^{-1} at 25cm depth. The total concentration of pollen at 0cm is ~15,000 grn gdw^{-1}, suggesting a decline in productivity in that one sample. *Alnus* grains show the greatest overall increase, reaching a peak of 17,850 grn gdw^{-1} from previous levels of < 200 grn gdw^{-1} in Zone I. *Betula* concentrations increase throughout Zone II, to a maximum of 2,500 grn gdw^{-1} at 0cm. Overall

Cyperaceae and Gramineae maxima are also reached here, these being ~3,000 and almost 1,000 grn gdw^{-1} respectively. Concentrations of all other taxa are higher in this zone, for example *Lycopodium* at 2,500 grn gdw^{-1}, *Filicales* at 500-840 grn gdw^{-1}, and *Picea* at 600-800 grn gdw^{-1}.

Core 108

Although composed of only three samples, this core indicates a major transition between the relative representation of *Alnus* and Cyperaceae. *Alnus* pollen are at a maximum of 60% at the 50cm and 25cm levels; Cyperaceae are at 10%. In the uppermost sample, *Alnus* decline to ~30%, while Cyperaceae rise to 30%. *Betula* grains are consistent at just under 15% throughout the core. Gramineae rise from 5% to about 8% in the 0-2cm sample. *Salix*, Ericaceae, *Myrica* and other herbs are also present, each with a relative abundance of 2-3%. Spores of *Lycopodium* and *Filicales* are consistent at 5-10% and 5% respectively. The relative representation of *Picea* rises from < 5% to ~8% in the topmost sample; *Pinus* remains present in trace amounts.

In core 108 concentrations decline toward the topmost sample; a maximum total concentration of > 24,000 grn gdw^{-1} drops to ~6,000 grn gdw^{-1}. Individual taxa show generally consistent concentrations, for example Cyperaceae (1,800-2,200 grn gdw^{-1}), Gramineae (500-1,100 grn gdw^{-1}). *Salix*, Ericaceae, and *Myrica* have < 300 grn gdw^{-1} in most samples. The conifers, *Picea* and *Pinus*, are also consistent with 300-600 grn gdw^{-1} and 100-250 grn gdw^{-1} respectively. Although considered a pollen assemblage zone in its own right, the top sample from core 107 might be included in core 108 as it bears similarities to the 0-2cm level where shrubs decline and herbs rise in frequency.

5.6.4. Correlation of Nachvak Fiord Cores with Other Cores

The Nachvak Fiord core 107 and 108 pollen spectra can be compared with the fossil pollen record of northern Labrador. Table 5-6 summarises the observed results from Lamb's Hebron Lake spectrum (1984), from the Square Lake core analysed by Clark *et al.* (*in press*), and from Adams Lake core 3b (J.B. Macpherson, personal communication, 1988). Also included is a synopsis of the Nachvak Fiord core results. These lake spectra are examples of the postglacial pollen assemblages recorded in this area; correlations with offshore continental shelf and deep sea spectra are not made as the pollen record is generally incomplete and/or undetailed, and may be disturbed in such locations. Where correlations of land and sea spectra have been made, similar sequences have been shown. The northern Labrador lake sites are considered to be more useful for correlation than any from Baffin Island. It should be noted that Cyperaceae is excluded from the pollen sum in the Square Lake spectrum from Clark *et al.* (*in press*); this makes the percentage frequencies of other taxa from that spectrum high compared with those from Nachvak Fiord and Hebron Lake.

Table 5-6 is drawn so that similar features within each pollen spectrum can be easily compared. Visible in each spectrum is an early relative dominance of Cyperaceae, sometimes with Gramineae and other herb taxa, and a later relative dominance of *Alnus*. The usually rapid rise in *Alnus* percentage frequencies is clearly visible in the Hebron Lake and Square Lake spectra (zones H-3 and II respectively), and in Nachvak Fiord core 107 Zone II. It is interpreted as a period of warming, possibly with the maximum temperatures of the postglacial period (Ives, Nichols and Short, 1976; Short and Nichols, 1977; Short, 1978; Lamb, 1984). It has high concentrations of grains, suggesting a productive vegetation. This assemblage zone is associated with relatively high percentages of *Betula* and decreases in the abundance of Cyperaceae and Gramineae. *Salix* is usually present, and the conifers begin to increase their representation. It is termed a shrub-tundra by Lamb (1984) and Clark *et al.* (*in press*), corresponding with Short and Nichols (1977) and Short (1978). These authors generally agree that spruce and pine pollen are blown northward from south-central Labrador.

One or two zones are present below the shrub-tundra episode; these generally indicate high relative representation of Cyperaceae and Gramineae and lower representation of *Alnus* and *Betula*. Concentrations are much reduced. Hebron Lake zone H-2 shows an episode of dominant *Betula*, where *Alnus* has relatively low frequencies and Cyperaceae and Gramineae representation is also low. Elsewhere, maximum *Betula* representation coincides with the phase of dominant *Alnus*.

Core 107 Zone I can be correlated with zones 1 or 2 in Adams Lake, with zone II in Square Lake, and zone H-1b in Hebron Lake. Dominant Cyperaceae and high Gramineae characterises the assemblage, although *Alnus*, *Betula* and the conifers are present. *Salix* representation is relatively high, perhaps because it is not obscured by higher percentages of the other shrubs. Herb pollen is more important in this zone than it is in Zone II, though there is no indication of the very high *Ranunculus* frequencies shown in Hebron Lake H-1a. Concentrations are low, indicating very low productivity; perhaps a result of sparse vegetation, or of a high sedimentation rate. This is typical of postglacial sedge-tundra communities.

Table 5-8: Summary of information in pollen spectra from northern Labrador lake sites.

Hebron Lake; *Lamb, 1984*		Square Lake; *Clark* et al., *in progress*		Adams Lake; *unpublished data*		Nachvak Fiord cores 107 & 108; *this study*	
Zone	Description	Zone	Description	Zone	Description	Zone	Description
		V	declining *Alnus*, 20% to 10% high *Betula*, 25-45% fluctuating *Picea* 20% to 35% consistent Gramineae ~10% increasing Cyperaceae, 50% to 125% < 5% *Pinus*, *Salix*, *Artemisia*	4	consistent *Alnus*, 10% to 15% consistent *Betula*, ~15% consistent Cyperaceae, 15% to 20% consistent *Picea*, ~20% consistent *Pinus*, ~10% trace Gramineae, *Salix*, *Lycopodium*, *Sphagnum*		
4	declining *Alnus*, 30% to 20% rising Cyperaceae, 15% to 20% maximum *Picea*, 20-30% consistent *Betula*, 40% *Pinus* <5%	1732 ±85 IV	slowly declining *Alnus*, 40% to 20% fluctuating *Betula*, ~30% fluctuating *Picea*, 20% to 35% consistent Gramineae 5-10% slowly rising Cyperaceae, 25% to 75% < 5% *Pinus*, *Salix*, *Artemisia*			108 (III?)	consistent/declining *Alnus* 60% to 30% consistent/increasing Cyperaceae 10% to 30% consistent *Betula* ~15% increasing Gramineae, 5% to 8% increasing *Pinus*, < 5% to 8% *Picea*, *Salix*, *Artemisia*, Ericaceae present consistent *Lycopodium*, ~10% consistent *Filicales*, ~5%
3 5600 ±100	dominant *Alnus*, 30-40% *Betula* declined to 40% rising *Picea*, 0% to 20% low Cyperaceae, < 5% trace *Lycopodium* & *Sphagnum*	III 7020 ±80	dominant *Alnus* ~40% dominant *Betula* 35% slowly rising *Picea* 5% to 25% consistent Gramineae, < 10% consistent Cyperaceae, < 10% trace of *Pinus*, *Salix*, *Artemisia*	3 6890* ±80	dominant *Alnus*, maximum 35% declining Cyperaceae 25% to 10% consistent *Betula*, ~15% rising *Picea*, 15% to 25% *Lycopodium* present	107 II 7323 ±110	dominant *Alnus*, maximum 75% (range 15-75%) declining Cyperaceae, 30% to 10% fluctuating *Betula*, 5-15% declining Gramineae, 20% to 5% < 5% *Picea*, *Salix*, *Artemisia* trace *Pinus* consistent *Lycopodium*, ~10% peak *Filicales*, 25%
2	dominant *Betula*, 60% low *Alnus*, ~10% consistent *Salix*, ~10% consistent Gramineae, 5-10% Cyperaceae ~10% *Lycopodium* ~5%						
7200 ±100 1b	dominant Cyperaceae, 50% declining *Ranunculus*, 30% to 5% increasing *Betula*, < 5% to 40% peak *Salix*, 20%	7950 ±200 II	dominant Cyperaceae, > 200% dominant Gramineae, 30-50% high *Betula*, 15-22% *Alnus* < 10% *Picea* < 10% maximum *Salix*, ~15%	2	dominant Cyperaceae, 30-40% Gramineae < 10% rising *Betula*, maximum 20% fluctuating *Alnus*, 0-25% *Picea*, *Pinus*, *Salix* ~10% few other herbs present	I 19720 ±400	dominant Cyperaceae, range 50-70% fluctuating Gramineae 10-20% low *Alnus*, < 10% low *Betula*, 5-15% consistent *Salix*, < 5% trace *Pinus*, *Picea* other herbs present fluctuating *Lycopodium* 5% to 20% fluctuating *Filicales* 5% to 10% 5-10% *Artemisia* at base
1a 8350 ±85	dominant *Ranunculus*, 45-60% maximum Gramineae, 20% high Cyperaceae, 20-35% trace *Betula* & other herbs no *Picea*, *Alnus*, *Salix*	I base 18,210 ±1900	high *Betula* 30-40% consistent *Alnus*, 15-20% consistent Gramineae, 15-20% trace Cyperaceae, *Picea*, *Salix* consistent *Pinus*, < 5% considerable eworking; *Alnus* & *Betula* unlikely to have grown at this time.	1 22090 ±170	dominant Cyperaceae, 40-50% maximum Gramineae 20%, declining to < 10% rising *Alnus* 10% to 20% trace *Betula*, *Pinus*, *Salix* other herbs present		

*

The subzone identified within Zone I is likely to represent a different depositional episode, perhaps a phase of input from a specific area, with species distinct from the regional pollen supplied to the fiord at other times; or a phase of reworking, during which older sediments containing a slightly different pollen assemblage became included in this profile. It is not thought to represent any change of major climatic importance. The sediments at this depth do not give any indication that reworking has taken place, consisting of fine silts and muds laid down with very little apparent disturbance.

Core 108 may be regarded as a correlative of core 107 Zone II. There being only three sample levels, it is difficult to tell whether the upper decline in *Alnus* representation is a real trend or a chance occurrence. Since Cyperaceae and Gramineae rise in their relative representation as *Alnus* fall, and a similar pattern is seen in the topmost assemblage zones of Hebron and Square Lakes as well as others analysed in northern Labrador, the core has been treated as a separate pollen assemblage. It is therefore compared with zones H-4 and IV from Hebron Lake and Square Lake respectively.

A dominant or high relative representation of *Picea* grains is not seen in the Nachvak Fiord cores. Other records indicate maximum *Picea* frequencies after an episode of dominant *Alnus/Betula*, when spruce woodland was firmly established in southern Labrador and provided abundant pollen input to the north (Lamb, 1984; 1985; Short and Nichols, 1977; Short, 1978). *Picea* representation does increase from Zone I to Zone II in core 107 and is higher again in core 108, indicating that spruce pollen did reach the fiord but that it was not present in very significant quantities.

The Nachvak Fiord cores correlate well with the terrestrial fossil pollen record for northern Labrador in terms of major vegetation changes in the postglacial period. Zone I is interpreted as a sedge-tundra episode, where the pollen assemblage is typical of a sedge-grass-willow community (Lamb, 1984; Clark *et al.*, *in press*; J.B.Macpherson, personal communication, 1988). Zone II represents a change to a shrub-tundra, where alder and birch occur alongside sedges and other herbs. The arrival of alder in northern Labrador lake sites occurred between 6500 and 5600 BP (Short and Nichols, 1977; Short, 1978; Lamb, 1984); Clark *et al.* recognise that it was earlier in Square Lake than has been previously observed (~7020 BP). The base of Zone II may therefore be tentatively dated at about 5600-7000 years BP.

Core 108 must be treated with more scepticism, since it is unknown whether it does contain a separate pollen assemblage zone. It possibly indicates an alteration in the fiord vegetation marking a return to a sedge-tundra community, following the shrub-dominated episode, which would correspond to the regional cooling believed to have occurred 2000-3000 years BP (Lamb, 1984; Short and Nichols 1977; Clark *et al., in press*). However, there is not enough evidence in the three samples of core 108 to definitively make this conclusion. In addition, the short length of core 108 makes it unlikely to cover such a long time period. An alternative explanation might be that core 108 does not represent very recent pollen deposition within the fiord; if the sediments have experienced recent erosion, the rise in herb pollen might represent a real change in vegetation communities, the rest of which has not been cored. This may also account for the low *Picea* representation in the topmost zone, as the period of maximum spruce pollen would not have been sampled.

5.6.5. Summary

The pollen record of Nachvak Fiord cores 107 and 108 can be interpreted as a spectrum typical of the Holocene in northern Labrador. An early sedge-grass-willow community cannot be dated, but probably occurred prior to 6000 or 7000 years BP. Clark *et al., in press*, suggest that this type of community existed in ice-proximal conditions, though Lamb indicates that stabilising slopes and developing soils in any recently deglaciated area might account for the vegetation pattern. Low pollen concentrations may be explained through high rates of sedimentation, partially caused by the unstable slopes of the fiord. Zone I of core 107 is therefore interpreted as a sedge-tundra episode, occurring in the earlier part of the Holocene, when land had recently become free of ice.

The beginning of the shrub-tundra episode is more positively dated at 5600-6000 BP; it might represent a climatic amelioration, or just the colonisation of the fiord area by *Alnus*. The increase in pollen concentrations suggests a rich vegetation community, and possibly more stable slopes due to their increased v getative cover. Spruce pollen is assumed to be exotic, as the fiord is well north of the tree-limit (Elliott and Short, 1979).

Core 108 has a more open interpretation. The pollen assemblage appears to be a continuation from Zone II of core 107, in which dominant shrubs give way to an increased relative representation of herbs (Cyperaceae and Gramineae). This corresponds to similar assemblage zones in lake cores which date to 2500-3000 BP; if the correlation is accurate, it seems unlikely that this gravity core contains recent sediments.

5.7. Discussion

5.7.1. Correlation of Core Chronostratigraphy and Lithostratigraphy

The pollen assemblage zones of cores 107 and 108 and their approximate times of occurrence in the fiord region correspond well with certain radiocarbon dates found within these cores. Shell fragments at 100cm in core 107 give a date of 7328±110; it is at about 100cm depth that the *Alnus* rise occurs, marking a transition from sedge-grass tundra to shrub-tundra. While other workers have found the *Alnus* rise to occur a little later than 7300 BP, it is believed to have happened at 7000 BP at Square Lake (Clark *et al.*, *in press*), and at about 6800-5600 BP in other locations (Short, Mode and Davis, 1985). The date for core 107 is therefore close to this accepted range. A date of 19,730±400 BP was obtained from the base of the core. While this age is considered to be a maximum, it does confirm that the sedge-grass tundra occurred in the early part of the Holocene. The core gives no indication of the timing or progression of deglaciation.

Although pollen analysis was not carried out on cores 105 and 106, a similar sequence might be expected. The 5170±80 BP date at 100cm depth indicates a faster rate of sedimentation at the site of core 105, suggesting that the *Alnus* rise might occur at greater depth within the core. An age of 6800-7800 BP from 422cm depth may be more likely to date the transition zone. As the fiord became ice-free from east to west, vegetational changes might have occurred earlier at this site, in which case shrub-tundra may occur at the base of core 105.

No radiocarbon dates are available from core 108. The pollen record appears to indicate fairly old sediments here, based on the dominant sedge-shrub tundra at the top of the core. If it can be assumed that this pattern is not coincidental, there is a possibility that erosion has taken place, removing recent pollen and deposits.

Core lithostratigraphy shows that there is a change from predominantly fine and fairly well-stratified deposits in the lower parts of both cores 105 and 107, to more coarse materials in their upper sections and in cores 106 and 108. The transition occurs at about 90cm depth in core 105 and 80cm depth in core 107. It is interpreted as representative of a change in the source of sediments and in their environment of deposition; fine-grained deposits were probably derived from local and regional glaciers and laid down under quiet conditions, while the coarse deposits are mainly fluvial. Stronger currents, increased tidal action and the availability of coarse debris around the fiord are believed to contribute to, and indicate, the higher energy environment of the upper facies. Sediments below 90cm and 80cm depth in cores 105 and 107 respectively are therefore classified as ice-proximal or ice-distal, while those above these levels are classified as postglacial and recent fluvial deposits.

Correlation of the chrono- and lithostratigraphies indicates that the fiord was dominated by a glacial environment in the lower sections of both piston cores. Sedimentary facies indicate an ice-distal, or perhaps ice-proximal, environment below 80-90cm depth. A sparse sedge-grass tundra vegetation grew in the fiord region for most of this period, probably lasting until approximately 7000 years BP. Fluvial sediments did not dominate the facies until about 5800 BP (based on a continuous rate of sedimentation). The fiord seems likely to have been ice-free beyond Townley Head throughout this period. As the ^{14}C date for the base of core 107 is in doubt, no conclusions can be made about the time or rate of ice retreat, except that it had completed by ~7000 years BP. If the radiocarbon dates from the base of core 105 can be assumed to be correct, all sediments in that core must have been laid down in ice-free conditions. Pollen analysis of sediments from core 105 may provide more information on the nature of deglaciation within the fiord.

After approximately 6000-7300 BP, regional vegetation altered to include more shrubs, predominantly alder and birch, and overall productivity increased. More complete vegetative cover probably reduced the deposition of fine sediments from the walls of the fiord. There was a change to predominantly fluvial sediments and a more active depositional environment shortly after this vegetation change. The influence of glaciers was greatly, if not entirely, reduced by this time, suggesting that retreat had progressed well into or beyond the fiord valley.

The fact that shrub-tundra vegetation appears such a short time before the change in sediment facies in core 107 may be coincidental. An earlier vegetation change might be expected in core 105, as it is further east and Ivitin Basin must have become ice-free before Townley Basin.

The topmost facies in cores 106 and 108 were assumed to include recent deposits. However, if the pollen record from core 108 is correct there is a change to a sedge-shrub tundra community in the fiord region at < 25cm depth, accompanied by a drop in concentrations of taxa. If this can be correlated with spectra from other lake sites, it occurred approximately 2000 years BP. It is thus suggested that core 108 has undergone some erosion, that the topmost sediments are not recent. This is possible, given the coarse nature of these deposits, the lack of fine material in the x-radiographs, and the interpreted high-energy depositional environment. Currents from Kogarsok Brook might, for example, prevent deposition and actively erode sediments from this location. The alternative is that the pollen record is coincidental. Pollen analysis of core 106 might resolve the problem.

5.7.2. Evaluation of the Acoustic/Seismic Records

The aim of this analysis was to evaluate the accuracy of acoustic and seismic survey interpretations (Rogerson, Josenhans and Bell, 1986; Bell, 1987) through cores 85027-105, 106, 107 and 108. It was hoped that the evaluation might be extended to sediments on the continental shelf at the latitude of Nachvak Fiord. Lithological analysis of the cores provided information on the types of sediments and their environments of deposition, and indirectly gave some idea of conditions within the fiord. Radiocarbon dating provided an absolute timescale for events (albeit flawed), while pollen analysis was used to give a relative timescale and an impression of the vegetative environment in the region of the fiord.

Core sites were chosen to penetrate a maximum number of sedimentary units. However, it appears that only one unit, as identified in acoustic and seismic interpretations, was cored. The topmost facies, seen above 90-80cm depth in cores 105 and 107, is not described in the acoustic/seismic records. Coarse, largely unstratified sediments suggesting a high-energy environment dominated by fluvial deposition are seen in core x-radiographs. This is the modern fiord environment, where sediments predominantly originate from large streams and weathered debris around the fiord walls. Acoustically, this facies may not be visible. It is clearly unlike the quiet rain-out of suspended sediments interpreted by and Bell and Rogerson, Josenhans and Bell to be the upper unit, which they assumed to continue into modern deposits.

The lower core facies bears considerable resemblance to Unit E in Rogerson, Josenhans and Bell and Unit F in Bell. Ice-distal or ice-proximal conditions are thought to have prevailed throughout this period, when a quiet, low-energy environment deposited fine-grained suspended sediments, occasional gravels and clasts were dropped from floating ice, and flow currents or density flows provided stratified sediments. It is difficult to say whether lower deposits in cores 105 and 107 were laid down close to an ice-margin, or whether the entire sequence is ice-distal. There is no obvious break in the lithology of the cores to indicate a transition from an ice-proximal unit (ie. Units D and E in Rogerson, Josenhans and Bell, and Bell respectively) to an ice-distal one.

This does not provide any new information on the acoustic identification of tills either within the fiord or on the continental shelf; longer cores are required if a real evaluation of the depositional units is to be carried out. Sedimentation rates are expected to be considerably faster than those of the Labrador shelf at this latitude. The fiord appears to have become ice-free by at least 7000 BP, and sedimentation ceased to be dominated by glacial input shortly thereafter. The pollen record provides an interesting comparison with records from northern lake sites, and might be correlated with spectra from the Labrador shelf at the mouth of Nachvak Fiord when those results become available. It also suggests that erosion is actively occurring in Townley Basin at the site of core 108, an interpretation that is not disputed by the coarse nature of deposits within the core.

Chapter 6
Discussion and Conclusions

6.1. Introduction

The information presented in the preceeding chapters suggests a chronology of Wisconsin glacial and deglacial events in inner Nachvak Fiord. Since this is the third major study of a localised part of the fiord, these results serve, in part, as an evaluation and extension of the two earlier studies. Results are generally consistent and lead to the development of a well-documented and fairly reliable chronology. This section of the thesis contains an outline of the main evidence for particular events within the study area, and correlates them with information from the Selamiut Range in the central fiord and the southern side of the outer fiord. The regional significance of detailed research into conditions within Nachvak Fiord during the Wisconsin period is presented with the debates over glacial extent in north-eastern Canada in mind; correlations on a broader scale are also suggested. Results are consistent with a particular interpretation of glacial history; they appear to refute the reconstruction of a very extensive Late Wisconsin ice-sheet. Suggestions for future research concentrate on testing this reconstruction, and evaluating the extent of Late Wisconsin ice in fiords to the north and south of Nachvak Fiord.

6.2. Glacial Activity in the Inner Fiord; Local and Regional Correlations

6.2.1. Geomorphological Evidence

Chapter 3 provides evidence for at least three glacial periods, visible primarily in moraines on the highland west of Kogarsok Brook. The earliest glaciation was most extensive, depositing moraine M0 at approximately 500m above high tide (aht). It is thought to have been a predominantly regional event because of the elevation and orientation of this moraine. The terrain above M0 is extensively weathered, displaying continuous felsenmeer and a number of tors. Striations are not preserved, there is very little fine-grained material, and soil development is rare. Similar conditions were observed on Mount Elizabeth, and were described by Daly (1902) on summits above 488m and 640m above sea level (asl). The presence of small, weathered erratics lying amongst the felsenmeer on Mount Elizabeth implies that these peaks were once glaciated, and that they belong to the Komaktorvik weathering zone (Ives, 1976; 1978). However, the degree of weathering suggests that that glaciation was pre-Sangamon.

Moraines M1 and M3 appear to have been formed at about the same time. There is evidence for their representing coalescing local and regional ice-sheets, though ice-flow indicators and drift geochemistry, and the morphology of moraine M3, do not provide an indisputable origin for M3. However, the abundant drift and numerous ridge crests in this area of the highland suggests that ice stagnated here, and that M1 is an interlobate moraine. If moraine M3 was deposited by regional ice, it may have continued into segment PP, which is now isolated in the west.

At lower elevations closer to Kogarsok Brook valley are moraines K1, K2 and M5. These appear to have been formed within a relatively short period of time. K1 may represent the maximum vertical extent of ice during the last glaciation; it is tentatively associated with the Kogarsok sill, though it cannot be traced east of Kogarsok Brook. Although the moraine has a very subdued crest and contains little deposited material, this is thought to be a function of its location. It follows a bedrock shoulder along the edge of the valley, which would have supplied very little sedimentary material. Its lack of prominence is not taken as an indication of great age, despite a solum depth of 37cm from a single soil pit.

Moraine M5 may have removed evidence of K1 in Kogarsok Brook valley, and certainly truncated M3 on the western highland. M5 was deposited by a local ice tongue, which moved southward toward the mouth of Kogarsok Brook. The relatively 'fresh' appearance of M5, and the suggestion that it formed after both K1 and M3, led to its interpretation as a local ice feature formed during the last glaciation. A wide standard deviation about the relatively deep mean solum depth of M5 soil pits indicates that the mean is not very reliable as an indicator of age; the date suggested by soil development rates is thus considered to be too old.

Moraine K2 is interpreted as being recessional to the maximum of the last glaciation, due to its unweathered appearance and its continuity over a long distance. It is thought to have formed while ice stood at or near the Kogarsok sill. Moraine M5 is likely to have been formed at approximately the same time, by a local ice tongue in Kogarsok Brook valley.

Moraines alongside the fiord to the west of K2 are also attributed to recessional phases from the last glaciation. The youngest and most westerly is in Tasiuyak Arm.

The large moraines in Kutyaupak valley indicate that regional ice entered the valley from Tasiuyak Arm and was able to extend across to Tallek Arm. This implies that Tallek Arm contained little or no ice at the time. Although Kutyaupak valley was probably occupied by ice on several occasions, the moraines visible today are attributed to the last glacial retreat, and they are thought to be similar in age to moraine K2. Ice is likely to have left the valley shortly before the formation of the Tasiuyak Arm moraine.

The moraine systems of the inner fiord can be correlated with glacial phases identified by Evans (1984) and Bell (1987) in other parts of the fiord, as there are similarities between their perceived ice origins, altitudinal ranges and relative ages. Four glaciations are believed to have taken place in Nachvak Fiord, these being the Ivitak, Adams Lake, Nachvak and Superguksoak I phases. Evans suggested that the Ivitak phase can be divided in two, the Late Ivitak being slightly less extensive than the Early Ivitak. Both included local and regional ice activity in the Selamiut Mountains, and both left nunataks standing above the ice-sheets. Bell correlated his M1 phase of the outer fiord with the Ivitak period, on the basis of it being an ancient and extensive regional glaciation ($<$ 180m aht trimline on outer coast). The Early Ivitak was dated at $>$ 70 ka BP, the Late Ivitak $\gg$40 ka BP, using Evans' estimates of soil development over time. The high and very old moraine M0 on Kogarsok highland is interpreted as being correlative with this period; it is of unknown age, but its high elevation and the presence of well-weathered blockfields above it suggest that it is similar to Evans' 300-900m Early Ivitak moraines and trimlines. Evans recorded nunataks and residuum or felsenmeer immediately above the level of Early Ivitak trimlines.

The Adams lake phase was identified by Bell in the outer fiord. It was marked by extensive local glacier advances, and had a recessional phase during which there was a fall in relative sea level, with a lake forming in Adams Lake valley. No evidence of regional ice advance during this period was observed in the outer fiord. Correlations with glaciations in the Selamiut Range were not suggested; Evans did not report any local ice advances taking place between the Ivitak and Nachvak phases. Bell gave the Adams Lake phase a date of 29-50 ka BP, with the maximum at approximately 38 ka BP and the recessional phase between 29-32 ka BP.

Moraines M1 and M3 may correlate with the Adams Lake phase. They appear to represent a predominantly local glaciation which, according to their topographic location, occurred before the glaciation which caused the formation of K1, and well after that which formed M0: ie. between the Ivitak and Nachvak glaciations. If the moraines are representative of an inland Adams Lake phase, glaciation must have been much more extensive here than on the coast. There are no nearby highlands from which the significant ice-sheets that appear to have deposited these moraines could have originated. If M3 was a product of regional ice activity, its high elevation implies that it derived from a large ice-sheet, which probably would have extended to Bell's study area. Such an ice sheet also would have influenced the Selamiut Mountain range, where no evidence for an extensive intermediate glaciation was recorded. It is possible that all evidence of such an event was eroded or masked by the later Nachvak glaciation, or that the 'Late Ivitak' (Evans, 1984) was a separate event occurring well after the Ivitak, perhaps concurrently with the Adams Lake phase.

Proof of this correlation, between moraines M1 and M3 and the Adams Lake glacial phase, requires detailed mapping and preferably dating of moraines at high elevations in other parts of the fiord. It does suggest that the Adams Lake phase included extensive regional ice movements.

The younger moraines around the mouth of Kogarsok Brook valley are associated with the Nachvak glacial phase. Moraine K1 is likely to represent the maximum of this phase within the study area, while K2 is recessional to that maximum, and M5 represents simultaneous local ice activity. Evans (1984) and Evans and Rogerson (1986) assigned an age of 17-23 ka BP to the

Nachvak phase moraines, while Bell (1987) suggested an age of 22 ka BP. K1 must be older than K2; M5 is thought to be of similar age to K2. Moraines along the fiord to the west are likely to have formed in succession at later dates. Ice retreat from Kutyaupak valley probably began less than 22-23 ka BP, as deglaciation of the inner fiord commenced.

Tasiuyak Arm moraine may be correlative with the Superguksoak I phase, which was dated at 5-12 ka BP by Evans and Rogerson (1986).

6.2.2. Shorelines and Relative Sea Level Change

Shorelines of the inner fiord are assumed to have formed after the maximum of the last glaciation. Evidence of older shorelines is likely to have been removed as the last ice-sheet occupied areas within ~200m of sea level throughout the entire study area. The shorelines can therefore be correlated with those of similar age in the outer fiord, ie. those that Bell attributes to the post-Nachvak period. This includes shorelines A to J, each of which was interpreted to be a result of the recovery of the earth's crust after ice retreat. In Chapter Four it was pointed out that there are more shorelines in the inner fiord than at the mouth; this may be because beach materials were more abundant inland, leading to well-developed beach formations, and perhaps because preservation is better away from the coast. 60-73m aht shorelines in Valley of the Flies were correlated with the Adams Lake glacial phase; other benches of up to 73m elevation (Sl-K) were recorded, though they were not all thought to be linked to a single event or time period (Bell, 1987).

Moraines in the inner fiord suggest that glacial retreat occurred in stages. Thirteen shorelines were recognised, and the general location for an ice-margin associated with the higher shorelines, Sl-7 to Sl-13, was identified. It may be argued that isostatic rebound and relative sea level change occurred rapidly, responding to each stage of deglaciation, although it is possible that some of these shorelines were produced by local factors other than relative sea level change. Ice-margins for shorelines 8 to 13 may exist within this study area, lower shorelines being related to margins beyond the head of the fiord or to postglacial transgressional phases. Particular moraines were related to some shorelines, although stillstands do not necessarily produce either moraines or shorelines. In the outer fiord, Bell's Sl-D was radiocarbon dated at ~9,000 years BP; this provides a minimum date for deglaciation for the length of that shoreline. It is interpreted as being synchronous with either Sl-8 or Sl-9, both of which terminate in Tasiuyak Arm, and thus it represents the deglaciation of all or most of the fiord trough. Although the full significance of a 8260±60 years BP date recently obtained from shells found in a 14m aht beach has not yet been investigated, the date concurs with the interpretation of an early deglaciation.

The shorelines in Tasiuyak Arm are of significance because they have such steep gradients and such high elevations. Although far inland and expected to be quite young, their elevations suggest that they have experienced considerable differential uplift, typical of older benches. As they are higher than the oldest Late Wisconsin shoreline in the outer fiord, they may be explained through fairly rapid ice retreat. This possibility requires rapid retreat even given the stage-like nature of recession and the obvious formation of some fairly large moraines. The extreme gradients of the Tasiuyak Arm benches (4.55m km^{-1} and 2.05m km^{-1} for A and B respectively) may suggest that the earth's crust was relatively flexible at this time, or that some factor additional to crustal rebound contributed to their degree of tilt.

Since the majority of inner fiord shorelines were not dated, no additional information on the age of the Kogarsok sill or moraine K2 was obtained. However, Bell associated shorelines in the outer fiord with stillstands and readvance phases, some of which occur in the inner fiord. Most of these cannot be evaluated by the inner fiord data, but their dates and correlations are of interest. A stillstand at Kogarsok (Sl-F, 26-55m aht) was given an estimated age of $<$ 22 ka BP (Bell, 1987, p.217); it was correlated with Loken's Two Loon readvance phase, a minor event which occurred 50km north of Nachvak Fiord. Sl-F is interpreted as being correlative to Sl-12 or Sl-13 in this study, both of which terminate at and east of the Kogarsok moraine. Given the estimated age of moraine K2 (17-23 ka BP, assuming it is equivalent to the Nachvak moraines of Evans and Rogerson, 1986), $<$ 22 ka BP for this shoreline is considered realistic. Whether or not this phase is correlative with that of Loken is unknown; Bell suggested that the Two Loon phase might, alternatively, be contemporaneous with a stillstand at Townley Head, or that it may not exist in Nachvak Fiord. Evidence for readvance phases appears to be minimal in both the Kogarsok and Townley Head cases; they are interpreted here as recessional stillstands.

The Tessersoak readvance was a major phase identified by Bell and associated with his Sl-D, which is interpreted here as extending up-fiord to Tasiuyak Arm, Sl-8 or Sl-9. The dated shells from Adams Lake valley allow a direct comparison with 9 ka BP shorelines identified by Clark

(56m aht, Two Loon and Coleman drift sheets; 1984) and Loken (Sl-3, 28-34m aht, Kangalaksiorvik Readvance; 1962*b*); Bell also suggested that this readvance might coincide with the Superguksoak I glacial period, 5-12 ka BP.

The Tasiuyak Arm moraine may be associated with the Superguksoak I phase. Shoreline 8 terminates at this moraine, so a date of less than 12 ka BP might apply to it. This suggests that Sl-9 is more likely to be the 9 ka BP shoreline synchronous with Sl-D in the outer fiord, and thus that in the Tessersoak phase ice occupied Nachvak Lake but little of Tasiuyak Arm. The new radiocarbon date of 8260±60 years BP (TO-1084) from shells at 14m aht in Bay Cove indirectly supports this interpretation of an early deglaciation by showing that the inner fiord was ice-free by 8200 BP.

Final correlation was between shorelines at and below ~20 m aht. In the inner fiord, shorelines 1, 2 and 3 had elevations of 8-10m, ~14m and 18-20m aht respectively. 8-10m aht beaches were also observed at Ivitak Cove (R.J. Rogerson, personal communication, 1988), and in other locations on the Labrador coast. Bell recorded ~13m and 15.5m aht shorelines in the outer fiord, tentatively correlating the latter with Loken's 15.5m shoreline in Kangalaksiorvik Fiord. A date of 4.7 ka BP was applied to this by Loken, after comparison with the Tapes transgression of Scandinavia. Although shells found in a 14m aht bench at Bay Cove had a radiocarbon age of 8260 years BP, they are not considered to be representative of the age of the bench; the species types and their normal living position suggests that they were buried in sediments now exposed at 14m aht. The transgression thus seem likely to have occurred between 4,000 and 8,000 years BP. The presence and frequency of horizontal shorelines in Labrador [eg. 8-10m along Porcupine Strand (Rogerson, 1977), 15.5m aht north of Nachvak Fiord (Loken, 1962*b*)] indicates that there have been major regional transgressions in northern Labrador; the regular elevations of raised benches suggest that they affected large areas equally and at the same time.

6.2.3. Lithostratigraphy and Chronostratigraphy of Fiord Cores

Four cores extracted from the centre of Ivitin and Townley Basins are described in Chapter 5. Since the cores penetrate only the uppermost lithographic units identified by acoustic surveys, they cannot be used in evaluation of the conflicting interpretations of fiord and Labrador Shelf acoustic units. However, the cores do provide information on the late- and postglacial environments of the fiord, as well as a chronology that compares well with other cores from northern Labrador.

The lithostratigraphy of the cores showed ice-proximal or ice-distal glacially-dominated sediments in the lower facies (cores 105 and 107, 90-590cm and 80-450cm respectively), and coarse fluvially-dominated deposits above (cores 105, 106, 107 and 108). Radiocarbon dates on shells and shell fragments found within the two piston cores indicate that the change in depositional environment occurred 3500-5800 years BP. Recognition of this topmost facies indicates an environment not seen in acoustic, seismic or air-gun surveys, which were interpreted as showing ice-distal deposits continuous with modern sedimentation (Rogerson, Josenhans and Bell, 1986; Bell, 1987). The lower facies is likely to be the uppermost unit identified by these authors, as it consists of fine-grained ice-distal sediments with frequent laminations and occasional dropstones. The slow rates of sedimentation shown by both cores are not typical of currently deglaciating sites, again suggesting an ice-distal environment. Large clasts indicate the presence of some floating ice, which does not appear to have been a major form of debris transport.

The upper 'fluvial' facies is very coarse and relatively unstructured in comparison with that below. It is considered to represent the modern environment of deposition, which is likely to have included erosion of fine-grained sediments; the pollen record of gravity core 108 suggests that sediments in the top 25cm are not modern, and implies substantial erosion or non-deposition in recent times. The coarsening-upward pattern of deposits throughout these cores is likely to have been caused primarily by a change in sediment source, as regional ice left the fiord and fluvial and meltwater debris from around the fiord became dominant. Changes in sea level, basin morphology, the abundance of loose debris, and perhaps in storm frequency and climate may also have been influential.

This change in the environment of deposition is significant as it shows that all glacial activity in and around the fiord had ceased by this time. As the lower facies is interpreted as ice-distal, radiocarbon ages of shells at 100cm depth in both cores 105 and 107 can be assumed to represent minimum dates for ice retreat from the vicinity of the fiord. Since ice left Townley Basin after it left Ivitin Basin, the Townley Basin date (7,328 years BP) is considered to be the absolute minimum, although the Ivitin Basin date is younger (5,170 years BP).

The lithofacics change is also taken to indicate the final influence of late glacial phases involving the regional ice-sheet. It thus indicates that readvance phases such as the Tessersoak occurred prior to approximately 7000 years BP. If the Superguksoak I period involved a regional ice advance, it must therefore have been over before 7000 years BP; Evans and Rogerson gave it a date of 5-12 ka BP (1986).

Pollen analysis of the Townley Basin cores 107 and 108 provided a basic outline of postglacial vegetation change for the region around Nachvak Fiord, which could be compared with other cores. Pollen assemblage zones in core 107 indicate a change from sedge-grass tundra to shrub-tundra, with a rise in *Alnus* frequency and concentration typical of that seen in cores from other terrestrial lake sites and offshore. The rise begins at 100cm depth, increasing rapidly after about 70cm depth, and thus has a date of approximately 7000 years BP. This is considered early for the immigration of *Alnus* to northern Labrador, although it corresponds with a similar early rise observed and dated in Square Lake by Clark *et al.* (*in press*) and is close to the accepted immigration time-range of 5600-6500 years BP (Short and Nichols, 1977; Lamb, 1981). The rise may represent a climatic amelioration, or simply the colonisation of the area by *Alnus*, though optimum climatic conditions in northern Labrador are thought to have occurred at about the time of the *Alnus* maximum.

The presence of sedge-grass tundra at the bottom of core 107 may be taken to suggest that the fiord was largely ice-free during deposition of the core, and that the herbs represented in the pollen spectrum grew immediately around Townley Basin. However, there is great potential for regional pollen input to this area, and it would be particularly noticeable when local pollen production was minimal, ie. during poor climatic/microclimatic conditions. Thus no vegetation reconstructions have been attempted, and the presence of pollen grains in the lower facies is not presumed to mean that the fiord walls were free of ice.

A third pollen assemblage zone was tentatively identified in core 108. Initially high frequencies and concentrations of shrub pollen, particularly *Alnus*, drop to low levels in the top 25cm of the core. Sedges and grasses become dominant. This may be interpreted as a return to a less productive tundra environment, where shrubs were of less importance; such environments were recognised by Lamb, Short and others in northern Labrador lake cores, and dated to approximately 2500 years BP.

6.3. Regional Significance and Summary of Events

Some attempt is made to relate this local study on the glacial history of a small part of Nachvak Fiord to the broader Quaternary history of northern Labrador. Previous studies in the 1960s and 1970s led to questions on the extent and age of the last ice-sheet and those of earlier glacial periods; more recently, controversy has surrounded interpretations of the horizontal extent of the Late Wisconsin ice-sheet at its maximum. By relating the information provided by detailed studies within small areas to the questions concerning the whole of Labrador, there is some movement toward solutions to these questions.

The Nachvak glacial phase is recognised as being the last major regional glaciation in Nachvak Fiord. During its maximum, ice appears to have occupied the fiord trough to at least Tinutyarvik Cove; beyond that point, raised shoreline and moraine evidence suggests that either a floating ice-shelf existed, or that the glacier remained thin and of low loading capacity (Bell, 1987). It may have terminated there. The elevations of moraines at Ivitak Cove (highest Nachvak Moraine 250m aht, Evans and Rogerson, 1986) and at Naksaluk Cove (Nachvak Moraine segments up to 80m aht, Bell, 1987) support this reconstruction.

Retreat from the glacial maximum occurred in a number of stages, several of which are marked by major moraines perpendicular to and crossing the fiord. Numerous shorelines suggest that there were more stillstands than there are surviving moraines, and that the earth's crust reacted rapidly to changing ice-loads as soon as deglaciation began. Rates of ice retreat are believed to have been slow enough to allow beach and moraine formation, although there is a possibility of rapid retreat; shorelines at 73-63m and 63-56m aht in Tasiuyak Arm must have undergone considerable differential uplift.

The Kogarsok stillstand is represented by the Kogarsok moraine and sill, and by moraine K2. The pronounced crest and fresh appearance of moraine K2 led to its correlation with other Nachvak-age moraines identified by Evans (1984) and Bell (1987), and so to an estimated age of 17-23 ka BP. Moraines further west represent progressively younger stillstands, the youngest recognised in the fiord trough so far being the Tasiuyak Arm moraine.

A radiocarbon dated shoreline (Sl-D) in the outer fiord places a minimum date of 9170 years BP on deglaciation for almost the entire fiord. Sl-D is considered to be synchronous with Sl-8 which appears to be related to an ice-margin located at the head of Tasiuyak Arm, or between that point and Tasiuyak Arm moraine. An 8260 years BP date from a shoreline above 14m aht in the inner fiord agrees with this interpretation of an early deglaciation. The lithology of cores from Ivitin and Townley Basins indicates that input of glacial sediments ceased soon after 7000 BP, and suggests that ice had retreated well beyond the head of Nachvak Lake by that time.

Major marine transgressions have occurred since complete deglaciation, resulting in at least three near-horizontal shorelines extending throughout the fiord. The transgressions appear to have been synchronous with others in northern Labrador, as Loken recorded a 15.5m shoreline in Kangalaksiorvik Fiord, and 8-10m transgressive shorelines have been reported from Porcupine Strand (Rogerson, 1977) and the St. Lawrence seaway (Dionne, 1988).

Evans identified a local glaciation that took place in the Selamiut Mountains after the Nachvak maximum, as well as two neoglacial phases. The Superguksoak I was dated at 5-12 ka BP, and is believed to have included only local ice in the vicinity of the fiord. Moraines in the cirque valley south-west of Kutyaupak valley (site KV-5) may be representative of this readvance phase in this study area. The Superguksoak II and III were interpreted as recent minor events, evident as restricted expansions of highland cirque glaciers in the Selamiut Mountains.

The Nachvak glacial phase occurred during the Late Wisconsin, and is believed to mark the maximum local glaciation of that period. It probably occurred at the same time as the Saglek glaciation. Evans dated the Nachvak period through pedologic analysis, and applied an age of 17-23 ka BP; Bell estimated an age of 20-24 ka BP. These ages correspond well with those suggested for the Saglek glaciation, which range between 18 and < 25 ka BP (eg. Short, 1981; Fulton and Prest, 1987). They all imply a fairly early Late Wisconsin maximum, and the fiord appears to have been largely free of ice by 9 ka BP.

This reconstruction of the Nachvak glaciation also implies a limited Late Wisconsin ice-sheet that did not extend to the fiord threshold. It therefore supports the interpretations of Evans, Rogerson and Bell (eg. Evans and Rogerson, 1986; Bell, 1987), while refuting the suggestions of Clark and Josenhans (eg. Clark and Josenhans, 1986; Clark, 1988); ice from Nachvak Fiord is not thought to have spread over much of the Labrador Shelf during the Late Wisconsin. Although evidence from the inner fiord is indirect, it is consistent with other terrestrial interpretations. Evaluation of the lithostratigraphic units observed on the shelf and within the fiord basins was not possible because piston cores did not penetrate through the upper acoustic units.

Earlier glacial phases recognised in the central and outer fiord study areas can also be correlated with regional glaciations. The Ivitak phase is the earliest recognised in Nachvak Fiord; it appears to have been an extensive regional glaciation, which produced moraines and trimlines at much higher elevations than those of the Nachvak period, and which almost certainly extended beyond the fiord threshold. Evans gave this period a tentative date of > 70 ka BP, and identified a slightly less extensive recessional phase that occurred > 40 ka BP. The < 180m aht M1 trimline of the outer fiord was correlated with the Early Ivitak, hence the conclusion that a fairly thick ice-sheet was grounded on the Labrador Shelf at this time. Moraines thought to relate to both Early and Late Ivitak phases were recognised on the Kogarsok highland.

The Adams Lake phase was dated by amino acid ratios, radiocarbon and pedologic analyses in Valley of the Flies. Its maximum appears to have occurred about 38 ka BP, with a recessional phase 29-32 ka BP. A 60-70m raised shoreline was associated with this phase, perhaps indicating considerable crustal depression at that time. Moraines on the Kogarsok highland may be related to it, although their location suggests that they were formed by extensive local and possibly regional ice-sheets. Glacier advances may have been more extensive inland during the Adams Lake phase; however, the Selamiut Mountains do not appear to have been influenced at all, so the correlation is not definite.

The Ivitak phase can be considered Early Wisconsin, the Adams Lake phase Middle Wisconsin. Both appear to have been characterised by high relative sea levels around the outer fiord, and ice almost certainly extended onto the continental shelf during the Ivitak phase. The glacial tills observed on the continental shelf are therefore likely to include deposits of Ivitak/Early Wisconsin age; any of Late Wisconsin or Nachvak age are not thought to have been derived from this particular fiord.

The Kogarsok highland in the inner fiord study area provided an opportunity to look at the extent and degree of weathering over a wide elevation range. At least three zones of differentially weathered bedrock and boulders were discerned, the lowest being below moraine K2, representing the most recent Nachvak (Late Wisconsin) glaciation. The highest and easily the most weathered zone occurs above moraine M0, at $\sim$500m aht. Felsenmeer and tors suggest that peaks above this elevation have not been glaciated since pre-Sangamon times. A tentative zone is suggested between moraines M0 and the level of M1, M3 and M5; only minor difference in 'measurable' weathering criteria were observed in the region, though qualitative observations indicate that the area has been exposed to weathering for a shorter period of time than the area above M0. Another zone of intermediate weathering exists between moraine K2 and the M1, M3, M5 crests. A three zone pattern can therefore be described, with an uppermost Komaktorvik zone, an intermediate Koroksoak zone, and a lower Saglek zone, equivalent to the Nachvak glaciation in this study area. This is summarised in Figure 6-1. The observation of these zones confirms that they are visible within Nachvak Fiord, as elsewhere in northern Labrador, and also shows that it is far from easy to recognise and even relatively date the different glaciations that affected this area.

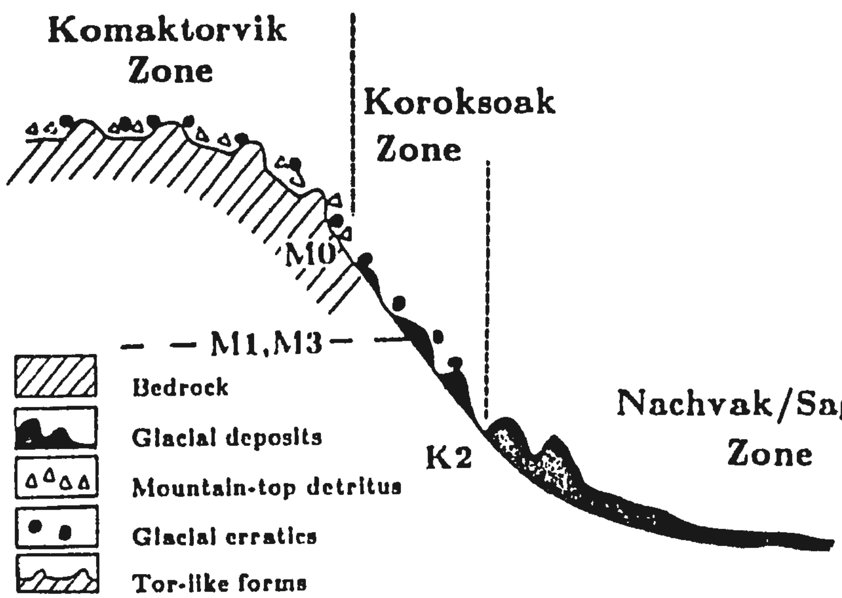


Figure 6-1: Diagrammatic representation of weathering zones identified in the inner fiord, west of Kogarsok Brook valley.

6.3.1. Quaternary Chronology

These results can be summarised into a description of the Quaternary chronology of Nachvak Fiord. Although information from the inner fiord relates to the entire Wisconsin period, Late Wisconsin events are known in most detail as they are best-preserved. In this summary, correlations are drawn to identify glacial events that took place throughout the fiord, but details of inner fiord events are specified.

Table 6-1 outlines the four glacial phases recognised as having taken place within Nachvak Fiord. Evidence of two or perhaps three phases can be seen in the inner fiord. The Ivitak phase occurred in two stages, estimated by Evans (1984) to have occurred > 70 ka BP and $\gg 40$ ka BP; it is considered to be an Early Wisconsin glaciation. The Early Ivitak was most extensive, with moraines reaching 180m aht on the south side of the outer fiord, and perhaps over 200m aht on the northern side (Clark and Josenhans, 1986). Given these dimensions, ice would have extended onto the Labrador Shelf and probably deposited at least some of the glacial till found there. In the inner fiord, ice thicknesses reached at least 590m in Kogarsok Brook valley. Local glaciers were active during both Early and Late Ivitak phases in the Selamiut Mountains. The Late Ivitak was less extensive and is thought to have deposited moraine K1 on the Kogarsok highland.

The Adams Lake phase was identified as a local glaciation, involving highland glaciers south of Nachvak Bay. It was not reported in the Selamiut Mountains and only tentative correlations can be drawn between it and moraines M1 and M3 on the Kogarsok highland. This event has a Middle Wisconsin age, 25-50 ka BP. If the correlation is accurate, it suggests considerable regional ice activity at this time.

Terrestrial evidence from Nachvak Fiord consistently points to a restricted Late Wisconsin or Nachvak glacial maximum. Regional ice is not thought to have extended beyond the fiord threshold, though it did backfill Tinutyarvik and Naksaluk valleys. The maximum is dated at 17-24 ka BP. A relatively rapid retreat is suggested by the elevations and gradients of shorelines in the inner fiord area. Deglaciation took place in several phases, as shown by the presence of numerous moraines along the fiord trough. Shorelines identified within the fiord may have been produced at individual stages of ice stillstand. A 9 ka BP shoreline extending from the outer fiord area to Tasiuyak Arm provides a minimum date for deglaciation of most of the fiord, and suggests that ice remained at the head of Tasiuyak Arm for some period of time, consistent with the formation of shorelines 8 and 9. This period was termed the Tessersoak, and appears to be correlative with other periods of major shoreline development in Kangalaksiorvik Fiord, Eclipse Channel and Ekortiarsok Fiord (Loken, 1962*b*; Clark, 1984). Ice had probably left the vicinity of the fiord by 7,000 years BP, as sediments of glacial origin ceased to be deposited in Townley Basin after that time.

Table 6-1: Glacial phases previously recognised by Evans (1984) and Bell (1987), with correlative data from inner Nachvak Fiord.

Glacial Period	Characteristics & Location	Inner fiord equivalent
Early Ivitak phase $>$ 75 ka BP Regional & local ice, extensive, occupied fiord and beyond.	High weathered moraines & trimlines; nunataks, felsenmeer & tors above. Selamiut Range, M1 trimline.	Moraine M0, $\sim$500m aht.
Late Ivitak phase $\ll$40 ka BP Regional and local ice, less extensive, whole fiord ?	Weathered moraines below Early Ivitak. Selamiut Range only.	
Adams Lake phase max. 33-38 ka BP recess. 29-32 ka BP.	Local cirque activity, outer fiord only; good dating controls, high shorelines.	M1 & M3 ? 200-300m aht local & regional ice ? More extensive inland glaciation, perhaps regional.
Nachvak phase 17-23 ka BP 22±2 ka BP regional & local ice, to fiord threshold at max.. Numerous phases of retreat.	Relatively unweathered moraines and glacial features; Selamiut range, Ivitak Cove area, outer fiord.	K1 maximum: $\sim$200m aht $\sim$23 ka BP; little material deposited. K2 recessional; 100-180m aht, well preserved, $<$ 22-23 ka BP.

The Superguksoak phases occurred in the late Late Wisconsin and Holocene periods; they appear to have involved only local glacier advances. Superguksoak I was identified in the Selamiut Mountains, and given a date of 5-12 ka BP. It appears to correlate with McCoy's Cirque Lake moraines (1983), but was unlikely to have included any regional ice activity although associations with the Tessersoak readvance were suggested by Bell (1987). Superguksoak II and

III are thought to be neoglacial phases, perhaps occurring in the very recent past (Evans and Rogerson, 1986; Rogerson, Evans and McCoy, 1986).

During the Holocene, patterns of climate and vegetation change in the area around inner Nachvak Fiord appear to have followed those typical of northern Labrador. Pollen analyses of one piston core and one gravity core from the centre of the fiord imply a regional tundra vegetation, with sedges and grasses dominant until approximately 7,000 years BP, followed by a more productive shrub tundra vegetation which was dominated by birch and alder. The arrival of shrub tundra may have marked a climatic amelioration. A return to sedge and grass dominated tundra is tentatively interpreted from a zone at the top of core 108.

6.4. Future Research

Future research in this area should probably concentrate firstly on consolidating the information gathered so far by detailed study within Nachvak Fiord, which would likely be best done through a number of small scale projects in different parts of the fiord, and secondly on assessing the extent of Late Wisconsin glaciation in other fiords of the Torngat Mountains. The Late Wisconsin period remains the topic of debate, since offshore and onshore reconstructions have not yet been reconciled. Deep coring of sediments at several points within the fiord and on the continental shelf at this latitude is probably the only method by which absolute evidence of the age and extent of tills will be found.

Examination of the elevation and age of moraines observed on the northern side of the fiord, at Schooner Cove and [illegible]ter Cove, began in 1986; it needs to be carried out in more detail to see if the moraines are M1-phase equivalents (Bell, 1987) or high Late Wisconsin remnants (Clark and Josenhans, 1986; Clark, 1988). In view of the variability of solum depths on moraine crests, it is clear that large data sets are necessary for realistic soils-based chronological reconstruction. More detailed soils studies are suggested for the outer fiord area in particular. Regional reconstruction based on 15 or 20 widely scattered soil pits must be viewed with extreme suspicion. The possibility of an extensive regional glaciation during the Middle Wisconsin (Adams Lake phase) should also be fully investigated.

The region would also benefit from a survey of potential postglacial faults, some of which have been identified from aerial photographs (Figure 4-9). Detailed ground reconnaissance would provide valuable geologic information on the nature of crustal activity in this area, and may help to explain some of the shoreline elevations and gradients in the region.

Terrestrial reconstructions for this fiord are remarkably consistent. Additional offshore analyses in the specific area off Nachvak Fiord are necessary to provide a link between marine and terrestrial reconstructions. Offshore palynological evidence may be of use in this regard; comparison of pollen spectra from cores collected throughout the fiord with those taken from the Labrador Shelf might provide additional information on the timing of Late Wisconsin deglaciation. The author is currently analysing pollen from fiord cores 85027-105 and -106, with the aim of carrying out such an evaluation.

Further analysis of high level moraines and trimlines in the mountains surrounding Nachvak Fiord would throw more light on the extent of earlier glacial periods, and might allow a more detailed reconstruction of Wisconsin events. The sea levels and extent of ice during the last two glacial periods are vital to a correct interpretation of Late Wisconsin events, and thus of marine sedimentary units.

It has been suggested that the Torngat Mountains acted to deflect ice-flow around Nachvak Fiord, causing greater amounts of ice to enter the fiords to the north and south (Clark and Josenhans, 1986; Bell, 1987). This hypothesis ought to be tested, again in order to evaluate the reconstructions of ice-sheets in Nachvak Fiord. It is recognised that the Torngat Mountains hold a large amount of information on the Quaternary glaciation of north-eastern Canada, and also that localised and detailed studies are necessary in order to uncover their history. Examination of the coastal bays and fiords north and south of Nachvak Fiord is probably the next step for this chronology, and would likely provide new interpretations for some of the Nachvak Fiord data.

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Appendix A
Drift Geochemistry Data

Table A-1: Results of Geochemical Analysis for all sample sites (concentrations are in ppm except where indicated; anomalously high concentrations are in bold face).

Site	Ag	Co	Cr	Cu	Fe[9]	Mo	Mn	Ni	Pb	Zn
EC1	0.2	31	100	145	6.53	<1	514	97	2	146
EC2	0.2	68	109	206	5.33	<1	1510	138	6	105
EC3	0.2	47	92	231	7.11	1	430	124	**12**	190
EC4	0.4	27	84	205	5.96	2	304	101	8	98
KM1	**1.0**	86	126	**553**	8.21	<1	1405	224	4	242
BC1	0.4	68	87	180	4.79	<1	814	128	2	105
BC2	0.4	9	54	134	2.85	1	92	32	<2	23
BC3	0.2	29	102	129	7.82	5	797	51	**18**	69
BC4	0.2	37	106	100	6.15	<1	590	83	<2	163
BC5	0.4	66	156	195	6.19	<1	1270	177	<2	108
BC6	0.2	33	**286**	198	3.91	3	174	159	2	99
KE1	0.2	35	147	95	3.38	4	373	64	8	38
KE2	0.2	38	135	84	4.45	2	970	73	8	73
KE3	0.2	47	96	121	5.67	3	889	105	4	90
KE4	0.2	73	126	164	5.67	<1	1240	177	8	127
KE5	0.2	74	100	249	4.67	<1	871	181	<2	133
KE6	0.2	54	109	206	5.65	<1	949	160	2	158
KW1	0.4	52	92	88	4.36	2	990	80	4	72
KW2	0.2	38	68	115	3.35	3	739	84	6	37
KW3	0.2	50	106	135	5.53	<1	982	103	10	72
KW4	0.4	107	104	324	6.40	1	1155	214	**14**	174
KW5	0.4	62	108	266	6.43	**17**	603	229	10	156
K1-1	0.2	118	95	**468**	4.04	1	691	300	<2	137
K2-1	0.4	90	92	287	4.89	3	823	184	2	100
K2-2	0.2	49	122	176	5.47	1	811	157	2	138
K2-3	**0.8**	55	97	223	5.88	3	742	162	8	110
K2-4	0.2	**185**	123	437	7.73	6	**1640**	**400**	2	221
K2-5	0.6	41	82	187	4.79	<1	590	108	2	74
K2-6	0.4	75	86	164	4.46	3	772	145	<2	62
M0-1	0.4	102	102	274	5.51	4	1515	220	2	131

[9]% conc.

Site	Ag	Co	Cr	Cu	Fe[10]	Mo	Mn	Ni	Pb	Zn
M1-1	0.2	53	148	169	6.94	<1	815	165	<2	179
M1-2	0.2	56	144	208	7.48	<1	1000	196	<2	181
M3-1	0.2	67	121	250	5.43	<1	867	210	4	153
M3-2	0.2	96	132	349	7.16	1	1205	300	4	196
M3-3	0.2	87	114	259	5.80	<1	1270	252	<2	139
M3-4	0.2	50	159	327	6.86	<1	691	223	<2	211
M3-5	0.2	86	116	200	5.39	2	862	176	8	153
PP	0.4	101	118	335	6.35	3	1410	275	6	174
M5-1	0.2	59	120	262	5.58	<1	659	256	6	199
M5-2	0.2	36	73	96	3.05	1	367	95	4	60
M5-3	0.2	65	115	203	6.89	<1	1110	207	<2	192
G1	0.2	98	161	192	7.62	<1	1535	226	<2	180
G2	0.2	71	169	243	8.78	<1	1465	348	<2	168
NF1	0.4	81	89	417	9.55	<1	626	**562**	6	**304**
NF2	0.2	42	86	215	6.66	<1	527	156	2	199
NF3	0.2	55	77	145	6.22	<1	585	190	<2	194
NF4	0.2	81	81	214	7.38	<1	679	265	10	**305**
NF5	0.2	86	75	305	7.68	1	1125	**410**	<2	**281**
KV1	0.4	56	**109**	**516**	**11.20**	**13**	490	96	6	106
KV2	0.2	30	75	335	9.25	6	534	93	<2	110
KV3	0.2	42	62	333	7.15	6	656	97	6	66
KV4	0.2	56	115	352	7.08	2	482	352	6	**322**
KV5	0.2	42	104	338	9.10	8	485	167	6	159
TM1	0.4	31	93	360	**10.20**	**14**	554	82	8	90

[10]% conc.

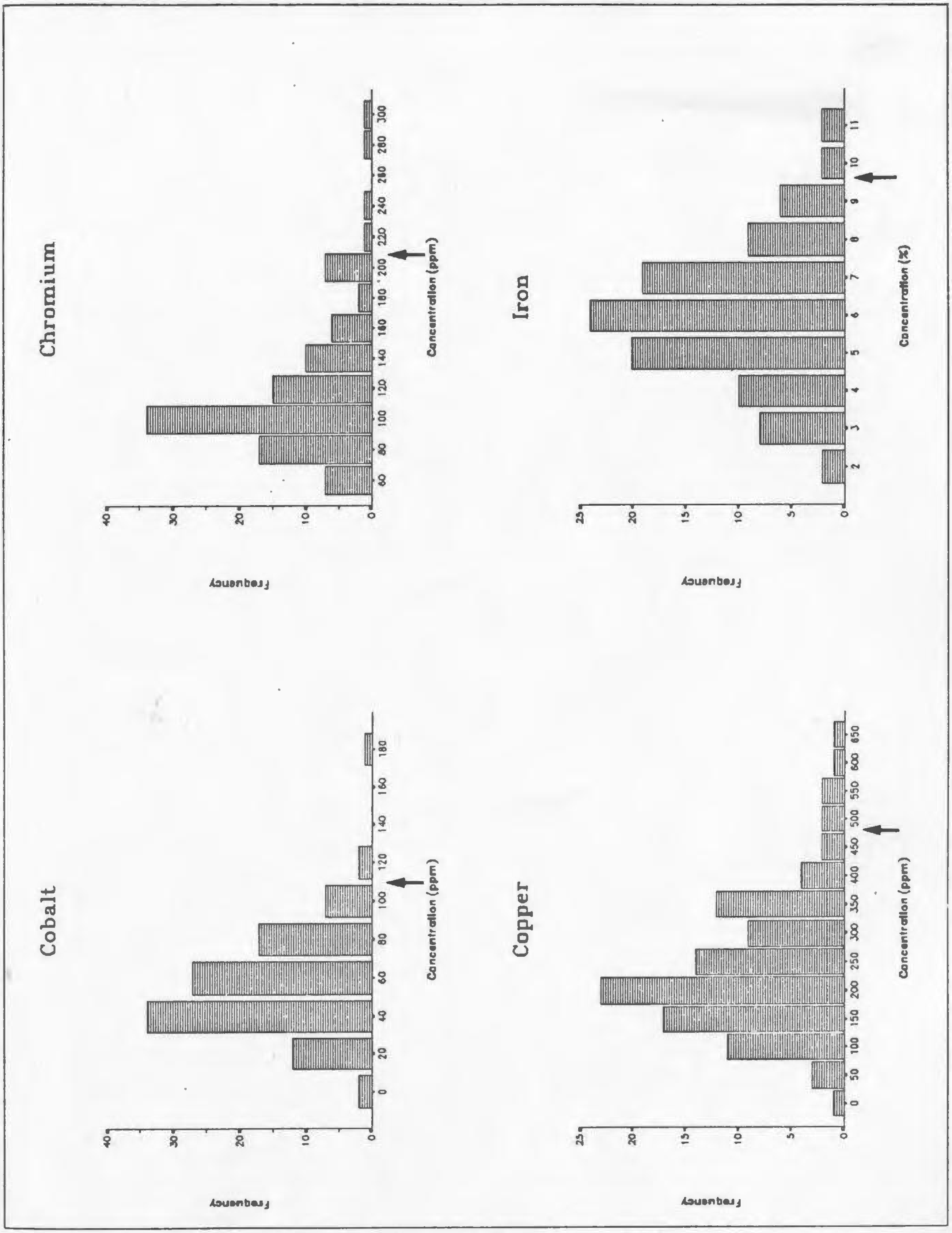

Figure A-1: Frequency histograms of metal concentration in $< 2\mu m$ sediment size fraction collected in 1983, 1984 and 1986. Arrow denotes threshold value of anomalous concentration.

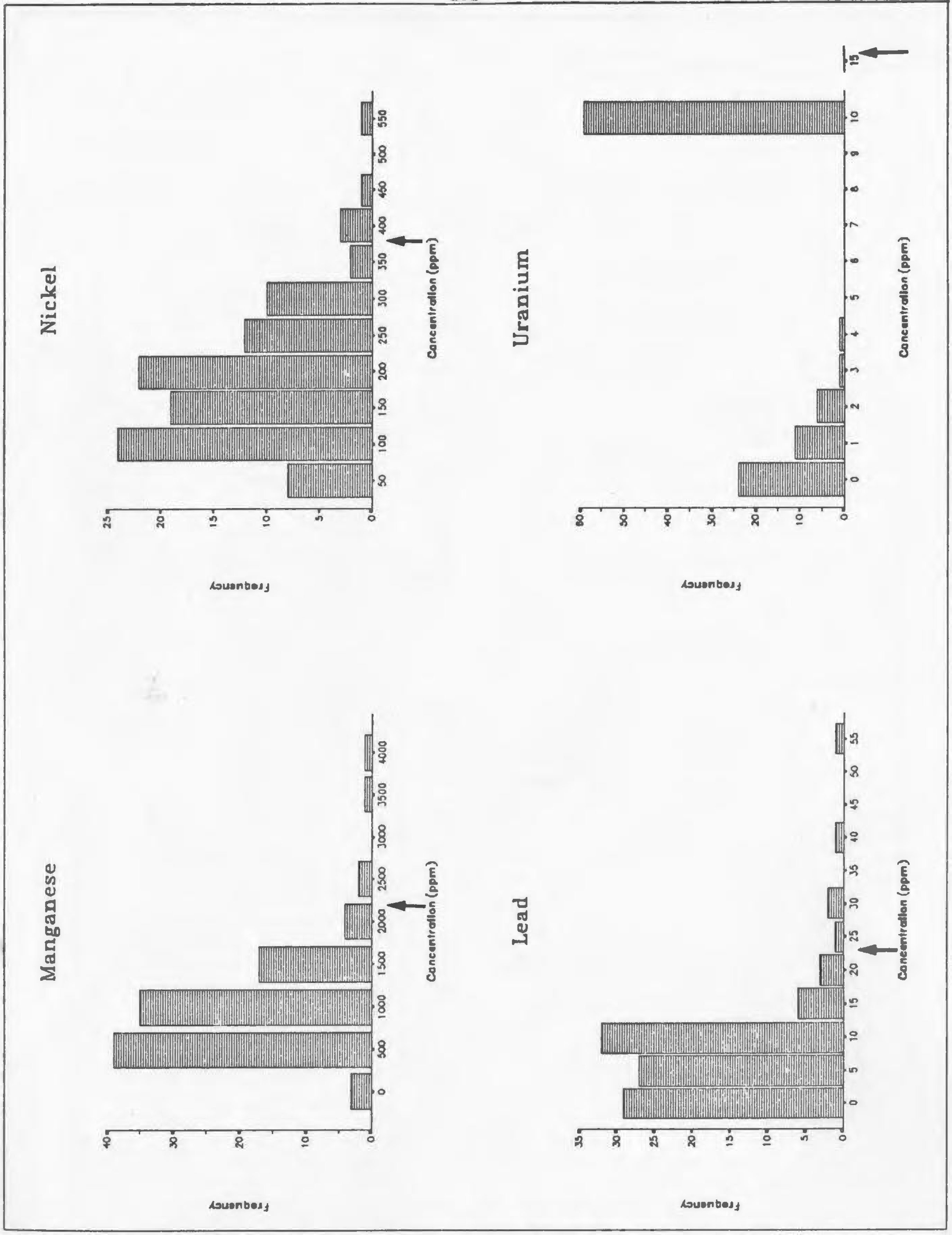

Figure A-1: Frequency histograms of metal concentration in $< 2\mu m$ sediment size fraction collected in 1983, 1984 and 1986. Arrow denotes threshold value of anomalous concentration.

Figure A-1: Frequency histograms of metal concentration in $< 2\mu m$ sediment size fraction collected in 1983, 1984 and 1986. Arrow denotes threshold value of anomalous concentration.

Figure A-2: Frequency of metal concentrations at selected locations in Nachvak Fiord.

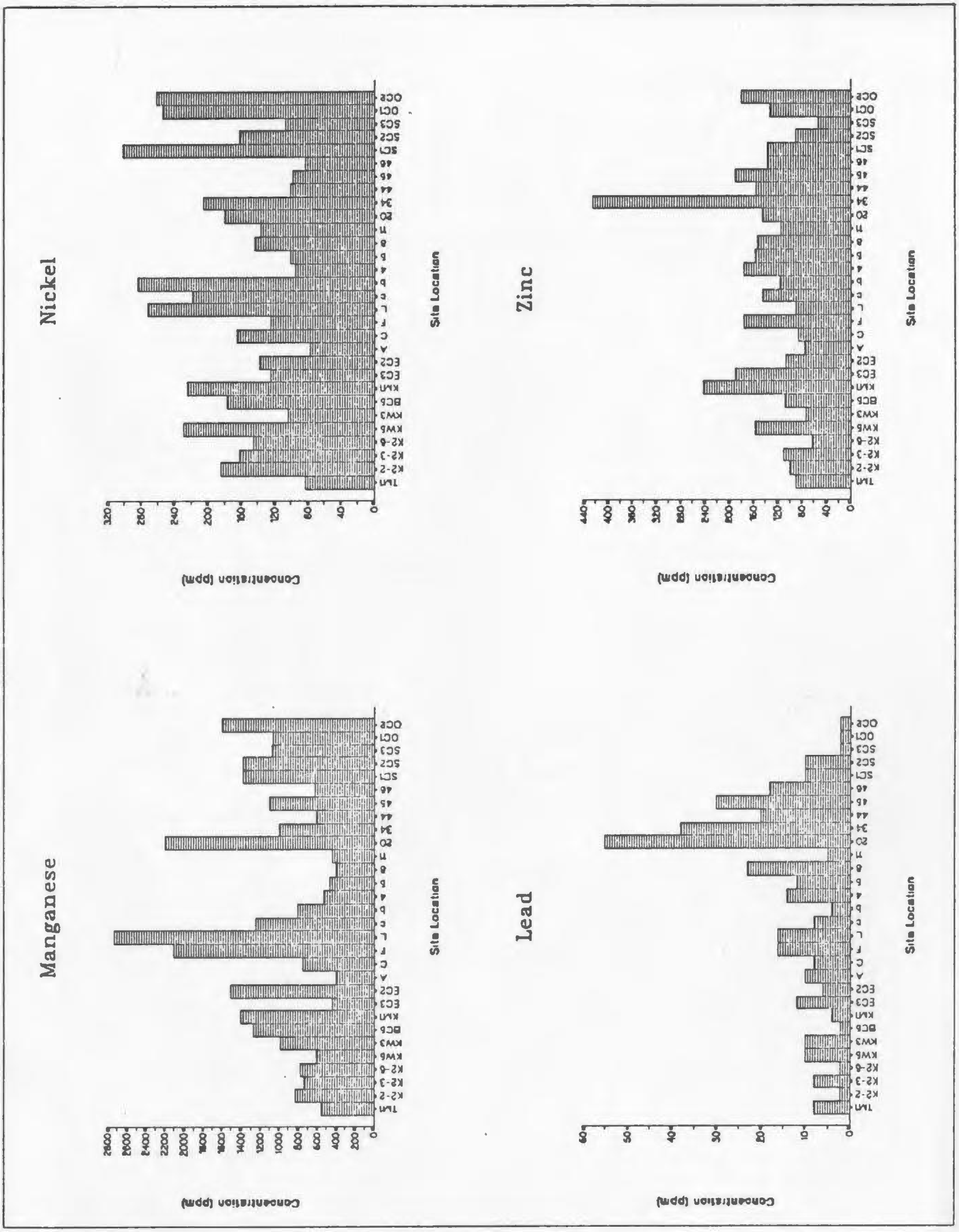

Figure A-2: Frequency of metal concentrations at selected locations in Nachvak Fiord.

Appendix B
Pedological Data

Table B-1: Soil depths and site information

Site	Alt. m	Depth cm	Colour	Location
EC1	27.6	A....1 B....6 C...54	- 10YR 2/2 2.5Y 5/2	Fine, clayey substrate, few large particles above 30cm. Site above poorly drained terrace, numerous frost boils herb & grass veg., willow in hollows.
EC2	46.5	A...10 B...11 BC...6 C...49	- 10YR 2/2 10YR 2/2 10YR 3/2	B/C very coarse; Cox more gravelly, rock size increasing with depth. Site at highest rise west of delta. Well vegetated, numerous boulders on terrace.
EC3	33.0	B....5 C...87	10YR 2/2 2.5YR 5/4	B fine sands; more clays with depth. No stones found. Orange banding at 56-66cm. Flat terrace, sparse grasses with bare sand.
EC4	49.4	A....4 B...17 BC..28 C...75	- 10YR 2/1 10YR 3/3 10YR 3/3	BC fine sands alternating light/dark. Cox lighter. Few stones, all <5cm. Site at rise in terrace at ML; thick grass & herb vegetation.
BC1	38.4	A....3 B...56 C...35	- 7.5YR 3/2 10YR 3/4	Layers in B pale grey/orange. BC less sandy with depth. C pale, fine texture, many small stones. Grass & shrub cover. Top beach on north-east face of Kipsimarvik Head.
BC2	32.0	B...13 ....4 ....5 ....8 ...21 ...13 ...11	10YR 2/1 10YR 3/3 10YR 2/1 10YR 4/4 varied 10YR 3/4 10YR 2/2	Banded layers of fine clay/silt texture, becoming more coarse and lighter with depth. Grey 'gley' continuing below pit. Rich grass veg. on short, narrow terrace. Mid-beach on north-east face of Kipsimarvik Head
BC3	23.8	A...11 B...20 BC..31 C...38	10YR 3/4 10YR 2/2 10YR 4/3 10YR 3/4	B coarse sands; BC fine/silty, with orange bands. Cox has beds of loose, coarse gravel. Lower beach on north-east face of Kipsimarvik Head.
BC5	18.7	A....2 B....5 C...45	- 10YR 2/2 10YR 3/2	Sand increasing with depth; Cox coarse & gritty,no fine matrix. Coarse grass veg., large boulders & rubble on terrace.
BC6	19.4	A....5 B...11 BC..41 C...14	- 10YR 4/4 10YR 3/2 10YR 4/2	Varied layers of silt/mud lenses in BC; generally a coarse mud, some layers appear oxidised, some water saturated. Cox more coarse, increasing sand with depth.
KE1	35.5	A....2 B....9 BC..31 C...25	- 10YR 5/4 10YR 4/4 7.5YR 3/4	Buried soil at Cox; soft sand, rich orange colouring, no grit. BC similar to Cox observed elsewhere: coarse grit & sand, poorly consolidated. Poor vegetation, terrace open to material falling from above.

Site	Alt. m	Depth cm	Colour	Location
KE2	18	B....7 BC...3 C...47	10YR 3/2 10YR 3/4 10YR 4/3	Very coarse sediments B & BC. Cox has almost no fines. On gravel/sand ridge at 122° GN; no vegetation, many large rocks & shingle.
KE3	34	A....3 B....6 BC..23 C...30	- 10YR 3/4 7.5YR 3/4 10YR 4/3	Coarse material increasing with depth, all poorly consolidated. BC gritty; Cox coarse sand with larger stones. Site on moraine crest. Coarse tussock grasses with herbs.
KE4	43.9	B....6 BC..26 C...31	10YR 3/2 10YR 3/4 10YR 4/2	Becomes more coarse with depth; Cox a coarse grit with larger stones. Site on fluvial terrace, very bouldery, little vegetation.
KE5	131	A....7 B....8 BC...9 C...37	- 10YR 2/2 10YR 4/4 2.5YR 5/4	Fine sediments generally more coarse with depth. Cox medium sand; numerous boulders/rocks within pit. Site on moraine crest ~opposite moraine M5.
KE6	237	B...28 C...23	no colours	Becoming sandier with depth, Cox gravelly. Vegetation well developed, grasses & herbs. Site a moraine or kame terrace ?
KW1	38.9	B....4 BC..19 C...33	10YR 3/1 10YR 2/2 10YR 3/4	Becoming more sandy with depth; BC slightly gritty, Cox has very few fines. Pebble bed separates BC & Cox. Veg. of tussock grass in patches. Site on 'graded terrace' - perhaps a moraine ?
KW2	43	B....8 BC..11 C...38	10YR 3/2 7.5YR 3/4 10YR 3/4	Poorly consolidated subsoil, gritty sand in BC, Cox very coarse, many large stones. Partial veg. cover of herbs & grasses, some willow. Site on rubbly terrace, appears to be opposite pit KE3.
KW3	50	A....13 B...22 C...28	- 10YR 2/2 10YR 3/4	Gritty subsoil, Cox very gritty, no fines. Numerous large stones, boulder at base of pit. Little/no vegetation. Site at outer terrace, area of patterned ground, definite frost action.
KW4	73	B...23 BC..12 C...28	10YR 2/1 10YR 3/3 10YR 5/3	Sediments very gritty. BC coarse, some sandy fines; Cox medium sand, many stones & larger rocks throughout. Partial veg. of grasses & herbs. Site on high terrace of uncertain origin.
KW5	76	B...10 BC..13 C...46	10YR 3/3 10YR 4/4 10YR 5/4	Becoming sandy with depth; Cox medium-coarse sand, many gritty particles & stones. Large boulders (>50cm) common. Sparse vegetation. Site on moraine crest (K2?).
K2-1	181	A....2 B...25 C...34	- 10YR 5/8 10YR 5/6	Becomes more sandy with depth; Cox a coarse crumbly sand. Stones numerous throughout. Good vegetation of grasses & herbs. Site at high crest of moraine.

Site	Alt. m	Depth cm	Colour	Location
K2-2	156	A....5 B...21 C...64	- 10YR 3/6 10YR 5/4	Becomes more sandy with depth. Stones numerous throughout. Well vegetated, grasses, herbs, willows. Site at moraine crest.
K2-3	124	A....2 B...15 C...43	- 10YR 3/6 10YR 5/4	B has fine texture, rusty orange colour. Cox has gravel, cobbles, numerous larger stones in very fine matrix. Little vegetation; mosses & lichen. Site on moraine crest, many boulders.
K2-4	122	A....5 B...24 BC..15 C...25	- 10YR 4/6 2.5Y 4/4 2.5Y 5/4	Becomes increasingly coarse with depth. Cox very coarse gravels & stones. Little vegetation. Site on moraine crest, many boulders on surface.
K2-5	124	A....8 B....9 BC...9 C...53	- 10YR 5/8 2.5YR 5/4 2.5YR 5/6	Sandy, increasingly coarse with depth. Stones throughout. Site on moraine crest, alongside recently drained ponds.
K2-6	124	A....7 B...25 BC..15 C...11	- 7.5YR 4/6 10YR 4/6 10YR 4/4	Becomes more sandy with depth, BC coarse with grits. Cox well consolidated sand. Vegetation of moss, lichen, grasses. Site on moraine crest.
M1-1	405	A....8 B...15 BC..15 C...29	- 2.5Y 4/2 2.5Y 4/4 2.5Y 5/4	B fine, clayey; BC coarse & sandy, Cox more so with grit & larger particles. Poor vegetation of small herbs & lichen. Site on moraine crest.
M1-2	398	B....7 BC..27 C...35	2.5Y 4/2 2.5Y 3/2 2.5Y 4/4	Fine sediments, increasingly sandy with depth. Cox coarse sand with gravel particles. Site on moraine crest, surrounded by polygons.
M3-1	383	A...10 B...24 BC..12 C...41	- 10YR 4/4 2.5Y 5/4 2.5Y 4/4	Becomes increasingly coarse with depth, numerous stones in BC, pebble bed in Cox below 18cm depth. Site on moraine crest, many boulders.
M3-2	387	A....4 B...12 C...62	- 10YR 3/6 10YR 5/4	Much rubble, many boulders throughout. Cox very coarse & sandy. Vegetation of tussock grasses, herbs & lichen. Site on moraine crest.
M3-3	370	B...24 C...39	10YR 3/4 10YR 6/3	Increasingly coarse with depth, numerous stones throughout. Vegetation of small herbs, lichen & grasses. Moraine crest, large boulders common.
M3-4	379	A....3 B...15 C...61	- 10YR 3/3 2.5YR 4/4	B very gritty, coarse, particles >1cm common. Cox sandy, many small stones in sandy matrix. Good veg. of grasses, herbs, shrubs. Moraine crest.

Site	Alt. m	Depth cm	Colour	Location
M3-5	371	A....4 B....4 C...13	- 10YR 3/6 2.5YR 4/4	Very coarse B, many small stones. Cox more sandy, less gravel, more large rocks than B. Vegetation herbs, shrubs, grasses. Site on moraine crest.
?PP	269	B...44 C...10	7.5YR 3/4 10YR 4/4	B fine, many plant roots. Cox more coarse: sparse vegetation, few grasses & herbs. Site on moraine crest, many large boulders.
M5-1	148	A....2 B...12 BC..12 C...26	- 10YR 3/3 2.5Y 5/4 2.5Y 6/4	Becomes more sandy with depth; Cox a coarse sand. Many large boulders below B. Sparse vegetation, grasses, herbs. Site on moraine crest.
M5-2	228	A....7 B....7 BC..36 C...33	- 7.5YR 3/4 7.5YR 4/6 10YR 4/6	Becomes more sandy with depth; Cox coarse sand with gravel. Vegetation of grasses, herbs, some willow. Site on moraine crest.
M5-3	380	B...17 BC..24 C...21	2.5Y 5/4 2.5Y 5/6 2.5Y 4/4	Become more sandy with depth. BC very coarse sand with grit. Cox more large stones. Veg. moss, lichen, herbs, grasses. Site on moraine crest.
K1-1	211	B...23 BC..14 C...29	10YR 2/2 10YR 5/4 2.5YR 4/4	Become more sandy with depth. Cox very coarse sand, many clasts. Very little veg., low crest on bedrock.
TM1	69	B...18 C...46	10YR 3/3 2.5YR 4/4	Becomes very coarse with depth; Cox full of stones except toward top. Herb & grass veg. Site on moraine crest, possibility of earth sliding.
KV1	219	A...10 B....8 BC...5 C...48	- 10YR 3/4 10YR 3/6 10YR 5/6	Becomes more sandy with depth. Cox deep, many stones in coarse sand. Poor veg of small herbs & grasses. Moraine crest with rubble.
KV2	217	A...10 B....6 BC..10 C...59	- 10YR 4/6 2.5Y 4/4 2.5Y 5/4	Becomes coarse with depth; Cox has many stones & larger rocks. Partial veg. of grasses & herbs. Moraine crest with rubble.
KV3	305	B...17 BC..24 C...26	10YR 3/6 10YR 4/4 10YR 4/6	Very coarse throughout. Many large boulders. Little soil or vegetation anywhere on moraine crest.
KV5	363	A...12 B...16 BC...9 C...15 C...14	- 10YR 4/4 10YR 4/6 2.5YR 5/4 2.5YR 5/6	Becomes sandy, less stony, with depth. C sandy, no stones; Cox many coarse stones. Poor vegetation of herbs & lichen; moraine crest, many boulders.

Site	Alt. m	Depth cm	Colour	Location
OC1		A...2.5 B...19 BC....5 C....9	10YR 3/2 10YR 3/4 10YR 3/5	Topmost moraine, west-facing slope in glacial valley. Unknown elevation. Moraine probably deposited by local valley ice.
OC2	180	B...13 BC..13 C...18	no colours	Crest of middle moraine, thought to be older than topmost (OC1). Frost-heaved surface, no vegetation, very deep Cox. Probably deposited by regional fiord ice.
SC1	335	B...10 BC....5 C...38	no colours	Crest of moraine on outer shoulder of cove. Windswept, little vegetation. Deposited by regional fiord ice.
SC2		B...23 C...13	10YR 3/2 10YR 4/2	Same moraine, site around shoulder toward cove.
SC3		B...30.5 BC....5 C...7.5	10YR 2/2 10YR 3/4	Crest of very steep high moraine overlooking lake. Edge of moraine complex with till ridges & kettle holes, frost-heaving evident. Course of moraine unclear inland.

Appendix C
Methods of Pollen Analysis

C.1. Methods of Pollen Analysis

Sediment samples for pollen analysis were extracted at the Bedford Institute of Oceanography, and sent to Memorial University for processing and counting. Samples from cores 85027-107 and 85027-108 were taken at approximately 25cm intervals, giving a total of 18 samples from the piston core and three samples from the gravity core. Laboratory processing and analysis of the samples was carried out by the author using conventional procedures. A standard method of pollen isolation was used (Faegri and Iversen, 1975), an outline of which is given below.

C.1.1. Laboratory Analysis: Processing

1. 5ml of sediment was added to an amount of sodium pyrophosphate solution ($Na_4P_2O_2$), along with 0.25ml of *Eucalyptus* pollen grains in a suspension of known concentration. The *Eucalyptus* serves as an exotic 'marker' pollen, and allows absolute pollen frequencies to be calculated; the $Na_4P_2O_2$ solution disaggregates clay particles, and was particularly necessary for the fiord samples. The mixture was thoroughly mixed, centrifuged and decanted. With some samples, however, the particles were so fine that no amount of centrifuging would settle them and they were in danger of being poured off in decanting. Thus samples were always fine-sieved in the next step, and, in the case of deeper samples, decanting the sodium pyrophosphate was abandoned.

2. Each sample was wet-sieved through a 7μm mesh, firstly in $Na_4P_2O_2$ and then in distilled water. This removed the majority of very fine clay particles and helped to thoroughly wash the sediment. Pollen grains and spores are almost all larger than 7μm in size, so, provided that care is taken against spillage, none of the sample is lost.

3. Samples were coarse-sieved through a Gooch crucible, to take out any debris or large grains of sand, etc. Following this, the sediment was resuspended in distilled water and decanted.

4. Acetolysis. This step dissolves any cellulose in the sample, and is most important for organic sediments. The samples were washed with glacial acetic acid in order to dehydrate them, following which acetic anhydride (CH_3CO_2O) and 4 drops of concentrated sulphuric acid (H_2SO_4) were added. This was mixed thoroughly and placed in a hot water bath to boil for 5 minutes. A final wash with glacial acetic acid removed any remaining traces of H_2SO_4, and the sediment was washed three times in distilled water. The acetolysis procedure may not have been necessary, since these fiord sediments contained little organic material, and no great reduction in the processed matter was noticed.

5. Treatment with hydrofluoric acid (HF). Silicious material (in this case mainly minerogenic sandy matter) was removed by placing the sediments in a cold concentrated hydrofluoric acid bath overnight or for a longer period. This must be carried out with extreme care. The mixture was subsequently balanced with ethanol in the centrifuge, and then boiled in a water bath with dilute hydrochloric acid (HCl). This removed most of the minerogenic material, although occasionally it was necessary to fine-sieve the samples for a second time afterwards. Again, a $7\mu m$ mesh was used.

6. Staining and dehydration. A single drop of safranin-O was added to each sample to stain the pollen and spores, making them more visible against remaining mineral matter. Tertiary butyl alcohol was used to dehydrate and transfer samples into individual vials, where they were thoroughly mixed with silicone oil to prevent them drying out. They were then labelled and sealed.

7. Mounting: silicone oil was chosen as a mounting medium, since it does not appear to alter grain size, it has a low refractive index which makes for good visual contrast, and, by applying pressure to the coverslip, grains may be rotated. This allows all faces of a grain to be seen and can greatly facilitate identification.

C.1.2. 'Absolute' Pollen Calculation Method

Euacaluptus pollen grains were added at the beginning of this process so that absolute pollen frequencies could be calculated for each taxon, as well as percentage frequencies. The concentration of fossil pollen was calculated in grains cm^{-3} as:

$$\frac{\text{fossil pollen counts}}{\text{exotic pollen counts}} \times \text{added pollen concentration} .$$

The rate of pollen influx per year can be calculated using the equation:

$$\text{fossil pollen concentration} \times \text{sedimentation rate} .$$

C.1.3. Microscopy

Pollen was identified and counted using a Carl Zeiss Jena Laboval 2 binocular microscope, at a total magnification of x800. A x40 objective was used with x12.5 oculars and a binocular inclined tube factor of x1.6. Slides were traversed at regular 2mm intervals so as to ensure that grains of different sizes that may have spread unevenly under the coverslip were incorporated into the total count. On average, 12 traverses were made per slide; a minimum of 4 slides per sample were counted, the maximum being 6 in one case. Grains that were difficult to identify were examined using a x100 oil-immersion objective.

C.1.4. Pollen Sum

The pollen sum is the total number of grains of selected pollen types, which should represent the abundance and species variation of pollen grains being deposited in the fiord sediment at any one time. Pollen from trees, shrubs and herbs was included in the pollen sum. The percentage frequency of each taxon (eg. *Alnus*) included in the total pollen sum was calculated:

$$\frac{\sum \textit{Alnus}}{\sum \text{pollen}} \times 100$$

For groups excluded from the pollen sum, the spores, indeterminable and unknown categories, percentage frequency was found by adding the sum of that group to the pollen sum. This ensures that no taxon can exceed 100% (Birks and Birks, 1980). For example,

$$\%\ \textit{Lycopodium} = \frac{\sum \textit{Lycopodium}}{\sum \text{spores} + \sum \text{pollen}} \times 100.$$

The pollen sum should be large enough to adequately represent the vegetation of the area. Ideally, counting would continue until each taxon maintained a constant percentage of the pollen sum at each depth (Birks and Birks, 1980). The pollen sum thus depends on the number of taxa in the sample, the proliferation of vegetation and the choice of the analyst. In most areas, a pollen sum of 300-500 would be considered normal; however, in sparsely vegetated northern latitudes, lower sums are more reasonable. A sum of 100 was considered acceptable for this study (Morrison, 1970; Andrews *et al.*, 1980; Macpherson and Anderson, 1985) although it was rarely reached in core 107 (3 samples out of 18 gave a sum of 100). Very low concentrations are assumed to be the cause of these low sums; as numerous slides were counted at each sample level, the sums are thought to be significant. Sums for each sample level are shown on the pollen diagrams, Figures 7a,7b and 8a,8b.

C.1.5. Pollen Identification

Identification of pollen and spores was made to the genus level. Although particular genera can be defined to the species level (eg. *Picea*) this often involves time-consuming measurement of the fossils, and requires a good working knowledge of their modern counterparts. The higher level was considered to be beyond the scope of the analyst, especially considering the sparsity and degeneration of the fossil grains. No samples of modern pollen were collected from the field area, although accurate identification of vascular plants collected from a wide area around the basecamp was provided by Terry Hedderson (personal communication 1987). Fossils were identified using a number of keys, primarily Bassett, Crompton and Parmlee (1978), McAndrews, Berti and Norris (1973), and Moore and Webb (1978), plus a large reference slide collection of modern samples.

No distinction was made between *Betula* fossil grains that may have been derived from either trees or shrubs, though this can be done using mean size characteristics of the grains (Birks and Birks, 1980). The *Betula* species is most likely to have been a shrub where it grew locally around the fiord; it is possible that pollen grains of birch trees were blown in from more southerly areas. *Alnus* pollen grains were assumed to be of shrub varieties, since alder does not grow as a tree in north-east North America.

Larix species were discounted from the survey altogether because of the danger of confusing their fossil grains with organisms also found in the deposit. This is apparently a common procedure (J. Macpherson, personal communication 1987), as it is preferable to exclude them rather than to include a dubious number of grains.

Coryloid was the category used for triporate grains which were sufficiently degenerated so as to prevent further identification. Although they were initially classified as a distinct group, they were later excluded from the list of taxa counted. It was found that examples re-examined by an external source (J. Macpherson) were almost certainly exotic *Eucalyptus* grains. As a result, '*Coryloid*' counts were added to the exotic sum, and concentrations and percentages were adjusted accordingly. The error varied between 0 and 30% of the new total exotic sum, though it was below 10% in all but four samples for both cores 107 and 108. It is not thought to be significant with regard to the overall pattern of the pollen diagrams.

Pollen grains and spores were classified as indeterminable when they were either concealed by organic or mineral matter, or they were so broken, folded or degenerated that they could not be identified confidently. 'Unknown' was used as a classification in cases where a grain had clear features but could not be positively placed in a specific genus.

Pollen grains from aquatic plants were not found. These are known to degenerate quickly and easily since they have a thin exine and are usually poorly preserved, if at all (Faegri and Iversen, 1975).

C.1.6. Diagram Construction

Results are presented as pollen percentage and concentration diagrams. The POLSTA computer-graphics programme (Green, 1985) was used to manipulate raw data and construct the diagrams. A standard format was used so as to aid comparisons and interpretation. Depth in centimeters below the surface of each core is given on the left hand side of the diagrams. To the right are curves of identified pollen and spore types, drawn to a standard scale. These are arranged according to recognised plant groups; trees, shrubs, herbs and spores, ranging from left to right respectively. Indeterminable and unknown grains are given separate curves on the far right. *Betula* is considered a shrub throughout these cores. On the far right of the concentration diagrams only a curve shows total pollen concentrations. The sum of total pollen, and the sum of pollen and spores, are listed on the percentage diagrams.