ZONATION OF SUBARCTIC TIDAL FLATS AT FROBISHER BAY

PHYSICAL AND BIOLOGICAL ZONATION OF SUBARCTIC TIDAL FLATS AT FROBISHER BAY, SOUTHEAST BAFFIN ISLAND

by

JANIS ELAINE DALE, B.Sc.

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AUTHOR: Janis Elaine Dale, B.Sc. (Hons.) (University of Guelph)

SUPERVISOR: Dr. S.B. McCann

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ABSTRACT

The interaction of biological and physical processes has resulted in distinct morphological and biological zonation across the Subarctic macrotidal tidal flats at the head of Frobisher Bay. The tidal flats have been divided into six morphological zones which are closely related to the three biological communities found there.

Faunal species of the Upper Flat inhabit the beach and fines flat morphological zones where ice action during breakup and freezeup has the greatest influence. Species inhabiting these zones are hardy, and freshwater tolerant. Many are highly motile and recolonize the area after ice breakup.

The Middle Flat extends from 5.0 m ALLT to 2.2 m ALLT. It is inhabited by motile polychaetes at its upper end (bouldery flat $>$4.5 m ALLT), with more sedentary species appearing towards its lower end (very bouldery flat). Below 2.2 m ALLT, on the Lower graded flat, sedentary infauna such as *Cyrtodaria kurriana*, *Mya truncata* and sabellid polychaetes, dominate the substrate.

The three major processes acting on the tidal flats are, in order of importance, tidal, ice and wave action. Exposure indices, generated from tidal data, reveal 2 critical tidal heights at around 4 m and 7.5 m ALLT, in Frobisher Bay. The boundary between motile and less motile fauna, and bouldery and very bouldery morphological zones, occurs around 4.0 m ALLT. Of the flora and fauna only *Fucus evanescens* is found beyond the 7.5 m ALLT limit.

Tidal action also influences the chemical and physical (i.e. temperature and velocity) properties of the water which affect zonation. High instantaneous velocities are generated during ebb tide, but average flood tide velocities are higher. Thus, a mixture of ebb and flood dominant bedforms is evident.

Ice action during freezeup and breakup removes and transports sediment, boulders and infauna across the flats. The biological community is also affected by the low saline melt water from ablating ice. Drift ice gouges and striations are short term features and are soon reworked by normal wave processes once the ice has disappeared.

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This thesis is dedicated to
my Grandparents.

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CHAPTER 1

INTRODUCTION

1.1 Statement of the Purpose

The purpose of this study is to determine the relationships between biological and physical components and physical processes across Subarctic macrotidal tidal flats. The data were obtained from field-work undertaken during the summer of 1980 and 1981 at the head of Frobisher Bay, on the southeast coast of Baffin Island (Fig. 1.1). This is a macrotidal environment with a mean tidal range of 7.8 m, and a large tidal range reaching 11.6 m. Tidal processes, in addition to the presence of the fast and mobile sea ice for up to 9 months of the year, produce a distinctive tidal flat morphology and zonation different to more temperate locations.

1.2 Objective and Scope

The objective of the research is twofold.

1. To define the nature of the zonation across the tidal flats by examining surficial features, sediment texture, and floral and faunal distribution.

2. To determine the relative effectiveness of the three dominant coastal processes; tidal, wave and ice action.

The relationship between these two objectives is evident in Table 1.1. The process -response concept was devised to illustrate how a given area with a specific substrate and geologic and glacial history will be affected by geomorphic processes, climate and human

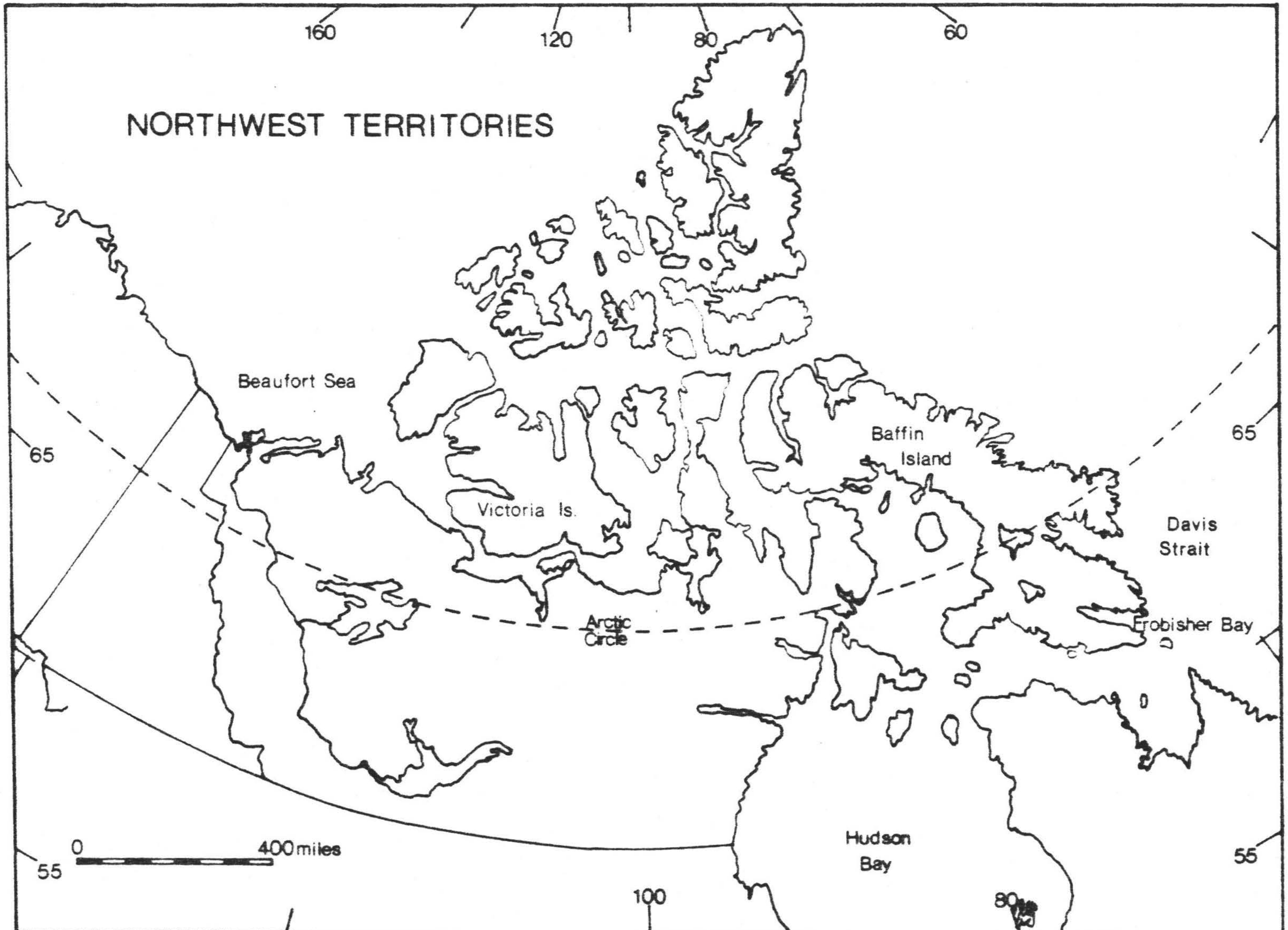
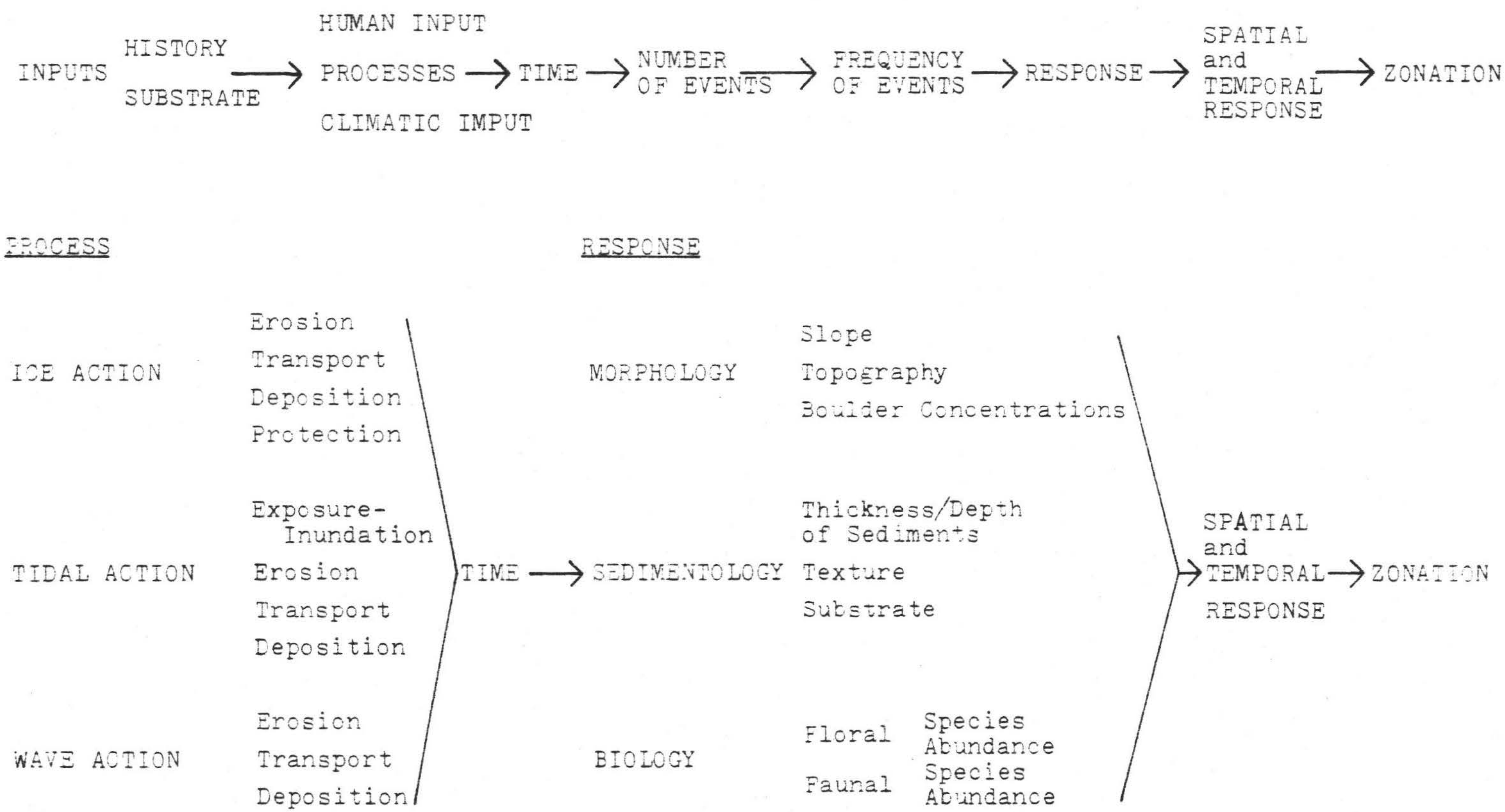


Figure 1.1 Location map of Frobisher Bay, southeast Baffin Island.

TABLE 1.1 Tidal flat - process - response concept.

TIDAL FLAT - PROCESS - RESPONSE CONCEPT



intrusion to produce its own peculiar assemblage of biological and morphological features. The effectiveness of the three dominant processes in Frobisher Bay is dominated by their duration, frequency and intensity. The subsequent temporal and spatial responses result in geomorphic and biologic zonation of the surface.

Zonation and exposure indices are two important concepts of this study which deserve further attention.

1.2.2 Zonation

The concept of zonation has been adequately reviewed by Doty (1957), Wilce (1959) and Stephenson and Stephenson (1972). Zones are major horizontal strips or regions on the coastline differentiated by disparate floral and faunal numbers and species. The zonation or vertical distribution is chiefly the result of "movements of the water surface such as tidal action, wave action, and currents, and is affected by the differences due to such factors as adsorption (capillarity) and diffusion related to the air-water interface." (Doty 1957).

Stephenson and Stephenson (1972) argue that zonation is not just the result of tidal action as it occurs in the sublittoral and supralittoral as well as the intertidal areas. Zonation is due to the air/water interface. In the sublittoral, changes in water depth affect light penetration and sedimentation rates which influence the zonation. Ice action also plays a role in the vertical distribution of biotic components (Wilce 1959, Stephenson and Stephenson 1972).

1.2.3 Exposure

In this research, exposure refers to the period of time a particular site in the intertidal zone is exposed to aerial elements. It is graphed as the percentage time exposed versus tidal height. Most researchers accept tidal changes as the primary cause of littoral zonation. The total time of exposure at various elevations results in "critical levels" (levels where a number of species reach their upper or lower limit) (Carnahan 1952, from Doty 1957). In turn, these critical tide factors expose organisms to secondary factors such as, oxygen availability, changes in salinity and temperature, ice action and dessication. The combination of tidal action plus these secondary factors plays a fundamental role in the distribution of floral and faunal organisms.

Secondary factors complicate the resultant zonation. Species are often found outside their preferred zone due to secondary factors, for example the appearance of low tidal species in tidal pools in high tide areas seen in Frobisher Bay. Zones may also be changed by differences in physiological responses by species. A third problem in assigning zones for organisms is due to lensing. This refers to the "attenuation at the lateral margins of the specific biospace" (Doty 1957).

The concept of the exposure index is not restricted to biological studies but can be used in geomorphological research. It has been used as a quantitative approach in defining the position of sedimentological features within the tidal zone (Hardie 1975). The exposure index is a quantitative measure which permits comparisons of tidal factors from one area to another, despite topographic and hydrologic differences. The precise tidal position of the feature can thus be determined (Hardie 1975). Use of the exposure index is a powerful tool in determining global trends and differences. Only a few tidal flat studies have successfully used exposure ratings for features found on tidal flats (Kellerhals and Murray1969, Reineck 1975, Larsonneur 1975 and Hardie 1975). This is the first time exposure indices have been used in an Arctic and Subarctic context.

1.2.4 Significance

This study will help reduce some of the many gaps in knowledge on cold region coasts. There are few geomorphological projects on Subarctic tidal flats, and even fewer projects which have combined a geomorphological and biological approach. Scientifically, the contribution stems from the attempt to relate biological and physical processes of tidal flat genesis, in an ice dominanted environment. Such research has not been undertaken in Frobisher Bay before. Useful comparisons can be made between northern flats and more temperate locales using the exposure indices calculated for the area. As noted earlier exposure index analysis has not previously been attempted in Subarctic tidal flat projects.

Some of the tidal flats at the head of Frobisher Bay have been modified by human interaction. The extent and importance of human activity on the Subarctic tidal flat environment can be evaluated using information from this project.

Finally, the study provides a base on which decisions concerning ecological concerns and coastal engineering and construction projects can be based.

1.3 Description of Field Area

The field area (Fig. 1.1) is located at the head of Frobisher Bay on the southeast corner of Baffin Island, in the Northwest Territories. Some 250 kilometres of coastline were covered during aerial studies of the shoreline. The notable features of which are extensive tidal flats, some reaching up to 3 km in width (Fig. 1.2). A macrotidal range dominates the coastal environment with semi-diurnal tides averaging 7.8 m ALLT and large tides of 11.6 m. Two high and two low tides are experienced daily even during solid ice cover some 8 to 9 months of the year.

Frobisher Bay is Subarctic, receiving mixed water from polar and non-polar origins (Wilce 1959). Dunbar (1953) noted that Subarctic waters extend almost the entire coast of West Greenland and coincide with the Arctic-Subarctic boundary introduced by Madsen (1936,1940). He suggested that the disappearance of *Mytilus edulis*, *Littorina saxatilis* and *Balanus balanoides* from the intertidal fauna provided a useful criterion for the Arctic-Subarctic boundary. Likewise, more recently Lubinsky (1980) used bivalve molluscs to determine the Arctic-Subarctic boundary, again Frobisher Bay was considered Subarctic.

Historically, the area has undergone heavy glaciation. The most recent glacier probably retreated some 6,750 ± 170 years B.P. (Blake 1966) leaving a well developed moraine at the head of the bay. Raised deltas along the present shoreline suggest that the area of present tidal flats was once under fairly deep water. Miller (1980) has suggested that the entire eastern Canadian seaboard has been dominated by local ice centres, nourished from nearby sources of moisture and which responded

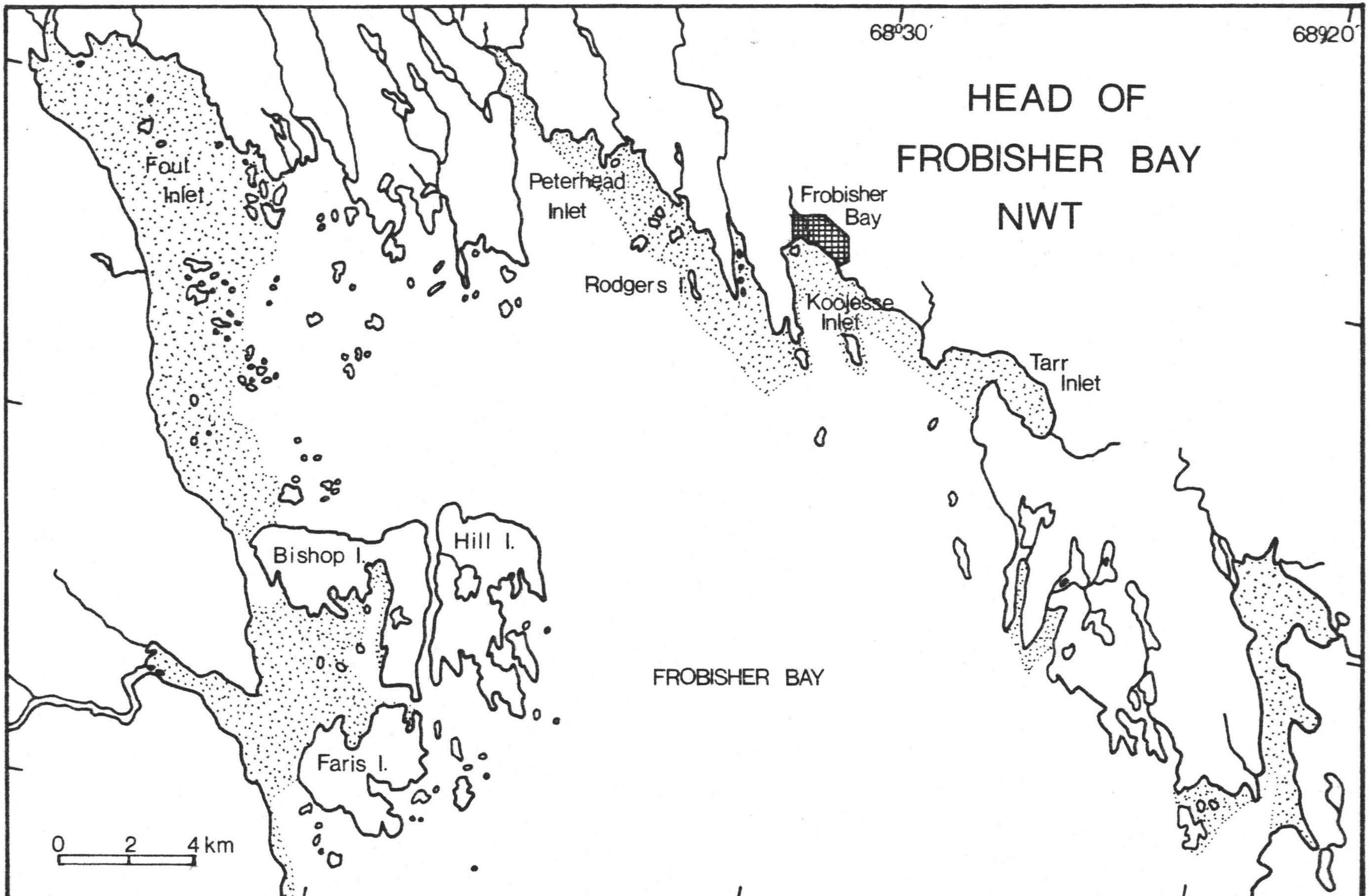


Figure 1.2 Tidal flats at the head of Frobisher Bay and prominent place names.

rapidly to climatic events.

1.4 Method of Investigation

The tidal flat process-response concept shown earlier (Table 1.1) illustrates the type of effects and responses observed and expected on the tidal flats. Ice, tidal and wave action are capable of erosion, transportation and deposition of materials. As well, ice action can protect substrate surfaces and tidal action affects exposure to aerial elements. The following Chapters, 2, 3, 4, 5, and 6 deal with the observed responses and attempt to determine the major contributing process. Sampling and laboratory techniques used will be covered in each chapter. However the overall scheme will be presented here.

The study involved three scales of investigation - regional, inlet and transect (Table 1.2). Different aspects of the tidal flat environment were studied at the different scales. At the regional scale aerial studies of 250 km of shoreline were undertaken using a video-cassette recorder. Field verification of the features was carried out in Koojesse and Peterhead Inlet. Coastal environments, tidal flat classification and ice breakup sequence and dynamics were determined from the flights flown in 1980.

At the inlet scale, Koojesse Inlet was studied intensively. It was chosen largely for logistical reasons. It also exhibited both human influences as well as the more natural influences of such less disturbed sites as Rodgers Island. Ice breakup was monitored in Koojesse Inlet in 1980 and 1981 and ice affects noted. Tidal flat morphology, sediment and boulder dis-

TABLE 1.2 Research at the three scales of investigation, regional, inlet and transect.

SCALES OF INVESTIGATION

REGIONAL	Head of Frobisher Bay	Coastal Types Tidal Flat Classification Ice Break-up sequence and dynamics, 1981.
INLET	Koojesse Inlet	Ice Break-up Ice effects Sediment zones Boulder distribution General biology Morphology (slope, drainage)
TRANSECT	Four transects from high to low tide	Ice zonation and ice effects Sediment distribution, and movement Boulder distribution and size Detailed biology - species and numbers Transect morphology

tribution was recorded at the inlet scale. Prominent morphological features were surveyed with stadia rod and level and sextant readings used to accurately position these features. The size and distribution of boulders on the ice and flat surface were surveyed.

The most intensive observations were undertaken at the transect scale. Four transects were chosen to typify the variety of tidal flat types observed in the area (Fig. 1.3). They varied in slope, length, surface cover, morphology and aspect (Table 1.3). These transects were used throughout the study and were named Apex, STB (Slow Tide Bay), Rock and Rodgers Island (RI) transects. They will be referred to extensively throughout the work. At this level of study, detailed surveying, and sampling programs were initiated in 1980 and continued in 1981. Information on the ice foot, the ice foot/fast ice boundary and ice effects, such as gouging and ice push, were measured. The size and distribution of sediments and boulders and resultant flat morphology by ice, wave and tidal action were intensively studied at this level. Finally, detailed floral and faunal sampling along the transects resulted in species lists and densities for the area.

At each scale of study the level of information increases. Information at the regional scale confirmed at the transect and inlet scale will be applicable over a wide area of Frobisher Bay and other northern tidal flats in the vicinity.

1.5 Important Literature

1.5.1 Introduction

In general, pertinent literature is reviewed at the beginning of

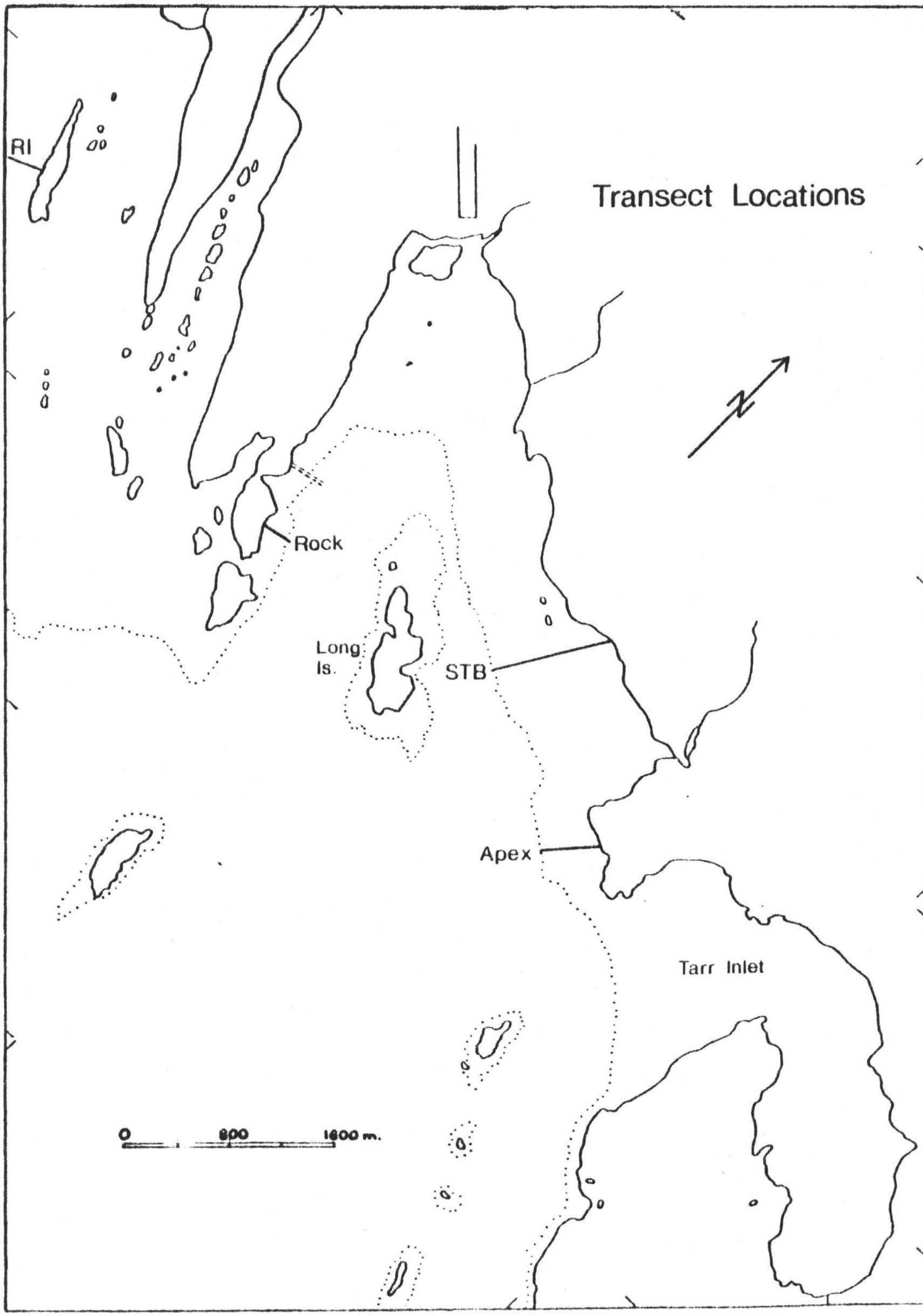


Figure 1.3 Location of the 4 transects studied Apex, STB, Rodgers Island and Rock transects.

Table 1.3 Description of the Frobisher Bay Transects

TRANSECT	ASPECTS	LENGTH	SLOPE	MAXIMUM HT. OF SEDIMENT ABOVE LOW TIDE	DISTINGUISHING FEATURES
STB Slow Tide Bay	S-W	850 m.	.0063	7.5 m	Low relief with sand mounds, from 100 to 350 m from shore. Boulder concentration forms low ridge at 350 m. Meandering drainage.
Apex	S-W	650 m	.01	5.0 m	Two boulder ridges parallel to shore with pools. Meandering drainage.
Rock	N-E	150 m	.038	5.0 m	One boulder ridge parallel to shore with pool. Distinct drainage network perpendicular to shore.
Rodgers Island	S-W	300 m	.0069	3.5 m	Small ice push boulder ridges at shore. Meandering drainage. Flat, little relief.

each chapter. However, a few notes are necessary on the more influential projects concerning tidal flat literature, Subarctic tidal flat studies and 'le glaciel'.

1.5.2 Tidal Flat Research

Tidal flats are low gradient, low relief, poorly vegetated intertidal coastal features, built largely of unconsolidated sediments. Tidal, rather than wave, processes dominate sedimentation.

Tidal flat research has been underway since the early 1900's. Notable contributions were made by Kindle (1917 in Klein, 1977) in the Bay of Fundy and Hantzschel (1939) along the North Sea coasts. Following the second World War, there was an increase in tidal flat studies particularly by Europeans such as Van Straaten (1952, 1954), Van Straaten & Kuenen (1957), along the Wadden Sea, and Postma (1961, 1967) and Reineck (1967, 1975, 1976) along the North Sea. These researchers noted the tidal flat zonation in terms of flora, fauna, surface structures and grain size. They proposed theories of scour lag, settling lag and vertical and lateral deposition to explain their geomorphic observations. They also recognized the importance of tidal exposure and inundation on flat morphology and development.

Evans' (1965) study on the Wash in England is considered to be one of the earliest and most comprehensive studies (Klein 1977). He denoted zones by biological, morphological and sedimentological characteristics and attempted to determine the importance of various processes on the resultant features.

Similar zonation studies have been made in North America in the Bay of Fundy, (Klein 1964, Knight and Dalrymple 1976) where ice is an important process, in California (Pestrong 1972, Thompson 1975) and in Boundary Bay, British Columbia (Kellerhals and Murray 1969, Swinbanks 1979).

1.5.3 Arctic Tidal Flat Research

Arctic tidal flat studies for the most part can be divided into biological and geological studies. Few studies have attempted to integrate biotic zonation with morphological zonation and the influencing processes. The work of Martini and Protz (1979, 1980) in James Bay, and Aitken and Gilbert (1981) at Pangnirtung are exceptions.

The most important biological contributions relating to the eastern Arctic have been on the Greenland coast (Thorson 1933, 1936, 1941, Vibe 1939 and Madsen 1936, 1940), on southeastern Baffin Island (Ellis 1955, 1966, Ellis and Wilce 1961, Den Beste and McCart 1978 and J. Wacasey pers. comm. 1980) and on molluscs (Lubinsky 1972, 1980 and Clarke 1974). A more detailed review of these projects is contained in Chapters 5 and 6.

The geomorphological aspects of tidal flats, and in particular the effectiveness of ice in northern environments have been studied in Leaf Basin, Ungava Bay (Lauriol and Gray 1980), Makkovic Region in Labrador (Rosen 1979, 1980), James Bay (Martini and Protz 1979, 1980) and James and Hudson Bay areas (Dionne 1974a, 1975, 1976, 1978, 1979). These findings are summarized in Chapter 4.

1.5.4 Le glaciel

The effect of ice on the biological and physical aspects of the tidal flat zonation cannot be overstated. It is the presence of this ice for such a long length of time which differentiates the Subarctic from temperate flats.

Ice effects were documented as long ago as 1865 by Lyell. Hamelin (1975) has proposed the term 'glaciel' be used to describe the entire field of research dealing with floating ice and its effects. Research on this topic and its physical and chemical effects in Frobisher Bay are discussed in Chapters 2, 3, 4 and its biological effects in Chapter 5, 6.

1.6 Format of Thesis

Chapter 2 provides an account of average ice conditions at the head of Frobisher Bay. Specific analysis is made of ice breakup from aerial observations and field monitoring. The sequence of events and its effectiveness as a process is highlighted in Chapter 2. In Chapter 3, the actual effect of ice as observed on the flats is discussed. Its ability to erode, and transport sediments, and its effect on the biological community are described. Chapter 4 concerns the geomorphology of the tidal flats from the regional to the transect scale. The effects of wave and tidal action as well as ice on the surficial geology are documented. Chapter 5 and 6 describe the biological zonation of the flats from the transect analyses. Macrofauna (> 1 mm in size), bivalves, gastropods and macroalgae distribution are presented in Chapter 5 and the meiofauna (< 1 mm in size), mainly polychaetes, are discussed in

Chapter 6. Chapter 7 lists the major conclusions reached in this thesis. Appendix 1a lists the species and numbers found from the polychaete sampling.

Appendix 2 describes the methodology employed in the geomorphological research presented in Chapter 4. Appendix 1 lists the polychaete species and numbers collected at the 4 transects in 1981 and Appendix 1 is a report on polychaete life habits.

Prominent place names, hereafter often identified by number on subsequent maps, are shown in Figure 1.2.

All tidal heights unless otherwise mentioned are measured from 0 tidal datum taken from tidal records supplied by C. O'Reilly (pers. comm.) and the Canadian Hydrographic Service. The 0 tidal datum used was the lowest, low spring water tide attained in 1979. All tidal heights are measured above this low low tide mark (ALLT).

Exposure curves were obtained from predicted tidal values which did not vary significantly from the actual tidal heights attained (See Chapter 4)(Canadian Tide and Current Tables 1980).

CHAPTER 2

ICE CONDITIONS IN FROBISHER BAY

2.1 Introduction

This chapter provides an assessment of sea ice conditions around the head of Frobisher Bay. An evaluation of long term information on average seasonal conditions provides the background for a detailed analysis of ice conditions during the critical breakup period, based on field observations made in 1980 and 1981. No observations were made during freezeup. The intent is to document the ice dominated character of the coastal environment, as a basis for a discussion of sea ice effects on intertidal sediments and biota.

2.2 Arctic Ice Conditions

Numerous studies have concentrated on the freezeup and breakup patterns along Arctic coastlines. Short and Wiseman (1974) observed the progression of freezeup along the northern Alaskan coast. They demonstrated that the presence of ice and snow in the beach nearshore zone, modified the normal processes found in temperate locales. In the Eastern Arctic, McCann and Taylor (1975) noted that the beach freezeup sequence and resultant ice type were mainly influenced by wind, wave and temperature conditions, principally the latter. The duration of freezing temperatures required to form first ice varied between locations and from year to year. Bilello (1961) found it took between 5 and 50 days for complete ice cover development. Once ice was established, as much as 10 cm of it could develop in the first 2 to 3 days (Jacobs, Barry and Weaver 1975).

Studies around south-east Baffin Island have shown a relationship between the early or late advance of ice formation with synoptic atmospheric circulation patterns. Crane (1978) noted that an early ice advance in this area was associated with a high frequency of north and west winds and their attendant lower temperatures. North winds were also capable of rafting multiyear ice into Davis Strait, although it was unlikely to move this ice to the head of Frobisher Bay. Late ice advance was related to above average temperatures experienced during easterly winds. Jacobs and Newell (1979) concurred with Crane's findings stating that winds and,more specifically synoptic conditions,best explained ice conditions. They did find a correlation between maximum ice thickness and temperatures in Frobisher Bay.

Most studies of breakup tended to concentrate on its effects on the shoreline as opposed to the direction, rate and sequence of ice decay itself. Large scale ice breakup in the Canadian Arctic is documented in the annual Ice Summary and Analysis reports (Canada Department of Transport Meteorological Branch, and Environment Canada, Atmospheric Environment Service). On a smaller scale, local breakup analyses were carried out along coastal areas in the Eastern Arctic by Owens (1969) and Taylor (1973) and Taylor and McCann (1976).

The average sequence and features of the ice cover during breakup was outlined by Jacobs et al (1975). A summary of their conclusions is presented in Figure 2.1. The first stage of thaw commenced in late May and early June when temperatures were still below freezing and the

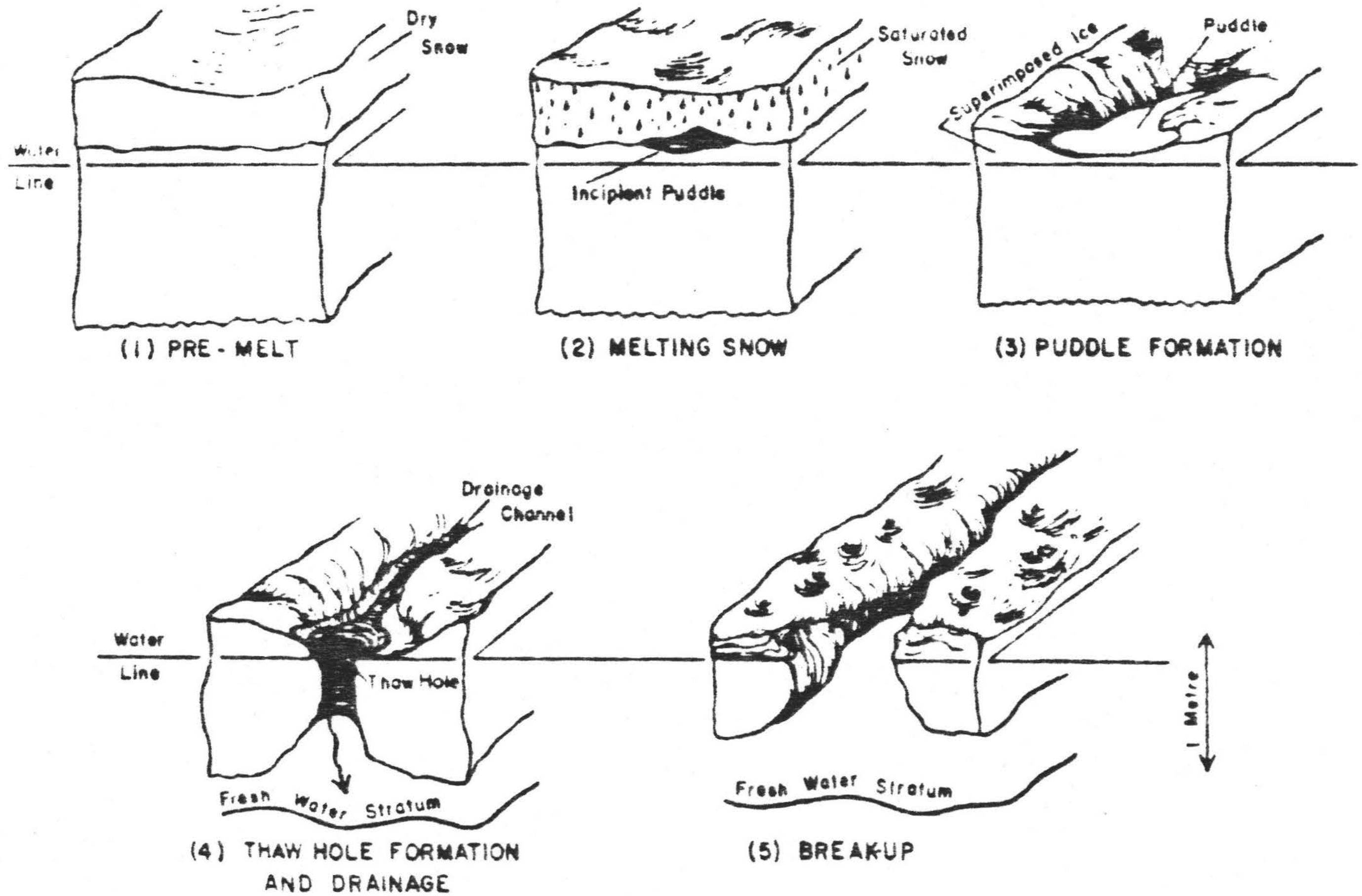


Figure 2.1 Idealized representation of the stages of decay and breakup of the fast ice sheet (From Jacobs, Barry and Weaver, 1975.)

ice was covered by snow. A decrease in the thickness of ice was detected during this stage once temperatures rose above -1.8^{o}C (the freezing point for salt water). Melting of the surficial snow and the development of incipient puddles on the ice surface characterized the second stage. Puddles and a chaotic drainage network in the surface developed during the third stage. In the fourth stage these pools melted through the ice to form thaw holes and initiate more efficient drainage. The final stage involves the mechanical breakdown of the ice by abrasion, and wave and wind stresses. The entire breakup took 6 to 8 weeks for ice less than 2 m in thickness (Jacobs et al 1975).

Bilello (1961) discovered a correlation between the cumulative degree days above -1.8^{o}C and a decrease in the thickness of ice during breakup (Fig. 2.2). Weller (1968) noted that ice albedo decreased from 75 to 37% following the disappearance of snow. This allowed 78% of the incoming solar radiation to be absorbed. This caused large heat fluxes to form towards the ice surface, increasing the evaporative capability of the ice.

The rate of ice breakup was also influenced by the thickness of ice and more importantly by temperatures and winds (Jacobs et al 1975). Early breakup in south-east Baffin Island corresponded to pressure patterns with dominant east-west gradients, which generated strong winds and the advection of warm southerly air (Crane 1978). Weaker pressure cells with fewer southerly winds resulted in lower ablation rates, with later ice retreat, especially in isolated locales like Frobisher Bay. The mean breakup date was defined by Jacobs and Newell (1979) as the first date on which the ice was considered unsafe,

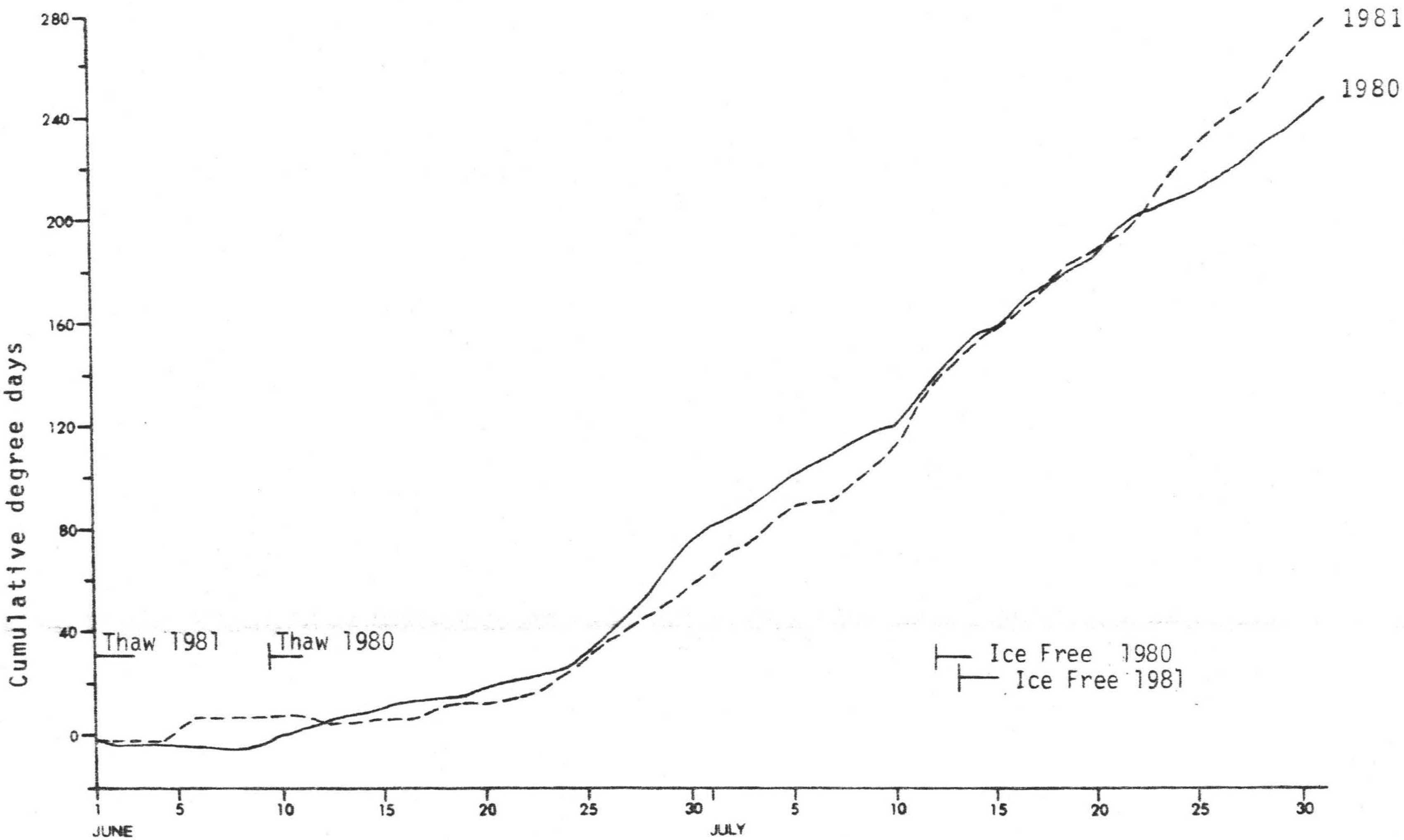


Figure 2.2 Cumulative degree days above -1.8°C.

presumably for vehicular traffic, and was calculated using data from 1958 to 1971. Their mean breakup date for Frobisher Bay was July 4, with a standard deviation of 14 days.

An analysis of ice freezeup and breakup dates was made by McCann, Dale and Hale (1982) for the head of Frobisher Bay (Fig. 2.3). Weather station records from 1969 to 1980 provided temporal information on ice conditions in Koojesse Inlet. On average, 25 days elapsed between the first observation of ice, and complete ice cover. This continuous ice cover was generally completed by November 14 and lasted on average 210 days a year. Thaw was usually initiated around June 12. Breakup lasted 37 days on average and culminated in ice free conditions by July 19 which lasted until October 20 when first ice again appeared. The great variability in the records from year to year reflected the changing synoptic conditions noted earlier. The data of McCann et al (1982) has now been updated with the addition of 1981 data and the ice records for the Sylvia Grinnell River (Fig. 2.4). This information is further supplemented by regional and local studies made on ice conditions in 1980 and 1981.

2.3 Average Ice Freezeup and Breakup Patterns

2.3.1 Introduction

Climatological and ice condition records were available for Frobisher Bay and the Sylvia Grinnell River from 1964 to 1981 and are summarized in Figures 2.3 and 2.4. The mean monthly temperatures shown in Figure 2.3 illustrate the short summer period. Only late July, August and September were essentially ice free. Monthly tem-

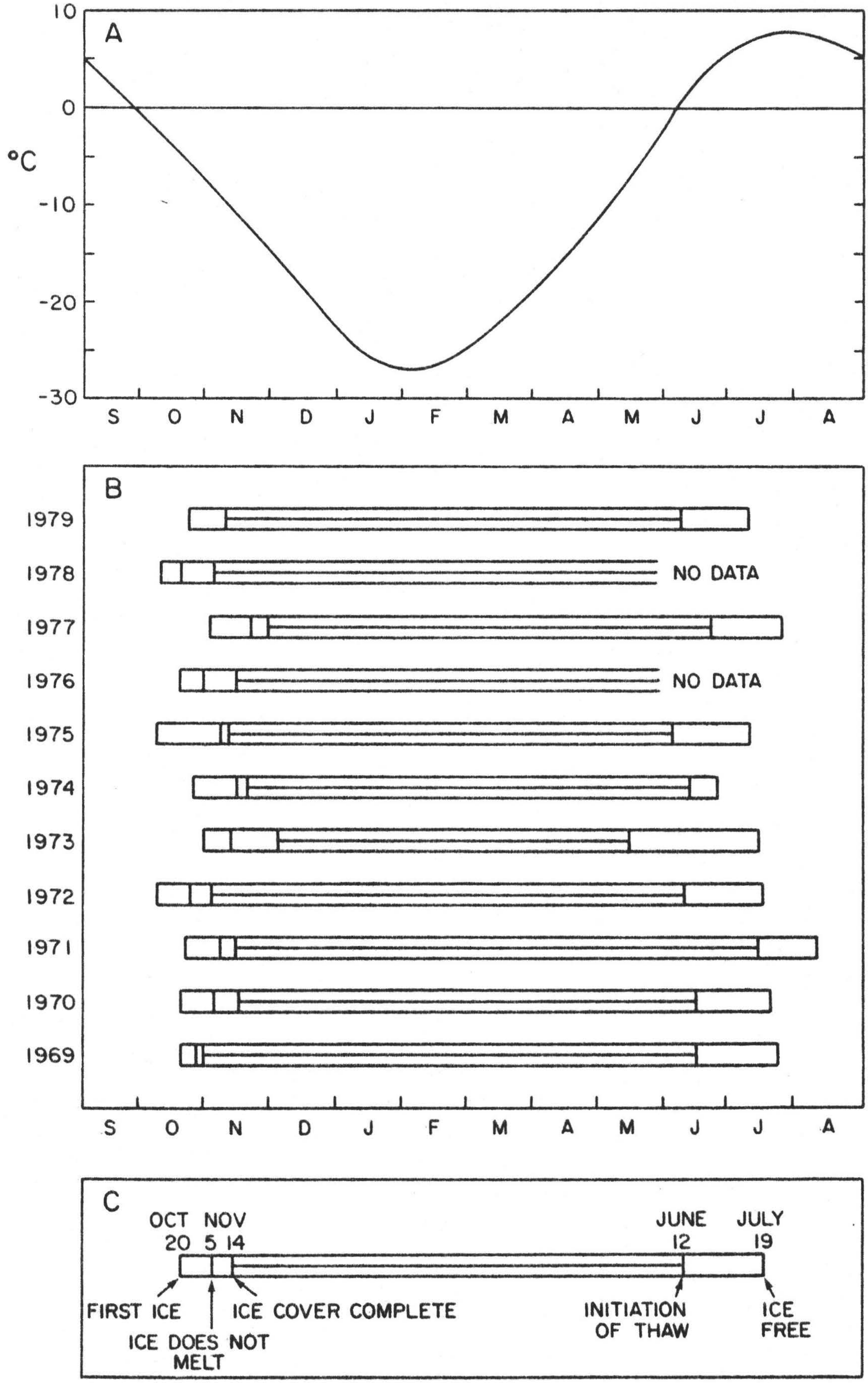


Figure 2.3 Ice breakup and freezeup dates for Koojesse Inlet (From McCann, Dale and Hale 1982.)

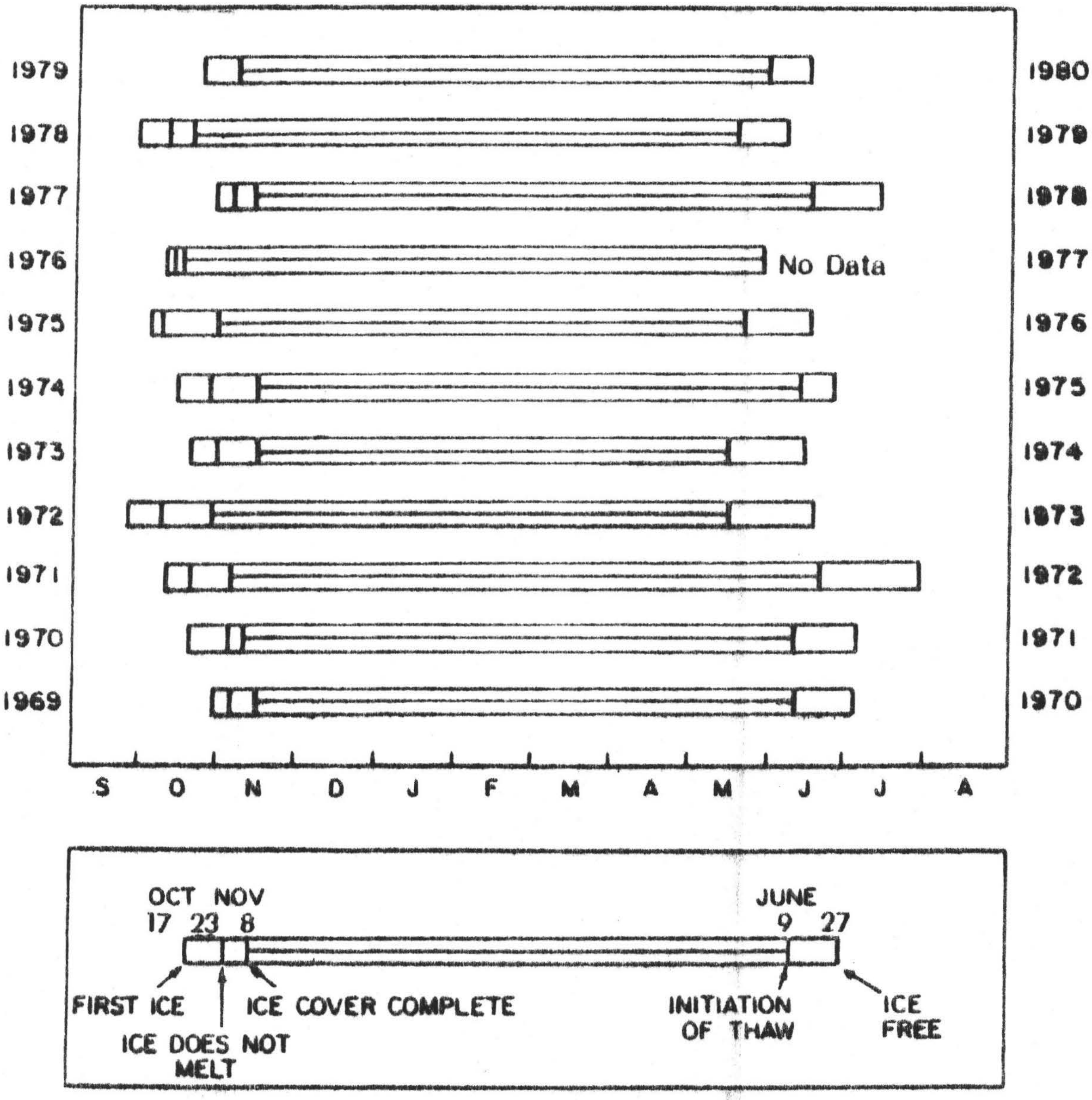


Figure 2.4 Ice breakup and freezeup dates for the Sylvia Grinnell River based on observations from the Frobisher Bay Meteorological Station.

peratures for the remainder of the year were below $0^{o}C$, with the ice solidly entrenched, thus suspending normal coastal activities (see Chapter 3).

2.3.2 Ice Freezeup

Sea water with a salinity of 33% similar to Frobisher Bay, freezes at $-1.8^{o}C$ (Weller 1968). On average, ice first appeared on the tidal flats by October 21 (Fig. 2.3). This ice formed thin sheets in sheltered pools or a fine coating on rock and sediment surfaces in the upper shoreline areas. November 4 was the average date on which these thin layers failed to melt, thus providing a base for subsequent layers. A complete ice cover was usually established by November 16, a mere 27 days from its first observation.

The ice layer continued to grow in thickness for most of the winter and reached an average thickness of 170.2 cm in Koojesse Inlet. The location of ice thickness measurements was never supplied. However measurements taken over the subtidal zone in 1980 and 1981 by the causeway corresponded to those supplied by the weather station, indicating this was the probable site. Ice in the intertidal zone varied greatly in thickness. Ballycatters, with ice accumulations greater than 2 m in thickness, were common over boulders and rock outcrops in the intertidal zone. The ice foot which formed from drift ice accumulations, wave spray and stranded floes was frequently greater than 6 m in thickness.

Ice formed over intertidal areas contained layers of sediment including cobbles and boulders which were incorporated into the ice during freezeup. There were three sources of the debris; aeolian transport of fines from other locations, boulders falling from nearby cliffs onto the ice and the tidal flats themselves. During low tide, the ice sheet was lowered to the tidal flat surface where it froze to the bed. During high tide the ice broke free of the bed, with some of the sediment frozen to its base. A clear layer of ice developed over the basal ice surface, thereby locking the sediments into the ice. This process repeated itself over the winter leaving numerous layers of sediment in the ice. The mechanism by which large boulders were incorporated into the ice is not well understood and will be considered in later chapters.

Fresh water areas like the Sylvia Grinnell River always froze earlier than surrounding sea water. On average, first ice was observed on October 17. By October 23 the ice was thick enough to resist daily melting and contributed to a solid ice cover usually completed by November 8. On average, it took 23 days for continuous ice cover to form on the river.

Twelve years of ice freezeup data were available for Koojesse Inlet. It took anywhere from 3 to 35 days (an average of 13) between the first ice observation to a continuous ice cover. During its formation, extensive coastal erosion and transportation of sediments in the ice was possible.

2.3.3 Ice Breakup

In Koojesse Inlet, the average date of thaw initiation was June 14 with the area ice free by July 17 (Fig. 2.3). Contributing to sea ice breakup was the influx of overland melt. The Sylvia Grinnell River had usually begun to thaw by June 9 and was ice free 18 days later, June 27.

Yearly variations in the breakup dates reflected synoptic climatic conditions and local effects. From Figure 2.2, the close fit of the cumulative degree days above -1.8^{o}C between 1980 and 1981, illustrates the similarity in temperature conditions over these two seasons. Variations between the lines will be discussed later.

Koojesse Inlet had a slower rate of breakup than those experienced in more northern locales, due to its sheltered location from high energy wave action. The presence of solid ice in the bay also acted to limit the fetch length available for wave formation in the early stages of breakup. Waves greater than 1 m in amplitude were encountered once during a storm after ice breakup in 1980.

In 1981, the presence and thickness of snow on the ice played an important role in breakup. Fifteen centimeters of snow fell that winter to effectively insulate the ice from warm air temperatures and raise the albedo. In 16 years of observation the complete ice breakup event took between 2 to 9 weeks.

2.4 Regional Ice Breakup Sequence and Pattern at the Head of Frobisher Bay, 1980

2.4.1 Regional Ice Study

The data collected by the weather station does not provide information on the spatial pattern of breakup in Koojesse Inlet, thus additional field work was required. Five aerial surveys were conducted to supplement ground work near the settlement and to obtain a broader perspective of breakup patterns around the headward reaches of Frobisher Bay. These flights were made at weekly intervals, from the inception of breakup on June 19, 1980 to July 13, 1980 when essentially ice free conditions prevailed. The surveys followed the route shown on Figure 2.5, at an altitude between 150 to 200 m, at 115 knots, and approximately 1 km from shore. A continuous record of shoreline and sea ice conditions was obtained on each flight using portable colour video equipment. The information from the 5, hour-long video cassettes, has been reduced to a series of maps, Figures 2.6, 2.7, 2.8, 2.9, 2.10 (McCann et al 1982).

The flight path included a wide variety of coastal types Figure 2.11. Wide intertidal flats are present in Foul (5), Koojesse (1) and Peterhead (6) Inlets. Estuarine intertidal deposits are found at the mouth of the Bay of Two Rivers (4) and Burton Bay (3). Steep rock cliffs with a narrow intertidal zone dominate the coasts of Hill (7), and Bishop (8) Islands and the mainland north-east of Mair Island (10). Shallow, rocky intertidal areas are prevalent around the islands between Foul (5) and Peterhead Inlets (11). These major groups of shoreline types all have distinctive patterns of ice breakup which contributed to the overall breakup sequence.

Sea ice conditions around the head of Frobisher Bay were mapped from the video cassettes using the five-fold ice classification scheme given in Table 2.1. This format was more appropriate for the present study than the conventional approach used in the Ice Summary and Analysis, reports noted earlier (Canada, 1964-69). Additional information on the time, tidal level and ice conditions during each survey are presented in Table 2.2.

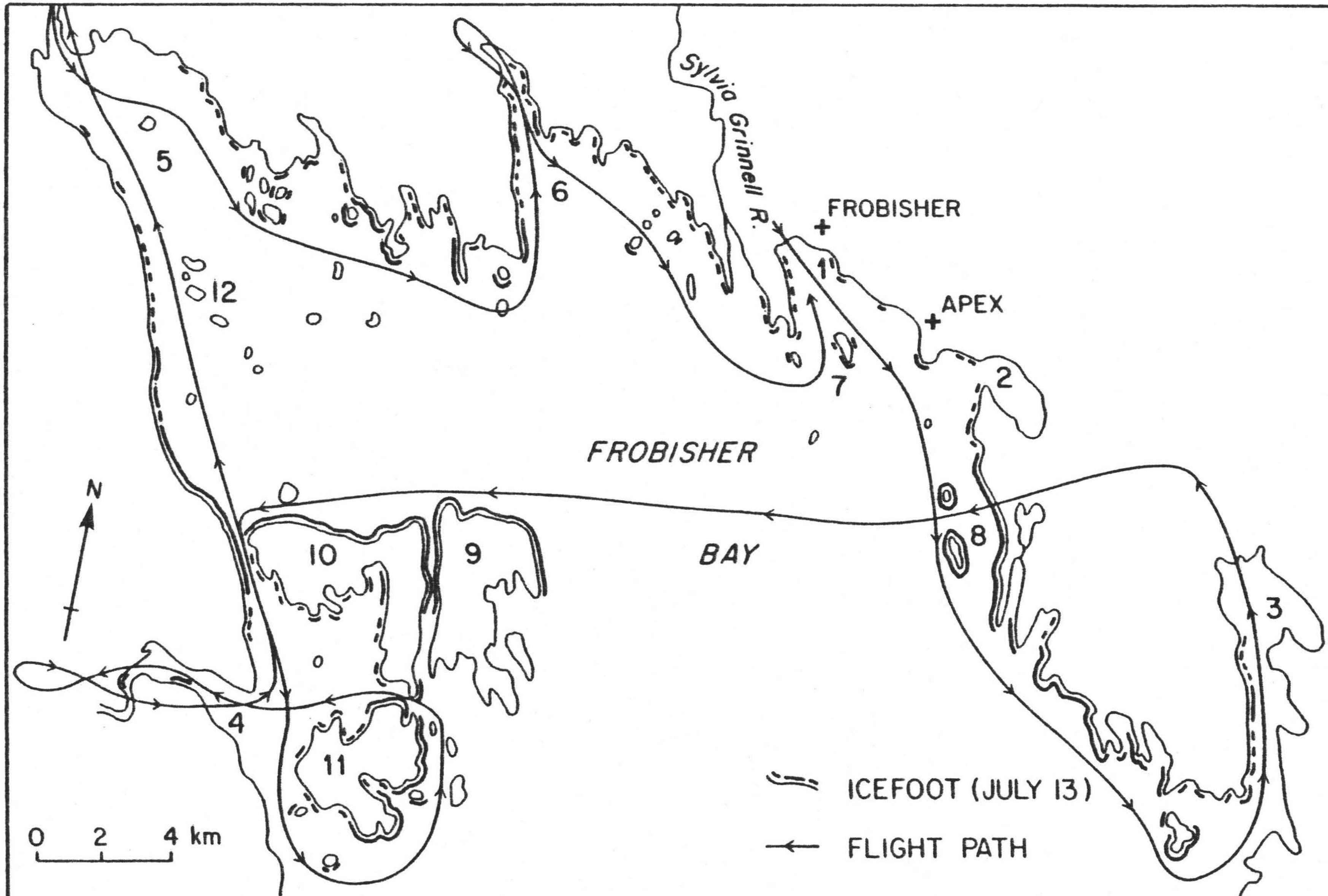


Figure 2.5 Flight path of the aerial surveys of ice breakup in 1980.

JUNE 19, 1980

ICE BREAK-UP: HEAD OF FROBISHER BAY

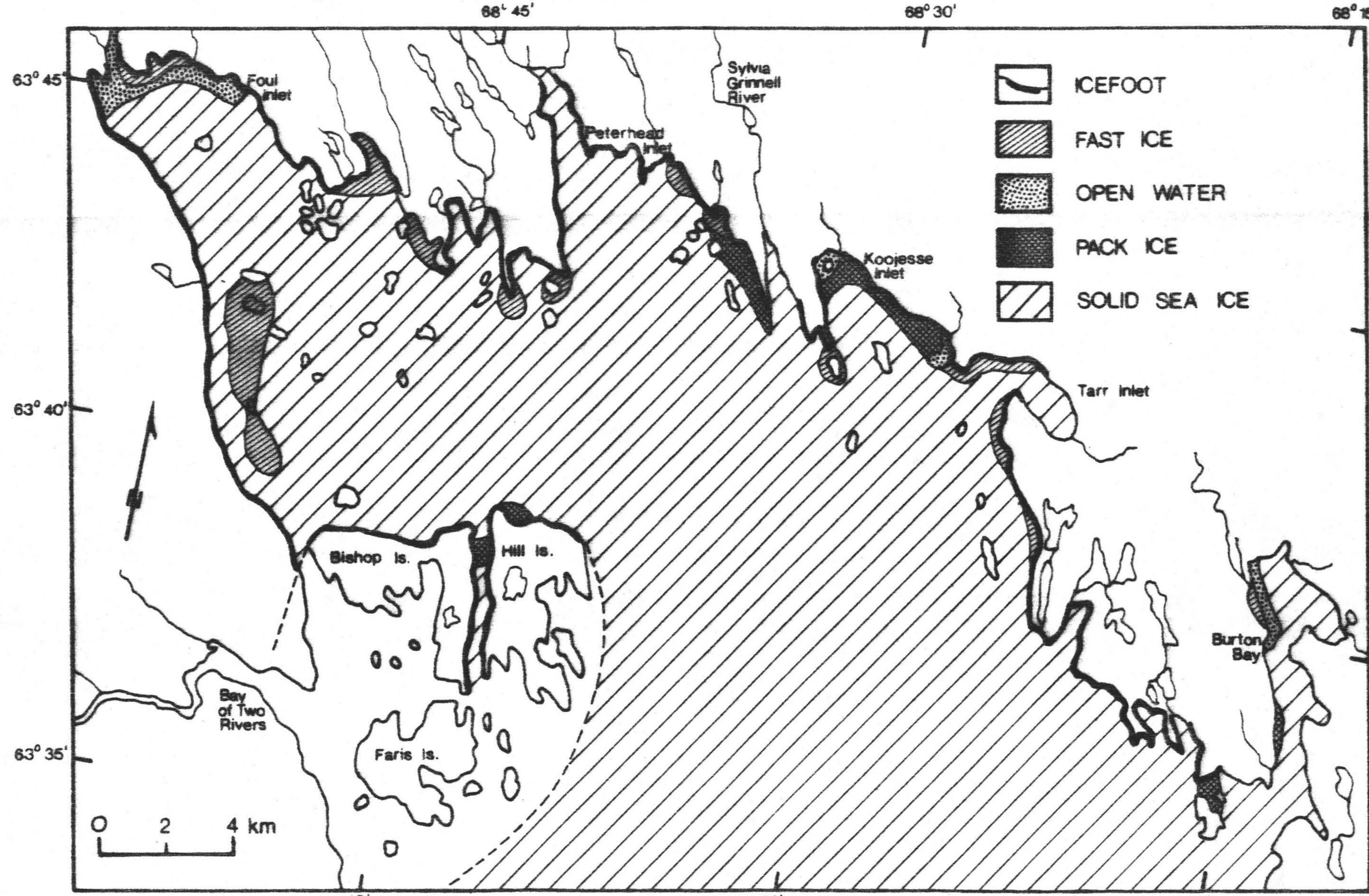


FIGURE 2.6 June 19, 1980 Ice breakup: head of Frobisher Bay.

JUNE 25, 1980

ICE BREAK-UP: HEAD OF FROBISHER BAY

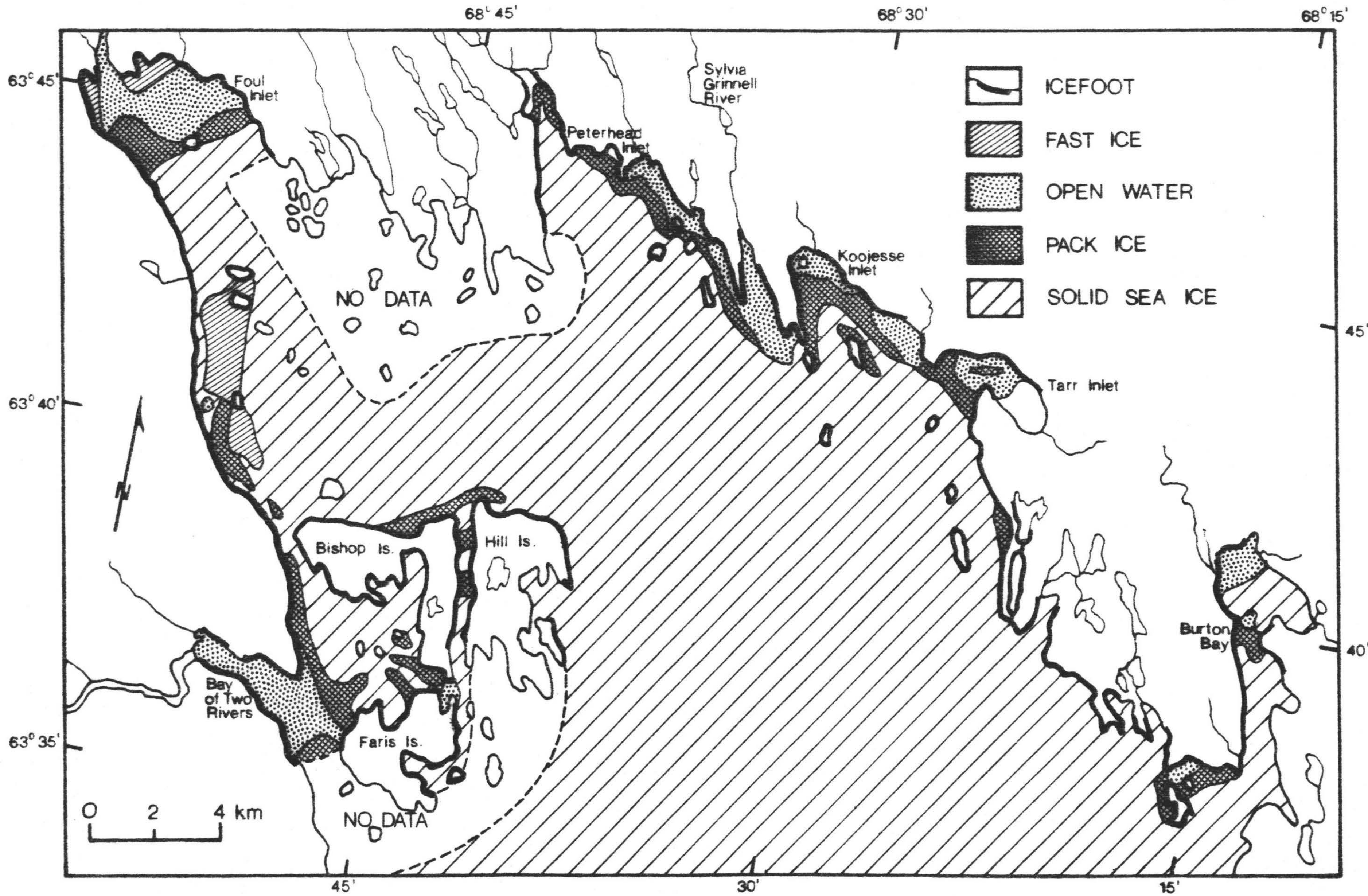


FIGURE 2.7 June 25, 1980 Ice breakup: head of Frobisher Bay.

JULY 1, 1980

ICE BREAK-UP: HEAD OF FROBISHER BAY

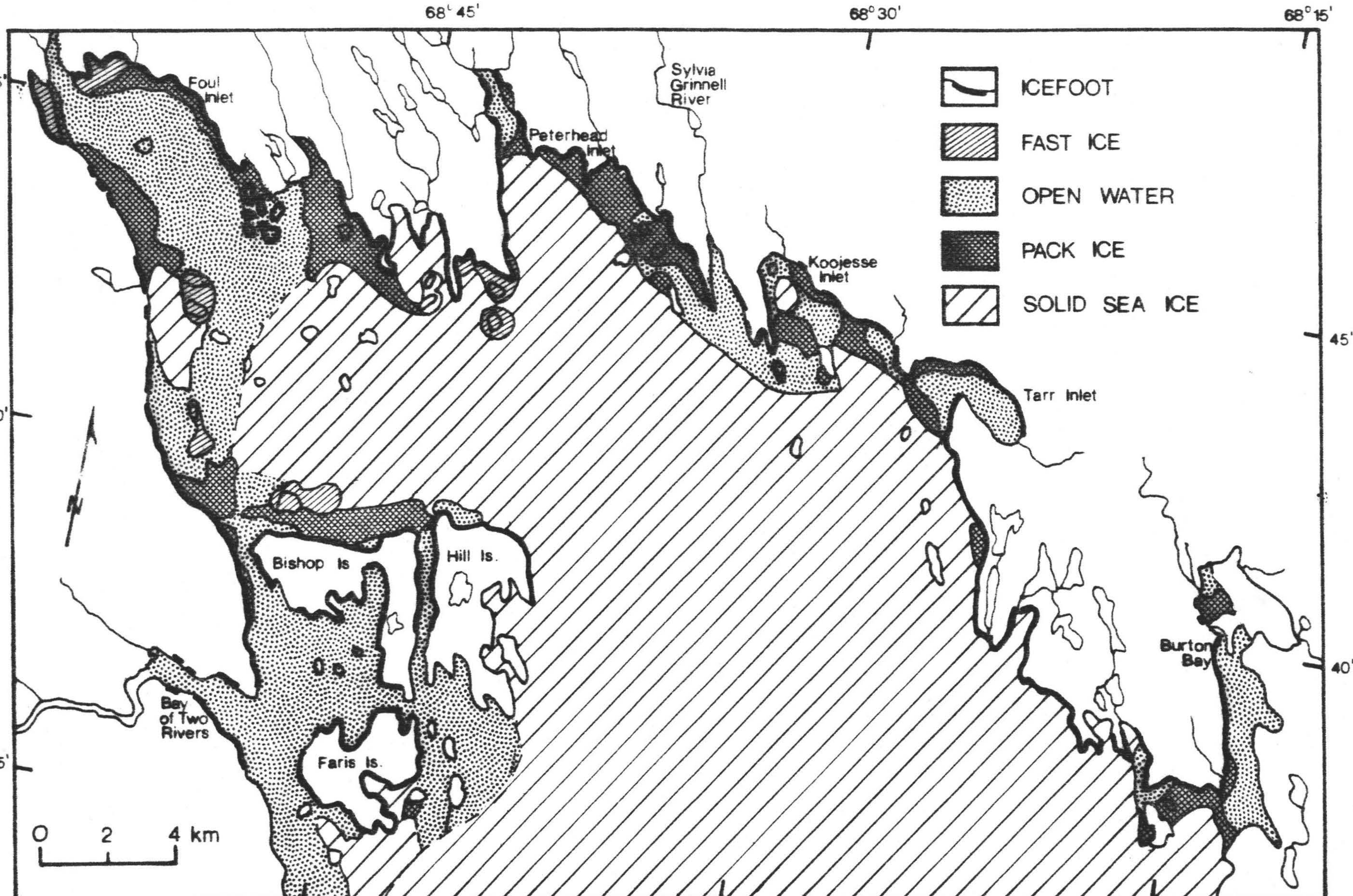


FIGURE 2.8 July 1, 1980 Ice breakup: head of Frobisher Bay.

JULY 7, 1980

ICE BREAK-UP: HEAD OF FROBISHER BAY

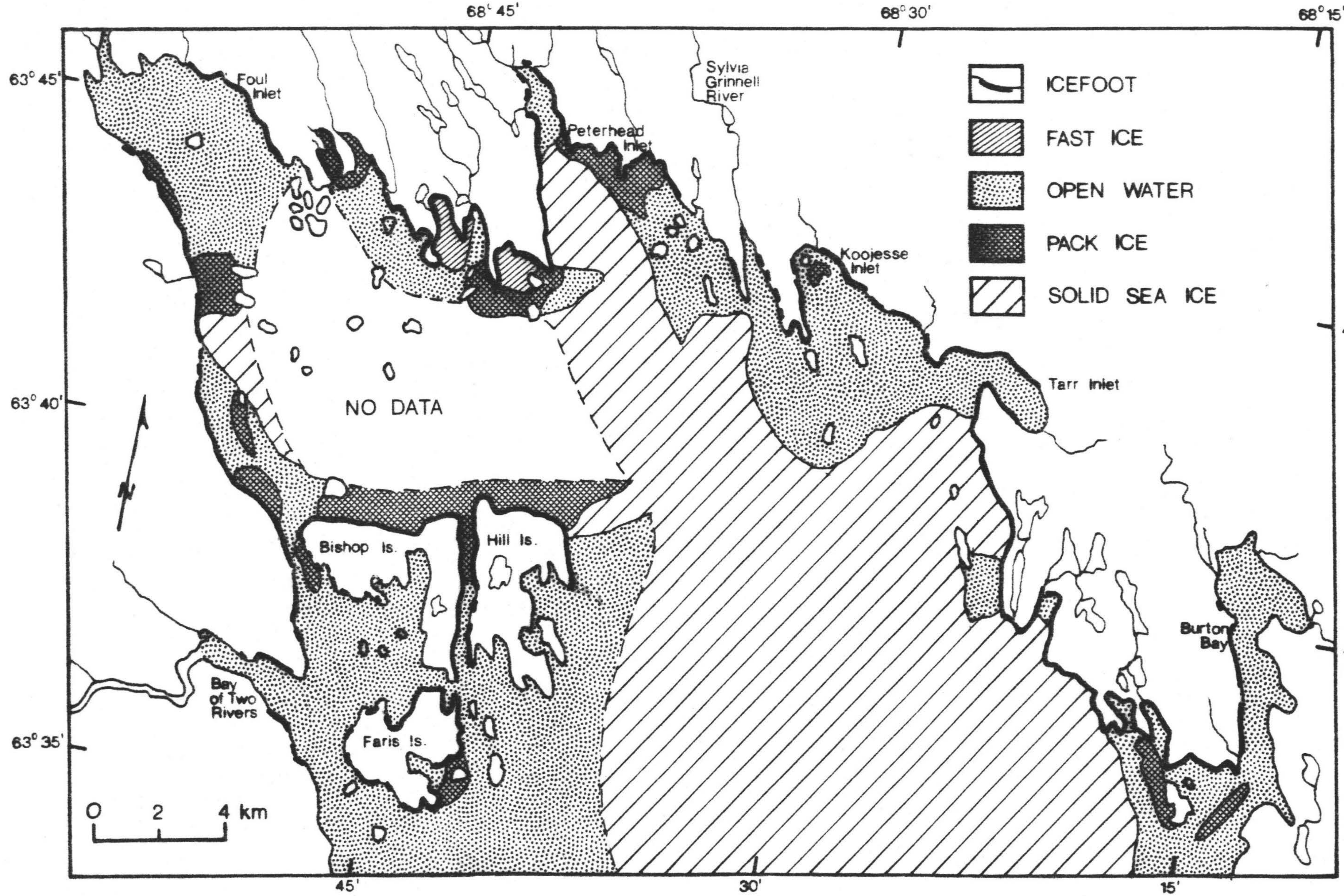


FIGURE 2.9 July 7, 1980 Ice breakup: head of Frobisher Bay

JULY 13, 1980

ICE BREAK-UP: HEAD OF FROBISHER BAY

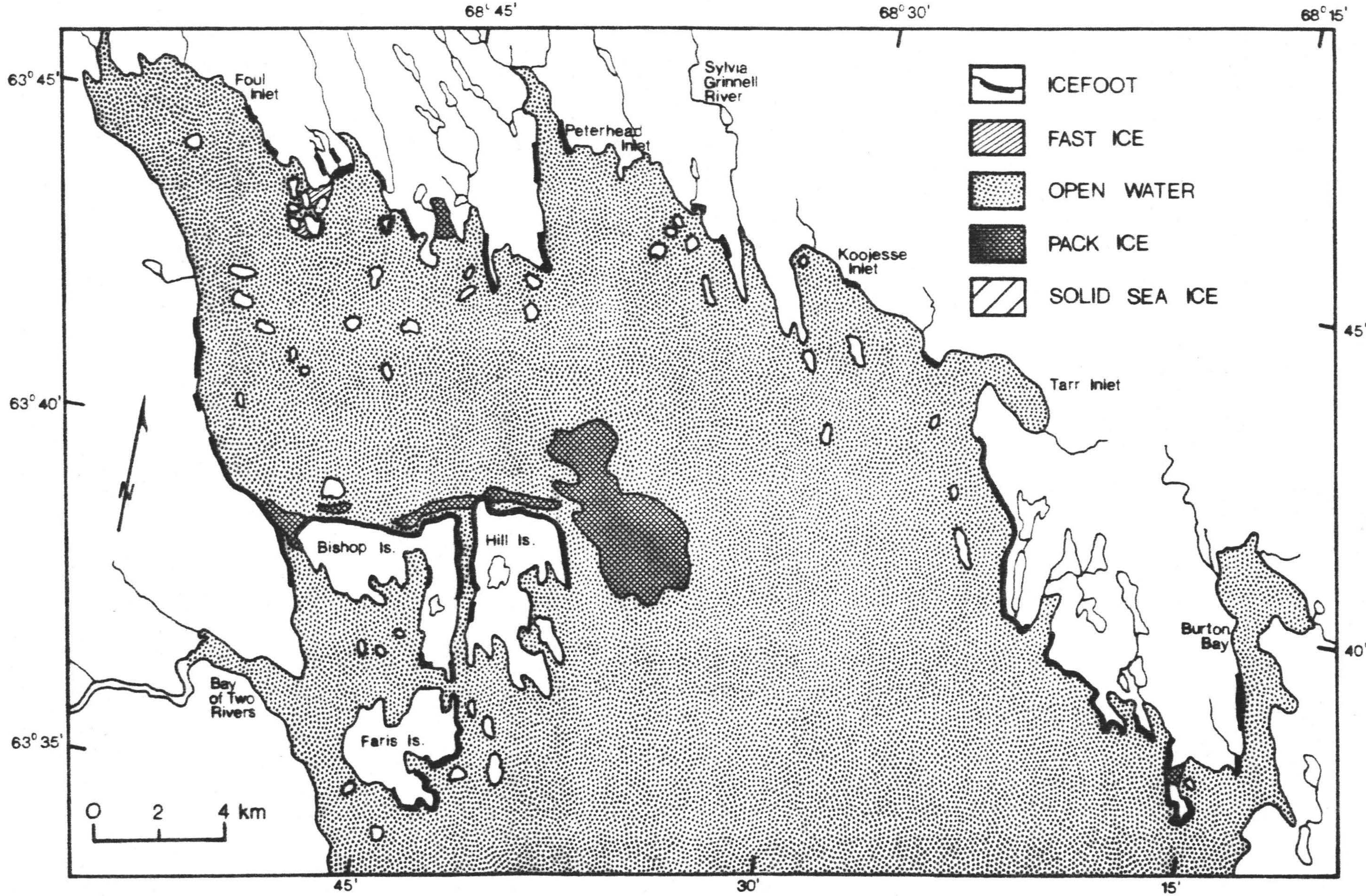


FIGURE 2.10 July 13, 1980 Ice breakup: head of Frobisher Bay.

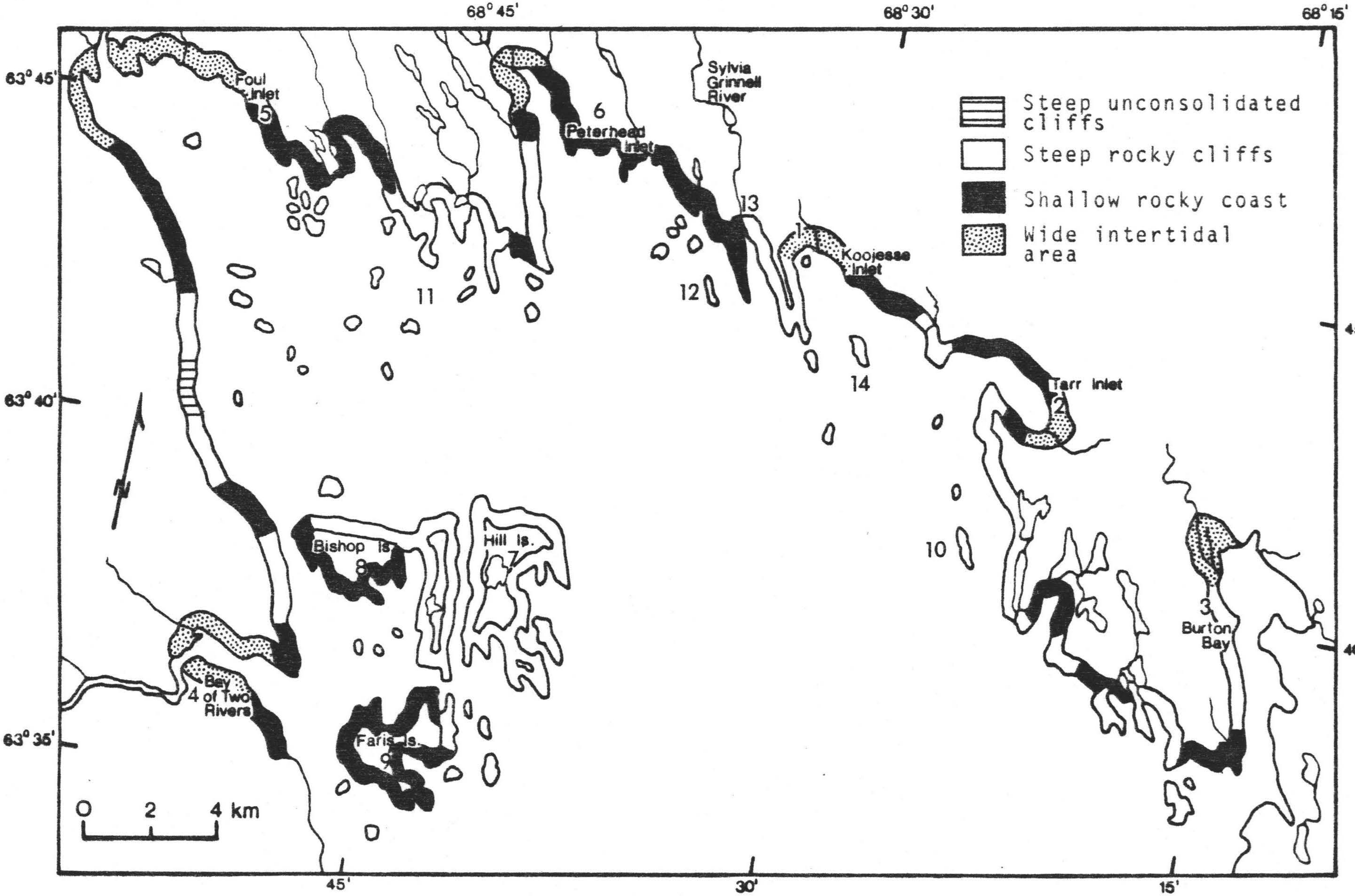


Figure 2.11 Prominent sites are numbered and coastal environments shown.

TABLE 2.1 Ice classification used in the Frobisher Bay study

Sea ice -	Any form of ice which develops from sea water.
Ice foot -	A narrow fringe of ice which is attached to the shoreline, is unmoved by tides, and remains after the fast ice has moved away.
Fast ice -	Sea ice which forms and remains fast along the coast, where it is attached to the shore. It may be moved by tides.
Pack ice -	Sea ice which is not fast ice.
Open water -	Navigable water with sea ice concentrations less than 1/10.

Table 2.2 Regional Sequence of 1980 Ice Breakup from Aerial Surveys

Aerial Survey	Date	Time Start Finish	Tidal Conditions	Comments
I	June 19	11:00 - 12:00	High Tide 8.7 m at 12:25	< 1% Open Water 99% Ice Cover Tidal flat ice fractured but still in place. Open water at river mouths and at the head of bay.
II	June 25	11:30 - 12:30	Low Tide 3 m at 11:45	5% Open Water 95% Ice Cover Leads more numerous and have widened. Tidal flat floes ablating rapidly Sylvia Grinnell open
III	July 1	15:00 - 16:00	Low Tide 1.6 m at 15:50	20% Open Water 80% Ice Cover Breakup of subtidal ice, which is now rafting onshore. Bay of 2 Rivers has extended 10 km south and east of mouth.
IV	July 7	9:00 - 10:00	Low Tide 2.5 m at 9:05	60% Open Water 40% Ice Cover Solid ice in the middle of the bay. Mainly pack ice accumulations. Large ice foot floes now apparent.
V	July 13	14:30 - 15:30	Low Tide 1.5 m at 14:40	99% Open Water 1% Ice Cover Discontinuous ice foot along steep rocky shorelines and low gradient beaches

2.4.1.1 Survey I, June 19, 1981, Figure 2.6

By June 19, 1980 ice breakup was well underway. The fast ice had broken into floes close to shore over the wide tidal flats at Koojesse Inlet (1) and by Rodgers Island (12). Small open water areas existed at the mouths of the rivers in Burton Bay (3) and Foul Inlet (5).

The tidal flat ice broke up first, from the development of tidal cracks between the ice foot and fast ice boundary parallel to shore. As thaw continued, more of these tidal cracks developed progressively seaward due to varying tidal oscillations. Bands of open water developed from these tidal cracks, providing space for wind and current action, to move floes with sufficient energy to gouge the underlying sediment and pile ice along the shoreline.

With continued ablation of the snow and ice surface, small pools developed which frequently drained through tidal cracks and holes left from boulders which had melted out. Further melt occurred from flooding by sea water percolating through these fissures in the ice at high tide. The presence of sediments and boulders in the intertidal ice lowered albedo and intensified the melting in these areas, to produce the greatest rate of ablation of any of the ice surfaces. Often the weight of incorporated sediments became greater than the floe could support. It would then settle to the flat surface where it was overridden by other floes. This most frequently occurred close to shore where the greatest amount of ice incorporated sediment existed. Ice cored sediment mounds, remnants of these floes remained as late as July 12.

River mouths were the second areas to open. This was due to increased melt by overland drainage. The river's melt water was forced to flow over the ice surface when the river mouth was still choked with solid ice. This was observed to aid the ablation process at the Sylvia Grinnell River. Pressure exerted from upstream water and ice also helped weaken the solid ice by river mouths. Shallow deltas and tidal flats by river mouths also contributed to ice breakup in the area.

By June 21, 1980, all of the major rivers at the headland reaches of Frobisher Bay were open. The Sylvia Grinnell River took 4 days between an initial open water patch upstream of the sea ice to achieve ice free conditions. Once open, the riverine influence spread and became an important factor in further breakup.

2.4.1.2 Survey II, June 25, 1980, Figure 2.7

Fluvial influence had spread considerably by the second flight, particularly near the broad intertidal areas of Foul Inlet (5), Bay of Two Rivers (4), and the Sylvia Grinnell (13). In these locations, as well as in other shallow intertidal areas, the decay of the ice continued through the process of tidal crack development discussed earlier.

Leads and tidal cracks began to develop in high stress locations between islands and along rocky shorelines with narrow intertidal zones. Major leads were evident between Bishop Island (8) and reefs to the north, between islands like Mair Island (10) and the mainland and off the north-east corner of Hill Island (7). Tidal cracks were filled with sea water but were not yet fully open along the north shore of Bishop (8) and Hill (7) Islands and the west shore of Foul Inlet (5).

The ice foot was still intact along all shorelines with the exception of river mouths at Foul (5), Peterhead (6) Inlets, Burton Bay (3) and the Bay of Two Rivers (4). Overland melt contributed to their disintegration. Surface ablation and wave undercutting in open water areas continued to reduce them for the remainder of the season.

2.4.1.3 Survey III, July 1,1980, Figure 2.8

By July 1, the progressive seaward breakup of ice over broad intertidal, tidal flats and deltas had extended into the subtidal zone. Burton Bay (3), Tarr Inlet (2), Foul Inlet (5) and the Bay of Two Rivers (4) were free of solid sea ice, but were subject to rafting of remnant intertidal ice by wave, wind and current action, especially the latter.

In Burton Bay (3) and Koojesse Inlet (1), large chunks of ice broke off the subtidal fast ice sheet and were rafted onshore by strong tidal flood currents. These vast floes, some almost a kilometre in width were frequently stranded in the intertidal area. Weakened by tidal oscillations which frequently stranded them on uneven tidal flat beds, they gradually broke up.

The expanding influence of fluvial discharge was especially evident around the Bay of Two Rivers (4) where an ice free zone extended 10 km to the south. Likewise, the Sylvia Grinnell River (13) had opened water to Rodgers Is. (12), and Long Is. (14). Burton Bay (3) had extended an ice free zone close to its mouth into Frobisher Bay. The ice foot in these locations was much reduced and frequently discontinuous. It had entirely disappeared along shorelines backed by steep, unconsolidated cliffs and narrow intertidal zones similar to those along the west shore of Foul Inlet (5). The ice foot remained intact along steep rocky shorelines.

The leads and tidal cracks noted in the previous survey had widened and increased in number. Leads had developed in the narrow channels around many islands (11) and between the mainland and islands, where tidal current action was concentrated (Mair Is. (10), Peterhead Inlet (6) and Peele Point (11)). The tidal cracks observed on June 25 along steep, rocky shorelines had fractured and now possessed numerous pack ice accumulations like those at the north end of Bishop Island (8), which was undoubtedly affected by the high spring discharge from the Bay of Two Rivers.

2.4.1.4 Survey IV, July 7, 1980, Figure 2.9

The greatest change in ice cover occurred between the third and fourth surveys, during which the percentage of open water along the shoreline rose from 20 to 60% in 6 days. Extensive ice cover persisted in the central and eastern section of the bay and Peterhead Inlet (6). This ice decayed rapidly, from the large melt water pools and the haphazard drainage channels across its surface. Most of the floes stranded on the tidal flats in Koojesse (1), Foul (5), and Peterhead Inlets (6) and on the shoals between the islands near Peele Point (11) came from this offshore ice. Only a few remnants of intertidal sea ice remained. The last major intertidal ice collection was observed on the tidal flats of Bishop (8) and Faris (9) Islands on July 7. The greatest amount of ice gouging by ice floes on the tidal flats occurred during this period. The shoreward movement of ice floes by strong flood currents often resulted in 10/10 concentrations of ice on the tidal flats and by Hill

(8) and Bishop (7) Islands.

The steep, rocky shoreline of eastern Frobisher Bay near, Mair Island (10) still retained a solid ice cover. This was due to minimal fluvial influence and subdued tidal affects caused by its narrow intertidal zone. One large patch of open water had developed south of Mair Is. (10) where leads were noted in the first survey. Water filled tidal cracks had formed along this shoreline and were targets of further breakup.

2.4.1.5 Survey V, July 13, 1980, Figure 2.10

By the last survey, essentially ice free conditions prevailed at the head of Frobisher Bay. Ice accounted for only 1% coverage of the shoreline areas. Fast ice remained around islands to the east of Foul Inlet (5) and pack ice had rafted into sheltered inlets by Burton Bay (3) and Peele Pt. (11). Large concentrations of brash ice existed to the north and east of Hill (7) and Bishop (8) Islands due to the strong north-west winds of the previous day. The disappearance of the fast ice observed in Survey IV was caused by the rapid decay of the ice into brash ice by high temperatures and high tidal conditions.

This final breakup episode was distinguished by continued ice foot degradation by melt and wave undercutting. The latter process caused large pieces of the ice foot to fall from the bedrock to the flat below, where many were carried away by the next high tide. The ice foot was retained for the longest period along low gradient unconsolidated beaches where it attained its greatest width, often in excess of 100 m

2.4.2 Summary

The pattern of breakup at the headward reaches of Frobisher Bay was dominated by fluvial influences, position above low tide, gradient and substrate. The wide variety of coastal environments exhibited definite differences in the timing and rate of breakup. In 5 weeks, the shoreline zone went from 1 to 99% open water coverage (Table 2.2). The open water of the tidal flat and river areas extended to subtidal and steeper shorelines with the progression of breakup. Between the third and fourth survey, open water rose from 20 to 60%. Intertidal ice floes disintegrated and subtidal ice dominated the shorelines where they were rafted by wave, wind and tidal action. The greatest period of erosion by ice floe gouging occurred at this time. By the fifth week, brash ice packs remained in a few locations. The final stage was dominated by continued ice foot decay.

2.5 Local Breakup in Koojesse Inlet, 1980, 1981

2.5.1 Local Breakup Information

Daily records of the extent, position and condition of the ice in Koojesse Inlet (1) were kept from mid-June to late August for 1980 and 1981 as illustrated in Figures 2.12 and 2.13. The percentage ice cover was calculated from these records and is summarized in Tables 2.3 and 2.4. A combination of this ice information with tidal and climatological records for the area reveals the complex relationship between ice breakup and the local environment (Fig. 2.14, 2.15).

For purposes of analysis the ice breakup in Koojesse Inlet was divided into 5 stages which are illustrated in Figures 2.12 and 2.13.

1980

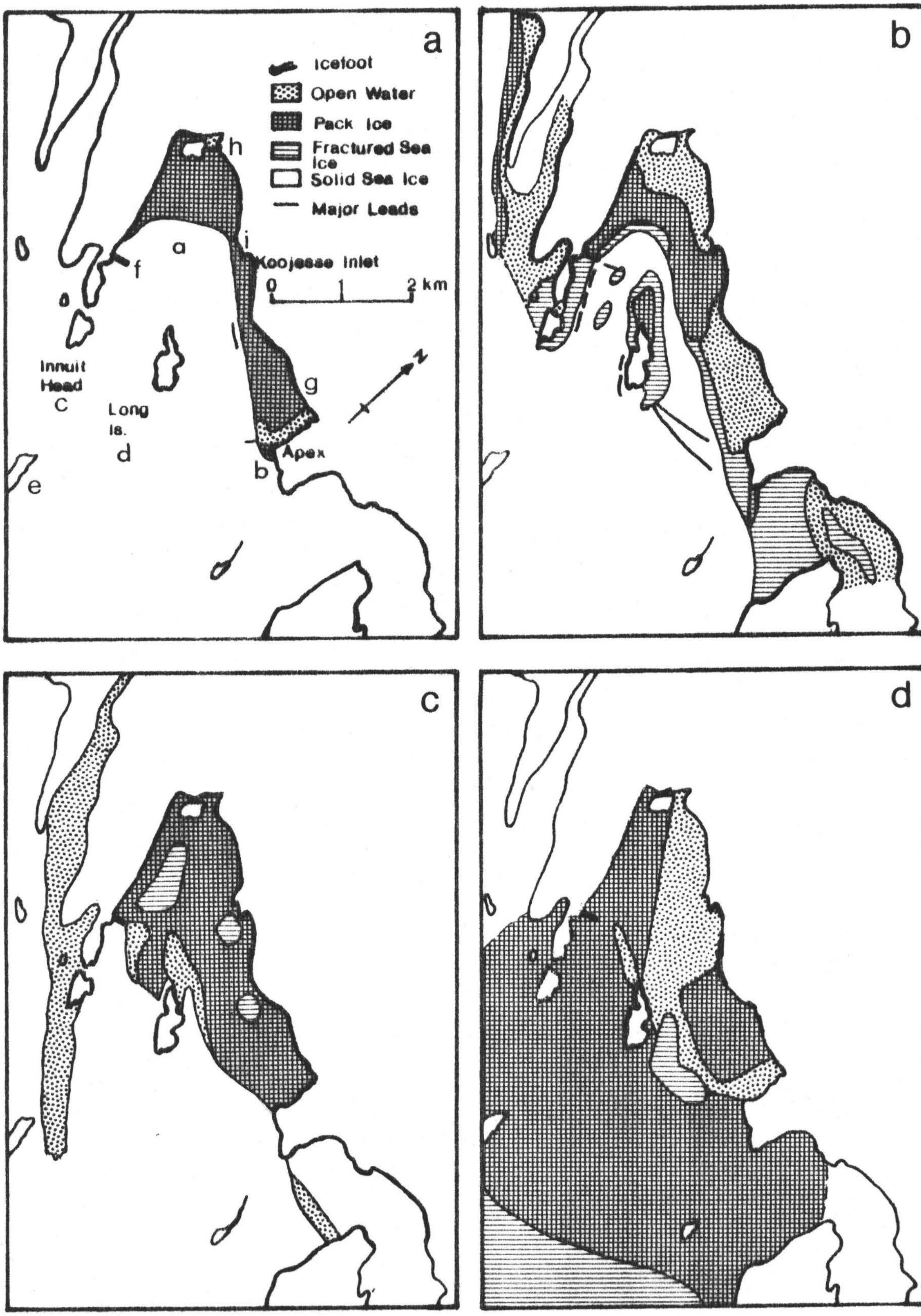


Figure 2.12 Koojesse Inlet Breakup in 1980
a) June 19, b) June 25, c) June 28, d) July 8

1981

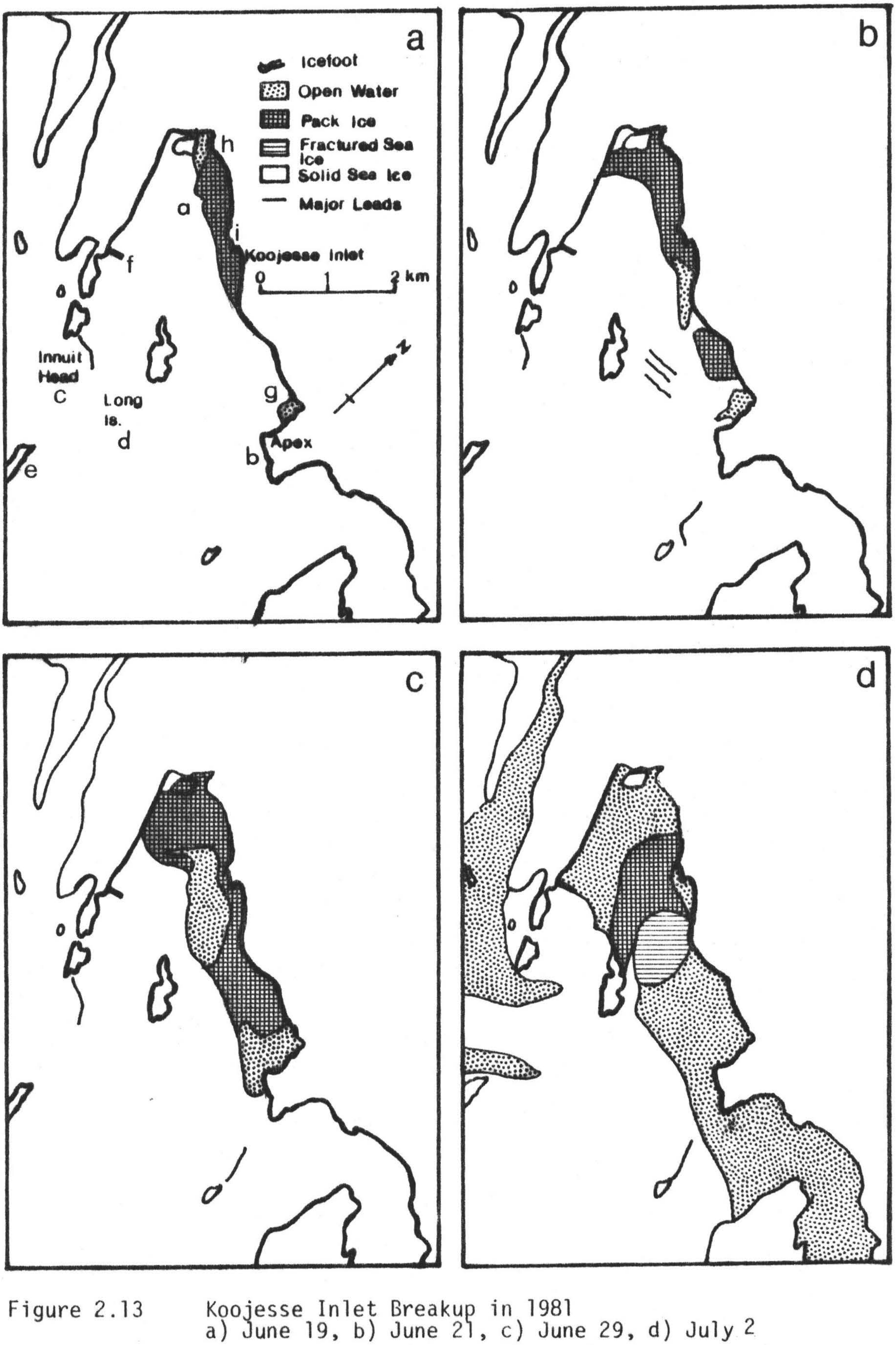


Figure 2.13 Koojesse Inlet Breakup in 1981
a) June 19, b) June 21, c) June 29, d) July 2

Table 2.3 1980 Ice Breakup in Koojesse Inlet
Percentage Ice Cover

Date 1980		% Total Ice Coverage	% Solid Ice Cover	% Rafted Floes	% Ice Pans	% Open Water
June	9	100	100	-	-	-
	16			-	-	-
	19	98.78	83.58	15.2	-	1.21
	25	87.84	76.7	11.14	-	12.16
	28	93.67	64.9	23.74	5.03	6.3
	30	80.7	63.9	12.9	3.9	19.2
July	1	74.13	59.8	9.78	4.55	25.86
	2	43.6	40.2	-	3.4	56.3
	3	52.0	37.43	9.48	5.09	47.99
	4	46.72	31.38	15.35	-	53.28
	5	41.95	26.93	14.0	1.02	58.05
	6	20.94	13.75	7.19	-	79.06
	8	22.08	.7	5.98	15.4	77.9
	9	3.25	-	-	3.25	96.75
	10	1.02	-	-	1.02	98.98
	11	-	-	-	-	100
	12	-	-	-	-	100
	13	-	-	-	-	100
	14	-	-	-	-	100

Table 2.4 1981 Ice Breakup in Koojesse Inlet
Percentage Ice Cover

Date 1981		% Total Ice Coverage	% Solid Ice Cover	% Rafted Floes	% Ice Pans	% Open Water
June	10	100	100	-	-	-
	11				-	
	12				-	
	13					
	14					
	15					
	16					
	17					
	18					
	19	98.1	96.4	1.7	-	1.8
	20	99.2	97	2.2	-	.9
	21	98.5	92	6.5	-	1.3
	22	98.5	91.5	7.0	-	1.5
	23	95.3	89.2	6.1	-	2.4
	24	94.7	96.9	7.8	-	5.3
	25				-	
	26	97.2	84.9	12.3	-	2.8
	27	96.4	82.3	14.1	-	3.6
	28				-	
	29	90.7	76.1	14.6	-	9.4
	30	84.6	75.6	9.0	-	15
July	1	84.2	67.3	13.2	3.7	15.8
	2	71.9	61.7	6.3	3.9	28.1
	3	68.8	43.2	13.7	11.9	31.2
	4	70.3	44.3	17.8	8.2	29.6
	5					
	6	42.6	13.05	29.5	-	57.4
	7	18.7	12.09	6.6	-	70.97
	8	11.8	5.0	6.8	-	88
	9	11.8	5.0	5.5	1.3	88
	10					
	11	.46	-	.4	.06	99.6
	12	2.53	-	.13	2.4	97.5
	13	10.7	-	6.8	3.9	89.2
	14	6.05	-	6.05	0	94
	15	2.9	-	-	(2.9)	(97.1)
	16	-	-	-	1.3	98.7
	17	-	-	-	-	100

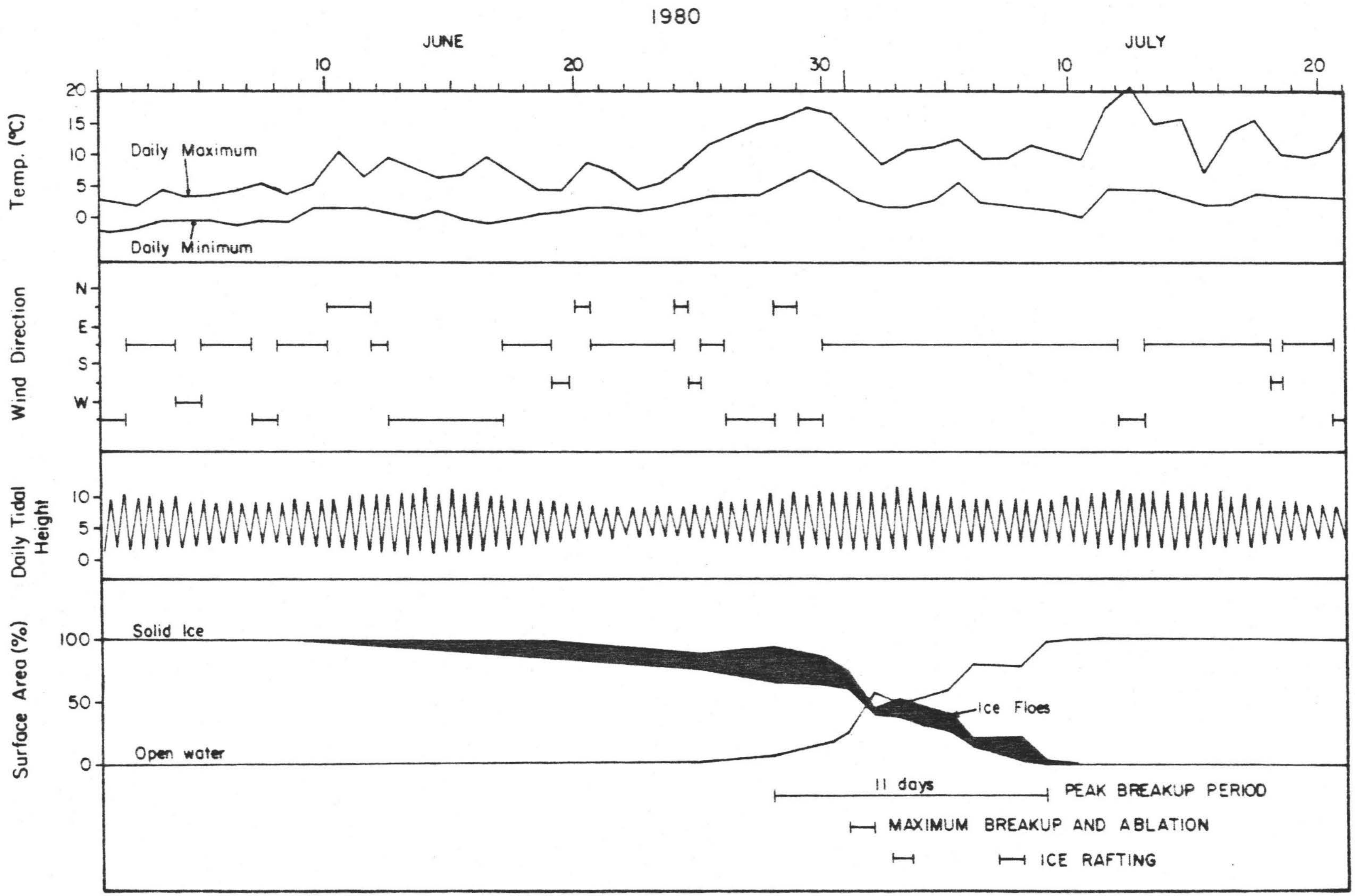


Figure 2.14 Ice cover during breakup and local environmental conditions 1980.

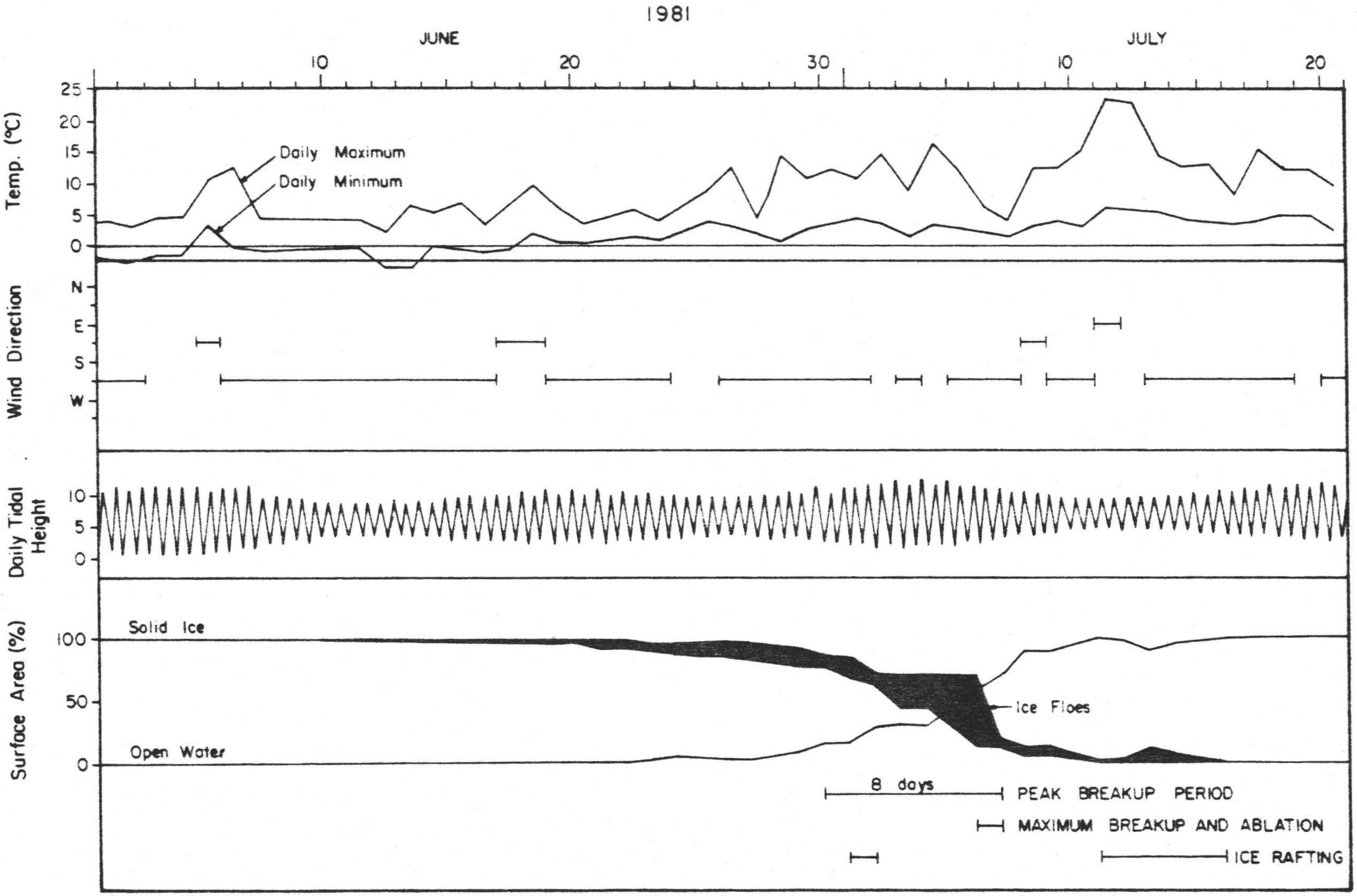


Figure 2.15 Ice cover during breakup and local environmental conditions 1981.

2.5.1.1 Stage One - Before June 16, 1980 and June 19, 1981
Fig. 2.13a

Intertidal ice broke up near the mouths of streams flowing into the bay. These were also the first locations of open water. A large lead developed off Innuit Head (c) towards Monument Island (e).

2.5.1.2 Stage Two - June 16 to 24, 1980. June 19 to 28, 1981
Fig. 2.12a, Fig. 2.13b

Tidal cracks developed between the ice foot and fast ice, parallel to shore, on the tidal flats. Continued surface ablation further weakend the ice. The presence of sediments and boulders, which lowered albedo, played an important role in the early development of floes on the flats. The boulders melted through the ice, generally before any large scale movement of floes occurred.

2.5.1.3 Stage Three - June 25-26, 1980. June 29-30, 1981
Fig. 2.12b, Fig. 2.13c

The influence of overland drainage and tidal oscillations spread along the shoreline to low intertidal areas, like the Apex Hill flats (b), and subtidal regions. Tidal action began to breakup the ice around Long Island (d) and between the causeway (f) and Innuit Head (c). Large leads developed between Long Island (d) and mainland promontories, the causeway (f) and Apex Hill (b).

2.5.1.4 Stage Four - June 27-July 10, 1980. July 1-16, 1981
Fig. 2.12c, Fig. 2.13d

The leads opened and large pans of ice drifted shoreward where they were stranded and eventually disintegrated. As larger open water areas formed, more subtidal ice was moved shoreward by wind, wave and tidal action. These floes accounted for the maximum period of ice gouging during breakup. Figure 2.12d taken on July 8, 1980, shows the large number of floes present at this stage.

2.5.1.5 Stage Five - July 10, 1980. July 16, 1981

The ice floes had disintegrated by this time leaving a few remanants of the ice foot in sheltered locations at Innuit Head (c) and Long Island (d). Low gradient beaches by the old and new Hudson Bay stores (g,h) and the cemetary (i) also retained some fragments of the ice foot.

2.5.2 Breakup in 1980 and 1981

Comparisons between the two years shown in Figures 2.14,2.15 indicate that, while general ice breakup trends were similar, average conditions in 1981 were a week later than in 1980. Thaw was initiated on June 9 in 1980 and on June 1 in 1981. This lag in 1980 was due to higher than normal daily temperatures on May 29 and 30, 1981 (-.3^{o}C and +.45^{o}C respectively). Favourable melt conditions occurred in early June of both years (Fig. 2.2). Cumulative degree day analysis showed temperatures above 0^{o}C by June 10, 1980 and June 5, 1981. Despite the slower start in 1980, after June 12, 1980 climatic conditions improved. Thereafter the heat index for 1980 stayed above that for 1981 for the remainder of the breakup season. This aided in the earlier breakup in 1980. Signs of the breakup were visible by June 16, 1980 and by June 19, 1981. The more favourable climatic conditions which increased ablation in 1980 were due to the predominance of south-west and north-east winds which were warmed after flowing over the land (Fig. 2.14). In 1981, predominantly south-east winds were cooled by flowing over the frozen bay, thereby slowing the melt rate of near-shore ice (Fig. 2.15).

The slower ablation rate in 1981 may also be explained by the effective insulation of the ice from 10 cm of snow which fell in the last week of May, 1981. Pools and streams developed more gradually in the snow and tended to concentrate at the base of the snow layer where it occasionally refroze. In 1980, the pools and streams flowed at the top of the crusty ice surface, enhancing melt. 48.9 mm of rain in June 1980 compared to 13.6 mm in June 1981 also contributed to the relative increase of snow and ice melt of 1980 over 1981.

The decrease in the amount of solid ice cover reflects the break-up rate. This cover fell from 75 to 25% in 10 days in 1980 (June 25 to July 5) and 6 days in 1981 (June 30 to July 5). From these dates it is evident that despite the earlier breakup in 1980, the actual rate was faster in 1981 (Fig. 2.14, 2.15). The rapid breakup in both years co-incided with spring tidal conditions, with large tidal current generation which rafted and abraded floes. Secondly, the ice at the low end of the intertidal zone settled to the flat surface during low tide, thus contributing to its breakup.

A dramatic reduction in ice cover occurred midway through break-up for both years. On July 1 and 2, 1980 the solid ice cover dropped from 60 to 40% and the percentage of rafted floes from 75 to 45% (Table 2.3). These decreases were caused by the advanced stage of decay of the ice by this time, coupled with 3.4 mm of rain, brisk southeast winds at 16.6 km per hr., and higher tidal levels (Fig. 2.14).

Similarly in 1981, the greatest drop occurred from July 4 to 6 when solid ice cover fell from 44 to 13%. Ice floe coverage decreased 30 to 6%, July 6 to 7, 1981 (Table 2.15). A warming trend by north-west winds on July 4, 1981 aided the rapid disintegration of solid ice into brash ice. The winds switched to the south-west and rafted the brash ice onshore at the head of Koojesse Inlet, in piles 2 to 3 floes in depth. These pile-ups helped reduce the total aerial coverage of ice. Lowering tidal levels, stranded many of these floes which then ablated over the flats. This resulted in a high intensity of ice gouging of the sediment surface.

As the open water areas increased, south-east winds generated higher energy waves which enhanced rafting and decay through abrasion. Pressure melting by wave action is well documented (Shumskii 1964, Dozier et al 1976). One form is ventilated shock which results when a breaking wave pushes air out between itself and the ice. This generates pressure and, more importantly spray, which enhances thermal melt. In Koojesse Inlet this kind of wave action was effective along the ice foot as well as the leading floe and fast ice edges.

The shaded areas in Figures 2.14, 2.15 show the amount of ice floe cover, including brash ice and pans. The densest concentration of floes (30% cover) was observed in the 1981 season from July 1 to July 6. Frequent south-east winds, the availability of floes and extensive fetches of open water permitted the influx of ice from well down the bay. This was very evident towards the end of breakup. On July 12, 1981 south-east winds up to 37 km/hr began moving ice down bay towards Koojesse Inlet. The ice arrived by July 13 and remained for 3 days until it had ablated.

Ice was rafted into Koojesse Inlet at the beginning of August 1980, from an unknown source down bay. It may have come from calving of the Sylvia Grinnell glacier or from ice bergs in Davis Strait borne by favourable wind and tidal conditions. The presence of this ice so late in the season after breakup, had an interesting effect on the biological and physical zonation of the tidal flats (see Chapter 3). Despite these unusual migrations, the last remnant of locally formed ice disappeared by July 10, 1980 and July 16, 1981.

2.6 Conclusions

Despite some small variations in breakup and freezeup between 1980 and 1981, a number of points on general ice conditions in Frobisher Bay can be made.

1. Frobisher Bay is ice covered for most of the year, on average some 210 days. Ice begins to form in late October and is complete by mid-November of most years. Sediments, including cobbles and boulders are incorporated in the ice during its formation. These sediments come from aeolian transport of terrestrial deposits, fall from cliffed shores onto the ice or are picked up from the tidal flat surface itself. These sediments probably experience a fair amount of ice transport during freezeup.

2. Thaw begins early in June as temperatures begin to rise. On average breakup is initiated by June 14, and concludes with ice free conditions by July 17. Breakup proceeds in a series of events

Table 2.5 Ice Breakup Sequence for Frobisher Bay

Stage No.	1980, 1981 Dates	Breakup Features
1	Before June 16/80 June 19/81	Ablation of sea ice by warming temperatures. Rate is increased on ice with a low albedo due to high sediment content as over unconsolidated intertidal areas and snow cover.
2	June 21/80	Break-up of tidal flats by river mouths due to overland meltwater input.
3	June 16-24/80 June 19-28/81	Development of tidal cracks and the break-up of ice on the tidal flats by the cracks.
4	June 25-26/80 June 29-30/81	River mouth ice breakup by overland meltwater. The riverine influence now exceeds the tidal range influence.
5	June 26/80 June 30/81	Increasing opportunity for ice floe movement.
6	June 27 to July 10/80 July 1-16/81	Progressive seaward breakup of ice over tidal flats by tidal crack development, and the eventual breakup of sub-tidal ice by tidal and wind pressures. Period of maximum Ice erosion on tidal flats.
7	July 1/80	Break-up of ice along steep unconsolidated sediment shorelines.
8	July 7-13/80	Break-up of ice along steep rock shorelines.
9	July 1-13/80	Off-shore ice movements often towards shore.
10	July 13/80 July 16/81	Tidal flats, steep shorelines relatively clear of ice.
11	July 13/80 July 16/81	Continued ice foot degradation, by wave and tidal action, and radiative heating.

which do not appear to vary much from year to year. An 11-stage sequence of ice breakup is proposed for the headward reaches of Frobisher Bay. This sequence shown in Table 2.5, is based upon the 1980 and 1981 seasons, which were typical breakup years. Only timing and the duration of the breakup sequence varied between 1980 and 1981. This variation was the result of local environmental factors, such as tidal oscillations, wind speed and direction, temperature, precipitation and snow cover.

The general sequence of ice breakup is dictated by the shoreline gradient, substrate and tidal height. These factors tend to vary only slowly from year to year, thus ice breakup prediction at various sites can be made using the breakup sequence.

CHAPTER 3

THE EFFECTS ON ICE IN THE INTERTIDAL ZONE

3.1 Introduction

This chapter examines the effects of ice in the intertidal zone at the head of Frobisher Bay, and is based on observations made during breakup in 1980 and 1981. Ice action contributes to the morphological and biological zonation of the tidal flats, by acting as both a protective and erosive agent, and transporting and depositing incorporated materials. The focus in this chapter is mainly on the morphological effects, which include ice protection, boulder and sediment transport and deposition, ice gouges and ice push ridges. A short discussion on the biological responses is included.

3.2 Literature Review

3.2.2 Ice Erosion, Transportation and Deposition

There have been four major contributors to the literature on the interaction of ice on tidal flats in the North American Subarctic, Dionne (1968, 1969, 1974a, b, 1975, 1978, 1979) studied tidal flats in James and Hudson Bay as well as in the temperate Gulf of St. Lawrence. Lauriol and Gray (1980) worked in Leaf Basin in Ungava Bay. Martini and Protz (1979, 1980) in James Bay and Rosen (1979, 1980) in the Makkovic Region in Labrador. In Northern Europe, contributions have been made by Mansikkaniemi (1976) in southern Finland, Reineck

(1976) and Pyökari (1978) along the North Sea.

Similar ice effects have been studied on temperate tidal flats where ice-made features are generally short lived, with a lower preservation potential. Sasseville and Anderson (1976) and Thompson (1977) worked in Great Bay, New Hampshire, and Knight and Dalrymple (1976), in the Bay of Fundy.

Dionne (1968) found that a 1 m^3 block of ice carried more than 100 lbs of sediment incorporated in the ice during freezeup. Movement of this ice provides a potentially important method of random sediment dispersal, capable of changing the normal grain size zonation induced by wave and current action. Sasseville and Anderson (1976) found that sediments 5 to 30 mm in thickness were removed from the tidal surface after one winter season. They also noted winnowing and resuspension of fines, particularly the clay size fraction, during the winter under the ice cover, which added to the net sediment loss. This was probably due to tidal current action, which was still effective at depth under ice cover, in resuspending fine sediments (Drake and Totsman 1979).

Large scale movement of ice is dependent upon reaching a threshold velocity, which is conditional on ice strength and local resistance to movement (Agerton 1977). Storms play a major role in the movement of suspended sediments and ice floes which account for significant sediment transport in the spring (Hume and Schalk, 1967, Reimnitz and Maurer 1979). Agerton (1977) noted that major landfast ice movement was associated with storm winds exceeding 10 to 13 m/sec and wind directional changes. Tsang (1974, 1975) concluded that the ice piling caused by changes in wind direction were important only after breakup when open leads developed, a phenomenon observed by this researcher in Koojesse Inlet. Significant ice push features and ice gouging of the shoreline were caused by surging ice packs from wind action. The longer the fetch length, the greater the affect of ice push on the beach (Taylor 1980).

Erratic boulders on Subarctic tidal flats are larger than those found in temperate areas, and are most extensive on shores with slopes between 2^{o}-3^{o} (Dionne 1976). The most popular theory explaining the presence of these boulders involves ice floe transport. Boulders which fall on the ice from surrounding cliffs or picked up from the flats during freezeup, are rafted by drift ice until the ice ablates (Lagarec 1976, Lauriol and Gray 1980). Lauriol and Gray (1980) proposed that the boulders were moving progressively down slope from ancient marine limits by gravity, water and ice related processes. This occurred over thousands of years during coastal emergence.

Boulders are moved about by the ice in a number of different ways. Drake and McCann (1981) calculated that an ice floe 13 m in diameter and .5 m in thickness could support a boulder up to 2 m in diameter. As well as drift ice transport, ice push is a second viable means of boulder movement.

Dionne (1978) examined grooves up to 300 m in length formed from ice pushed boulders along river and lake shorelines. He noted that this process appeared less active in tidal flat locales, a view also held by Lauriol and Gray (1980) who found no evidence of boulder gouges by boulder ridge developments as one might expect. Mansikkaniemi (1976) noted small scale multidirectional movements between 10 and 100 cm for blocks. Pyökari (1978) observed the movement of stones embedded in the ice foot which collapsed seaward carrying the stones with it.

From Dionne's (1968, 1979) numerous studies, there are 10 common formations which develop from ice action along shorelines. These are listed in Table 3.1. Many of these formations can have a disruptive effect on normal drainage patterns (Hume and Schalk 1967, McCann 1973, Owens 1976, Taylor 1978). They can also influence subsequent bedform development during the ice free months.

Dionne (1976, 1979) found that ice push ridges and grooves with a boulder at their head are the most common ice-made features on beaches. Ice push ridges develop from pack ice rafted onshore, which pushes beach material into ridges .5 to 4.5 m in height (Hume and Schalk 1964, Taylor 1978). Ice gouges, grooves and striations are eroded by ice blocks pushed across the tidal flat surface by wind, wave or current action. Gouges and grooves are many metres in length and centimetres in width and depth. Striations are centimetres in length and millimetres in width (Dionne 1974).

3.2.2 Ice Protection

During ice freezeup, pore water in the sediments freezes, first in the upper shore areas and gradually extending downward and seaward. The freezing of coastal sediments helped preserve features formed during the previous ice free season (Hume and Schalk 1967,

Table 3.1 Common Ice Action Features on Tidal Flats

1. ice push ridges
2. grooves with a boulder at the head
3. ice rafted sediments
4. boulder ridges
5. stone (boulder) pavements
6. beach micro-relief
7. shore ice kettles
9. drift ice striations and gouges, and scratching on boulders and soft rock outcrops
10. collapsed depressions from the melting of buried ice in unconsolidated sediment

Short and Wiseman 1974). It also protected the shore from further erosion by halting aeolian transport of fines, normal bedload movement and bedform development, preventing extensive ice gouging, and decreasing water percolation, thereby increasing the lateral movement of water (Short and Wiseman 1974, Knight and Dalrymple 1976). Vertical walled ebb run-off channels, scour pits and pseudo-monroes develop from the removal of the ice crust by wave and current action (Knight and Dalrymple 1976).

3.2.3 Effects of Ice on Flora and Fauna

The most important effect of ice on the biological community is that it shortens the biological season, the period of primary production of carbon (Carey and Ruff 1977). Secondly, an ice cover shortens the settling time available for pelagic larvæ, thereby limiting their dispersal (Petersen 1977).

Researchers have noted the ability of certain intertidal molluscs to survive under or frozen into the ice (Madsen 1936, Dunbar 1946, Ellis 1955). The large thermal tolerances exhibited by many intertidal species is well documented (Williams 1970, Myren and Pella 1977, George 1977). Littorina sp. can survive for 6 to 8 months embedded in ice at -20°C with little harm (Kanwisher 1955). Barnacles (Crisp, Davenport and Gabbott 1977) and mussels likewise exhibit this ability (Williams 1970). These animals can be transported to new locations by ice drift and subsequent ablation (Reineck 1976, Petersen 1977).

As the ice ablates in the spring, an upper layer of fresh water develops just under the ice which does not mix with the underlying saline waters (Ellis 1960). This layer has been recorded to reach thicknesses of 4 to 6 m by large rivers before ice breakup disrupts it (Barber and Murty 1977). Most marine species cannot tolerate fresh water. Even icebergs can have a small localized effect with their meltwaters killing pelagic plankton (Petersen 1977). The presence of sea ice also changes the volume of water in which the biological community may reside. This can result in oxygen depletion which can kill some members of the community (Adams 1976, Reichert and Dörjes 1981).

Grounded ice can destroy organisms by physical gouging and increased turbidity, developed by currents scouring around the grounded ice (Carey and Ruff 1977). The scraping of sediment, rock and marsh surfaces was frequently noted as the cause of high mortality or the absence of flora and fauna in the intertidal area (Wilce 1968, Jones 1970, Stephenson and Stephenson 1972, Wacasey 1975, Adams 1977, Carey and Ruff 1977). Petersen (1977) challenged this hypothesis stating that ice action only destroyed highly localized organisms. He felt exposure and moisture requirements played a more important role in the distribution of organisms in the intertidal and ice affected zones.

3.3 Ice Action in Koojesse Inlet

3.3.1 The Role of Fast Ice and the Ice Foot

The ice foot, for the purpose of this discussion, was defined as that part of the ice which rarely floated, was granular in nature, with little to no incorporated sediment layers and usually greater than 2 m thick. Using this criterion the boundary between the ice foot and fast ice was easily identified on the STB transect (Fig. 3.1). Ballycatters which developed over the boulder ridges at Apex and Rock Transect disrupted the ice surface making the boundary more difficult to delimit (Fig. 3.2, 3.3).

The ice cover and underlying substrate undergo great stresses during tidal oscillations, particularly at the tidal lead (or crack) which developed at the ice foot/fast ice boundary. This junction probably migrated seaward during ice formation, as the ice grew in thickness. Consequently, a wide area of the ice froze to the substrate. During breakup, as the ice ablated and thinned, the ice began to float and the tidal lead began to move shoreward between the floating and frozen boundary.

The ice foot protected the shoreline from wave and current action and ice floe abrasion during breakup. In contrast the fast ice exerted a lot of erosive energy across the flats. These stresses were reflected by the chaotic surficial appearance of the intertidal area (Fig. 3.4). Small ice push ridges and ice imprints were common in areas of high intensity ice action from tidal oscillations such as at the tidal lead and over ballycatters (Fig. 3.4).

The ice foot also acted as a sediment and boulder trap. Ice floes with incorporated materials, were frequently stranded on top of the ice foot by lowering tides. These floes ablated and deposited their material on the ice foot. This process accounted for the large number of boulders and sediment deposits encountered in the upper

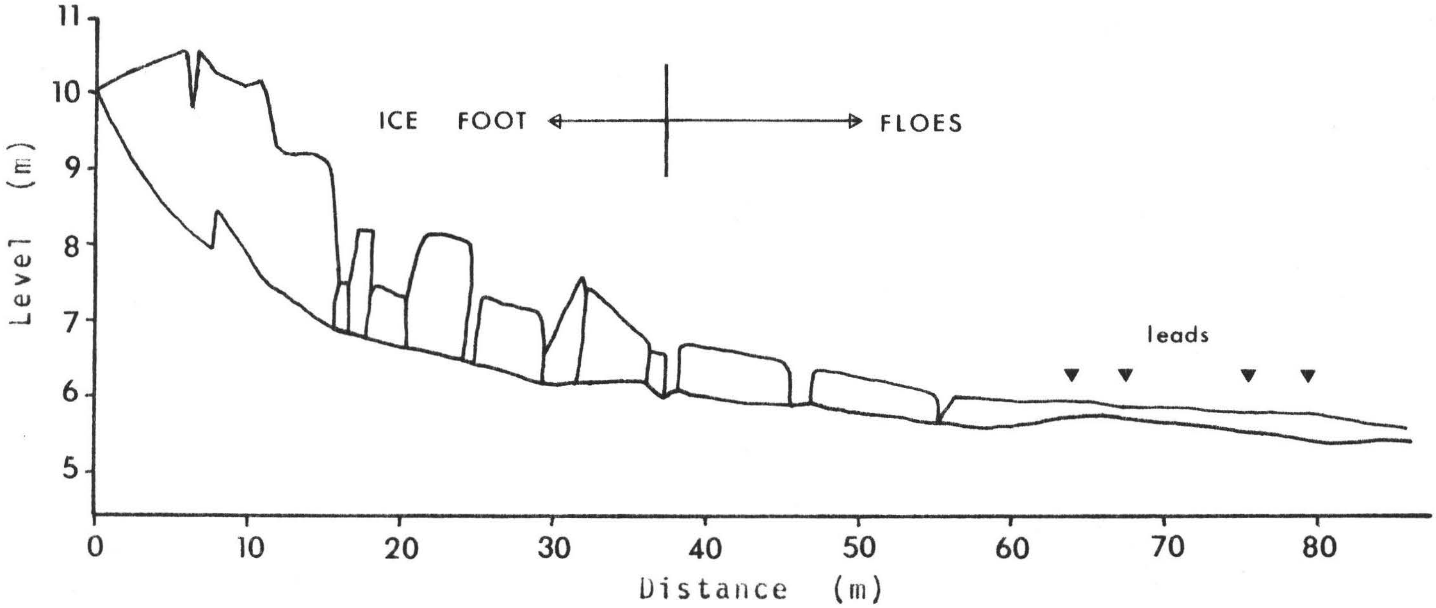


Figure 3.1 Ice foot and fast ice boundary at STB, June 18, 1981

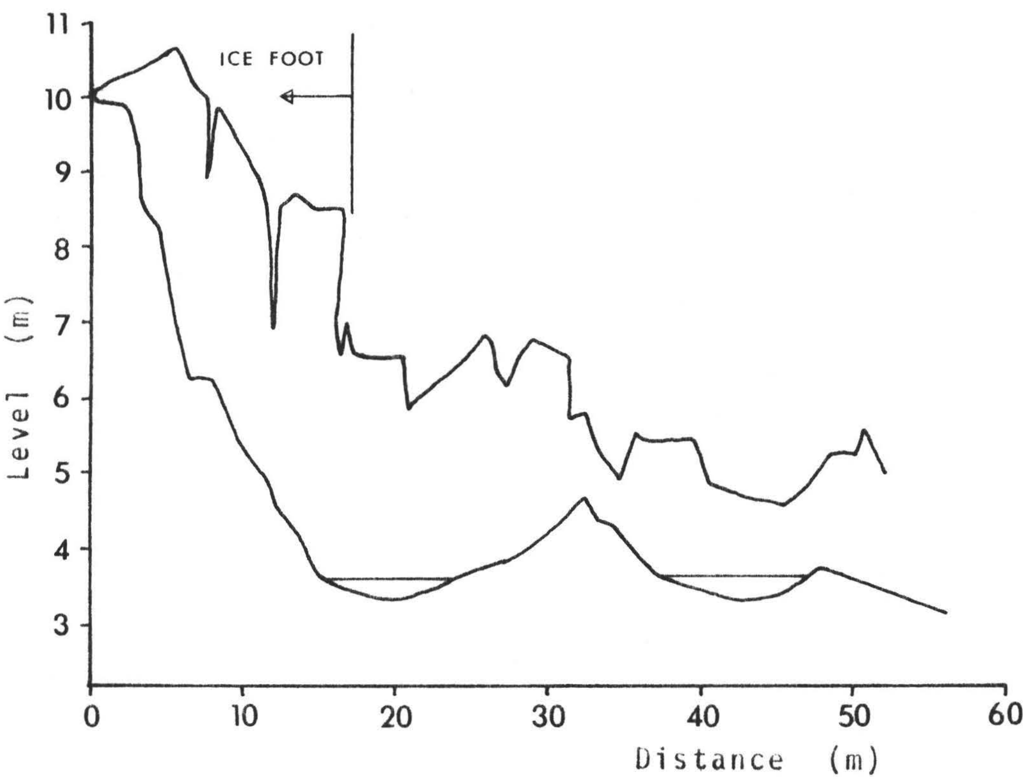


Figure 3.2 Ice foot and fast ice boundary at Apex transect June 19, 1981.

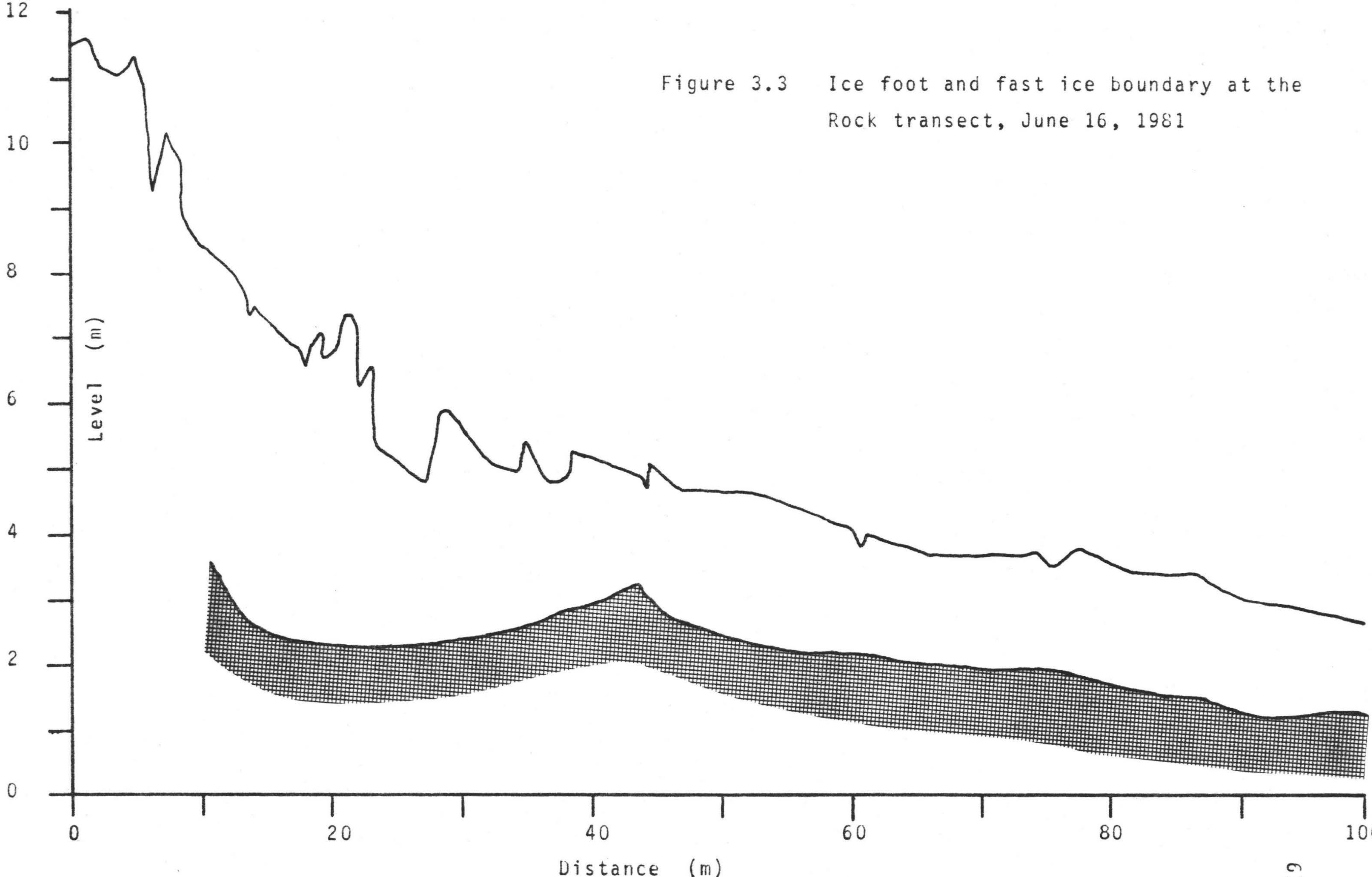


Figure 3.3 Ice foot and fast ice boundary at the Rock transect, June 16, 1981

FIGURE 3.4a Ice foot and fast ice boundary with incorporated sediments.

FIGURE 3.4b Ice push depression and debris ridges on the boulder ridge (ballycatter zone) at the Rock transect.

shoreline area.

As breakup progressed, large fractures developed in the ice foot, enhanced by wave undercutting throughout the season. As the ice foot pulled away from the bedrock it often pulled rock, flora and fauna with it.

By June 23, 1981, the ice had fractured sufficiently to allow measurement of the substrate temperature (See Chapter 4 Methodology) and frostline depths (Fig. 3.5). The frostline retreated rapidly once the ice was broken, thus values were only obtained for STB (Table 3.2). In 1981, the frostline was absent out to 138 m, and was encountered progressively deeper seaward of 188 m. Typically, one would expect the upper shoreline areas to have the frostline closer to the surface, since the area has more frequent and longer periods of exposure to the ice. The absence of the frostline in the upper flat was due to the earlier breakup which occurred by the tidal crack some 7 days earlier.

Substrate temperatures were warmer close to shore where the earlier breakup had occurred, and decreased seaward (Table 3.2). Surface temperatures were consistently highest, with values decreasing with depth, except at Site 10 where cool melt water from the ice foot reduced the surface temperature. Active polychaetes (spionidae and maldanidae) were observed at Site 7 which had warmer temperatures than surrounding sites. Only Site 9 had similar high temperatures but no fauna were observed, the reason is unknown.

3.3.2 Ice Ablation

Fresh water from ice ablation affected the tidal flat floral

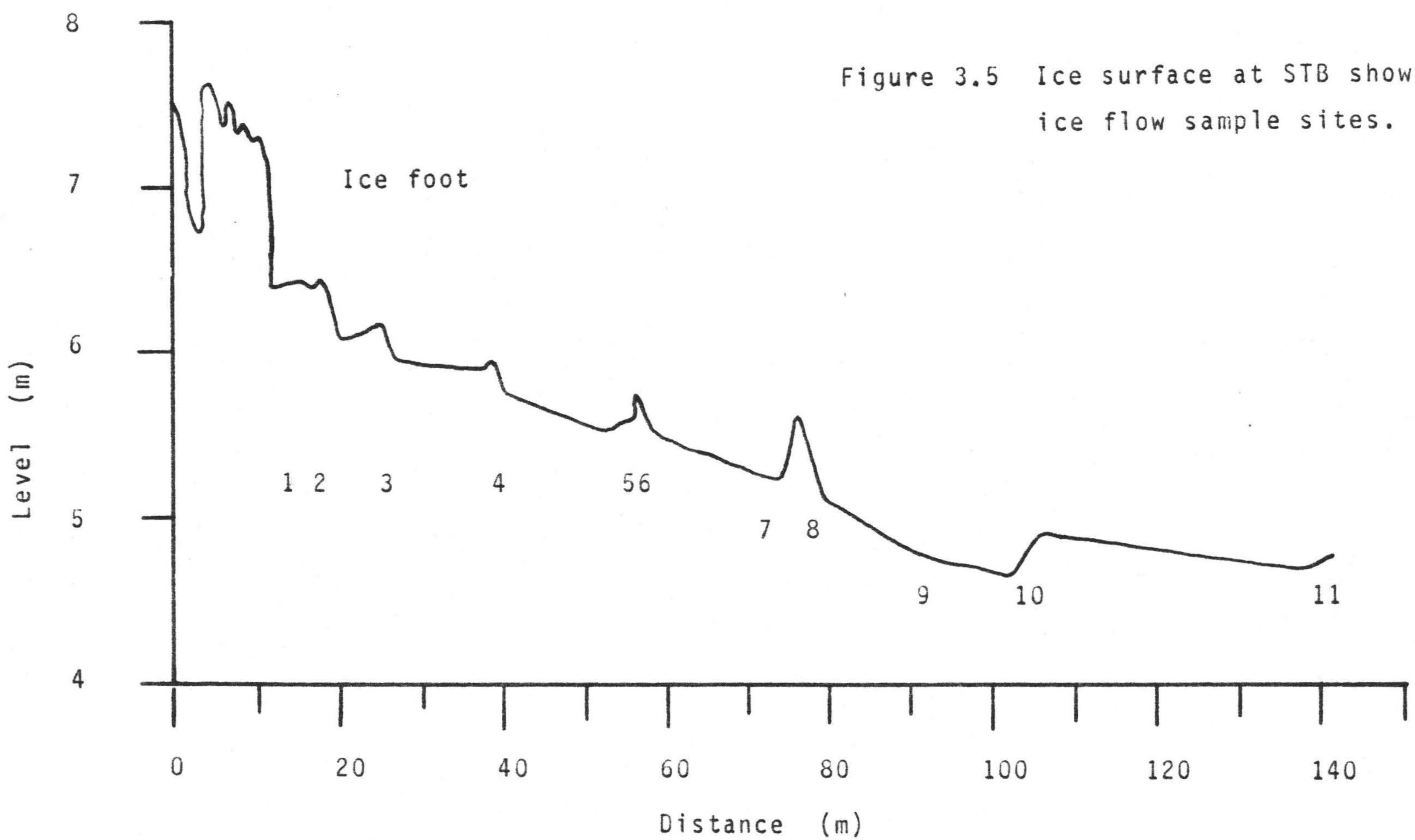


Figure 3.5 Ice surface at STB showing ice flow sample sites.

Table 3.2 Frostline Depths and Substrate Temperatures at STB on June 23, 1981

Site No.	Position From Shore (m)	Floe No.	Frostline Depth (cm)	Substrate Temperature °C			Comments
				Surface	5 cm depth	10 cm depth	
1	375		4.7	-	-	-	Little to no ice incorporated debris
2	337.5		13	2.0	1.0	.7	Fine sediments on ice surface
3	287.5		1	2.0	1.5	.7	
4	252.4		3.4	1.43	1.2	.7	
5	237.5		1	2.0	1.2	.7	Discontinuous sediment layers in ice
6	187.5		2	2.0	1.5	1.0	Some sediment layers in ice
7	137.5	11	-	4.0	3.0	2.5	
8	102.3	10	-	2.0	2.0	1.5	Many sediment layers in ice
9	69.5	7	-	5.5	5.0	4.5	Many sediment layers in ice
10	11.3	1	-	3.2	3.2	3.2	Many sediment layers in ice

and faunal communities. Littorina saxatilis were observed in great numbers in areas where the ice was no longer ablating. Fucus evanescens were absent in ideal locations where the ice foot was present. This probably reflected melt water input as well as ice erosion.

In fast ice areas, the average salinity ranged between 29 and 32 %. It reached values of .1% in pools on the ice surface and ranged between 1 and 10% within 50 cm under the ice cover during melt (See Chapter 4). This lens of relatively fresh water probably played an important role in the movement and reproductive activity of the fauna. This water dictated the success of new spat and controlled the "awakening" of many species.

The influence of ice floe ablation later in the ice free season was demonstrated in a rare occurrence in 1980 when floes from down bay drifted into Koojesse Inlet. They collected on the flats by the Rock Transect when driven by north winds on August 1. Investigations two weeks later revealed that large colonies of Hiatella arctica and Cyrtodaria kurriana which were found previously at the low end of the flats, (1.4 m ALLT) had been killed. Some of the shells of the dead animals remained in situ, but were partially exposed by erosion of the surrounding sediments. These observations suggested that during low tide, extra run off from the ice floes had eroded sediments across the flats. Fresh water influx had likely killed the molluscs. Deep infaunal species such as the Mya truncata survived this episode. These ice floes also left gouges in the surface and eroded the active layer by the boulder ridge to expose the underlying clay layer.

Melting ice floes frequently left dimples in fine sediments from melt water drips landing on the substrate. When the drips contained sediments, small cones (< 1 cm in height) built up. Drips which fell the entire length of the floe edge, built up ridges, thus outlining the shape of the floe.

3.4 Sediments and Boulders in the Ice

The locations where boulders and/or sediments were observed in or on the ice surface is shown in Figure 3.6. The sediments were incorporated in the ice during freezeup. They were found in layers which decreased in number and in thickness in a seaward direction. Samples of ice taken at STB (Fig. 3.5) also showed a decrease in the amount of sediment by weight in a seaward direction (Table 3.3). Varying tidal levels during freezeup accounted for the decrease in sediment content from shore.

From grain size analyses of ice incorporated sediments, no grain size selectivity by the ice was apparent. The presence of coquina in these samples left no doubt that the origin of the sediments was the tidal flat itself.

Early in the season, measurements of the thickness of sediment which accumulated on the ablating ice surface, were taken near the airport. The mean thickness of this layer was 8.17 cm, thus illustrating the great amount of sediment which was removed from the flat surface by the ice. This zone extended 40 m from the tidal lead and ended abruptly at its shoreward and seaward extent. A strip of this zone 1 m by 40 m would weigh approximately 1,250 kg.

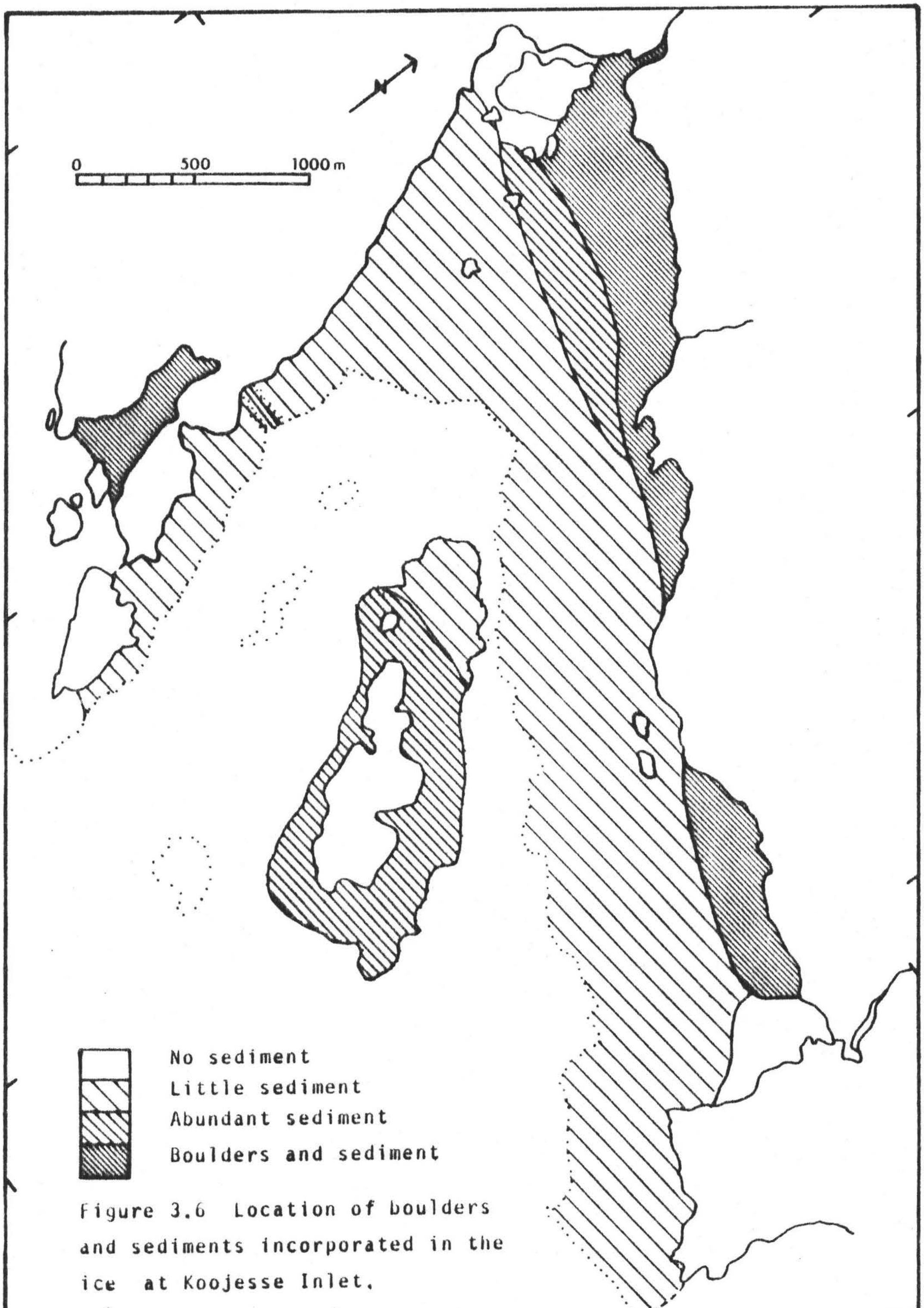


Figure 3.6 Location of boulders and sediments incorporated in the ice at Koojesse Inlet.

Table 3.3 STB Ice Floe Volumes and Sediment Weights

Floe No.	Position from shore (m)	Ice Type IF - Ice Foot S - Sea Ice	Length of Floe (m)	Width of Floe (m)	Average Thickness of Floe (m)	Ice Sample Taken	Volume of Ice Floe (ℓ)	Volume of Ice sample (ℓ)	Wt. of Seds. in Ice sample (g)	Wt. of Seds. in Ice Floe (kg)	Wt. of Seds. in a 1000 ℓ Floe (kg)
1	11.3	IF	3.2	4.0	1.4	-	17,920	No Sample			
2	17.2	IF	3.7	2.2	.95	-	7.730	No Sample			
3	24.9	IF	6.6	1.6	1	Yes	10,560	.427	383.2	9476.8	897.4
4	37.5	S	6.3	2.7	.7	Yes	11,910	.844	263.34	3716.1	312.0
5	52.6	S	4.4	3.4	.4	Yes	5,980	.599	233.245	1995.4	333.7
6	55.9	S	4.0	2.6	.4	Yes	4,160	.495	464.5	3903.7	938.4
7	69.5	S	5.6	4.6	.3	Yes	7,730	.595	226.23	2939.1	380.2
8	76.1	S	3.9	3.2	.3	Yes	3,740	.702	67.22	358.1	95.8
9	89.6	S	4.5	3.2	.55	Yes	7.920	.505	1.655	26.0	3.28
10	102.3	S	4.0	4.0	.4	Yes	6,400	.208	42.54	1308.9	204.5
11	137.5	S	6.9	3.7	.4	No	10,200	No Sample	-		-
	187.5		-	-	-	Yes		.290	79.96		275.7

The areas with the greatest amount of sediment and boulder accumulation in the ice occurred in the upper parts of the flat, usually above 4.0 m ALLT (Fig. 3.6). Low gradient tidal flats such as STB also had greater amounts than steeper locales. Flats with a greater boulder coverage likewise had fewer sediments incorporated in the ice, since less of the substrate was available for incorporation. Secondly, small developing floes could settle between boulders, but as the floes grew in size, the boulders impeded their settlement to the bed resulting in less debris incorporation.

From Figure 3.6 estimates of the total amount of sediment incorporated in the ice can be made. Using the 8.17 cm depth of sediments approximately 22,500,000 kg of material were incorporated in the ice in the major sediment and boulder accumulation zone above.

The exact mechanism by which boulders were incorporated in the ice is not well understood. From observations boulders were more likely to be lifted by the ice if they were isolated and not embedded in the substrate. Many of the transported boulders were angular and less rounded than more permanently placed boulders. Common boulder/ice observations are shown in Figure 3.7. It appeared that the ice cover was well formed by the time most boulders were embedded as multiple sediment layers were often found in the ice above the rocks (Fig 3.7a, b). Once embedded the boulder prevented the ice from settling on the substrate and no further sediment incorporation was evident (Fig. 3.7a). If the bottom of the boulder was covered by ice then it could once again settle to the substrate and collect more sediment (Fig. 3.7b). The boulder illustrated in Figure 3.7b broke

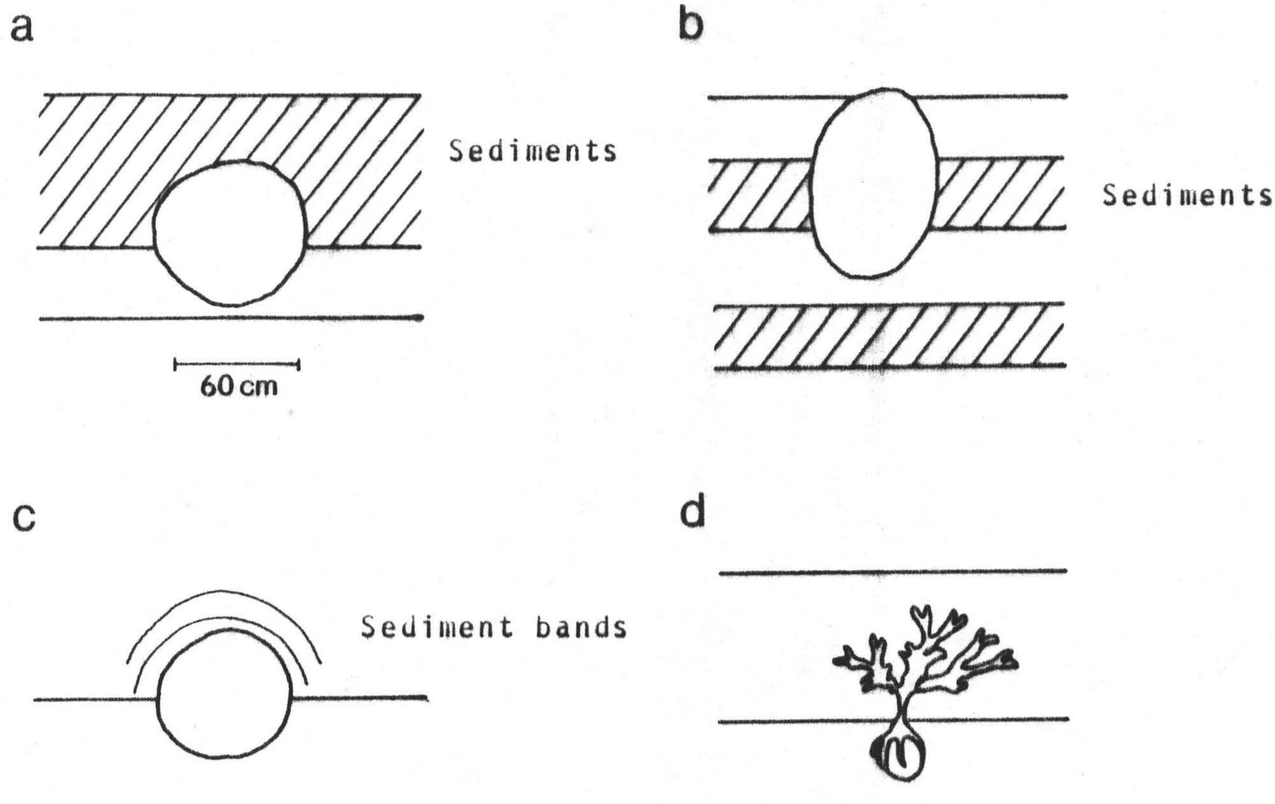


Figure 3.7a,b,c,d Illustrations of boulders embedded in the ice at Koojesse Inlet in 1981.

the ice sheet during low tide until it was finally embedded. The fast ice often failed to break over smaller boulders but bent over its surface as illustrated in Figure 3.7c. Sediments in the ice above boulders also showed that the ice cover must have experienced horizontal as well as vertical shifts in position. Algae also froze into the ice and could carry small stones with it (Fig. 3.7d).

3.5 Drift Ice Action

3.5.1 Introduction

Drift ice action accounted for many of the features observed in Koojesse Inlet. The movement and subsequent ablation of ice floes resulted in the transport and deposition of fine sediments and boulders throughout the bay. This activity destroyed the zonation and the smaller bedforms created by wave and current action during the ice-free months. Drift ice also formed striations, gouges and imprints on the unconsolidated and soft rock surfaces.

3.5.2 Drift Ice Movement

On June 23, 1981, 11 floes were surveyed and marked across the STB transect before breakup (Fig. 3.5). Following breakup, four of the floes were relocated. Floes 1 and 2 had moved 50 m to the west and had been stranded on the ice foot. Floes 8 and 10 moved 600 m to the east where they were marooned on a sandy beach and subsequently ablated (Table 3.4). The different directions of movement were largely the result of the breakup pattern, topography and wind direction. The outer floes (No. 8, 10) were moved east by strong north-west winds on

Table 3.4 Movement of Marked Floes in Koojesse Inlet

Floe #	Site	Length	Width	Thickness	(Volume) m^3	Distance Moved (m)	Direction	Description
June 23/81								
1	STB	3.2	4.0	1.4	17.92	50	West	Found at edge of bedrock shoreline
2	STB	3.7	2.2	.95	7.73	50	West	
3	STB	6.6	1.6	1	10.56			
4	STB	6.3	2.7	.7	11.91			
5	STB	4.4	3.4	.4	5.98			
6	STB	4.0	2.6	.4	4.16			
7	STB	5.6	4.6	.3	7.73			
8	STB	3.9	3.2	.3	3.74	600	East	Found on beach by Apex River
9	STB	4.5	3.2	.55	7.92			
10	STB	4.0	4.0	.4	6.4	610	East	"
11	STB	6.9	3.7	.4	10.2			
June 27/81								
1	Cemetary	3.8	4.05	1.8	27.7	225	West	Found 9 hrs later on the tidal flat surface
2	Cemetary	6.1	3.4	1.4	29.04	425	West	
3	Cemetary	7.0	4.2	1.7	49.98	350	West	
4	Cemetary	4.8	3.7	1.2	21.3	-	-	
5	Cemetary	4.4	3.9	1.6	27.5	500	West	"

June 24 and 25. The inner floes (No. 1, 2) were stranded in the enbayment. On June 26, the inner floes were rafted to the west by east winds.

From the samples taken from these floes, estimates were made on the amount of sediment transported by the ice (Table 3.4). Floe 8 contained approximately 360 kg of material and floe 10,1310 kg. Thus, a significant amount of material was distributed across the flats by this ice.

The movement of floes over one tidal cycle was monitored during peak ice floe cover, June 27, 1981 (Table 3.4). The floes moved between 225 and 500 m to the west due to south-east winds and flood currents. A number of ice gouges parallel to shore, approximately 9 m in length were observed after this ice movement.

Other observations were made on ice floe movement during breakup. During low wind conditions the movement was due to tidal currents and thus reflected the local tidal circulation patterns. Floes moved at rates of 18 to 51 m/hr during flood tide With the addition of wind action the floes moved at rates of 1 to 3 km/hr. Wind and current action is crucial to the movement and distribution of incorporated sediments. Strong north-west winds on July 8, 1981 generated 0.6 m waves which piled all of the ice on the flats on the south-east side of Koojesse Inlet. Substantial deposition of sediments, ice gouging and imprints resulted from this event.

3.5.3 Drift Ice Gouges

3.5.3.1 Introduction

Drift ice gouges were most prominent during the peak breakup period (June 27-July 10, 1981; July 1-16, 1981) when the maximum number of floes was available. They were best developed early in this break-up period when large keeled ice floes from the ice foot and fast ice boundary existed. Smaller and fewer gouges were formed from the smoother subtidal ice floes rafted onshore later in the season. In some cases, the gouges were still visible the end of August, but usually they were short-lived features soon reworked by subsequent ice, wave and current action.

The greatest concentration of gouges was observed near the mouth of the Apex River, where two transect lines were established to study them (HB1, HB2). A third line was surveyed at Apex Point. Few major gouges were noted elsewhere, although many short-lived ones were seen on the flats close to town. The continual movement and settlement of ice floes into this area by the prevailing south-east winds precluded any serious measurements in this area.

3.5.3.2 Gouge Length

The length of the ice gouge was determined by the size of the floe, gradient and substrate of the tidal flat, boulder cover, and the momentum of the ice floe. The cumulative percent of ice gouges smaller than a given length for all the gouges measured in Koojesse Inlet is illustrated in Figure 3.8. Fifty percent were less than 5 m in length and 89% less than 30 m.

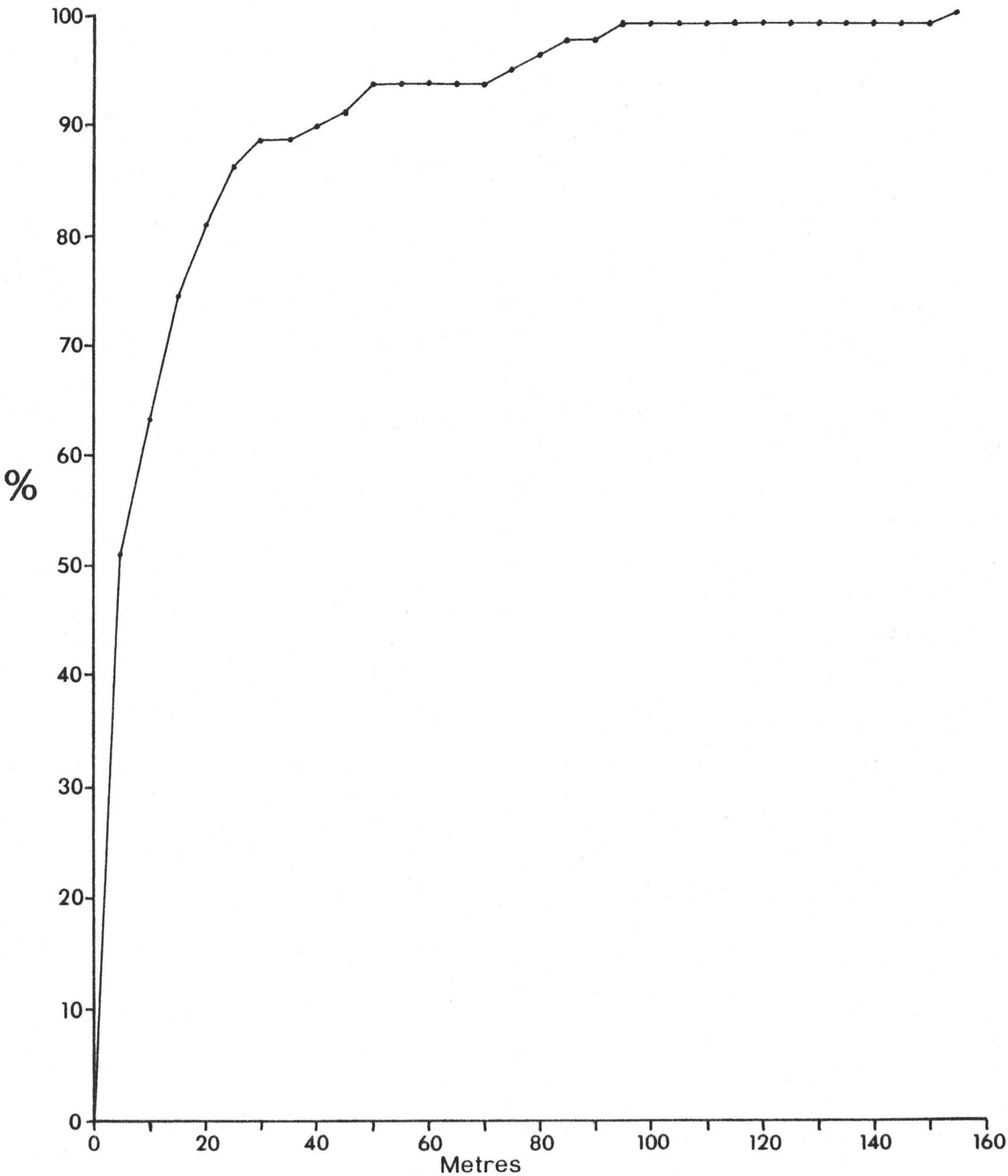


Figure 3.8 Cumulative percent of ice gouges versus length.

There was little difference in gouge length between the 3 transects (Fig. 3.9). In each case most gouges were less than 5 m long. However, at Apex no gouges were longer than 15 m, due to the extensive boulder coverage which impeded floe movement, and protected the substrate.

3.5.3.3 Position of Gouges

In Figure 3.10 the greatest number of gouges occurred approximately 150 m from shore. This concentration at this distance occurred at 2 of the lines, Apex and H.B. 1 (Fig. 3.11). Tidal heights at 150 m on both lines were different. At Apex the greatest number of gouges occurred between 2.4 and 3.5 m ALLT and between 5.0 and 7.0 m at HB1. Thus, the tidal influence expected on the locations of maximum ice gouging did not materialize. One would expect an optimal location given the decrease in water depth onshore would strand floes of a given thickness before reaching the high water mark. Conversely, the deeper water at low tide discouraged ice floe gouging when deeper than the floe draft. Instead pack ice was driven onshore at HB1, HB2 and gouged the beach surface to the high water mark. However, the longest gouges were encountered at the midpoint of the gouged area, thus indicating optimal water depth for floe draft conditions, as expected.

3.5.3.4 Orientation of Gouges

The orientation of all the gouges surveyed in Koojesse Inlet are plotted in Figure 3.12. The majority of the gouges were oriented parallel to shore and a fewer number perpendicular to shore. The

Ice Floe Gouges on the Koojesse Flats

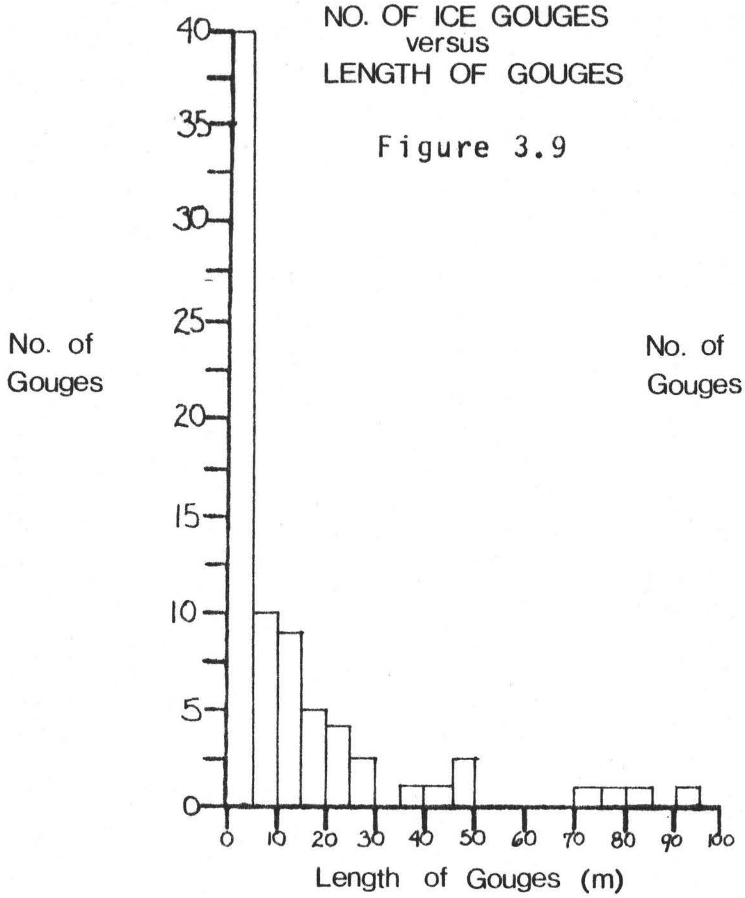


Figure 3.9

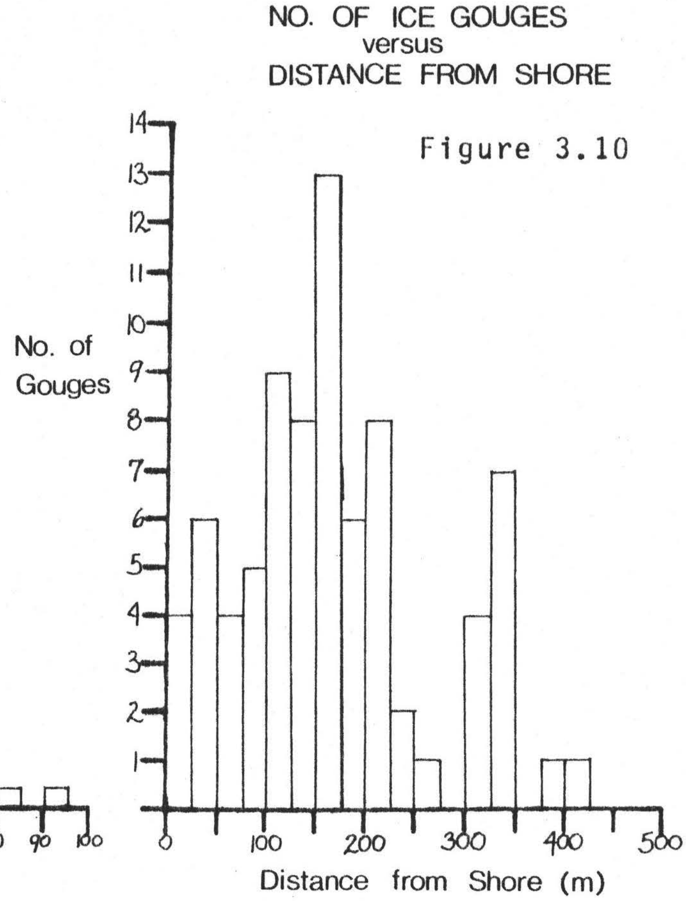


Figure 3.10

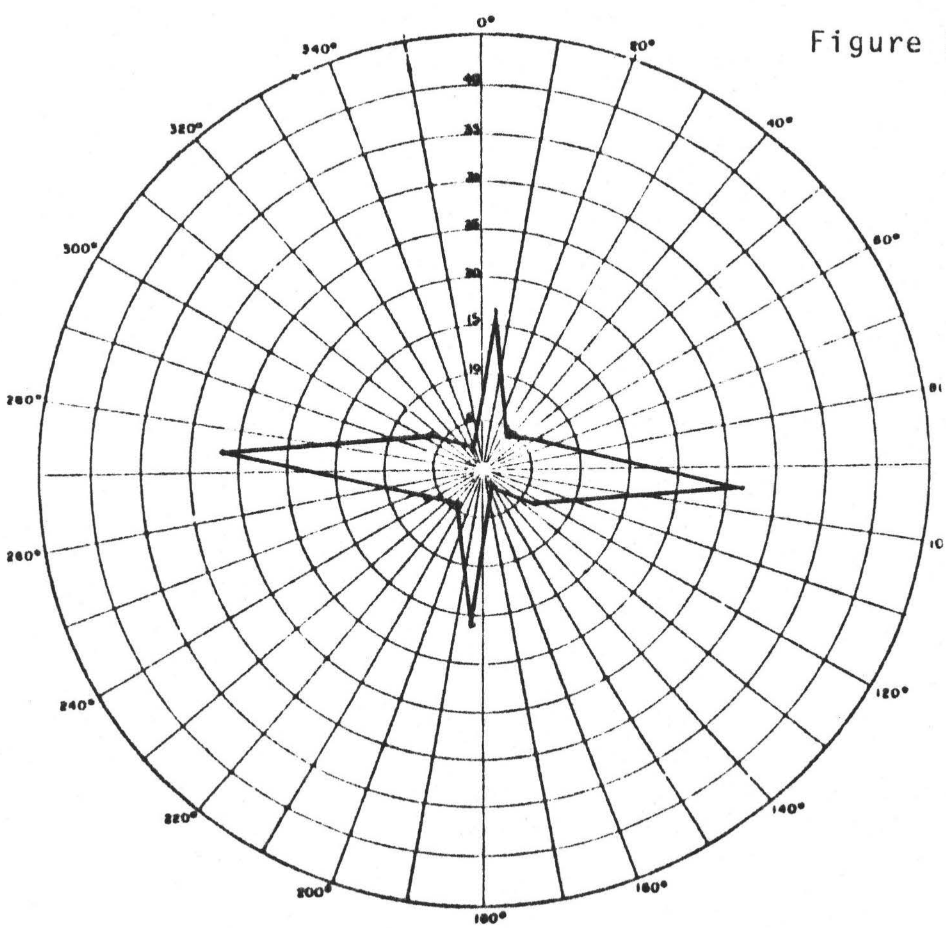
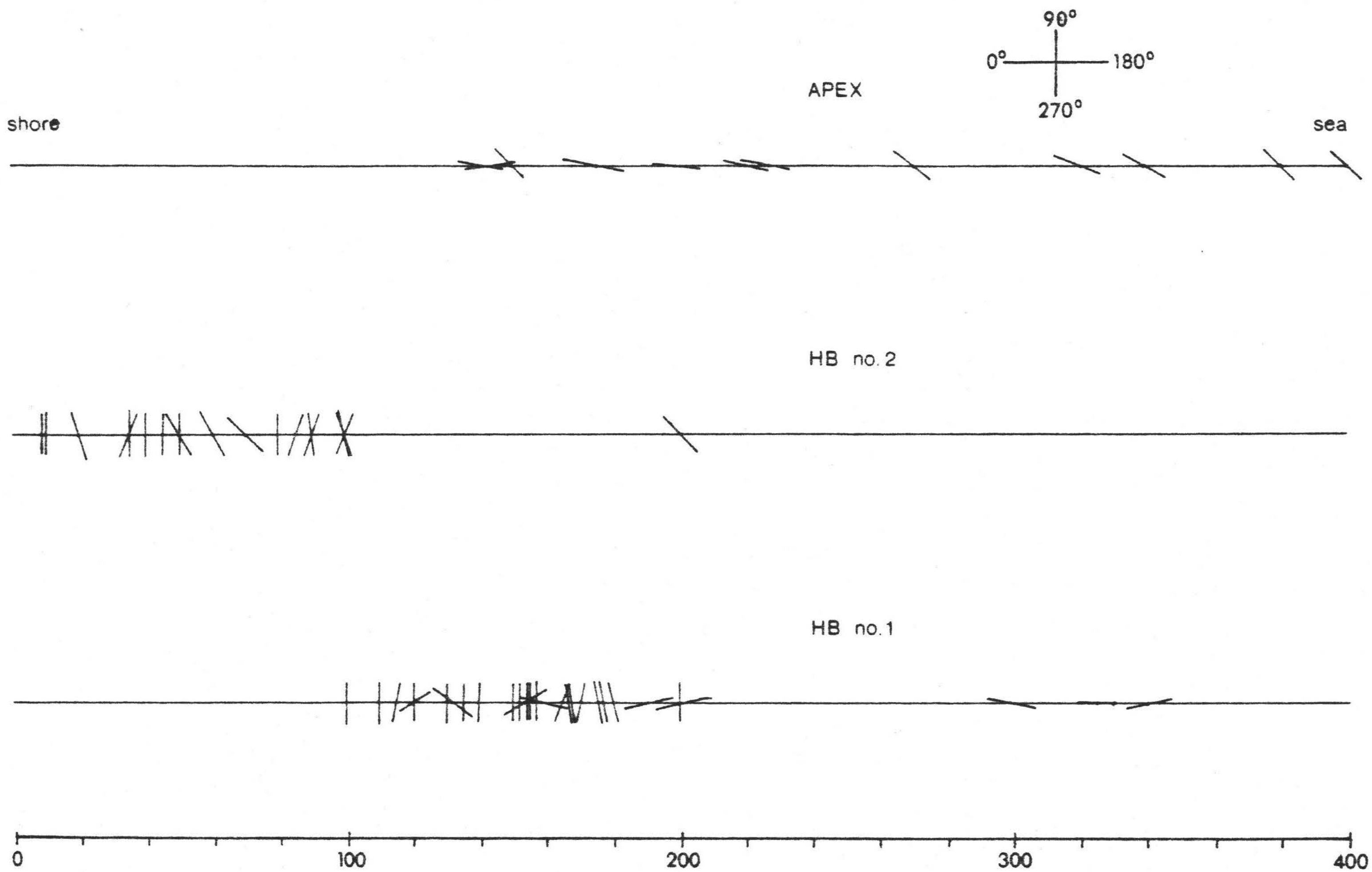


Figure 3.12

NUMBER & ORIENTATION OF ICE GOUGES: 0°–180° perpendicular to shore

Figure 3.11 Orientation of ice gouges down HB#1, HB#2 and Apex Transect.



orientation of ice gouges against distance from shore is plotted for Apex, HB1 and HB2 in Figure 3.11. The orientations at HB1 and HB2 reflected flood and ebb tidal directions. A large vortex of water was set up by the tides which moved perpendicularly onshore and then swung to the east within 200 m of shore. Similarly, at Apex the gouge reflected the tidal currents which moved perpendicularly on and off-shore. Thus, these gouges were largely tidally controlled. Wind action was more important at high and low tidal conditions.

A few ice gouges from boulders entrained in the ice were observed. Ones 20 to 3 metres in length were noted in Koojesse Inlet. Large ones on the tidal flats by Rodgers Island were still visible by August 3, 1981. They were 14.1 m and 91 m in length, oriented perpendicular to shore. Another,20 cm in depth and 40 m in length,reflected tidal oscillations and was V shaped.

3.5.4 Boulder Movement

The movement of boulders by drift ice was documented during 1981 breakup. Although few boulders were observed in transport, comparisons of surveys made in 1980 and 1981 indicated that numerous boulders had been moved during the one year period. This suggests that freezeup is probably as important as ice breakup, especially for small boulders, given that many boulders melted out of the ice before any large scale movement had occurred.

To determine if boulders were transported during the winter, 2 boulder transects were surveyed in 1980, and again in 1981 at STB and Apex. Surveyed boulders were marked by paint and steel rods. The position of the boulders in 1980 and 1981 are given in Tables 3.5, 3.6 and are illustrated in Figures 3.13, 3.14.

At STB 5 boulders moved substantially, four of which had been within 85 m of shore and higher than 5 m ALLT in 1980. Boulder 1 moved 50 m to the west of the line to the high tide position (10 m ALLT) as did a steel rod. Boulder 5 was observed on the ice surface during breakup, it moved 3.6 m in a seaward direction. The remaining transported boulders were not found.

Of the 10 boulders transported at Apex, none were relocated. Six of these boulders had been within 170 m of shore above 3.0 m ALLT. The other 4 had been between 350 and 460 m and below 2.5 m ALLT.

The bulk of the movement occurred close to shore by the ice foot/ fast ice boundary where high energy ice action occurred. As noted earlier the boulders most likely to be incorporated in the ice were small, isolated, angular rocks which were not firmly embedded in the substrate. Boulder 13 at Apex appeared to have been subject to ice push some .8 m shoreward. The significance of the apparent movement of the other boulders is not known.

In Figures 3.13 and 3.14, the boulders close to shore had an apparent build up of sediment on the shoreward side of the boulder and the reverse pattern towards low water. This accumulation probably reflected flood and ebb tidal deposits as opposed to ice push. This will be discussed further in Chapter 4.

At STB measurements taken of the boulders on the ice surface, compared with those taken of the same boulders after ice breakup indicated that the ice moved shoreward transporting these boulders

Table 3.5 STB Transect Boulder Movement, 1980 to 1981

Rock	Movement Yes/No	1980 Distance	1981 from Om	Distance Difference (m)	1980 (m)	1981 (m)	Height Difference (m)	Size of Boulder (m)
1	Yes	2.6			7.32			.3 x .1 x .11
2		5.0	4.3	+ .7	7.171	7.028	+.143	.3 x .2
3		6.2	5.7	+ .5	8.321	8.179	+.142	
4	Yes	7.7			7.061			.4 x .35
5	Yes	21.8	25.4	-3.6	6.774	6.618	+.156	.7 x .4
6		48.8	49.7	- .9	6.174	5.994	+.18	1.0 x .6
7	Yes	83.7						.2 x .2
8		106.7	107.2	- .5	5.324	4.956	+.368	.7 x .6
9		136.6	135.6	+1.0	5.334	4.954	+.38	
10		154.6	153.7	+ .9	5.014	4.644	+.37	1.3 x .6
11		191.7	190.6	+1.1	5.234	4.804	+.43	1.0 x .6
12		203.9	203.5	+ .4	4.724	4.396	+.33	.8 x .5
13		239.5	237.7	+1.8	4.844	4.449	+.395	.8 x .8
14		254.2	252.4	+1.8	4.784	4.404	+.38	1.0 x .9
15		282.1	279.7	+2.4	5.044	4.644	+.4	1.5 x 1.0
16		306.6	304.1	+2.5	4.594	4.189	+.405	.6 x .9 x .3
17	Yes	344.0			4.954			1.2 x .8
18		360	357.5	+2.5	4.834	4.474	+.36	.6 x .7
19		382.8	380.3	+2.5	5.024	4.634	+.3	1.0 x .9 x .5
20		409.6	407.0	+2.6	4.624	4.2	+.424	.6 x .8

Table 3.6 Apex Transect Boulder Movement, 1980 to 1981

Rock	Movement Yes/No	1980 Distance	1981 from 0m	Distance Difference (m)	1980 (m)	1981 (m)	Height Difference (m)	Size of Boulder (m)
1	Yes	4.05			4.217			.35 x .27
2	Yes	20.75			-			.35 x .25
3	Yes	48.5			4.133			1.0 x .5
4	Yes	71.22			-			.7 x .55
5	No	99.7	99.5	+ .2	3.905	3.923	-.01	1.2 x 1.1
6	Yes	122.97			-			.45 x .39
7	No	150.1	148.2	+1.9	3.232	3.443	-.211	.58 x .6
8	Yes	167.77			-			.45 x .29
9	No	202.5	201.4	+1.1	2.920	3.104	-.184	.65 x .4
10	No	236.98	233.6	+3.38	-	2.721		.6 x .45 x .2
11	No	252.2	249.4	+3.1	2.729	2.726	+.003	.5 x .3 x .1
12	No	281.0	277.1	+3.9	-	2.591		.6 x .43 x .1
13	No	302.5	301.7	+ .8	2.610	2.718	-.108	.9 x 1.3 x .16
14	No	323.4	321.3	+2.1	-	2.693		.75 x .5 x .36
15	Yes	354.5			2.633			.65 x .35
16	No	382.4	382.2	+ .2	-	2.332		.4 x .3
17	Yes	405.8	398.8	+7.0	2.484	2.375	+.109	1.3 x .75 x .29
18	Yes	433.25	Not observed					
19	Yes	458.6	Not observed					
20	No	480.0	Observed but not surveyed					

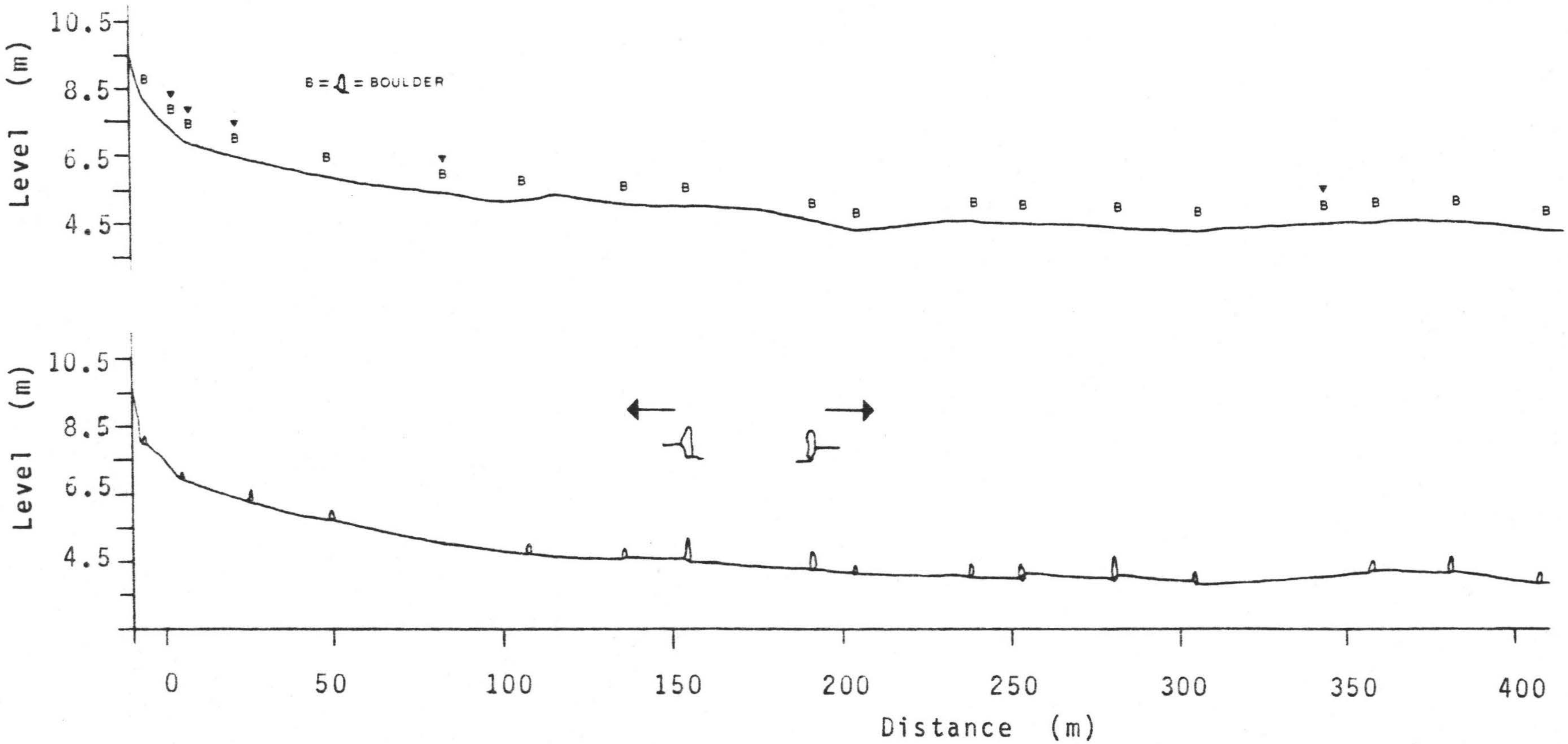


Figure 3.13 Surveyed boulders in 1980 and 1981 at STB transect.

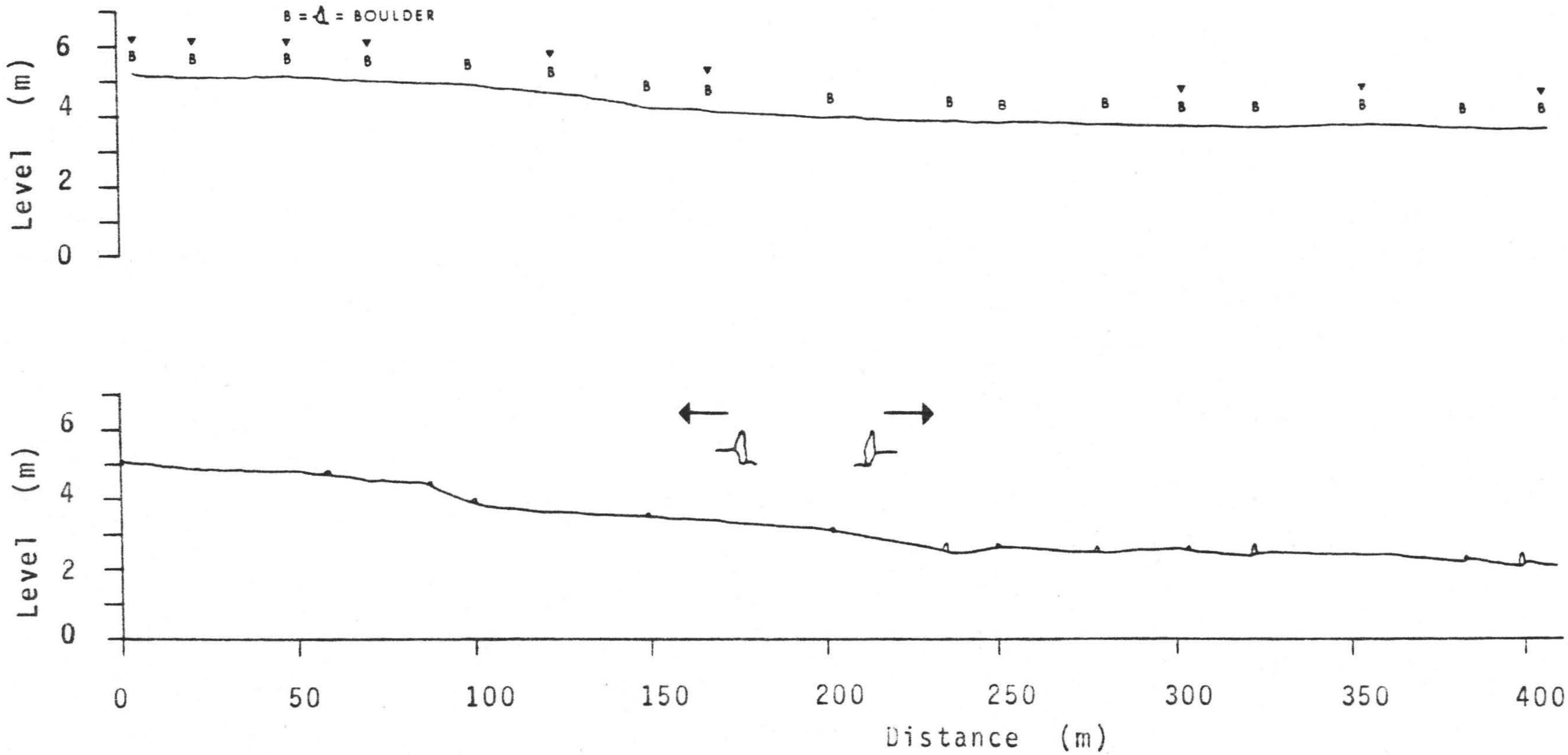


Figure 3.14 Surveyed boulders in 1980 and 1981 at Apex transect.

some 100 m landward. Conversely, boulders surveyed at the head of Frobisher Bay moved on average 30 m seaward. The development of the tidal crack probably accounted for the mass movement of the intertidal fast ice sheet early in breakup.

3.5.5 Boulder Concentration

Measurements were taken of boulders embedded in the ice at STB, and in the ice foot at the causeway. Boulders known to have been moved by the ice were also measured on the previously graded ship runway at the head of Frobisher Bay (Table 3.7). The sizes of the boulders varied widely between the lines. The largest boulders occurred at STB, with a mean volume of 219,000cm^3, followed by the causeway 52,000 cm^3, and the ship runway 3 600 cm^3 This variation reflected the availability of boulders, rather than size selectivity by the ice, although size does play a part in large boulder inclusion.

The boulders were distributed normally around an area of maximum accumulation, their numbers decreased shoreward and seaward of this area. Strong normal score correlation supports the significance of this area of maximum boulder accumulation (Table 3.7). This maximum location occurred at 5.0 m ALLT on both STB (160 m from shore) and the ship runway (650 m from shore). These areas of maximum ice rafted boulder accumulations are similar to the areas of maximum boulder cover on the tidal flats at the ship runway. Ice action plays an important role in the boulder cover exhibited by the tidal flats.

On the ice foot, at the causeway, most of the boulders appeared to come from the causeway itself. They were probably embedded during

Table 3.7 Statistics on Boulders Found in the Ice

Location	Mean Longest Length cm	Mean	Mean Shortest Length cm	Mean Volume cm^3	Correlation	Maximum Conc. of Boulders
STB	95.5	68.1	54.0	219,113	.915	5.0 m ALLT 150-170 m
Boat Runway	22.3	16.9	11.5	3,566.4	.857	5.0 m ALLT 600-700 m
Causeway	60.1	41.3	26.5	52,000	.954	> 10 m ALLT 17.5 to 22.5 m
						10 m ALLT 42.5 to 47.5 m

ice formation. Two major areas of concentration were observed, the first 20 m from shore above 10 m in height and the second at 45 m and 10 m ALLT. This bimodal distribution probably reflected separate ice push events at slightly different tidal levels.

3.6 Ice Influenced Boulder and Sediment Ridges

Sediment and boulder ridges occurred in a variety of locations at the head of Frobisher Bay. The large boulder ridges encountered at the Apex, and Rock transects will be discussed later in greater detail in Chapter 4. The smaller, more ephemeral rock and sediment ridges, will be covered here. Surveys of the ice cover and the underlying ridge morphology at STB and Long Island are shown in Figure 3.15,-16,-17

Boulder ridges appeared to have formed between the ice foot and fast ice boundary. Other boulder ridges at Rodgers Island and at the Rock Transect had ice scour marks and boulder pavements formed from ice push. Boulder ridges at 45^{o} angles along the shore of Peterhead Inlet and Rodgers Island, were lined up perpendicularly to the main fetch length which indicated ice push development. These ridges were probably initially influenced by the position of tidal cracks thus ensuring their continual development. Tidal cracks often developed over the ridge peaks and in the ridge troughs, which allowed movement of the ice, which caused the boulder pavements. Likewise, debris could fall through the leads adding to the available material.

The sediment ridges by STB (Fig. 3.15 ,3.18) and those near the townsite were also caused by the ice. The ice foot and fast ice boundary played an important role in their formation. Sediment slumped off the ice foot and sea ice down the tidal crack leaving

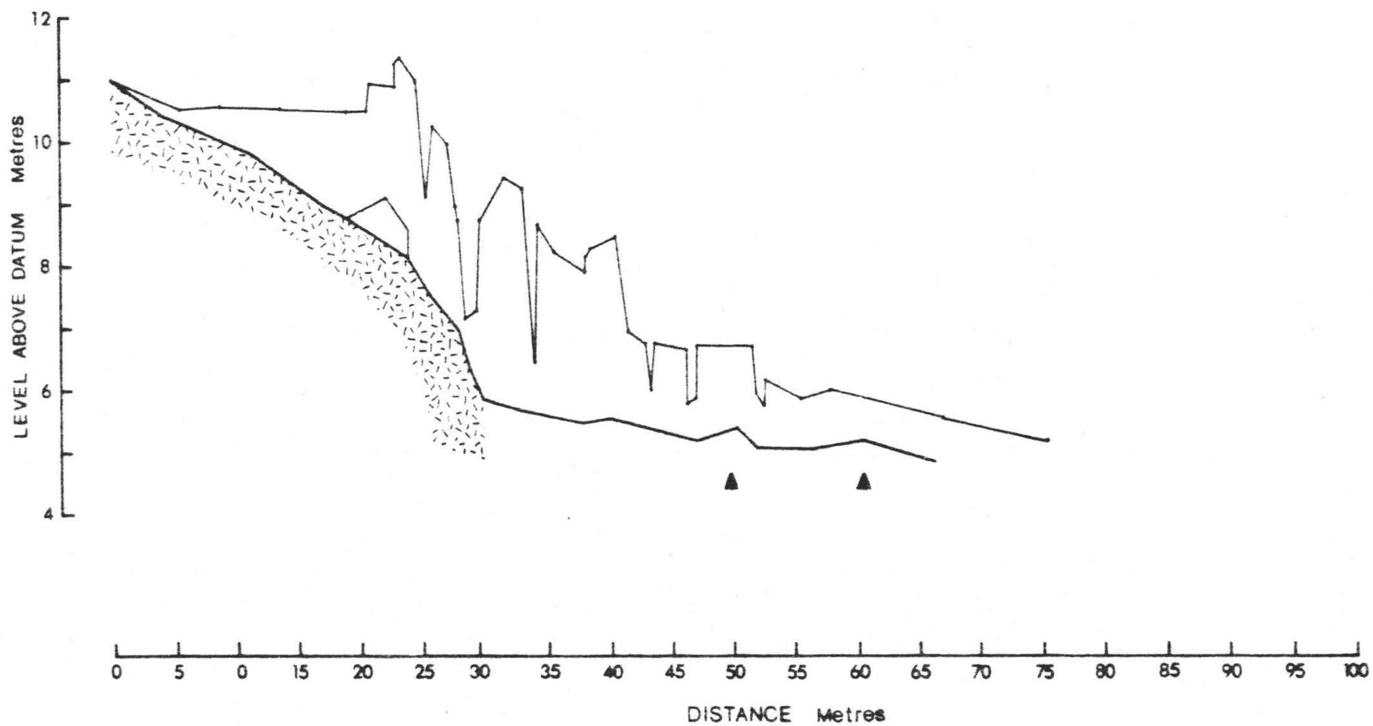


Figure 3. 15 Sediment ridges at STB.

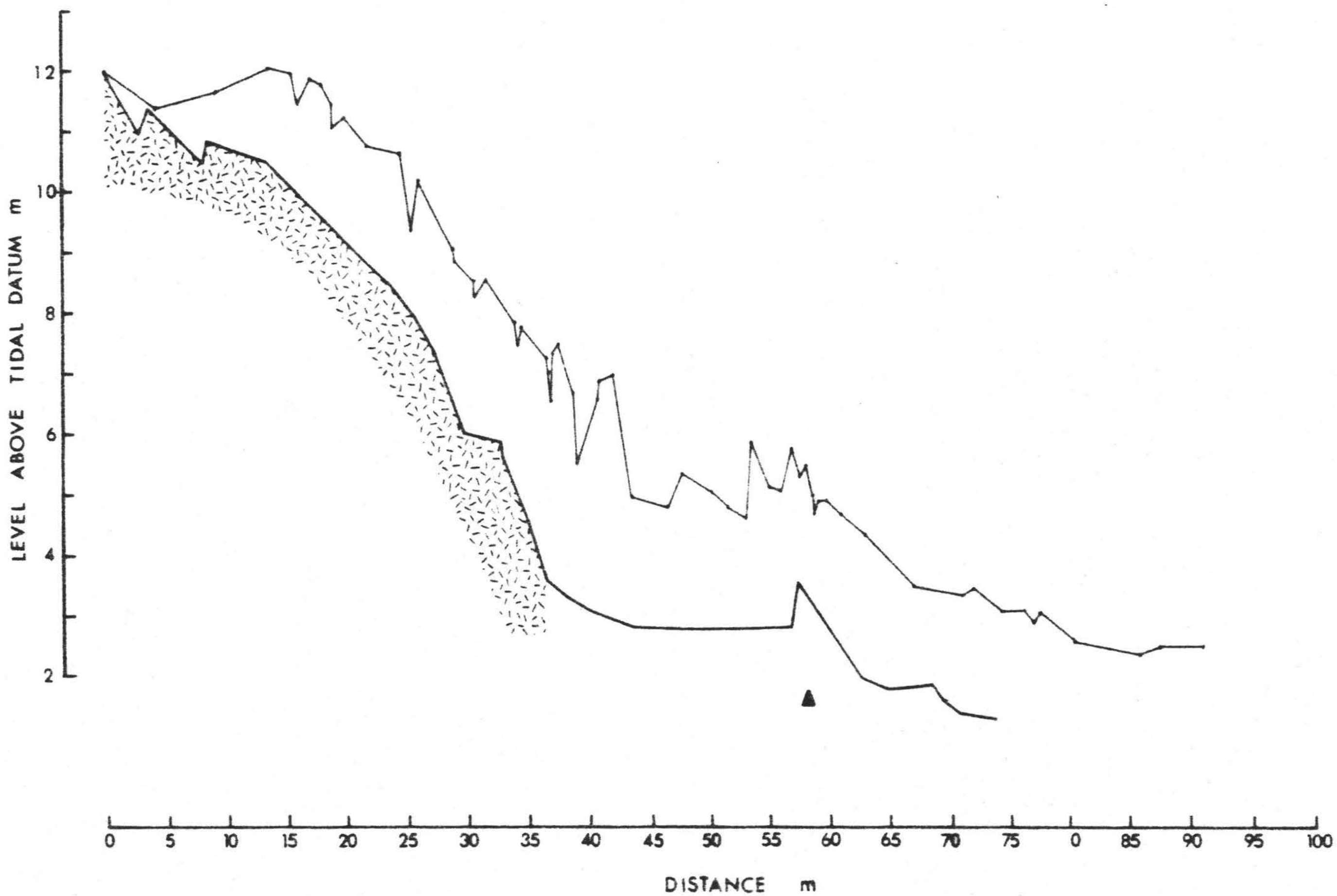


Figure 3.16 Boulder ridge at Long Island.

FIGURE 3.17 Boulder ridge at Long Island at low tide.

FIGURE 3.18 Sediment ridges at STB.

debris in a long chaotic ridge some 75 m in length. Some of the ridges had an ice core, the ice having sediment bands within it, thus indicating it was from intertidal fast ice. Ice floes unable to support the weight of its sediment , sunk to the substrate where it was overridden by other floes and covered with sediments from the melt of the surrounding ice and ice foot. Formation by the ice foot insured the sediment ridge of continued sediment input from stranded floes on and near the ice foot, drift ice push and the debris from the ice foot itself. Depending on the size to which the ridge developed they either disappeared once normal wave processes began such as by the townsite or they remained, as at STB, and were enhanced by wave action.

3.7 Conclusions

Ice plays an important role on biological and physical aspects of the intertidal zone. The major conclusions of this chapter are summarized as follows.

1. The ice foot/fast ice boundary undergoes high energy activity, especially during breakup. It marks the position of ice push boulder ridges on Long Island and the Apex and Rock transects as well as sediment ridges by STB. The ice foot protects the shoreline from extensive erosion during breakup. It also erodes the bedrock and pulls flora and fauna away from the shoreline when it collapses, usually from wave undercutting. The ice foot also acts as a sediment and boulder trap by stranding ice floes on its surface. The fast ice often creates ice micro-relief in the upper flat areas (Chapter 4).

2. Sea water salinity is greatly reduced during breakup. This

relatively fresh water affects the distribution of flora and fauna especially during ice ablation. Fresh water input from ice later in the season can also have drastic effects by eroding the thawed surface and killing infaunal species.

3. Boulders up to 1.0 m in diameter were regularly transported by ice during the winter. Results suggest that the movement of boulders during freezeup may be as important as during breakup. Boulders were most likely to be incorporated in the ice if they were small, isolated and lying on top of the substrate. Most of the transported boulders were deposited around 5.0 m ALLT.

4. Sediments incorporated in the ice mainly came from the tidal flat itself. At the head of the bay, sediments 8.17 cm in thickness were contained in the ice. At this thickness, 22,500,000 kg of sediment was incorporated in the ice over the low gradient tidal flats close to shore. The erosion, transportation and deposition of this material creates a large turnover in sediments. This mixing destroys the normal wave and current created sediment zonation more typical of the ice free period. This mixing also affects the faunal zonation.

5. Drift ice moves by wind, wave and tidal action. It transports sediments and boulders to new locations and helps create ice push ridges and boulder pavements on the flats. Drift ice is also erosive and exposes the underlying clay and mixes the active layer by gouging the tidal bed. It also leaves ice imprints and melt water dimples in fine substrates. Most of these features are short lived once normal wave action resumes.

CHAPTER 4

PROCESSES AND GEOMORPHOLOGY IN THE INTERTIDAL ZONE

4.1 Introduction

This chapter is in 2 parts. The first considers the role of the 2 major processes operating on the Frobisher Bay tidal flats - tidal and wave action. The second part documents in some detail the morphological and sedimentological characteristics of the 4 transects. The emphasis throughout is on the characterization of tidal zonation. First there is a brief review of tidal flat literature relating to the above subjects. The methodology and instrumentation employed is described in Appendix 2.

4.2 Literature Review

4.2.1 Temperate Tidal Flats

Van Straaten and Kuenen (1957), Evans (1965) and Reineck (1975) have made significant contributions towards knowledge of temperate tidal flat zonation and the effectiveness of wave and current action on the resultant zonation (See Section 1.5). Largely through their efforts, temperate tidal flats are recognized by 4 characteristic features:

1. landward fining of sediments;
2. changes in the type and amount of bedding structures over their surfaces;
3. floral and faunal changes down the flat;

4. presence of channels and gullies which usually decrease in size in a landward direction, (Hayes and Kana 1977).

The landward fining of sediments has been explained by vertical sedimentation which occurs on the higher parts of the flats. Scour and settling lag theories (Van Straaten and Kuenen 1957) and the time-velocity assymetry model (Postma 1961) are explanations for vertical sedimentation.

Storm action (Van Straaten 1952, McCave 1970, Hardie 1975) and wave action (Hayes and Kana 1977) play an important role in bedform development. Still other flats are dominated by aeolian transport of fines, which appears to become more important as vegetation develops on the surface (Miller 1975, Frey and Basan 1978).

A significant amount of sedimentation occurs from meandering tidal channels. This lateral sedimentation has been studied by Van Straaten and Kuenen (1957), Van Straaten (1961) and Ahnert (1963). The absence of meandering streams in Arctic and Subarctic areas was explained by high rebound rates by Ahnert (1963). Yet flats studied along James Bay are greatly influenced by these channels, despite the Subarctic location and high rebound rates (Martini et al 1979).

Some temperate flats are influenced by ice action. Ice mixes the upper layers of sediment, gouges the surface, and transports and deposits sediments including boulders on temperate tidal flats (Knight and Dalrymple 1976, Thompson 1977, Dionne 1968, 1969, 1974b). A more complete discussion on ice is given in Chapter 2.

4.2.2 Subarctic Tidal Flat Studies

Dionne (1972) noted that no real distinction could be drawn between Arctic and temperate beaches. The only difference being in degree. Both have similar characteristics except that in northern regions, frost and ice inhibited the action of normal shore processes like wave, current and tidal action, to a greater extent. Thompson (1977) noted that the longer the ice free period, the fewer ice formed features survived. Also ice effectiveness is governed as much by ice thickness and strength as by wind and current action (Croasdale, Metge and Verity 1978). Thus, different latitudes will be affected to varying extents by glaciel processes.

There have been numerous studies which document the geomorphological characteristics of the coastal zone in the Beaufort Sea (Rex 1964, Beaufort Sea Project, Department of the Environment 1975, Reimnitz, Toimil, Barnes and Barnes 1978) and in the eastern Arctic (Owens and McCann, 1970, McCann and Carlisle 1972, McCann 1973, McCann and Taylor 1975, Owens 1976, Owens and Harper 1977, Taylor 1978, 1980).

There has been less attention spent on tidal flat morphology. Most Subarctic tidal flat literature has concentrated first on biological aspects, and secondly on ice effects as opposed to geomorphology and process studies. Biological projects which noted geomorphology are covered in Chapters 5 and 6. Thorson (1933), Ellis (1955, 1966), Ellis and Wilce (1961) and Den Beste and McCart (1978) are biological studies which note the surficial characteristics of coastal zones. Tidal flat projects noted in Chapter 3, on the interaction of ice on tidal flats include Dionne (1968, 1972), Rosen (1979, 1980) and

Lauriol and Gray (1980).

In a more comprehensive geomorphological treatment of tidal flats, publications by Martini et al (1979, 1980), Aitken and Gilbert (1981) and McCann, Dale and Hale (1981) are most notable. Small scale sedimentary structures were preserved on James Bay tidal flats (Martini et al 1979, 1980). These included ripples, straight, sinuous crested or lunate in form across the entire width of the flats. They exhibited flood dominance except on the lower flats. Mud cracks, horizontal bedding, and lenticular and flaser bedding were preserved in the silt and clayey silt of the middle flats. Reworked ice-rafted deposits and surficial ice gouges were also recognized.

In Pangnirtung fiord, sediment and boulder distributions were analysed (Aitken and Gilbert 1981). Boulders concentrated in boulder garlands and ridges in the low tidal area of the flats. Some shoreward fining of sediments was observed in some locales and the reverse in others, probably the result of ice action. Wave-shaped sand bars were observed migrating shoreward from tidal and wave action. Scour pits and sediment trails from current action were also observed across the tidal flat.

General sedimentological characteristics and boulder accumulations in Koojesse Inlet were presented by McCann et al 1981. This information is expanded in this chapter.

4.3 Effective Processes in the Intertidal Zone

Ice, tidal and wave action are the three dominant processes acting on the Frobisher Bay tidal flats. Ice action and its effects were examined in Chapter 3. The contribution of tidal and wave action to intertidal morphology is the subject of this section. It has been subdivided into three parts, tidal exposure, tidal waters and wave action. For tidal waters, changes in current velocities, temperatures and salinities during the tidal cycle will be examined.

4.3.1 Tidal Exposure

The Frobisher Bay exposure curve from July and August 1981 is shown in Figure 4.1. No appreciable differences existed between exposure curves drawn separately for July and August 1981. However, when exposure information is applied to the irregular surface of the 4 transects, zonation related trends appear (Fig. 4.2, 4.3., 4.4, 4.5). Tidal exposure and current velocity information was averaged for the months of July and August 1981 and shown in Tables 4.1, 4.2, 4.3, 4.4.

A number of general trends became apparent in the tidal analysis. In Figure 4.6 the number of tidal exposures are plotted against tidal height in July and August 1981. Prominent breaks in slope occurred at 4.25 m ALLT and at 7.5 in July and 7.75 m in August. Sixty exposures per month occurred between these heights. Below 4.25 m ALLT the number of exposures decreased abruptly and above 7.5 m in July and 7.75 m in August, total exposure time increased but the number of times the water advanced and retreated over the area decreased.

Similarly, when the log of maximum duration of exposure and inundation in hours was plotted against tidal height, prominent breaks again occurred at 4.25 m and 7.75 m ALLT (Fig. 4.7). Additional breaks in slope occur towards the upper and lower limits of the tidal range at 3.75 m ALLT on the inundation line and 8.5 m in July and 8.0 m in

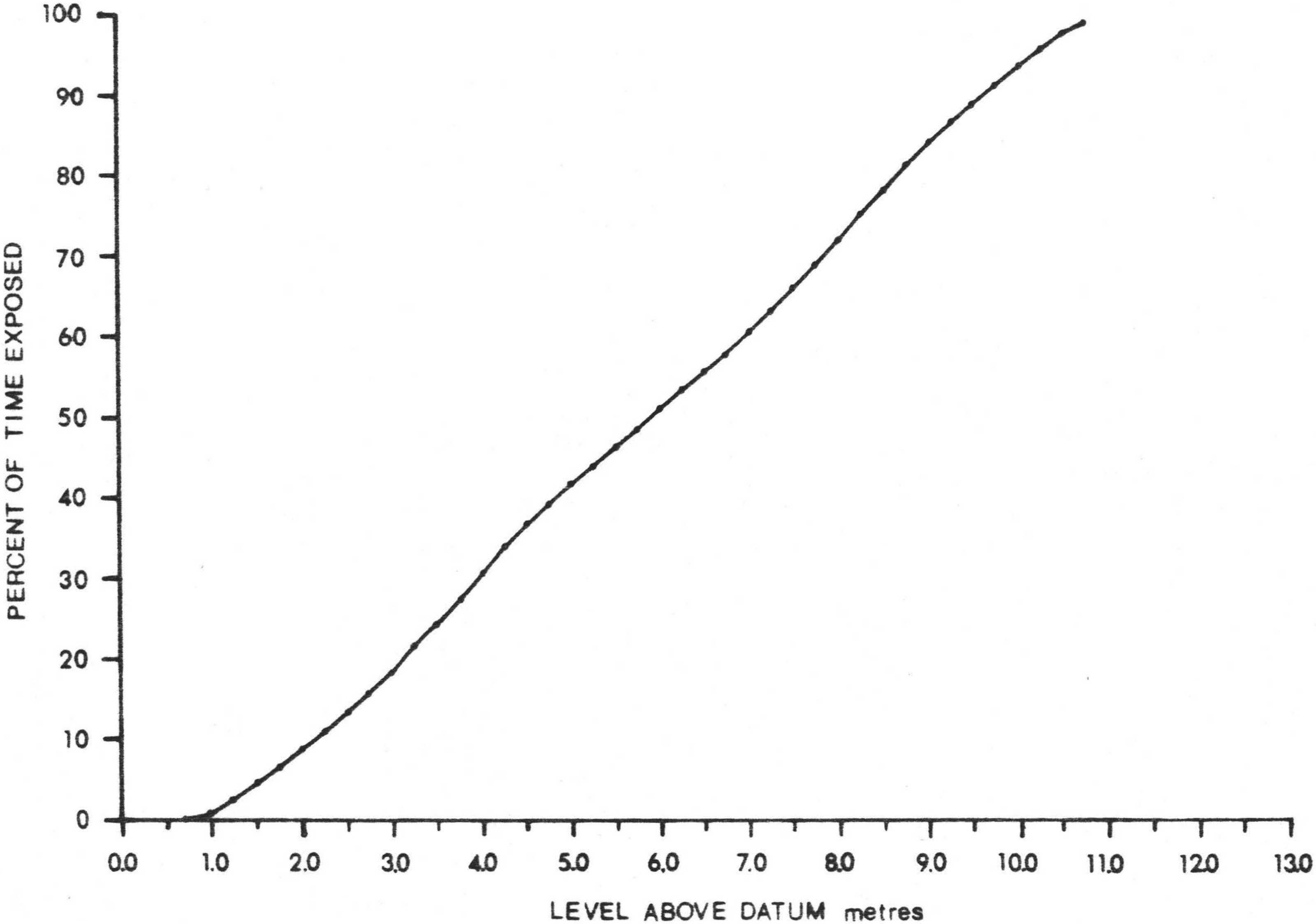


Figure 4.1 Frobisher Bay Exposure Curve for July and August 1981.

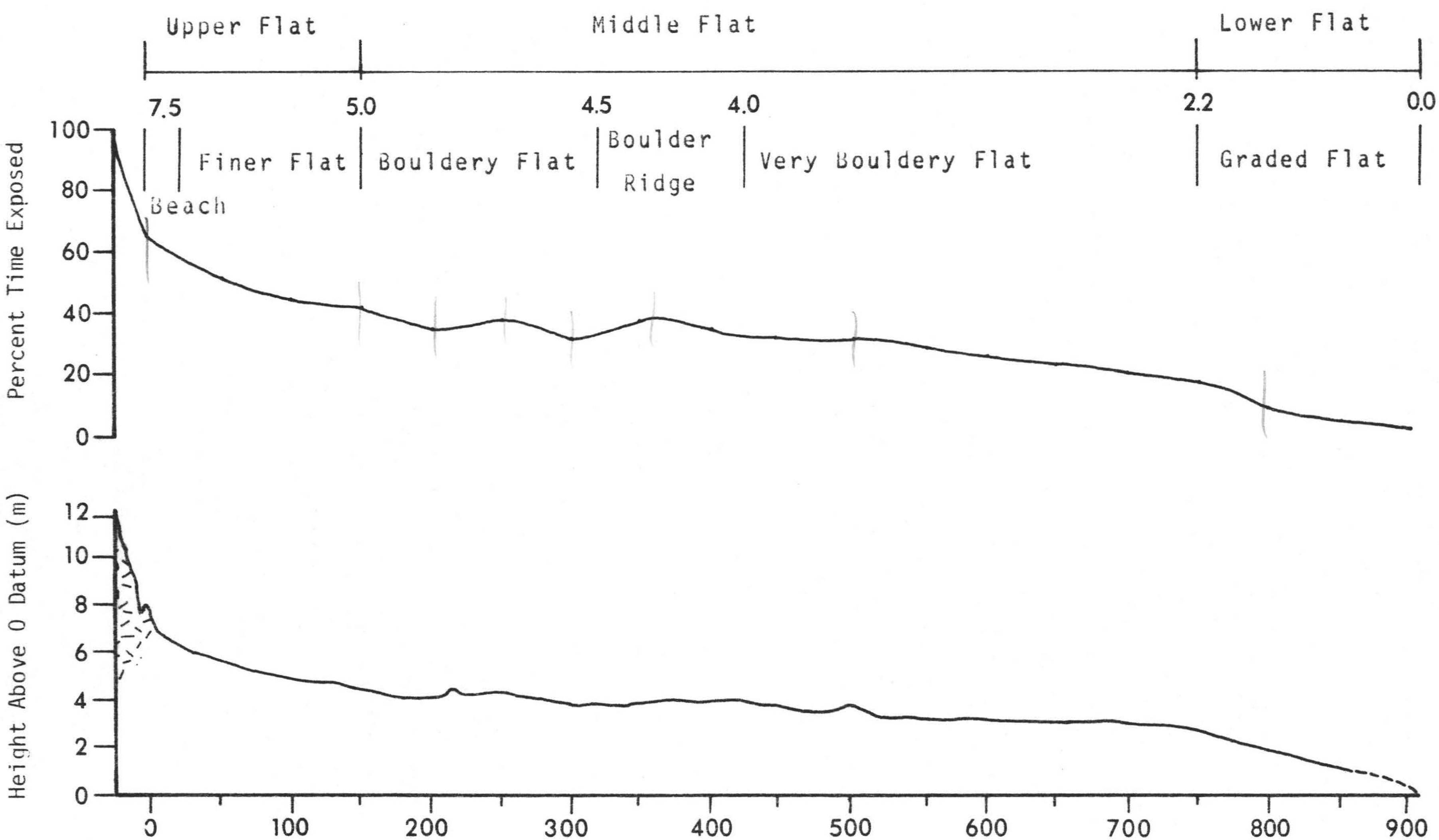


Figure 4.2 STB Transect Profile and 1981 Exposure Curve.

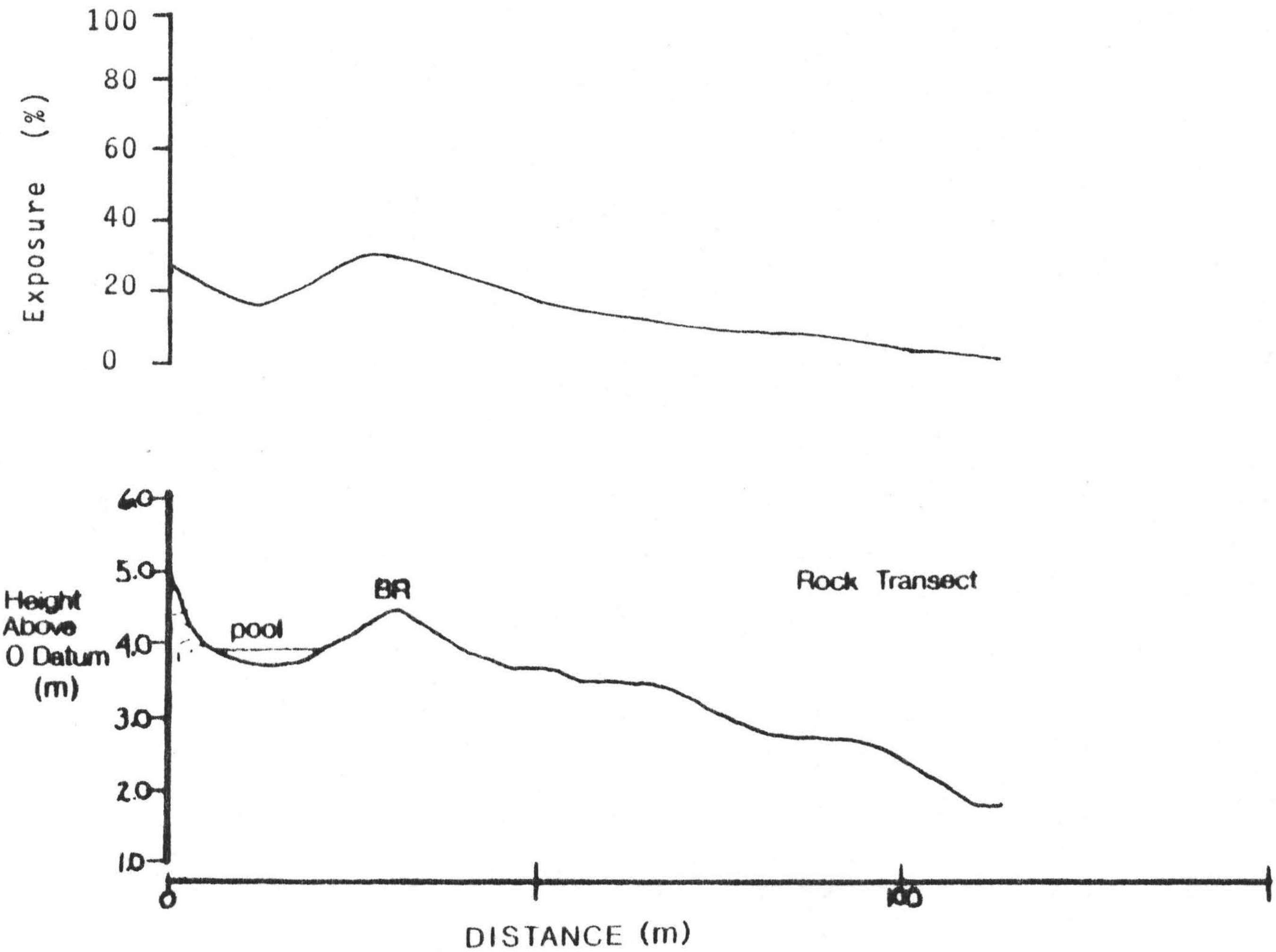


Figure 4.3 Apex transect profile and 1981 exposure curve.

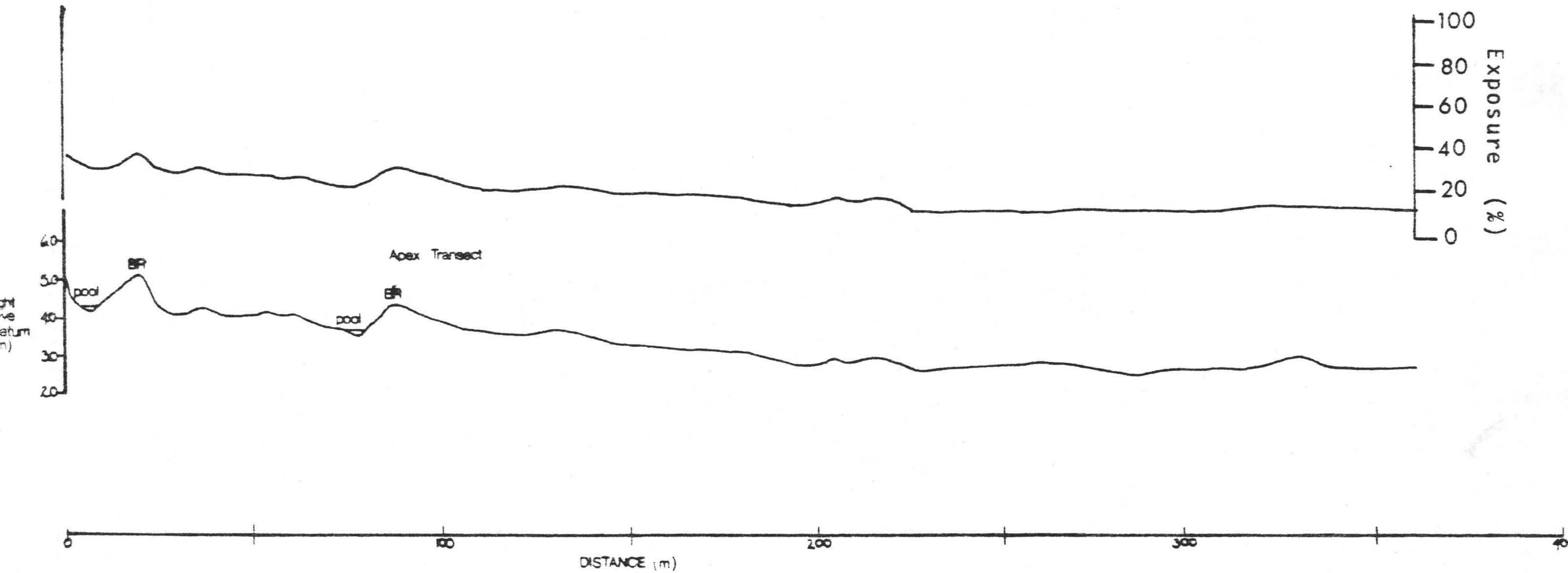


Figure 4.4 Rock transect profile and 1981 exposure curve.

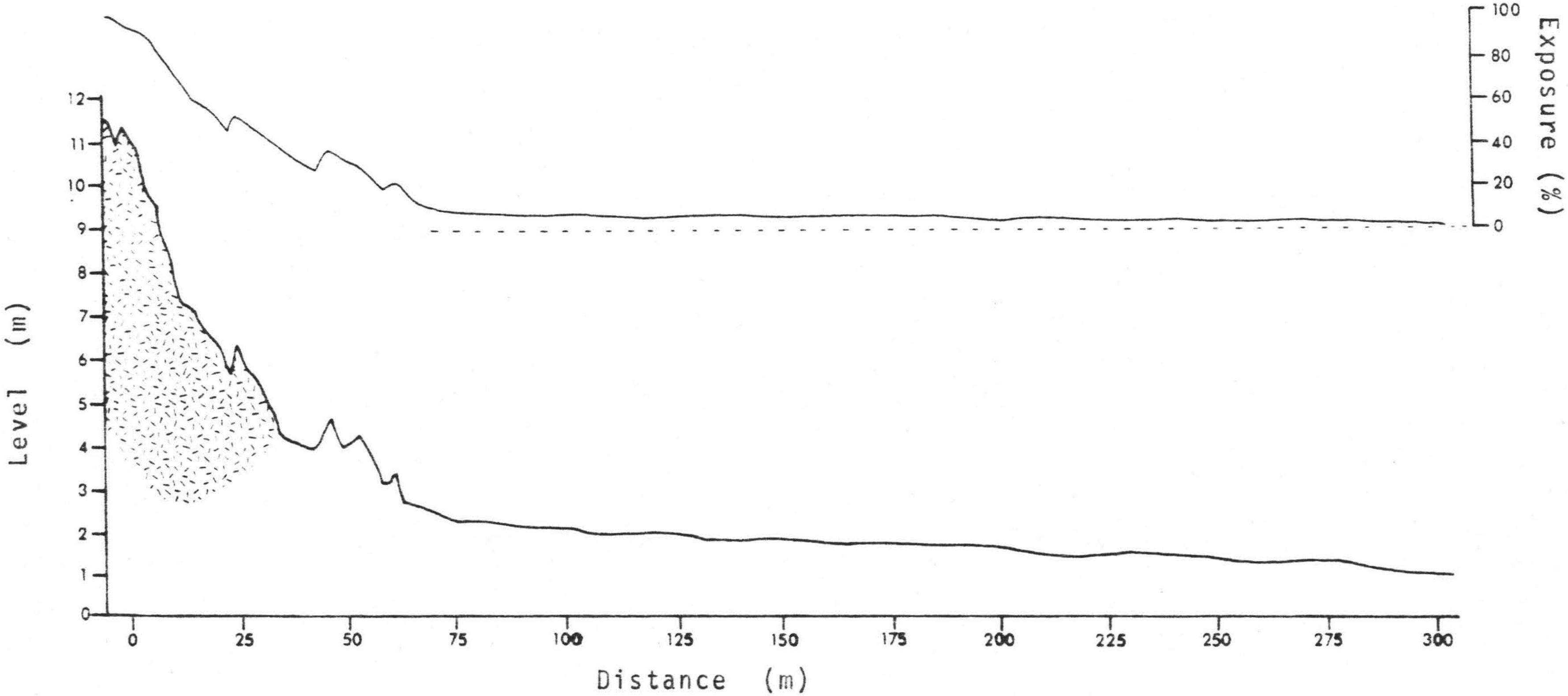


Figure 4.5 Rodgers Island profile and 1981 exposure curve.

Table 4.1 STB Transect, tidal exposures and current velocities, July and August 1981

Position (m)	Tidal Ht. ALLT (m)	Total No. of Exposures	Total Time Exposed (Hrs.)	% Total Time Exposed	Average duration of Exposure	Maximum duration of Exposure	Average Flood Velocity (m/sec)	Maximum Flood Velocity (m/sec)	Average Ebb Velocity (m/sec)	Maximum Ebb Velocity (m/sec)	Slope
0	7.5	120	972.45	65.79	8.10	9.94	.031	.04	.03	.042	.032
50	5.9	120	756.78	51.2	6.31	6.64	.075	.1	.07	.102	.014
100	5.2	120	654.75	44.3	5.46	5.86	.21	.27	.20	.284	.005
150	5.0	120	619.87	41.93	5.17	5.66	.072	.096	.071	.100	.014
200	4.3	120	507.38	34.33	4.23	5.04	.46	.66	.45	.688	.002
250	4.4	120	546.81	37.0	4.56	5.26	.24	.33	.23	.349	.004
300	4.1	118	462.51	31.3	3.92	4.84	.074	.11	.072	.113	.012
350	4.5	120	546.81	37.0	4.56	5.26	.10	.13	.09	.138	.010
400	4.2	120	507.38	34.33	4.23	5.04	.92	1.32	.90	1.38	.001
450	4.1	118	462.51	31.3	3.92	4.84	.89	1.30	.872	1.35	.001
500	4.1	118	462.51	31.3	3.92	4.84	.08	.12	.079	.123	.011
550	3.8	115	415.55	28.11	3.62	4.62	.21	.32	.209	.331	.004
600	3.6	107	366.48	24.8	3.42	4.41	.17	.25	.166	.258	.005

Table 4.2 Apex Transect, tidal exposures and current velocities, July and August 1981

Position (m)	Tidal Ht. ALLT (m)	Total No. of Exposures	Total Time Exposed (Hrs.)	% Total Time Exposed	Average duration of Exposure	Maximum duration of Exposure	Average Flood Velocity (m/sec)	Maximum Flood Velocity (m/sec)	Average Ebb Velocity (m/sec)	Maximum Ebb Velocity (m/sec)	Slope
0	5.1	120	619.87	41.9	5.17	5.7	.012	.016	.011	.017	.083
7	4.2	120	507.38	34.3	4.23	5.04					
20	5.5	120	689.03	46.6	5.74	6.07					
30	4.1	118	462.51	31.3	3.92	4.84					
50	4.1	118	462.51	31.3	3.92	4.84	.178	.259	.174	.270	.005
75	3.6	107	366.5	24.8	3.43	4.41					
100	3.9 4.4	118	462.51	31.3	3.92	4.84	.069	.0998	.067	.104	.013
150	3.2	103	323.13	21.9	3.14	4.19	.135	.201	.131	.209	.006
200	2.9	95	275.4	18.6	2.91	3.96	.195	.292	.190	.302	.004
250	2.7	87	229.8	15.5	2.65	3.73	.371	.561	.360	.581	.002
300	2.6	78	188.95	12.79	2.43	3.48	1.41	2.14	1.36	2.21	-.0005
350	2.6	78	188.94	12.79	2.43	3.48	.235	.356	.227	.369	.003
400	2.5	78	188.95	12.79	2.43	3.48					

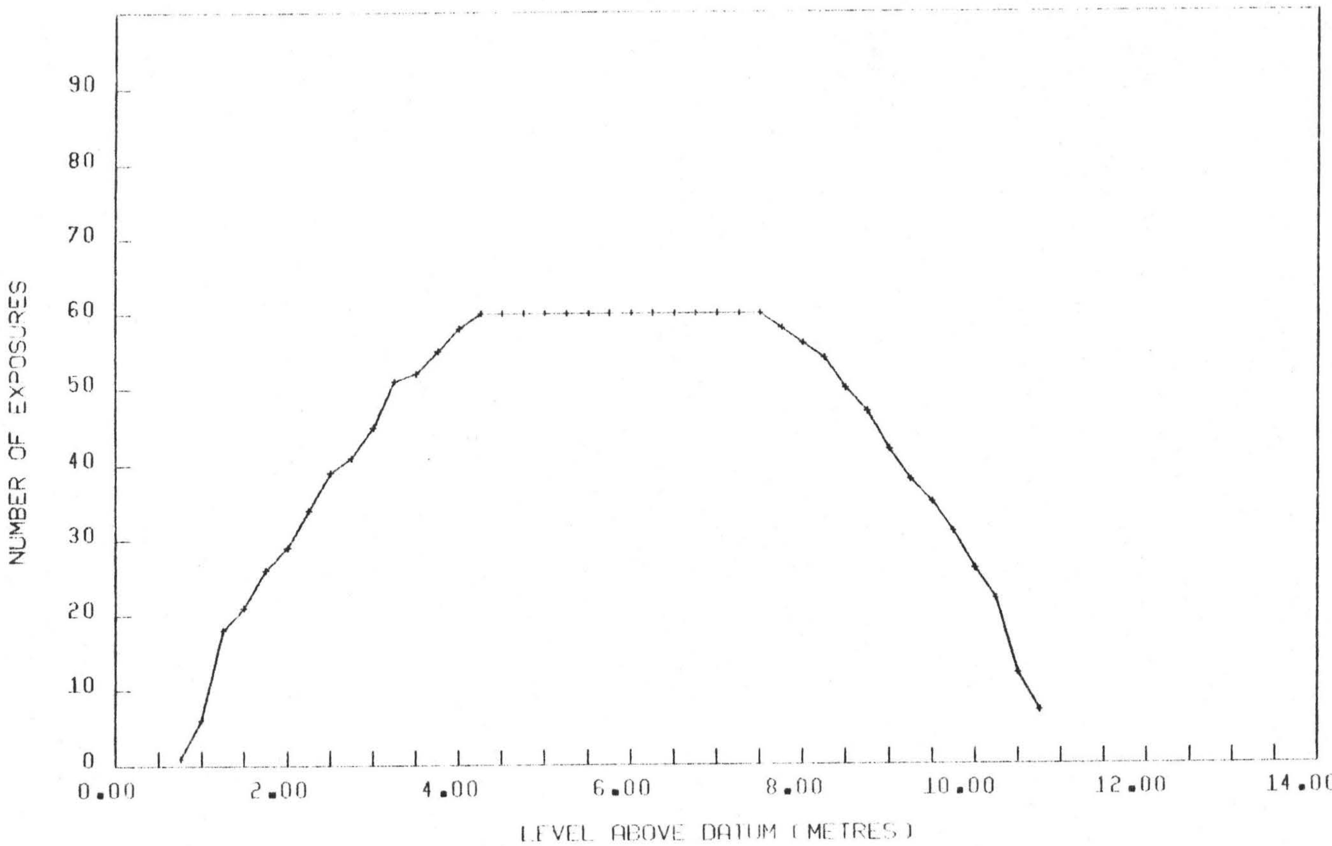
Table 4.3 Rock Transect, tidal exposures and current velocities, July and August 1981

Position (m)	Tidal Ht. ALLT (m)	Total No. of Exposures	Total Time Exposed (Hrs.)	% Total Time Exposed	Average duration of Exposure	Maximum duration of Exposure	Average Flood Velocity (m/sec)	Maximum Flood Velocity (m/sec)	Average Ebb Velocity (m/sec)	Maximum Ebb Velocity (m/sec)	Slope
0	3.5	107	366.5	24.8	3.43	4.41	.026	.038	.025	.039	.033
12.5	3.1	95	275.4	18.6	2.91	3.96	.016	.024	.016	.024	.048
25	3.7	115	415.6	28.1	3.62	4.62	.030	.044	.029	.046	.029
50	3.0	95	275.4	18.6	2.91	3.96	.025	.038	.024	.039	.031
75	2.2	67	149.62	10.1	2.23	3.22	.021	.032	.020	.033	.032
100	1.4	33	51.57	3.5	1.58	2.3					

Table 4.4 Rodgers Island Transect, tidal exposures and current velocities, July and August 1981

Position (m)	Tidal Ht. ALLT (m)	Total No. of Exposures	Total Time Exposed (Hrs.)	% Total Time Exposed	Average duration of Exposure	Maximum duration of Exposure	Average Flood Velocity (m/sec)	Maximum Flood Velocity (m/sec)	Average Ebb Velocity (m/sec)	Maximum Ebb Velocity (m/sec)	Slope
0	11.0										.205
	10.75	12	1467.3	99.3	125.8	502.1	.0017	.002	.0015	.0023	.205
25	5.0	120	756.78	51.2	6.3	6.6	.013	.018	.0128	.018	.079
50	3.9	118	462.51	31.3	3.92	4.8	.0129	.0188	.0126	.0196	.069
75	2.2	67	149.62	10.1	2.23	3.2	.084	.126	.081	.130	.008
100	2.0	56	113.25	7.7	2.02	2.95	.105	.157	.191	.162	.006
125	1.9	56	113.25	7.7	2.02	29.5	.126	.188	.121	.194	.005
150	1.7	46	82.13	5.6	1.1	2.7	.144	.215	.137	.22	.004
175	1.6	33	51.57	3.5	1.58	2.3	.133	.192	.125	.198	.004
200	1.5	33	51.57	3.5	1.58	2.3	.265	.385	.25	.396	.002
225	1.5	33	51.57	3.5	1.58	2.3	.976	.110	.071	.113	.007
250	1.3	27	29.59	2.0	1.13	1.94	4.86	8.10	4.62	8.44	.00008
275	1.3	27	29.59	2.0	1.13	1.94	.032	.055	.031	.056	.012
300	1.0	10	9.82	.67	1.01	1.47					

Figure 4.6 The number of exposures occurring at various tidal heights in July and August 1981 in Frobisher Bay.



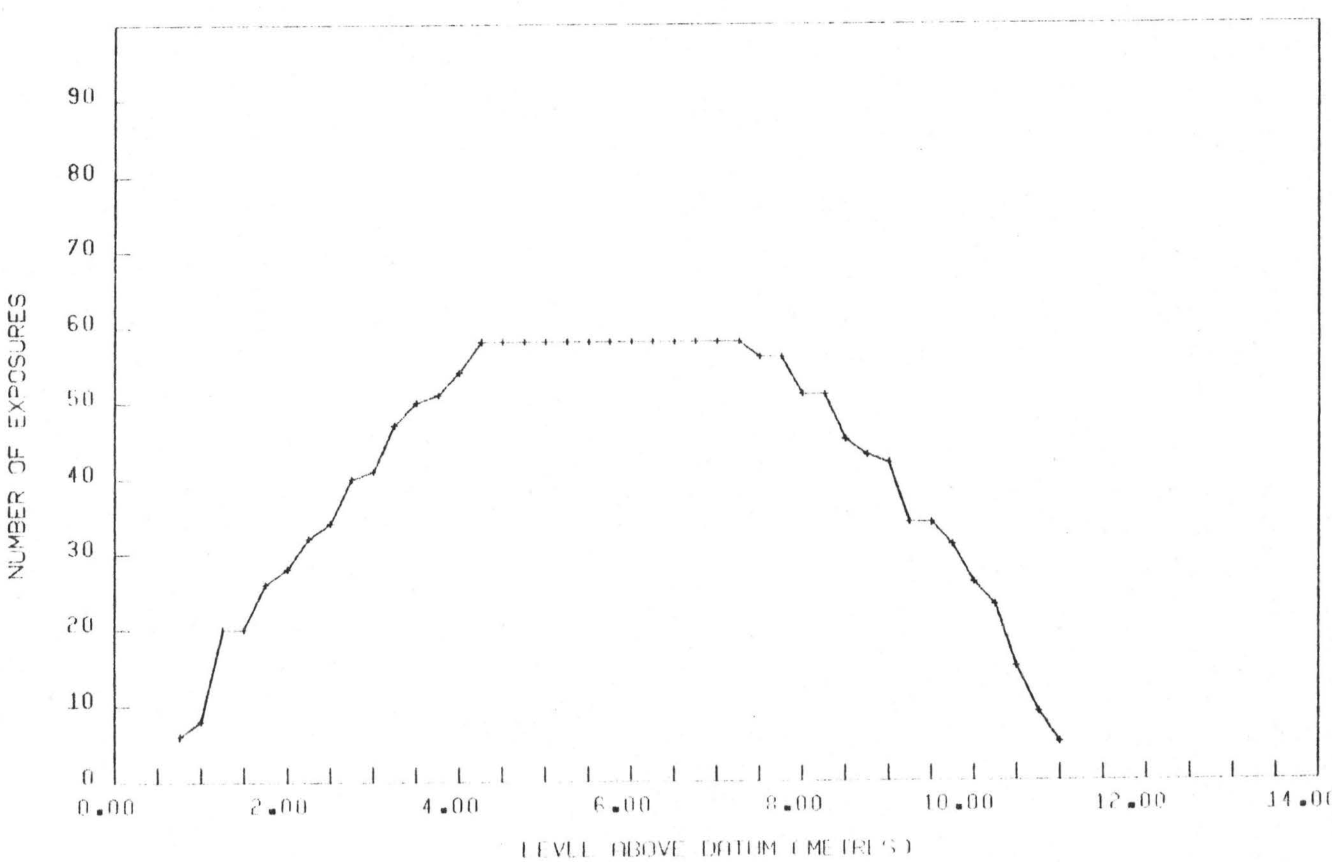
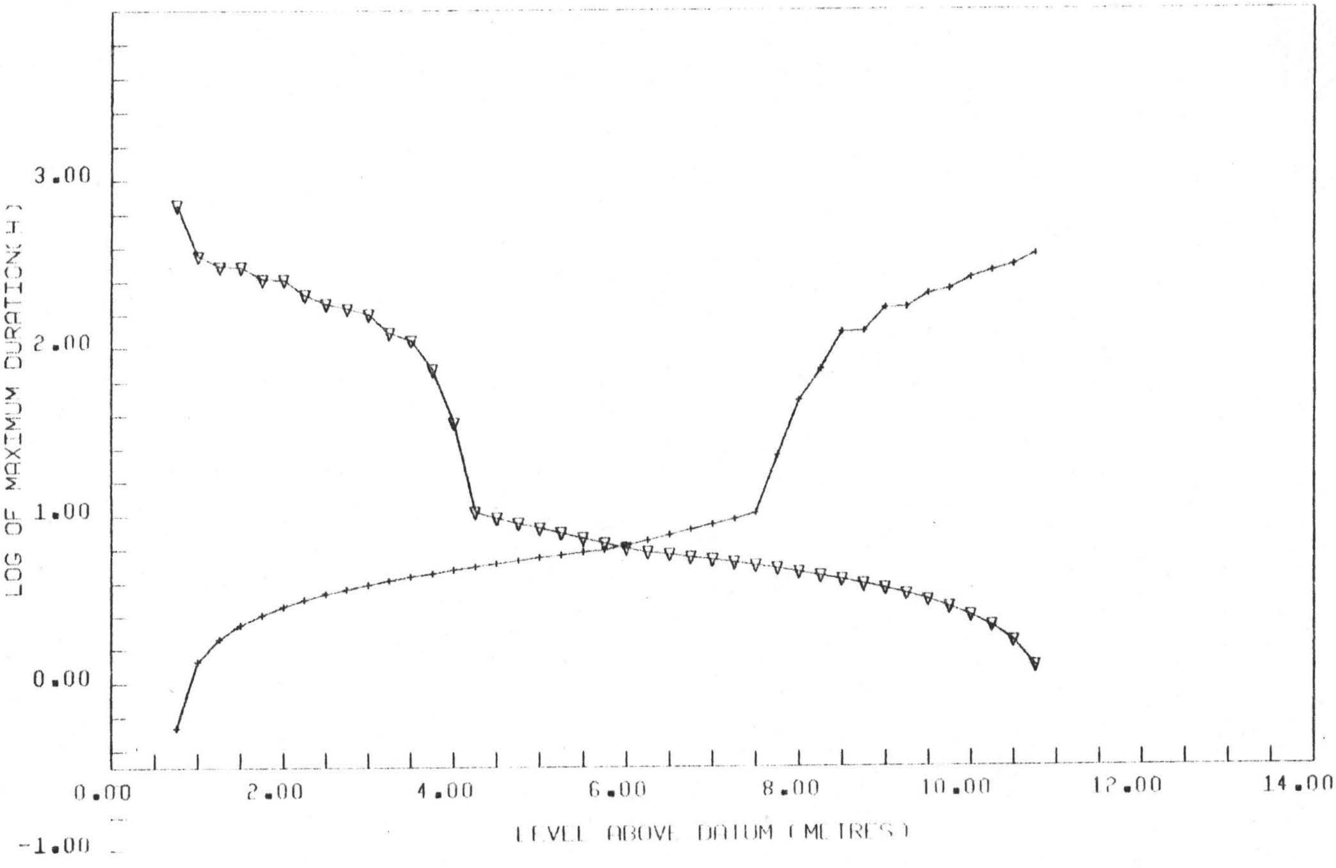
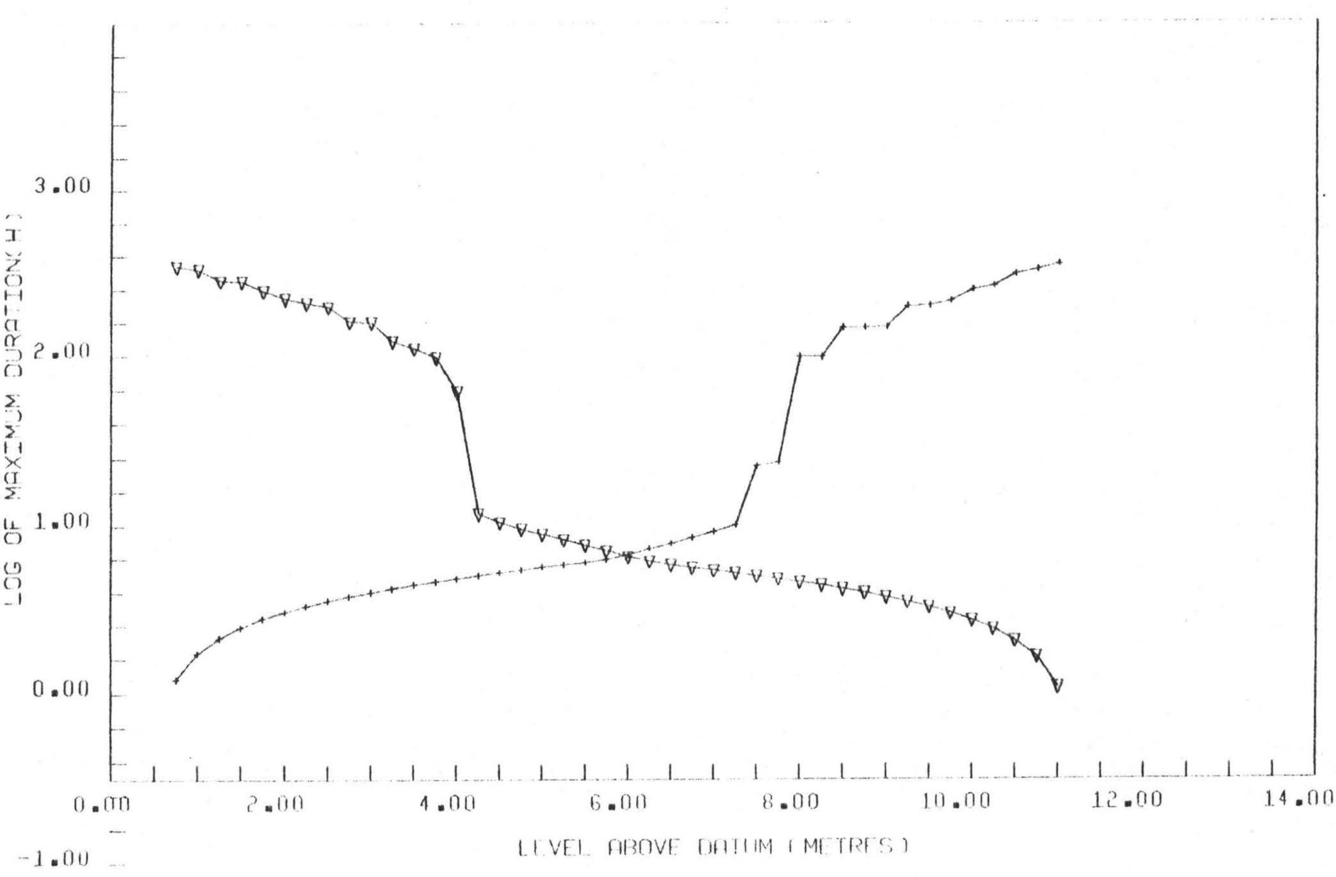


Figure 4.7 The log of maximum duration of exposure and inundation in hours versus tidal height in July and August 1981.





August on the exposure line. These slope changes reflect the boundary between those tidal heights which undergo regular tidal oscillations and the high and low tidal heights which are affected by the variations in tidal range. Differences between the months reflect minor tidal variations which occur.

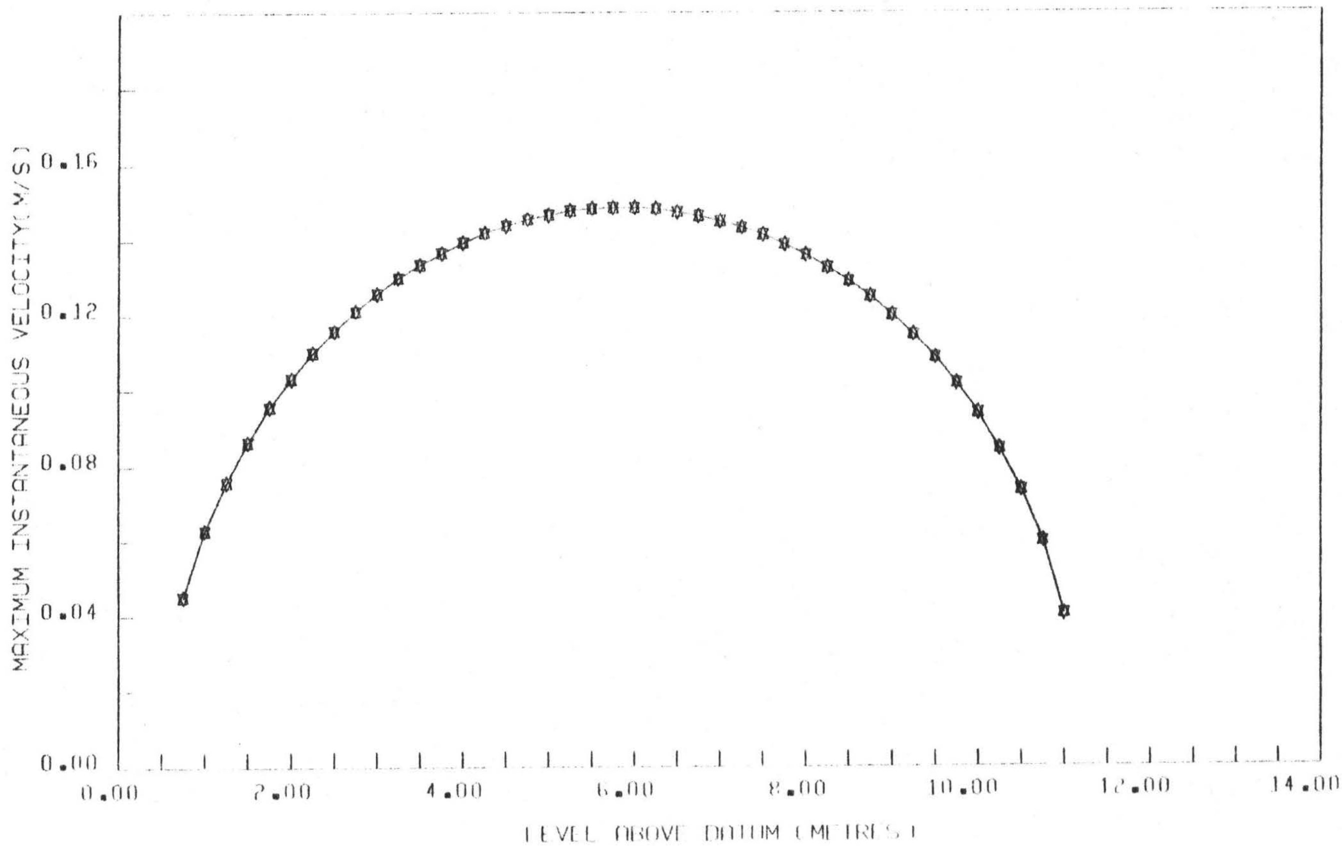
The prominent heights of 4.0 m and 7.75 m ALLT are reflected in the morphological and biological zonation of the flats to be discussed in later chapters.

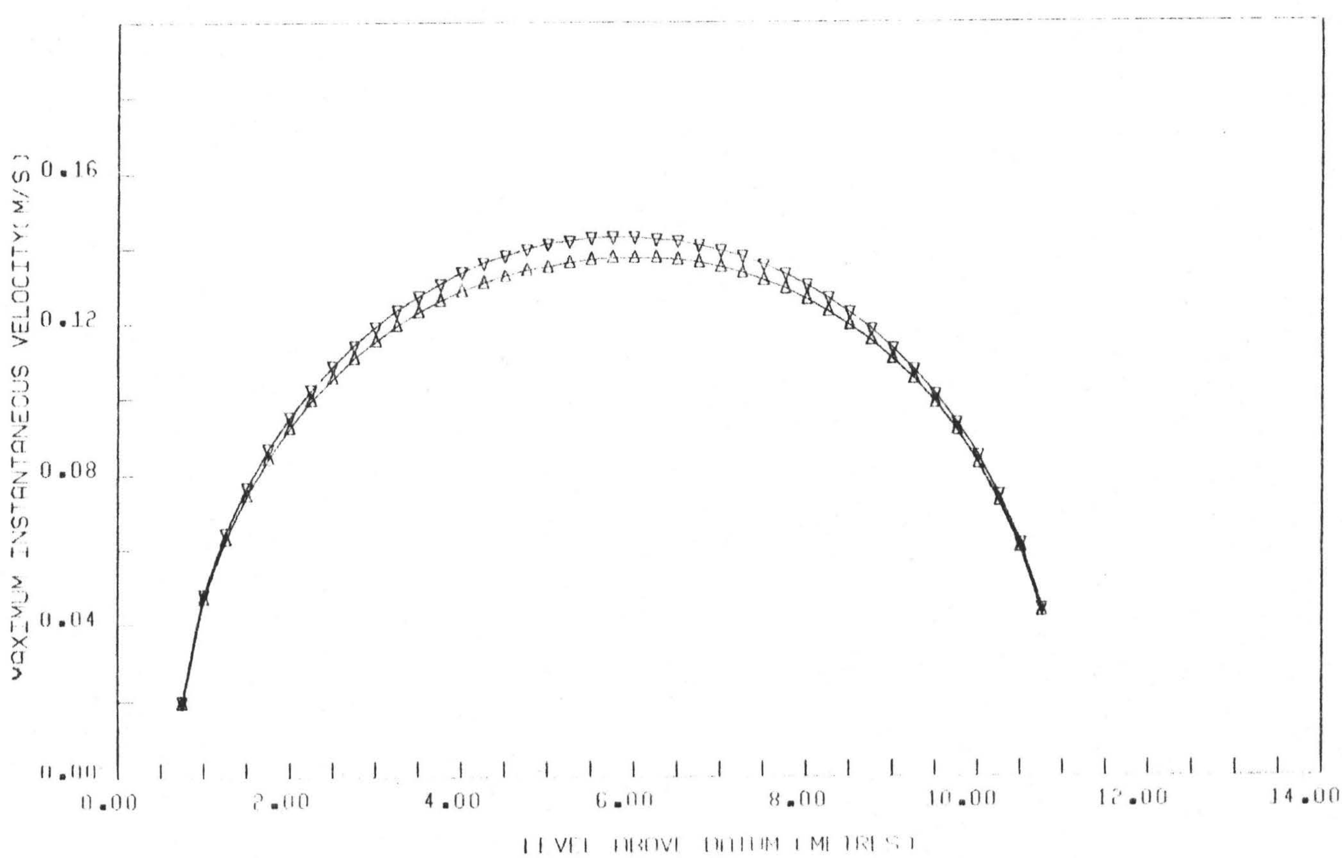
4.3.2 Tidal Waters

Using the tidal curves, maximum instantaneous vertical velocities were calculated. The rise of water in metres per second at .25 m intervals of tidal height for ebb and flood tides in July and August 1981 is shown in Figure 4.8. Velocities appear to reach their highest values around 6.0 m ALLT, approximately midway between the 4.0 and 7.5 m marks noted previously. While ebb and flood velocities were similar in August, ebb velocities were noticeably higher in July, probably a result of variations in global tidal fluctuations, as opposed to local controls.

The actual horizontal velocities achieved on the flats relate to the gradient of the surface (Appendix 2). The average and maximum flood and ebb velocities which could occur at each 50 m interval down the transects was calculated from the predicted vertical velocities. Their values are listed in Tables 4.1, 4.2, 4.3, 4.4. As expected, the steeper slopes experienced lower tidal velocities and the shallower gradients the fastest. The highest ebb and flood velocities generated

Figure 4.8 Maximum instantaneious vertical ebb and flood tidal velocities versus tidal height in July and August 1981.





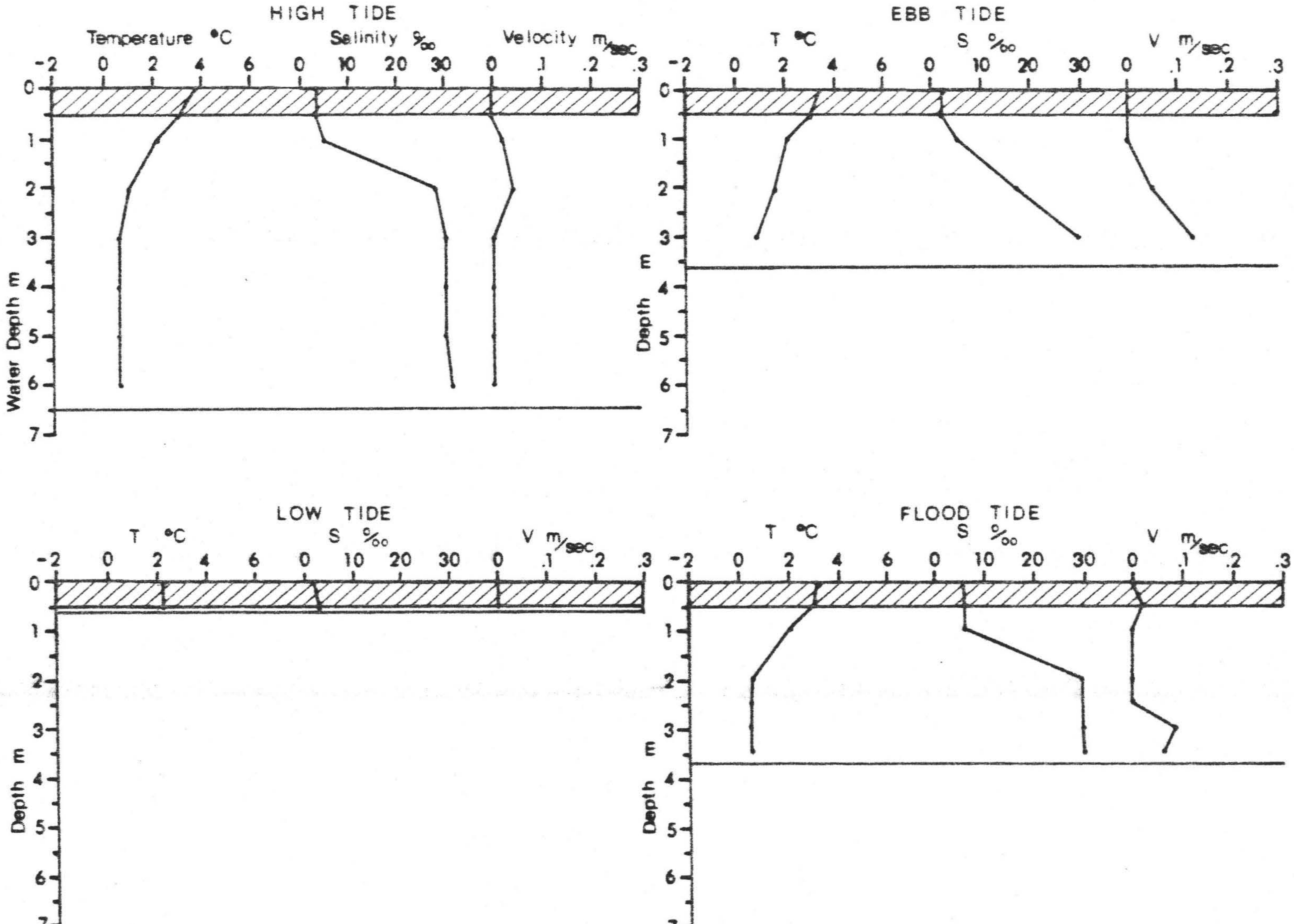
at STB were at 400 m, 4.2 m ALLT at 1.38 m/sec and 1.32 m/sec respectively. At Apex they occurred at 300 m, 2.6 m ALLT at 2.2 m/sec (ebb) and 2.1 m/sec (flood). Peak values of .05 m/sec (ebb) and .04 m/sec (flood) were attained at 25 m, 3.7 m ALLT at the Rock transect and at 250 m, 1.3 m ALLT at Rodgers Island at 8.4 m/sec (ebb) and 8.2 m/sec (flood). In general, the substrate in these vicinities contained fewer fine grained sediments and a greater percentage of coarse grained sands and gravels, than other sites on the transect. The locations with high current velocities also had smaller macrofaunal and meiofaunal densities (See Chapter 5.6).

Average flood velocities were higher than average ebb velocities (Tables 4.1, 4.2, 4.3, 4.4). However, the largest velocities attained were always during ebb tide. Consequently a mixture of flood and ebb dominant features were observed.

The changes in water temperature, salinity and velocity were monitored over 4 tidal cycles in 1980 and 1981. Two were run at STB at 800 m from shore with ice cover on June 25 and without ice cover on July 29. Similarly at 100 m from shore at the Rock transect, one cycle was monitored on June 28 with ice present and without ice on August 10.

Temperature, salinity and velocity measures at high and low tide, and at the midpoint of flood and ebb tides are graphed in Figures 4.9, 4.10, 4.11, 4.12. Wide variations occur throughout the tidal cycle. In general, the highest water velocities almost always occurred in the upper 3 metres of water, regardless of total depth. This is illustrated in Figure 4.13 where the depth of maximum velocities are plotted against

Figure 4.9 Temperature, salinity and velocity measurements at 3-hour intervals at STB on June 25, 1981 with an ice cover.



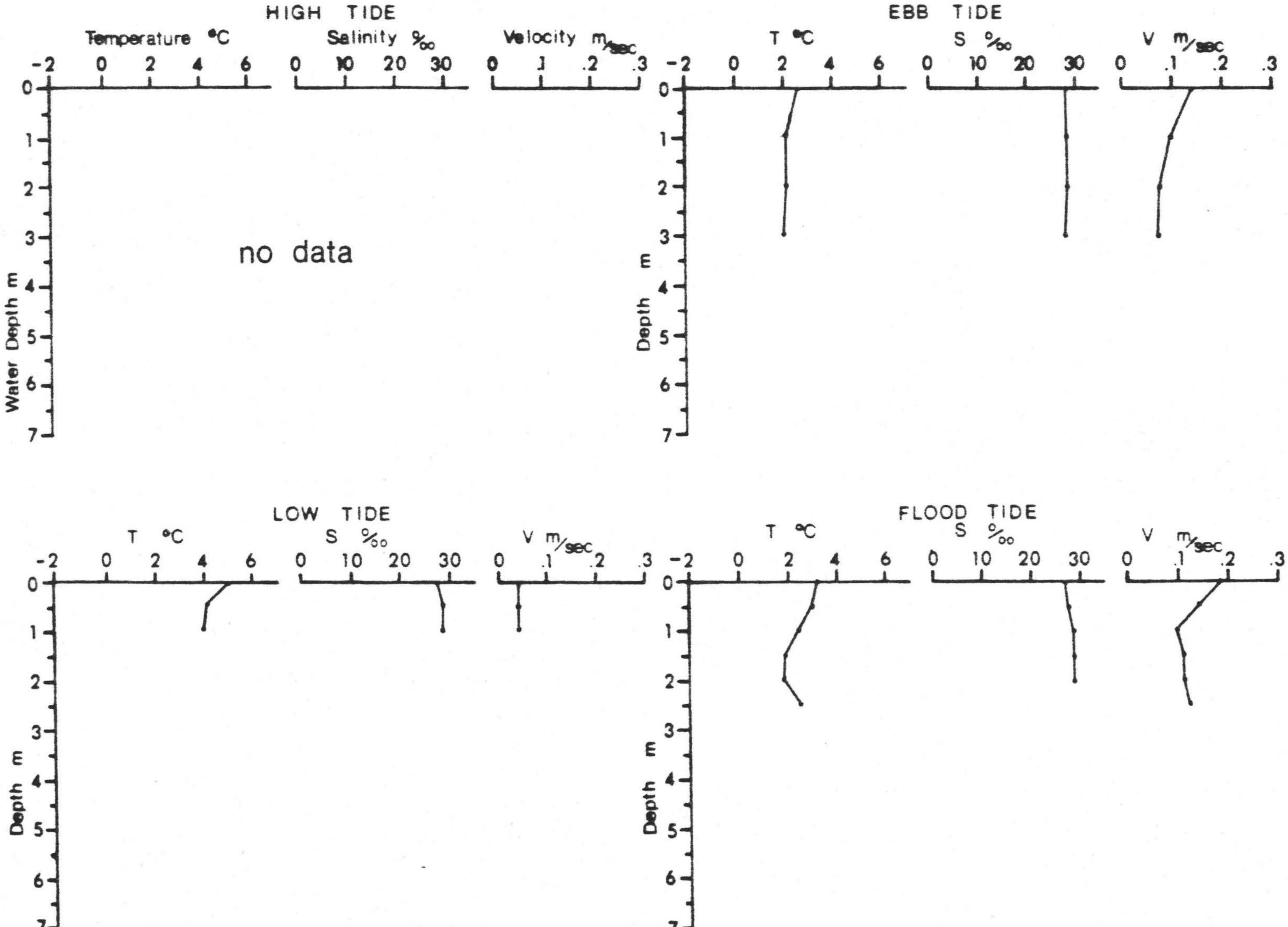


Figure 4.10 Temperature, Salinity and Velocity Measurements at 3-hour Intervals versus Tidal Height in July and August 1981

Figure 4.11 Temperature, salinity and velocity measurements at 3-hour intervals at the Rock Transect on June 28, 1981 with an ice cover.

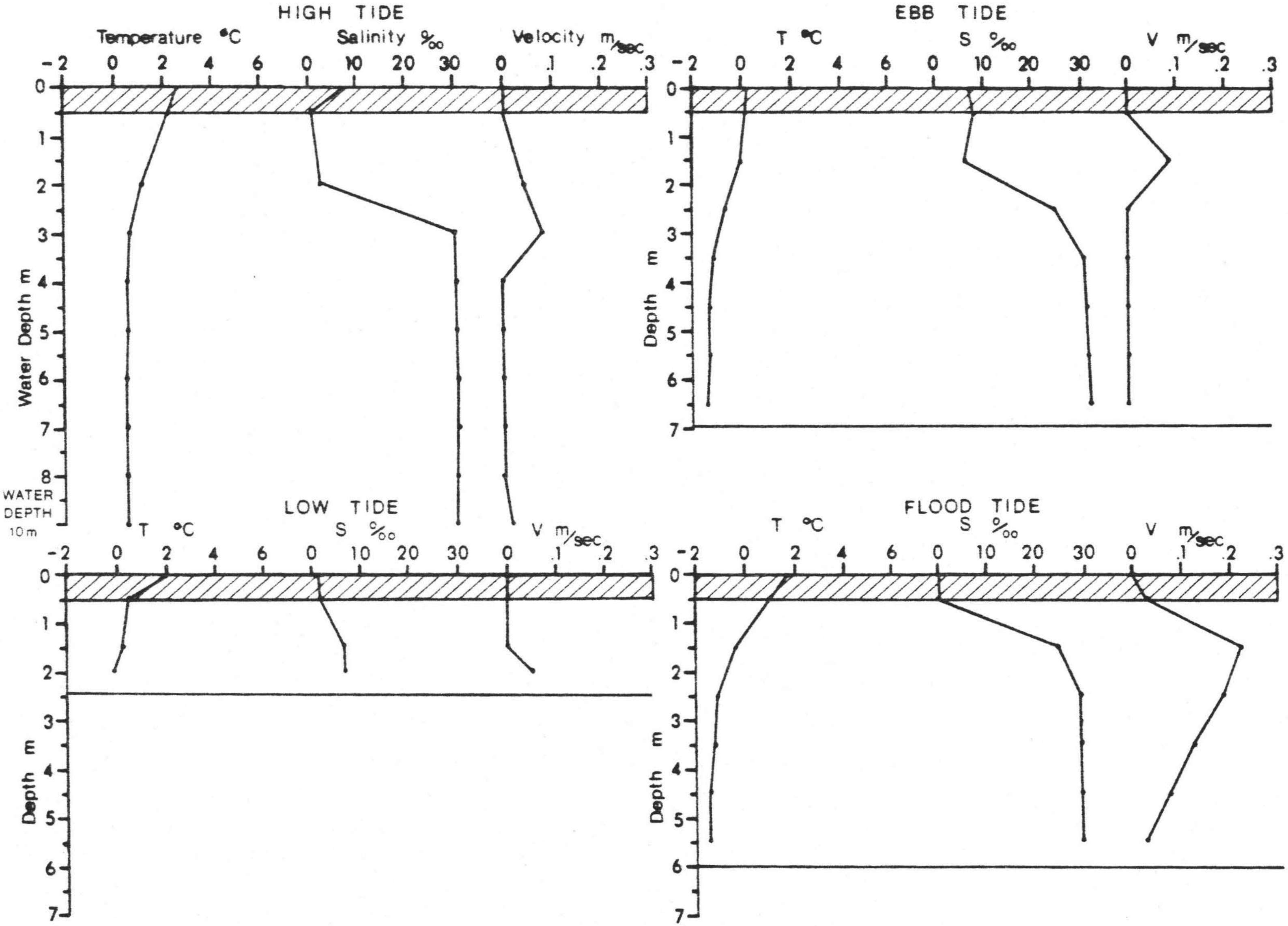
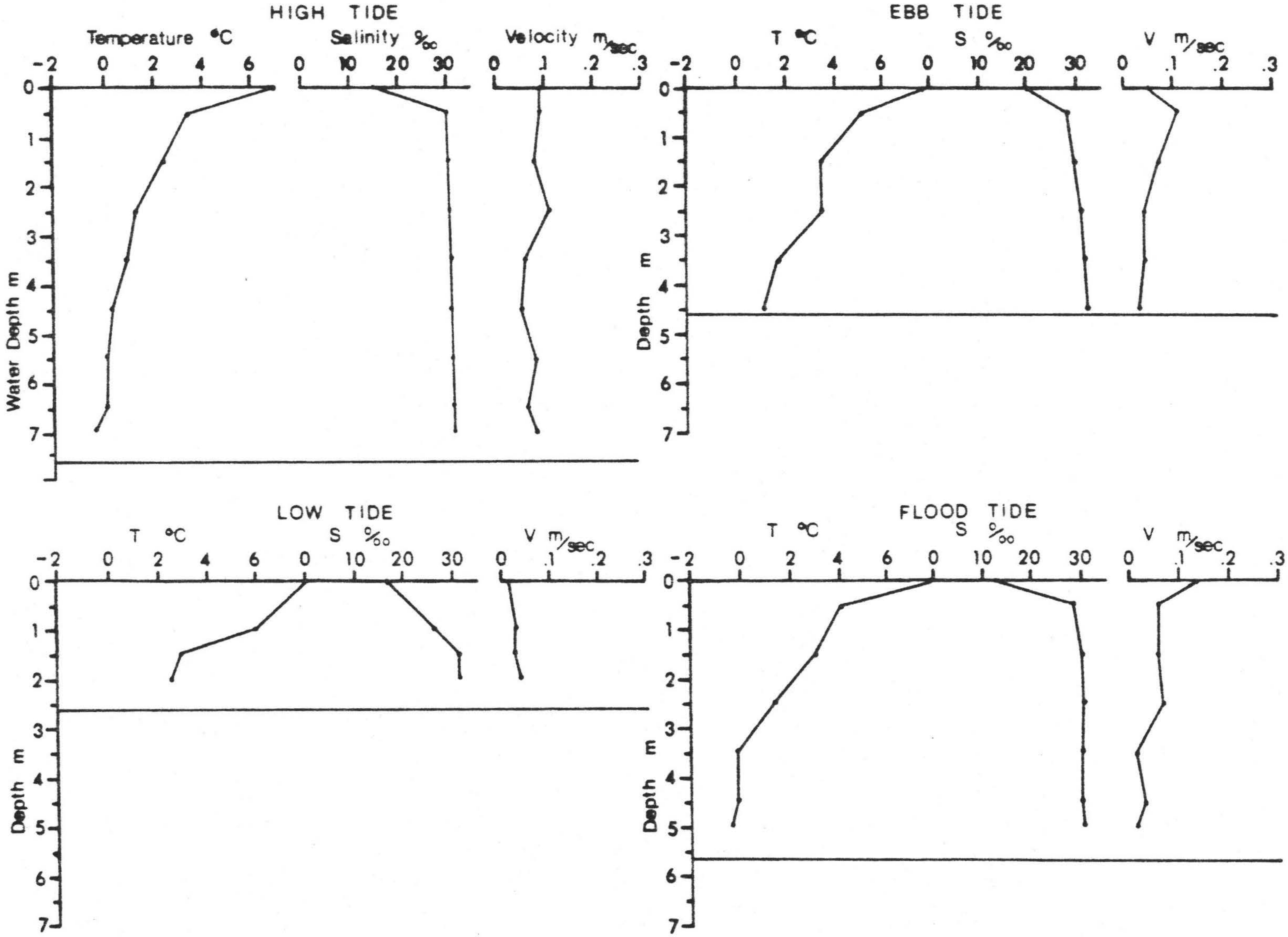


Figure 4.12 Temperature, salinity and velocity measurements at 3-hour intervals at the Rock Transect on August 10, 1981.



the total water depth. Thus, the highest velocities occur at the bed when the water level is less than 3 metres in depth, during the early stages of flood tide, and the later stages of ebb tide. Figure 4.13 also shows that maximum currents are generated at ebb tide. Ebb tidal currents do not increase regularly, but appear to pulse with higher values every 1½ hours during the ebb part of the cycle. This probably relates to the shape and bathymetry of Frobisher Bay rather than more local effects. The presence or absence of ice did not appear to influence current velocities at the bed, except when strong winds and waves were set up in the ice free period. At this time the velocities increased, with the highest velocities at the water surface.

4.3.2.2 Temperatures

Changes in temperature were apparent throughout the tidal cycle (Figs. 4.9, 4.10, 4.11, 4.12). The highest temperatures always occurred at the surface and varied between +3.0°C and 0°C during ice cover, and between 5°C and 8°C with no ice cover. The coldest temperatures occurred by the bed. They averaged -1.5°C below 3.0 m during the winter and +.2°C at similar depths in the summer. Waters less than 3.0 m in depth averaged 0°C in the winter and 2°C in the summer. The warmest temperatures were achieved at the bed during low tide. The variations in water temperatures during the tidal cycle probably do not affect the marine life at the bed. However, exposure to sunlight could raise the temperatures up to 10°C in a short space of time and this could have some effect on sedentary infauna.

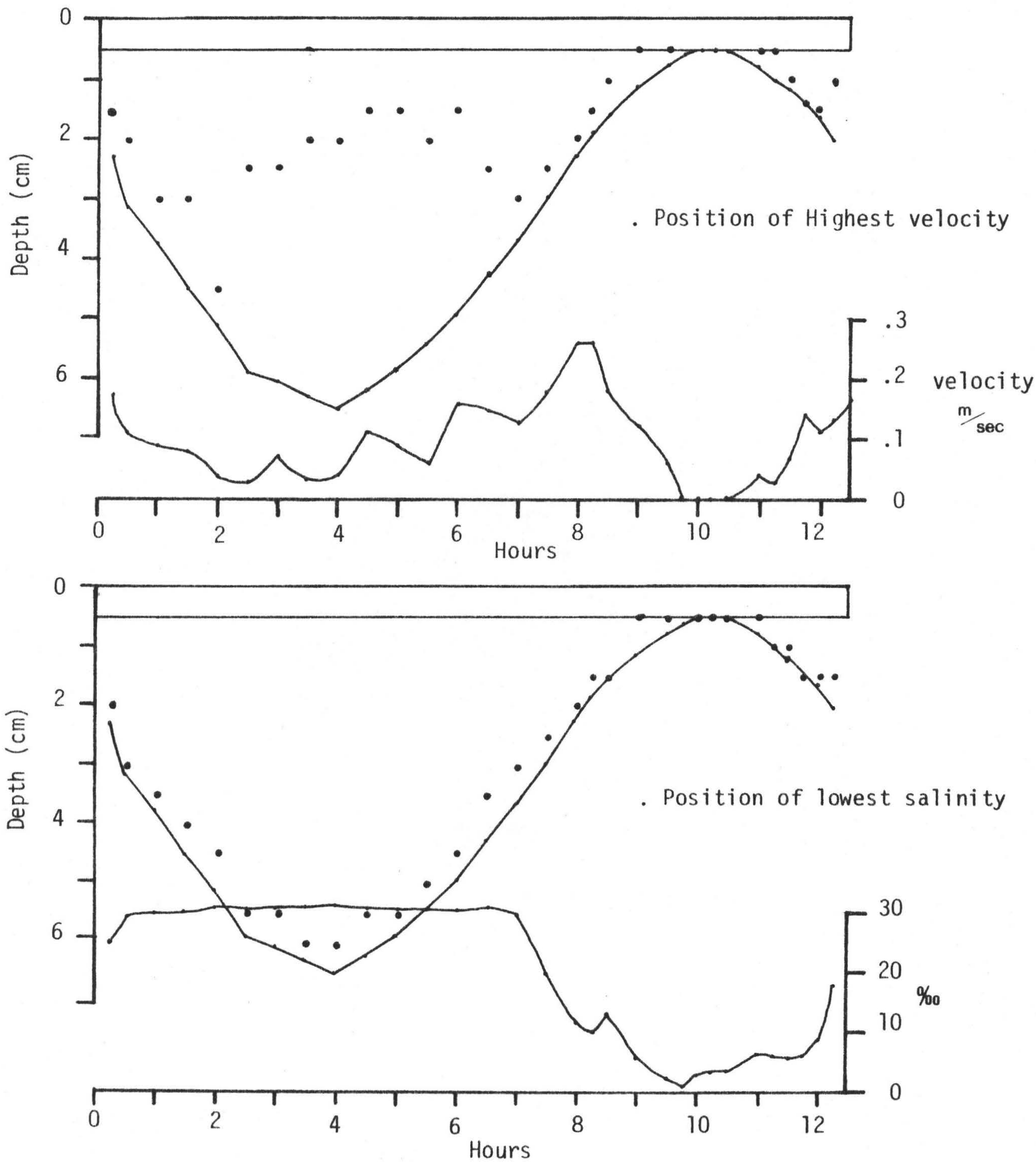


Figure 4.13 Maximum current velocity and salinity values at STB over 12-hour tidal cycle on June 25, 1981.

4.3.2.2 Salinity

More important is the variation in salinity particularly evident during sea ice ablation. The salinity was always greatest at depth, with the fresher, less dense water at the surface. During ebb tides the lens of fresher water was lowered towards the bed (Figs. 4.9, 4.10, 4.11, 4.12). At STB during breakup, the salinity lowered significantly in water less than 3.0 m in depth (Fig. 4.13). Salinities between 8% to 0% were frequently encountered at the bed at the Rock and STB transects during breakup at low tide. Thus, intertidal areas are subject to great variations in salinity during the ice breakup period. This affects the less fresh water tolerant species directly by causing death, or indirectly by discouraging planktonic settlement in those areas affected by fresh water.

The average salinity during the summer months ranged between 29 and 32%, with much less variation than that noted in the spring. Again, lower salinities occurred at the top of the water column, this time restricted to the upper .5 m. The lowest salinity recorded was 12%, which conceivably, could cause some biological hardship over an extended length of time. However, wind and wave action in the summer months probably help to mix the water substantially at shallow depths thereby reducing its effectiveness. In the summer, the fresh water comes from terrestrial runoff, streams and occasionally from ice rafted from down bay, as in early August 1980.

4.3.3 Wave Action

The contribution of wave action on the tidal flat morphology is difficult to ascertain. In 1980, fewer than 10 episodes of waves great-than 10 cm occurred on the flats. Similarly in 1981, most days were calm with waves less than 5 cm. However, the presence of wave modified sediment ridges at STB, the crescentic sand bar at Apex River and the presence of sinuous crested ripples on isolated sand patches indicates that wave action is of some importance. During one storm encountered in 1980, the sand beaches at the head of the bay were heavily pounded by waves reaching 1 m in height, which removed substantial amounts of sediment. On the following days, ripples 2.5 cm in amplitude were measured on sand patches at Apex and STB transects. Thus infrequent, but high intensity wave action is probably more important to the Koojesse flats, than frequent but low intensity wave action. These infrequent episodes have shaped the sediment beaches and formed the large sand waves found at Tarr Inlet and by the Apex River. The high frequency of southeast winds in the direction of maximum fetch give further credence to the possibility of high energy wave action in Koojesse Inlet. Outside of the inlet by Rodgers Island higher and more frequent wave action was evident. In the lee of Rodgers Island 2 m sand waves, modified by tidal currents had formed. White cap waves were often noted in the open stretch of water by Foul and Peterhead Inlets.

4.4 Geomorphology of the Frobisher Bay Transects

4.4.1 Introduction

The location and basic characteristics of the 4 transects are given in Chapter 1, Table 1.3. The following analysis will deal with the geomorphological features of each line starting with STB, which exhibits the most complete tidal flat zonation found. Many of the features recognized along this transect were found on the others. STB has been divided into 6 geomorphological zones which will be compared to the zones present on the other transects.

4.4.1 STB Transect

4.4.2.1 Preamble

The STB transect was the longest line studied, reaching 850 m in length and beginning 7.5 m ALLT. Due to unfavourable tidal conditions much of the flat was inundated during the field season, so that much of the research was restricted to within 400 m of shore. It is open to wave action from the southeast and is protected by the Apex headland and limited fetch lengths in the other directions. STB has a gradient of .0063 with little relief (Fig. 4.1). It is distinguished by sediment mounds from 10 m to 350 m from shore, and has a concentration of boulders which form a loosely structured ridge at 350 m.

4.4.2.2 Substrate

A grey, indurated clay/silt layer underlies the tidal flats in Koojesse Inlet and Rodgers Island. This layer was also observed in pits some 30 m higher than the present high water level on the mainland at the head of Koojesse Inlet. This clay is important since it appears to be the major source of sediment for the active layer of the present day flats. The clay was exposed by ice gouging, high energy wave activity, and by the burrowing activities of infaunal species such as Mya truncata, echiuris and some of the sabellidae, the tubiculous worms, which ejected the clays at the surface. Once exposed, the clay was rapidly reworked by suspended transport and the coarser grain sizes incorporated into the active layer.

The clay layer was similar on all of the transect lines (Fig. 4.14). It is a poorly sorted slightly gravelly, sandy mud with a mean grain size of 5.70 ø. Eighty percent of the samples from Rodgers Island and Apex were finer than 4.0 ø (the silt boundary) and 22% of the sample was 8.5 ø in size. A larger coarse fraction was found in the STB sample which had a mean grain size of 2.7 ø and 11% of the sample was 7.5 ø in size. The abundance of the grains at such specific phi sizes indicates a selective process was at work.

The clay layer probably represents sedimentation in a glacially dammed lake. This occurred during the last glacial retreat some 6,750 ± 170 years B.P. (Blake 1966). The predominance of fines (8.5 ø, 7.5 ø) indicate sedimentation in a deep water environment. The admixture of coarser materials represent periodic influxes of coarser material from the ice, typical in glacial lakes. Forams were not present in the samples, suggesting a lacustrine as opposed to a marine environment.

4.4.2.3 Sediment Distribution

As noted earlier, changes in slope result in changes in current velocity which affects grain size distribution. Thus, coarser sediments would be expected between 400 and 500 m where the shallowest slopes occur (Table 4.1). Finer sediments would be expected in the steeper areas from 0 to 50 m. In addition ebb and flood vertical sedimentation theories predict fining onshore trends. Grain size analyses weakly support this trend with a mean grain size of 2.92 ø at 9 m and 2.02 ø

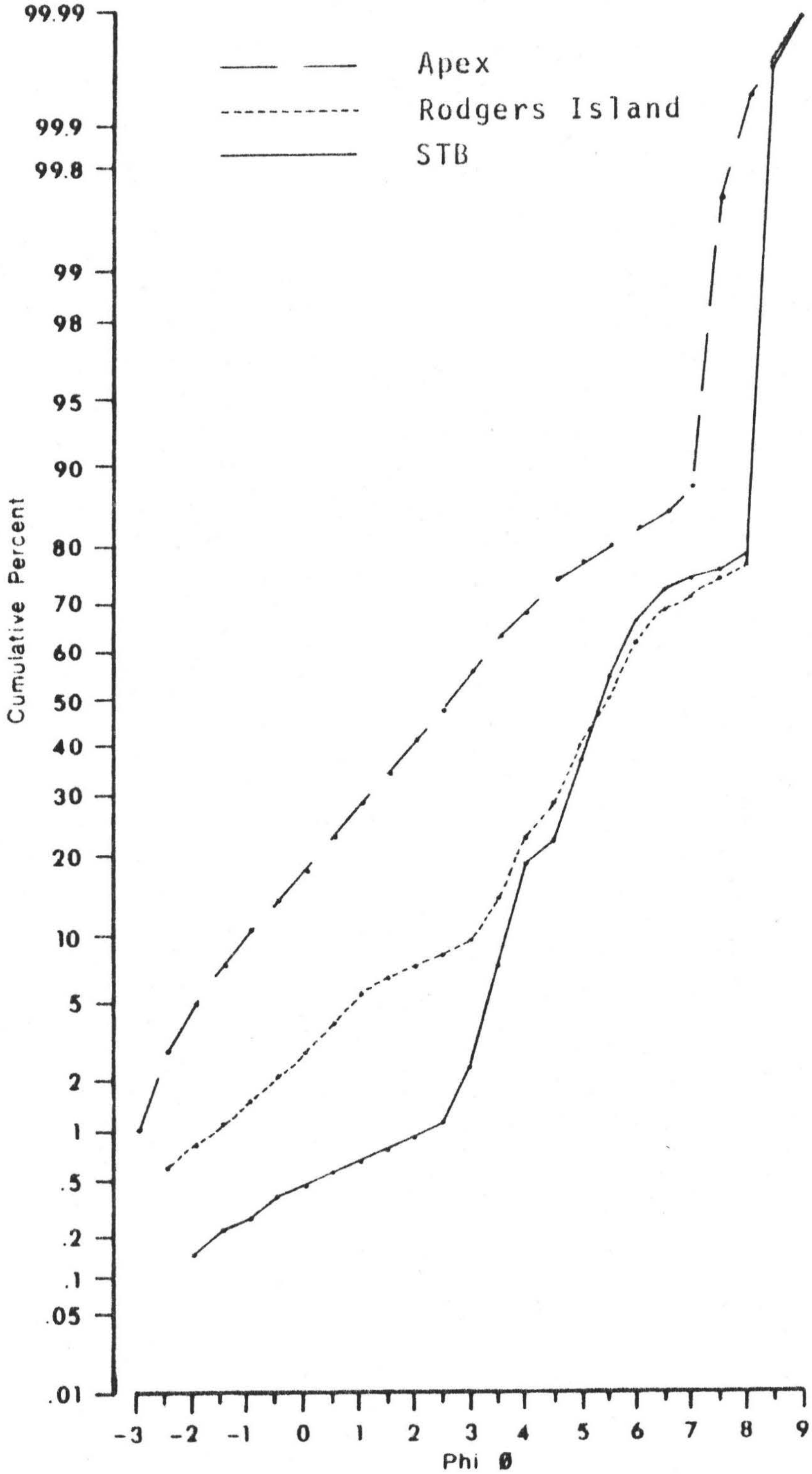


Figure 4.14 Grain size of the clay layer at Apex and Rodgers Island.

at 400 m and an R^2 value of 57.2% (Table 4.5, Fig. 4.15a, b). The coarsest materials (.83 ø) occur at 350 m where the boulder ridge begins and where intense ice and tidal currents action operate. Overall, the sediment was a slightly gravelly sand, poorly sorted, the result of ice mixing, and coarsely skewed since many of the fines were removed by tidal action.

STB has a thin active layer which averages 6.2 cm to the clay layer (Fig. 4.15c). From DOD rod measurements taken in 1980 and 1981, very little movement of this active layer occurs during the summer months, despite sufficient tidal current velocities. Since less than 10% of the sediment is finer than 4.0 ø (silt boundary) few sediments are available for movement by suspension from the tidal currents. Most of the sediments on STB would move by saltation which requires high velocities for longer durations than that initiated by the tides, which as noted earlier change in intensity throughout the cycle. The absence of frequent, high energy wave action has restricted large scale changes in the active layer depth. The DOD rod analysis did indicate an overall net erosion of the sediment surfaces no where greater than 2.0 cm.

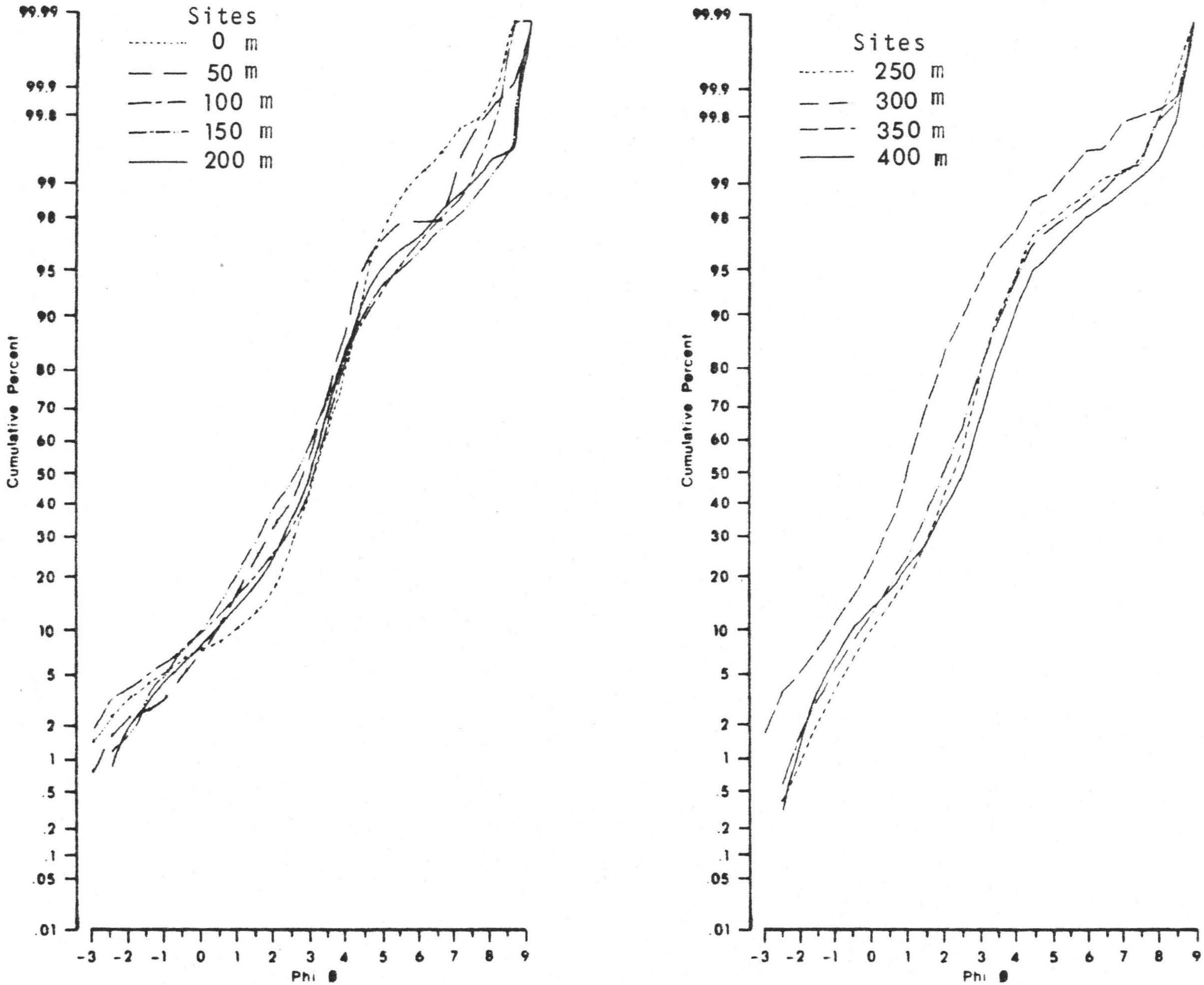
4.4.2.4 Bedforms

As the ice free season progressed, surface features were increasingly influenced by tidal and wave processes. The poorly sorted, chaotic surface left by the ice was eroded, sorted and smoothed into a variety of bedforms. A narrow, well sorted sand beach, 10 m in width developed at the shoreward edge of the flat from low energy wave action at high tide. The sediment ridges east of STB became more distinct and

Table 4.5 Grain Size Analysis at STB

Distance	Tidal Height (m) (ALLT)	Mean Grain Size 0	Standard Deviation	Sorting	Skewness	
0	7.5	2.92	1.66	1.45	-.29	slightly gravelly muddy sand
50	5.9	2.52	1.64	1.48	-.30	slightly gravelly sand
100	5.2	2.59	2.09	1.87	-.30	slightly gravelly muddy sand
150	5.0	2.35	1.88	1.82	-.15	slightly gravelly muddy sand
200	4.3	2.62	1.68	1.56	-.28	slightly gravelly muddy sand
250	4.4	2.16	1.79	1.70	-.33	slightly gravelly sand
300	4.1	1.82	1.61	1.54	-.15	slightly gravelly sand
350	4.5	.83	1.55	1.46	-.15	gravelly sand
400	4.2	2.02	1.5	1.39	-.23	slightly gravelly sand

Figure 4.15 Grain sizes across the STB transect.



their surfaces covered with sorted sands. Even the ice-made microrelief became more prominent, as waves and tidal currents smoothed the sediment surface and deepened depressions between sediment deposits, thus forming sediment mounds which dotted the surface out to 350 m. Surficial drainage of the flats followed the ice-made relief to further embellish the pattern. From 100 to 350 m the mounds frequently formed in association with a boulder.

The presence of the boulder ridge at 350 m aided the development of these shoreward sediment features, in particular the mounds, by stranding ice floes which would otherwise have destroyed the microrelief. Secondly the ridge protected the bedforms by disrupting oncoming waves and by directing the tidal floods down specific channels, the major one just shoreward of the ridge. The effectiveness of the ridge is illustrated by the presence of the sediment mounds and the relative absence of wave formed ripples shoreward of the ridge. Occasionally, ripples were observed in the fines within 50 m of shore, an area some 3.5 m higher than the ridge. Ripples averaging 2.5 cm in height were frequently found seaward of 350 m, particularly from 400 m to 700 m, in isolated sand patches.

Apart from the boulder associated sediment mounds and the shoreline sediment ridges, very few permanent bedforms were observed. Flood dominant deltas were noted in tidal channels emptying into tidal pools, particularly in the drainage network shoreward of 350 m. Ebb cut notches, and planation surfaces on these deltas were also observed on these features.

Scour pits were found surrounding many of the boulders across the flat, particularly seaward of 350 m. Current action had eroded the sediments around the boulder, occasionally into the silty, clay layer. No preferred sides of erosion were evident. Sediment tails often developed on the low energy side of the boulder. In Chapter 3, greater sediment deposition on the shoreward and seaward side of boulders was observed (Fig. 3.14, 3.15) and which probably reflect ebb and flood dominance. On STB, shoreward of 175 m (4.6 m ALLT) flood dominance occurred with sediment tails pointing shoreward. Seaward of 175 m the reverse was true. The same feature was observed on Apex with the boundary at 300 m (2.5 m ALLT).

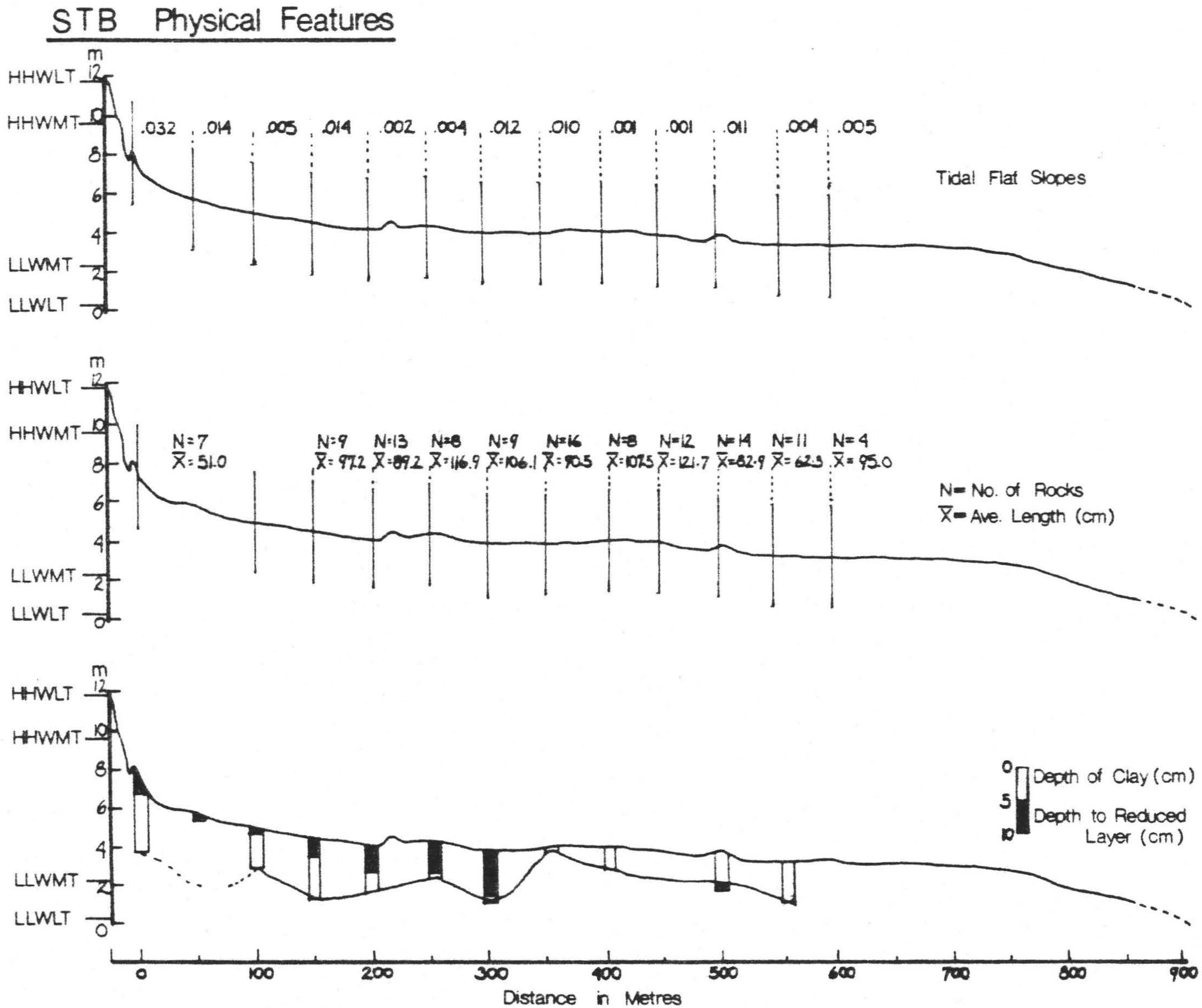
Seaward of 700 m little relief was encountered. The sediment appeared to be a well sorted sand, with gravels restricted to shallow tidal channels. Flood and ebb dominant ripples and deltas were observed.

4.4.2.5 Boulder Distribution

Boulders occured across most of the tidal flat surface (Fig. 4.16b). The fewest number and smallest boulders were found within 150 m of shore and seaward of 600 m. The major concentration of boulders occurred between 350 m and 500 m, 4.5 m to 5.1 m ALLT. This location had the greatest number of rocks deposited by ice action (Chapter 2). It was also the tidal height where a major change in the number and duration of exposure events occurred, thus indicating some tidal control.

Ice floes were frequently grounded on the boulder ridge at 350 m where they ablated depositing sediments and boulders. The ridge has probably formed primarily from this kind of ice deposition. The mechanism which originally induced the deposition of boulders in this area

Figure 4.16 a,b,c STB physical features; gradients, boulder distribution and sediments.



was probably tidally controlled. No structural controls were evident as the area appears to be underlain entirely by the clay layer. It could be that this location represents a former boundary of fast and ice foot ice at lower sea levels. Ice push and ice rafting deposition probably initiated the development of this ridge similar to the small ridges presently forming along some of the shorelines at Long Island, and the Rock Transect (Chapter 2). Similar present day processes are enhancing this feature, which has boulder pavements on its seaward side from ice push.

The boulders at 350 m have protected the underlying clay layer from erosion (Fig. 4.16c). Elsewhere, the clay layer is on average 6.2 cm from the surface, but it is near the surface at 350 m. It appears from this that the boulders have been present at 350 m for some time. They rest on top of the clay surface, which indicates they have been transported to this site.

At present the boulder ridge sits at an important tidal height, 4.0 m ALLT discussed earlier. There appears to be more transport of boulders, shoreward of 350 m > 4.0 m ALLT, as many were observed embedded in the ice but few were observed seaward of this point. Consequently boulders seaward of 350 m undergo less movement and so appear to be in relatively permanent positions. Many are partly embedded in the substrate. Shoreward, the boulders were fewer in number and often lay loosely on the surface. Many were found on top of sediment mounds and were probably transported there by ice floes which stranded on the mounds. The addition of the boulder to the mound makes the feature more permanent since subsequent wave and current action around the boulder can enhance the shape. The boulder also helped strand more floes which added to the sediment collection. Shoreward of 100 m the sediment mounds were devoid of boulders.

Seaward of 350 m to 500 m collections of boulders embedded in the substrate formed boulder mounds. Ice push scours and ice-made rock pavements were noted on the seaward side of these mounds. These mounds are ice push dominated as opposed to ice rafting dominated like the sediment mounds. The greater permanence of boulders seaward of 350 m has resulted in further sediment accumulation thus increasing the size of the mounds.

4.4.3 STB Geomorphological Zonation

The foregoing information suggests that there are 6 physically distinct zones. These are differentiated by characteristic surficial features which appear to form within specific tidal heights. The zones, their tidal ranges and distinctive features are listed in Table 4.6. The following discussion briefly describes each zone based upon the STB transect. An analysis of the other transects will follow using these zones.

Zone 1 - Beach-Lower tidal limit 7.5 m ALLT

At the STB bedrock/sediment interface, a narrow, wave sorted beach developed during the ice free period from ice rafted deposits. Occasionally, sediment ridges exist in this zone as at STB which are enhanced by wave and current activities (See Fig. 3.15). At STB this zone was approximtely 10 m in width and underwent a net increase in sediment deposition from wave action.

Table 4.6 Geomorphological Zonation of the Frobisher Bay Tidal Flats

Zone	Zone Name	Tidal Range (ALLT) (m)	Characteristics	Tidal Unit
1	Beach	10.0 - 7.0	Wave sorted beach during ice free months. Sediment ridges (Ice formed).	Upper Flat
2	Fines Flat	7.0 - 5.2	Fine sediment accumulation and a few, small boulders. Sediment mounds. Shallow indistinct drainage channels.	Upper Flat
3	Bouldery Flat	5.2 - 4.0	Boulder and sediment mounds. Gravels in meandering drainage channels. Boulders lie on flat surface. Flood dominant bedforms.	Middle Flat
4	Boulder Ridge	4.5 - 4.0	Permanent boulder ridge formed from ice push and ice rafting. Undergoes heavy ice action. Protects clay layer and shoreward regions from wave and ice action.	Middle Flat
5	Very Bouldery Flat	4.0 - 2.2	Greatest boulder coverage. Numerous boulder mounds, with boulders embedded in the substrate and boulder pavements common. Ebb and flood dominant bedforms, ripples on sand patches.	Middle Flat
6	Graded Flat	< 2.2	Little relief. Well sorted sands. Few boulders. Tidal channels with some gravels.	Lower Flat

Zone 2 - Fines Flat - Beach to 5.0 m ALLT

This zone has fine sediment accumulation and few boulders (Fig. 4.17). It develops during the ice free period from ebb and flood vertical sedimentation processes discussed earlier. At STB the zone extended from 10 to 150 m and had a fairly low relief at its shoreward end. The seaward end of the zone had sediment mounds which had originated from the ice micro-relief pattern discussed earlier. Drainage channels are shallow and follow the ice micro-relief pattern.

Zone 3 - Bouldery Flat - 5.0 to 4.0 m ALLT

This zone is characterized by boulder and sediment mounds, initiated by ice micro-relief (Fig. 4.18). The addition of boulders has made the mounds more permanent. Tidal run-off channels are more evident winding around the sediment mounds. Gravels commonly line these channels, which have flood dominant features. At STB, the zone extends from approximately 150 to 350 m.

Zone 4 - Boulder Ridges - 4.0 to 4.5 m ALLT

These ridges can appear anywhere within 4.0 and 4.5 m ALLT (Fig. 4.19). The ridges are old, perennial features which protect the underlying clay substrate from erosion. They also protect the inner flats from wave action and drifting ice, thus helping to preserve the more ephemeral sediment mounds. Ice freezes to the ridge in the winter, forming massive ballycatters. The area undergoes heavy ice action as illustrated by the eroded clay surfaces in the vicinity, the scraped but smoothed boulder surfaces and boulder payements.

Zone 5 - Very Bouldery Flat - 4.0 to 2.2 m ALLT

This flat differs from the bouldery flat by possessing a

FIGURE 4.17 The fines flat at STB with small tidal channels and low relief.

FIGURE 4.18 Bouldery flat at STB with sediment mounds.

FIGURE 4.19 Boulder ridge and very bouldery flat at Koojesse Inlet.

greater coverage of boulders, which unlike the previous flat, are usually embedded in the substrate (Fig. 4.19). Large boulder accumulations occur forming boulder mounds around which later sediments have accumulated. Boulder pavements are frequently found on the sides of these boulder mounds, a testimony to the importance of ice push in the area. Gravel channels, with flood and ebb formed deltas, and ripples on isolated sand patches dominate the scene.

Zone 6 - Graded Flat - < 2.2 m ALLT

This area has little relief with a cover of well sorted medium sands and a few, small boulders. Some gravels are found in the tidal channels which often exhibit flood dominant features in the lower gradient areas. At about 1.0 m ALLT the slope steepens and deeper, tidal channels are cut into the substrate, often parallel to each other. This lower flat probably receives most of the sediment removed from the upper flats.

4.4.4 Apex Transect

Apex transect was 650 m in length, with an average gradient of .01 . Like STB it has a meandering drainage network which is controlled by sediment and boulder mounds. This flat has two, well defined, crescentic shaped ridges parallel to shore (Fig. 4.2). In terms of tidal height, the transect falls within Zones 4, 5, 6 and its surficial characteristics fit in exactly with those found on the STB line (Fig 4.2).

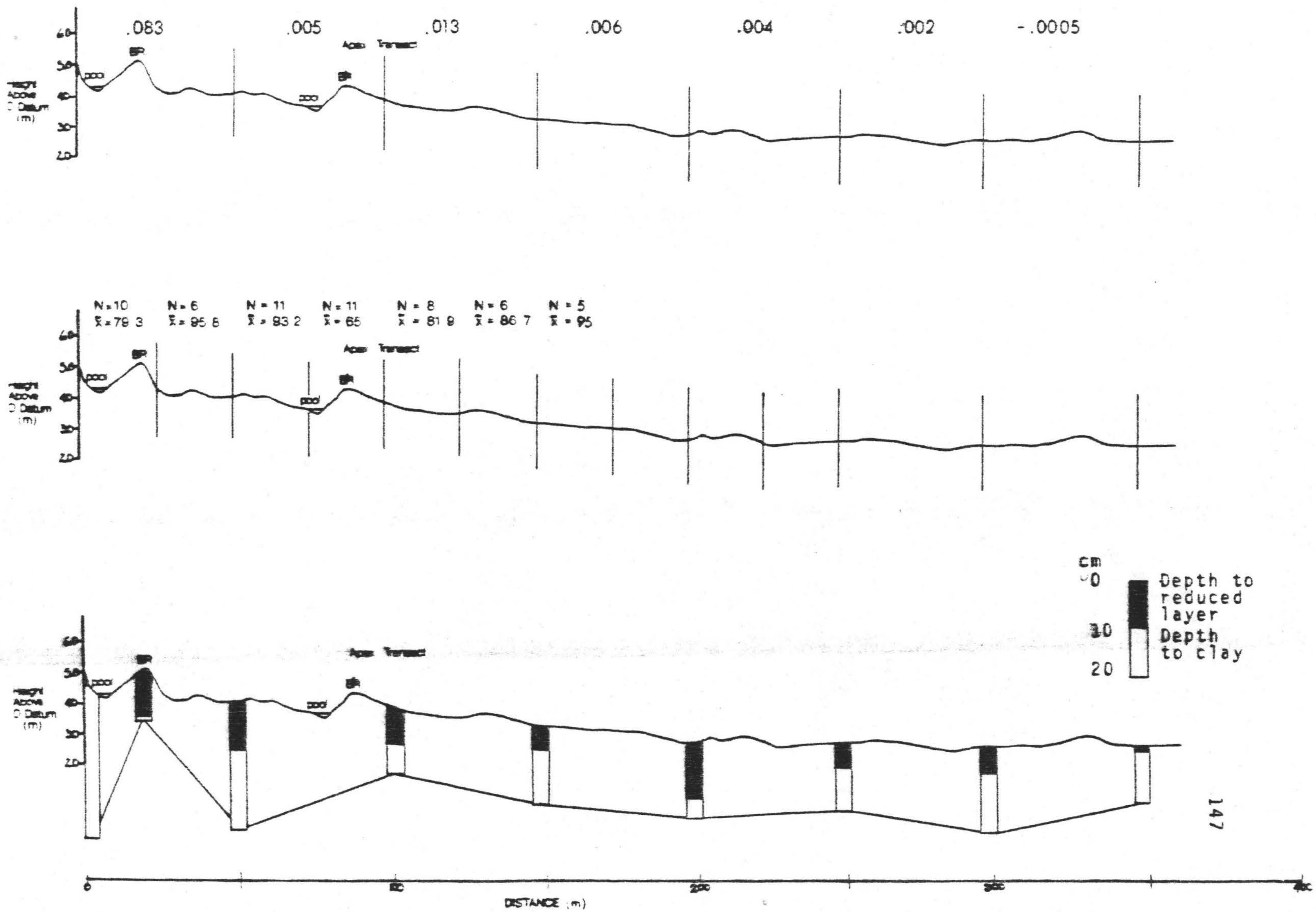
The boulder ridges lie between 4 and 5 m ALLT and reach a maximum of 2 m in height. Two parallel sets of these ridges have developed at Apex (Fig. 4.20). They lie approximately the same distance from shore (20 m, 90 m) and reach similar tidal levels. Like STB these ridges have protected the underlying substrate from erosion (Fig. 4.21c). They all have boulder pavements on their shoreward side, which tends to be steeper, while their seaward side is more gentle in relief and its boulder coverage more scattered. Ice push erosion and scours were more evident on the shoreward side of these ridges, although ice drift gouges were numerous on their upper surface. These ridges appear to have had a similar origin to the STB ridge. Their greater exposure to wave and ice action from down bay accounted for their greater development. Some underlying bedrock control may be at work in their regular arrangement and shape. Present processes such as ebb and flood tides are enhancing the shape by erosion at the ends and shoreward side.

Most of the flat lies within zone 5, a very bouldery flat (Fig. 4.21a, b). Its low gradients between 150 and 400 m are similar to those found across STB, although there are slightly fewer boulder mounds on this flat.

The active layer overlying the clay was deeper at this transect and averaged 17 cm in depth. Average depth to the reduced layer was 5 cm, thus only the upper 5 cm were actively being reworked by ice and wave action. Unconsolidated sediments were accumulating to a greater depth since the lower tidal height of the flat meant fewer sediments were removed during ice formation and resulting in less disruption to the active layer. Ripples were also more common due to the more exposed location of the flat. Ripples were frequently

FIGURE 4.20 The boulder ridges at Apex transect.

Figure 4.21 Apex physical features, gradients, boulder distribution and sediments.



observed on sand patches seaward of the boulder ridges.

Sediment movement during the summer like STB was minimal and confined mainly to channel areas. However, on the whole a very slight increase in sediment occurred, particularly in the outer reaches of the flat. This fits into the description of zone 6 on STB, where the deposition of material from the upper flats appeared probable.

Surface sediments showed little variation. Fines were found in the tidal pools shoreward of the ridges. The lower flats (Zone 6) had well sorted, medium sands with flood dominant features like STB. The very bouldery flats had poorly sorted gravelly sands.

4.4.5 Rock Transect

The Rock Transect is a shorter version of the Apex Transect having Zones 4, 5, and 6 within 150 m as opposed to 650 m. Accordingly it has a steeper gradient, .038 (Fig. 4.3, Fig. 4.22).

Major boulder accumulations again occurred at 4.5 m ALLT and formed a shore parallel ridge a metre in height (Fig. 4.3). Ice push and gouging was evident at this ridge. The boulders are subrounded and protect the clay layer as at the other lines. Like Apex, the clay became progressively deeper farther from shore. A large tidal pool has formed shoreward of the ridge and contains fine sediments which support a wide variety of infaunal life.

Probably due to the steepness of the shore, few sediment and boulder mounds exist. Instead, the mounds have elongated into ridges perpendicular to shore which channel tidal runoff. Tidal drainage, as opposed to ice-made micro-relief is probably the source of the

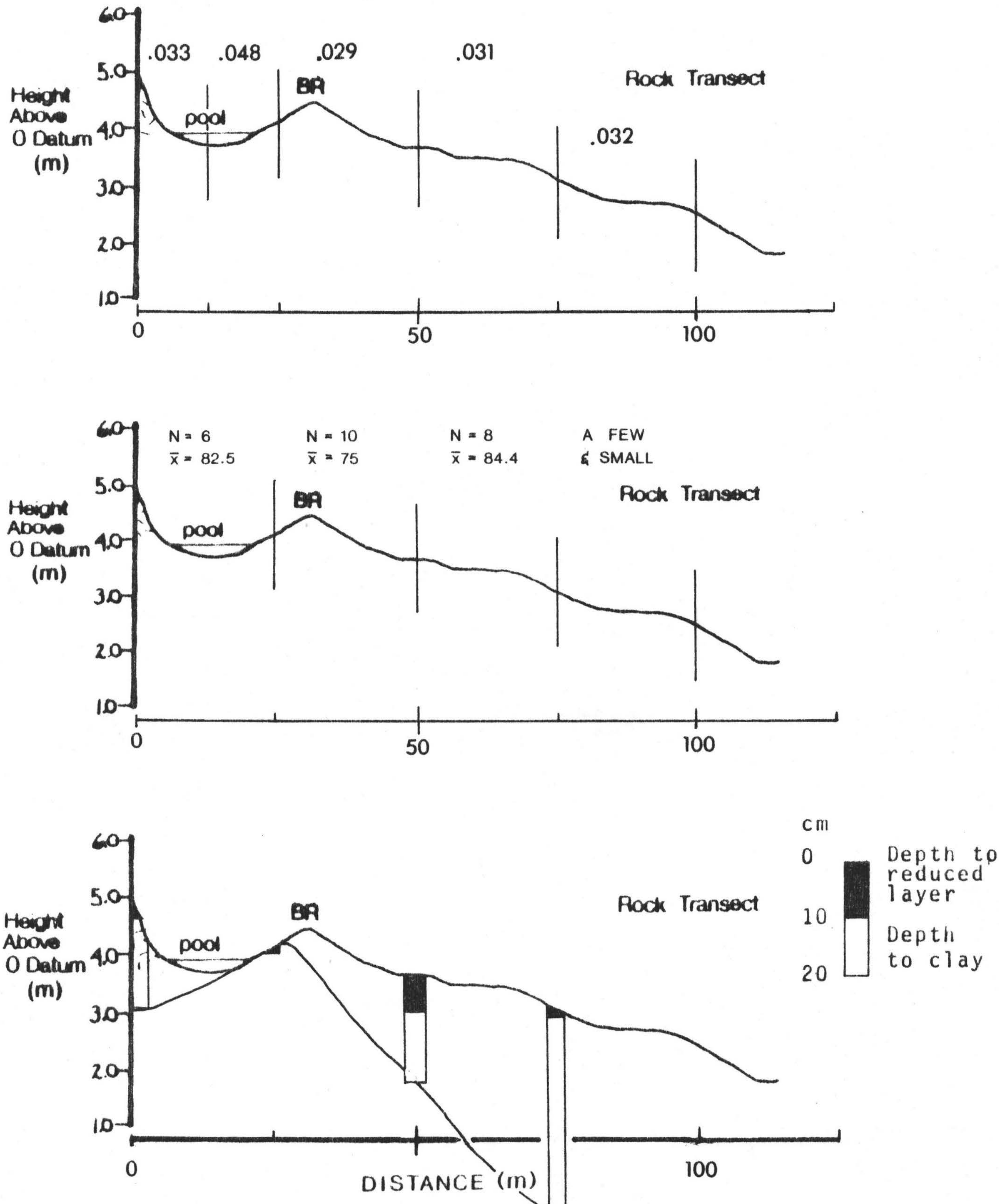


Figure 4.22 Rock Transect Physical Features, Gradients, Boulder Distribution and Sediments

shore perpendicular ridges and runnels.

At low water, the well sorted sands, and few boulders typical of zone 6 were apparent.

4.4.6 Rodgers Island

This transect typifies zone 6. It faces the south-west, perpendicular to the coast of Rodgers Island and is the most exposed of any of the lines (Fig. 4.23). Sediments start at 3.5 m ALLT between ice push boulder ridges. The flat proper begins at 2.2 m ALLT. There is little relief, and few bedforms. The line has medium, fairly well sorted sands with a few small boulders.

Great exposure, plus a low gradient have created large tidal velocities which have planed the bed surface. These velocities (ebb 8.44 m/sec, flood 8.2 m/sec) also whip algal fronds to produce scour pits around the plant.

The clay layer is deep (23 cm) with little to protect it from erosion. Oxidized layers are also deep reaching an average depth of 15 cm. Wave action and bioturbation from the high densities of Cyrtodaria kurriana and Sabellid tubiculous polychaetes has caused this deep active layer out to 200 m. By 225 m both the active and clay layer are closer to the surface, this may reflect the substantial drop in the density of the bivalve species notably Cyrtodaria kurriana (Chapter 5).

Very few ripples were found on the flat surface, most were planed away by high tidal velocities. A number of large ice floe gouges were evident across the flat (see Chapter 3).

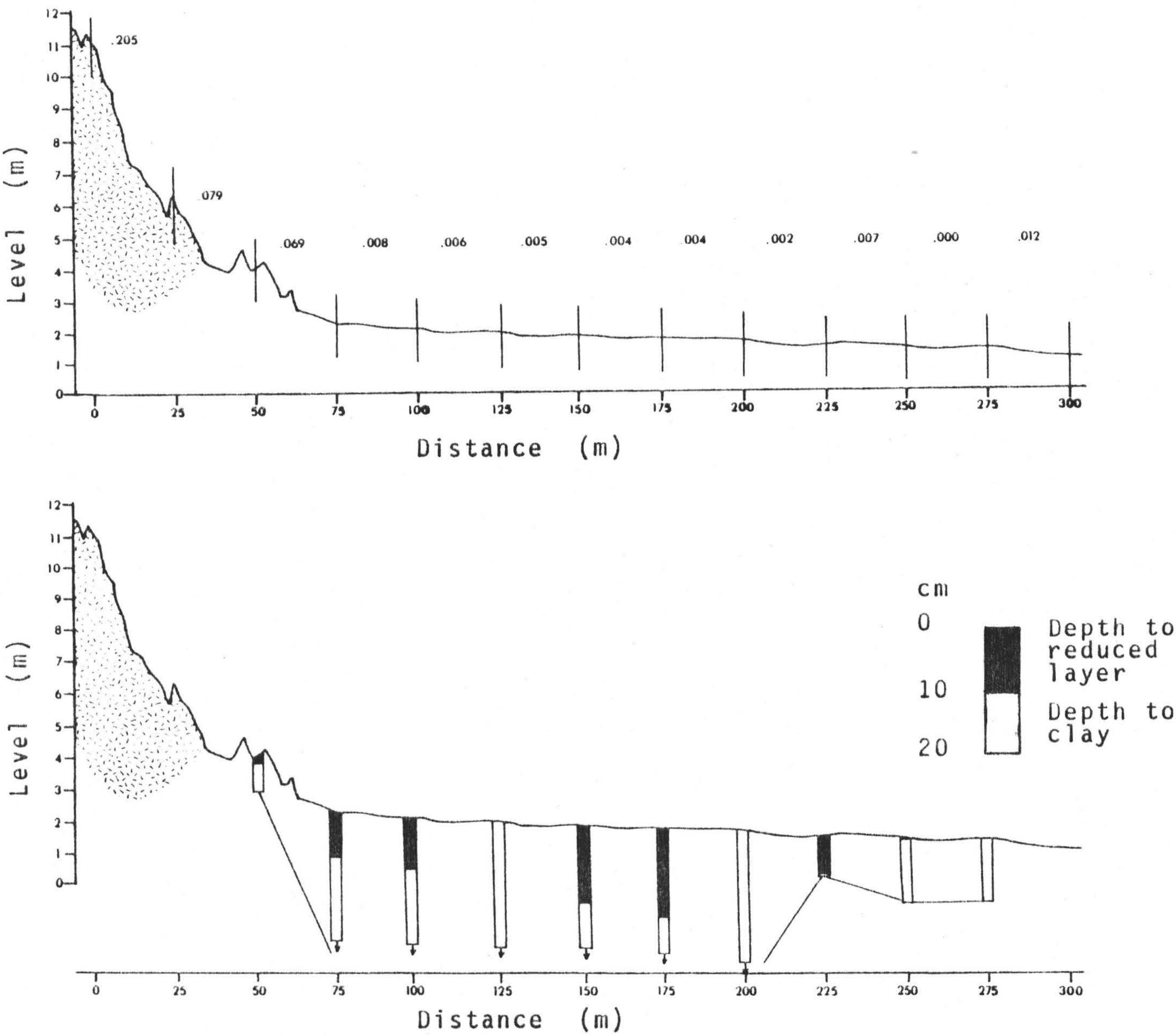


Figure 4.23 Rodgers Island physical features, gradients and sediments.

A weak, meandering drainage system existed across the flats, some gravels were found in these channels. Fewer tidal pools were found on the surface of this tidal flat, presumably since it is exposed on average (only 10 to 67 times in 2 months for a total of 10 to 150 hours) only 10% of the time.

4.5 Conclusions

Tidal and wave processes play a role in the geomorphological zonation of the tidal flats. The major conclusions drawn concerning the physical aspects of the flats at the head of Frobisher Bay are as follows.

1. Ice action in conjunction with tidal fluctuations is a dominant process on the surficial expression of the tidal flats. It accounts for the development of the bouldery flats, boulder mounds, sediment mounds, boulder ridges and the disruption of current and wave induced sedimentological zonation.

2. Tidal action has two important roles, first it affects the exposure of the flats to varying degrees of aerial and marine processes. Secondly, the tides influence the chemical (salinity) and physical (temperature and current velocity) properties of the water coming in contact with the tidal flat. Such fresh water at low tide over the substrates at breakup affects the biota.

3. Two important tidal heights are evident from exposure curve analysis. At 4.0 m ALLT and 7.5 m ALLT the number & duration of exposure varies abruptly. These heights are reflected by biological and morphological changes on the flat. Morphologically the 4.0 m mark

is the boundary between bouldery and very bouldery tidal flats. This height also marks the location of many of the boulder ridges present in the area. 7.5 m marks the average upper tidal limit, sand beaches and sediment ridges, where formed, occur in this zone.

4. Tidal currents vary over the tidal cycle in velocity and in depth of maximum velocity. The highest currents are generated at ebb tide but the highest average velocity occurs at flood tide. Consequently, mixtures of ebb and flood dominant bedforms are common Often flood dominant features occur in shoreward reaches of the flat and ebb dominance towards low water. This may reflect the steepness of the slope; greater the slope, greater the ebb dominance.

5. The tidal flats at Frobisher Bay appear to be erosional features. Net erosion over two summers of study, the relative absence of large scale depositional forms and the thin active layer support this conclusion. Present sediments appear to be derived from a glacio-lacustrine clay layer which underlies all of the flats studied.

6. The flats exhibit surficial zonation. The sedimentological and morphological characteristics of STB and the other transects suggest that a 6-fold division is appropriate. The zonation is based upon the following criteria - sediments, boulder distribution, bedforms (boulder or sediment mounds), drainage patterns and tidal height. Table 4.6 illustrates the zones, their tidal range and characteristic features. In more general terms these 6 zones are referred to under 3 headings which will be referred to in subsequent chapters. Zones 1 and 2,-beach and fines flat make up the upper flat area. The middle flat corresponds to zones 3, 4, and 5-bouldery

flat, very bouldery flat and boulder ridge. The lower flat includes the graded flat zone. From these basic divisions the morphologic zonation can be extended to other tidal flats in the area using maps and aerial photos without recourse to added fieldwork.

CHAPTER 5

ZONATION OF THE INTERTIDAL FLORA AND MACROFAUNA

5.1 Introduction

This chapter is concerned with the macrofauna and macroalgae collected in Frobisher Bay, in 1980 and 1981. The macrofauna includes those species $\geq$ 1 mm in size, living on or in the substrate. This includes bivalves, gastropods, priapulids, echiura and crustacea. A complete list of the macrofauna is given in Table 5.1 and of the algae in Table 5.2. The purpose is to show the vertical and horizontal zonation of the macrofauna and algal communities across the transects at the head of Frobisher Bay. Densities and species diversity for all of the transects are examined. The chapter concludes with a discussion on the distribution and migration of *Littorina saxatilis*, and the growth rate and distribution of *Balanus balanoides*.

5.2 Literature Review

5.2.1 Eastern Arctic Studies

Records of faunal collections made in the Canadian Arctic go back to the 1800's. This early period was characterized by incidental collections, and poor labelling, which has lead to much confusion in the present taxonomic listings (Lubinsky 1980). Since 1900 numerous expeditions have been launched to solve some of the problems, particularly around Baffin Island, Western Greenland and Northern Labrador.

Table 5.1 Macrofauna species collected in 1980 and 1981 at the Head of Frobisher Bay.

Phylum	Class	Genus and Species
Coelenterata	Anthozoa	Stomphia coccinea
		Tealia tellina
Priapuloidea		Priapulis caudatum
Sipunculoidea		Halcampa sp.
Mollusca	Gastropoda	Acmaea testudinalis
		Buccinum belcheri
		Buccinum finmarkianum
		Buccinum nivale
		Buccinum scalariforme
		Buccinum sericatum
		Cingula castanea
		Colus pubescens
		Cylichna alba
		Lacuna vincta
		Littorina saxatilis
		Margarites helicinus
		Margarites olivaceus
		Margarites umbilicalis
		Margarites vahli
		Oenopota bicarinata
	Bivalvia	Astarte borealis
		Astarte striata
		Axinopsida orbiculata
		Crenella faba
		Cyrtodaria kurriana
		Hiatella arctica
		Macoma calcarea
		Musculus discors
		Musculus discors laevigatus
		Musculus niger
		Mya truncata
		Serripes groenlandicus
		Thracia myopsis
		Thyasira flexuosa
Arthropoda	Crustacea	
	Subclass-Cirripedia	Balanus balanoides
	Malacostraca	Amphipods

Table 5.2 Macroalgal species collected in 1980 and 1981 at the Head of Frobisher Bay

Class	Genus and Species
Chlorophyceae	Ulvaria obscurra
	Chaetomorpha melagonium
Phaeophyceae	Pilayella littoralis
	Alaria esculenta
	Laminaria longicruris
	Fucus edentatus
	Fucus evanescens
	Fucus vesiculosus
	Stictyosiphon tortilis
	Sphacelaria arctica
Rhodophyceae	Neodilsea integra
	Halosaccion ramentaceum
	Palmaria palmata
	Rhodomela confervoides

The Canadian Arctic Expedition, 1913-1918 (Dall 1924) has provided much useful information still relevant today.

Studies along the western Greenland coast by Thorson (1933, 1936), Vibe (1939) and Madsen (1936, 1940) have added much to Arctic biological knowledge. Their early research permits useful comparisons with Canadian shorelines at the same latitude. Significant Canadian contributions to Arctic research have come from Dunbar (1951), and Ellis (1955).

In general, the mollusc family has been better studied than other Arctic families. Recent reports by MacPherson (1971), Lubinsky (1972, 1980) and Clarke (1974) have contributed greatly to our understanding of Arctic species and their distribution.

5.2.2 Southeast Baffin Island Studies

Projects undertaken closer to Frobisher Bay include those by Ellis and Wilce (1961 see also Ellis 1955, 1966), Den Beste and McCart (1978) and Wacasey (pers. comm. 1980). These projects (excluding Wacasey) likewise utilized the zonation approach, relating floral and faunal characteristics to their spatial distribution. Ellis and Wilce (1961) found that intertidal species could be divided into 2 groups, "Specific intertidal species such as Balanus balanoides and Littorina saxatilis; and a second group of shallow water species which can tolerate exposure to air for short times such as Modiolaria discors (now called Musculus discors) and Harmothoe imbricata". They found that despite faunal differences due to local variations in sediment size, the zonation of the floral and faunal communities was essentially similar along all of the sedimentary shores examined in southeast Baffin Island.

Den Beste and McCart (1978) examined the biological zonation along Davis Strait, and the Frobisher Bay headlands. Subtidal and intertidal collections were taken of the sedimentary, and floral and faunal constituents, and densities calculated. The exposure to both Atlantic and Polar waters in their study area, played an important role in species composition, which varied somewhat from the headward reaches of Frobisher Bay.

The species list shown on Table 5.3 is a compilation of the collections of bivalves, gastropods and polychaetes made by Ellis (1955, 1966) and Wilce (1961), Den Beste and McCart (1978), Wacasey (pers. comm. 1980) and McCann, Dale and Hale (1982). This list includes mainly intertidal species, although some subtidal species washed up on the tidal flat were included (McCann et al 1982). Wacasey's list includes only principal species found, and does not include results from his current research in Frobisher Bay. The short list from Den Beste and McCart (1978) reflects their study sites which were narrow beaches, as opposed to wide intertidal flats. The list reflects the species found in a wide variety of habitats with differing substrates, wave, current and tidal exposures.

5.2.3 Animal/Substrate Relationships

The relationship between organisms and substrate is best reviewed by Rhoads (1970, 1974). He noted the relationship between grain size and the diversity of species. Bubnova (1972)

Table 5.3 Intertidal species list (Bivalvia, Gastropoda and Polychaeta), Frobisher Bay Vicinity, Baffin Island

	Ellis (1955, 1960, 1961)	DenBeste and McCart 1978)[1]	Wacasey (pers.comm., 1980)[2]	Dale (collected 1980)
Bivalvia (Pelecypoda)				
Astarte borealis	X		X	X D[3]
Astarte montagui	X			
Astarte striata				X D
Axinopsida orbiculata	X		X	
Crenella faba	X	X		X
Cyrtodaria kurriana	X			X
Hiatella arctica	X			X
Macoma balthica	X			
Macoma calcarea	X			
Musculus discors	X	X		X
Musculus discors laevigatus				X D
Musculus niger	X			X D
Mya truncata	X		X	X
Mytilus edulis	X			
Serripes groenlandicus	X		X	X D
Thracia cf. myopsis				X D
Thyasira flexuosa			X	
Gastropoda				
Acmaea testudinalis	X			X D
Boreotrophon clathratus		X		
Buccinum sp.	X			
Buccinum sp. (bayani)		X		
Buccinum finmarkianum				X D
Buccinum nivale				X D
Buccinum scalariforme				X D
Colus pubescens				X D
Coryphella salmonacea	X			
Cylichna alba				X D
Cylichna occulta	X	X		
Lacuna cf. vincta				X D
Lepeta caeca		X		
Littorina littorea		X		
Littorina sp.			X	
Littorina saxatilis	X			X
Lora scalaris		X		
Margarites sp.		X		
Margarites groenlandicus	X D			
Margarites helicinus	X			X D
Margarites olivaceus				X D
Margarites umbilicalis		X		X D
Polychaeta				
Ampharete acutifrons				X
Ampharete grubei	X			
Capitella capitata	X	X		X
Cistenides granulata	X			
Eteone flava	X			X
Eteone longa	X			X
Eulalia sp.		X		
Flabelligera affinis				X D
Harmothoe imbricata	X			X
Harmothoe truncata		X		
Laonice cirrata				X
Nephtys caeca				X
Nephtys ciliata				X
Pareurythoe borealis		X		
Phyllodoce groenlandica				X
Polydora caeca	X			X[4]
Polydora quadrilobata			X	
Praxillella praetermissa			X	X
Pygospio elegans			X	
Sabella crassicornis				X
Scolelepis (Nerinides)sp.sensu				X
Scoloplos armiger	X			
Spio filicornis	X			
Spiophanes wigleyi		X		
Spirorbis sp.		X		
Spirorbis spirillum	X			
Syllis cornuta		X		

studied the relationship between the substrate and two Arctic species, one of which was Macoma balthica, which has been found in Koojesse Inlet. Seven M. balthica per m^2 processed 4,252 gm of sediment per day, thus providing contributions significantly to bioturbation of the active layer. Some species exhibit specific grain size preferences for their habitat. Purchon (1968) found that some infaunal species such as Mya truncata, which maintain burrows to the surface, require certain sediment strengths to support their burrows.

5.2.4 Balanus balanoides

The Crustacea, Balanus balanoides are found living on boulders across most of the tidal flats in Koojesse Inlet. These animals can tolerate a wide range of temperature and salinity conditions. They can survive being frozen in ice and cold temperatures down to -18.6^{o}C (Madsen, 1936, 1940, Kanwisher 1955, Williams 1970, Crisp, Davenport and Gabbott 1977). These species can tolerate temperature ranges up to 25^{o}C in magnitude and their larvae can live in salinities as low as 8% (Cawthorne and Davenport 1980). These tolerances permit the barnacle to settle even in the upper levels of the tidal flat, where they have purportedly reached 5 years of age (Madsen 1936).

B. balanoides release free swimming larvae from its mantle cavity early in the spring (Lucas, Walker, Holland and Crisp 1979, Achituv, Blackstock, Barnes and Barnes 1980). The larvae can survive 3 to 4 weeks before settling (Lucas et al 1979) and must certainly be affected by low salinities during breakup (Chapter 4). The barnacle must settle at an optimal distance from other barnacles. Too close, the larvæ can be crushed by mature members, and too far, other competing species can settle between them. Crisp (1961) observed densities of of 3.05 per cm along grooves in the rock. These densities can change as the animal can modify its shape during growth.

Once settled, there is rapid growth in the spring, moderate growth in the summer and often cessation of development in the autumn and winter (Barnes and Barnes 1959, Lucas et al 1979). It takes 1 to 1¼ weeks for the larva to develop its protective plates, thereafter spring growth ranges from 1 mm per week (Crisp 1961) to 1 mm per month (Barnes and Barnes 1959). The rate is dependent on the quantity of available food and microclimate conditions. Barnes and Barnes (1959) observed that total growth was greatest on seaward facing boulders, but spring growth rates were higher on the landward side. They also found that protective overhangs and south facing exposures in the cooler months contributed to faster growth rates.

5.2.6 *Littorina saxatilis* (Olivi)

Littorina saxatilis (Olivi) was found on all of the transects studied. It is viviparous, producing small independent snails with no larval stage. Most of the young are released in the spring, with inhabitants in upper tidal locations having a greater number of offspring and a longer reproductive season (Roberts and Hughes 1980).

L. saxatilis feed on algae scraped from rock surfaces and pieces torn from macroalgae like *Ulva* and *Enteromorpha*. They do not appear to migrate in any particular direction nor cover long distances during the year. Berry (1956) recovered up to 74% of marked animals over an 8-week period. They reach their greatest densities in their upper tidal range limit. Densities of 370 per .1 m^2 have been obtained in Iceland (Thorson 1933) and 305 per m^2 on the east coast of England (Berry 1956). Little migration and higher reproductive rates in the upshore areas account for these high densities. Optimal living conditions for the L. saxtilis are encountered in the upper shore areas since the animal feeds only when the substrate is wet, but not totally inundated. Greater exposure in the upper tidal flats, permits longer feeding periods where coincidently the greatest algae cover also occurs (Berry 1956).

5.2.6 Botanical Studies

Since the Canadian Arctic Expedition, 1913-1916 (Dall 1924) much of the work on Arctic algae has been incidential and the results of biological resource studies, as opposed to direct studies on attached algae. Thorson (1933) examined the algal community in terms of its relationship to the faunal species. Madsen (1936) noted the well developed littoral flora along rocky shorelines, of which Fucus vesiculosus and Ascophyllum nodosum were particularly conspicuous.

In more recent years, the marine algae of the northeastern coast of North America has been studied by Taylor (1957), Wilce (1959, 1968) and South (1970, 1976). Species living along the coasts of Newfoundland, and Labrador are also found in Frobisher Bay. Ellis and Wilce (1961) collected some of the notable intertidal algae present across the tidal flats in Frobisher Bay.

5.3 Macrofauna Collection Methodology

The macrofaunal community was intensively studied along the four transect lines: Apex, Rock, Rodgers Island and STB. Based on information obtained from preliminary research in 1980, a variety of sampling schemes were employed to ensure proper coverage of the numerous species.

Infaunal species identification and abundance studies were carried out using numerous 4 m^2 quadrats at 50 m intervals at Apex and 25 m intervals at Rock and Rodgers Island transects. Collections of bivalves, anthozoans, priapulids and sipunculids were made at this time, of which the bivalves were of particular interest. Substrate cover and grain size estimates were also made at this time.

Studies of the dominant gastropod, Littorina saxatilis were undertaken at the Apex, Rock and STB transects. A line perpendicular to the shore was followed from high to low water. A 50^2 cm^2 grid was placed on every boulder encountered on the line with a surface area greater or equal to the grid. The boulder was measured and the number of L. saxatilis in the grid recorded. Their migration habits were studied at Apex and STB. Ten L. saxatilis were marked with coloured polish at 50 m intervals at STB and randomly at Apex. Over the following 19 and 24 days counts of the animals were taken to determine their rates of migration.

The low relief and wide tidal range experienced at STB, were ideal for intensive research on the optimal habitat of the Balanus balanoides. At STB, the four largest boulders between each 50 m interval were selected for study. The boulders were measured and estimates made on the barnacle coverage and position (orientation) of maximum barnacle density. On each boulder, the two sides with the largest population were chosen for more intensive study. Densities were determined from a 10 by 10 cm grid placed on the 5 largest barnacles. Their sizes were taken with a set of precision calipers.

An estimate of barnacle growth during the ice free period was made at Apex and STB. The height, width and breadth of 26 marked barnacles, within the area of maximum concentration, were recorded twice - at the end of July and again, 24 days later.

5.4 Infaunal Studies

5.4.1 Introduction

From the 4 m^2 quadrat studies the total density of macrofauna at each site was calculated and shown in Tables 5.4, 5.5, 5.6 for each transect studied. The macrofauna observed were divided into 9 categories for ease of collection and data analysis. The first 5 categories contained the bivalves, *Cyrtodaria kurriana*, *Hiatella arctica*, *Mya truncata* and *Thracia myopsis* which were all infaunal and *Musculus discors* and *M. niger* which were not. They were frequently found attached to the surface substrate, rock and algae by byssal threads. Category 6 pertained to the presence or absence of the gastropod *Margarites* sp. (no distinction made of the various species) which lived on algal fronds. The total number of sea anemones (anthozoa) were recorded since it was not always possible to distinguish between the two species (*Tealia tellina*, *Stomphia coccinea*). Priapulids, of which *Priapulis caudatum* was identified, were counted, as were the infaunal

Table 5.4 Apex Transect Macrofauna Densities

Distance from shore (m)	Ht. above tidal datum (m)	Density No/ 4 m^2	Standard Deviation	Number of Species 1.
0	5.1	0	-	2
50	4.1	3	-	3
100	3.9	4.2	6.7	5
150	3.2	.33	.6	3
200	2.9	18.5	26.2	3
250	2.7	4	-	2
300	2.6	1.7	1.2	3
350	2.6	2.8	3.8	3
400	2.5	1.9	3.7	5
450	1.8	18	11.05	8

1. Includes Littorina and Balanus balanoides

Table 5.5 Rock Transect Macrofauna Densities

Distance from shore (m)		Height above tidal datum (m)	Density No/ 4 m^2	Standard Deviation	Number of Species
Line #1	0	3.5	0	-	1
	12.5	3.1	0	-	1
	25	3.7	0	-	2
	50	3.0	.5	.71	3
	75	2.2	0	-	3
	100	1.4	14.7	6.8	5
Line #2	0	≃ 3.5	0	-	
	12.5	≃ 3.1	0	-	
	25	≃ 3.7	0	-	
	50	≃ 3.0	.5	.71	
	75	≃ 2.2	.5	.71	
	100	≃ 1.4	17	6.78	
Line #3	0	≃ 3.5	0	-	
	12.5	≃ 3.1	0	-	
	25	≃ 3.7	0	-	
	50	≃ 3.0	0	-	
	75	≃ 2.2	1.0	1.4	
	100	≃ 1.4	10.25	2.2	

Table 5.6 Rodgers Island Macrofauna Densities

Distance from shore (m)	Ht. above tidal datum (m)	Density No/ 4 m^2	Standard Deviation	Number of Species
35.5	4.2	3.75	2.6	2
50	3.9	16.0	29.3	4
75	2.2	54.2	41.2	4
100	2.0	91.75	32.7	5
125	1.9	85	11.2	9
150	1.7	110.2	24.0	5
175	1.6	109.0	68.6	5
200	1.5	89.7	58.4	6
225	1.5	44	1.0	6
250	1.3	18.5	2.12	4
275	1.3	14.7	4.7	5

echiura, possibly from the bonelliidae family and a new find in the area. The density of the macrofauna in each category per 4 m^2 is given in Tables 5.7, 5.8, 5.9 for each line.

This section begins with a discussion on the results obtained for each transect and concludes with a comparison between the transects.

5.4.2 Apex Transect

Examination of Table 5.4 and Figure 5.1a,b reveals that there are two major concentrations of animals on the flats, one at 200 m (2.9 m ALLT) and another at 450 m (2.5 m ALLT). The density of 18.5/4 m^2 at 200 m is not truly representative of the area, as it has an abnormally high number of echiura. Thirty-seven were encountered living in a patch of fine sands, which were significantly finer than the surrounding substrate. The high density of 18 at 450 m reflects the lower tidal height, the profusion of pools, and the coarse sands particularly ideal for infaunal molluscs. At this level, an increasing number of molluscs, notably M. truncata, M. discors and H. arctica and sea anemones were encountered.

Figure 5.2 illustrates the tidal range occupied by the species sampled at Apex. The actual densities obtained by these species at the sampling sites, is shown in Figure 5.3. The Apex transect was dominated by sea anemones which accounted for 60.8% of the total animals counted. Sea anemones reached a maximum density of 9.9 per 4 m^2 at 450 m. Likewise, priapulids had a maximum density of 6.5 at this low tidal site. The peak in densities at 350 m for both of these species was due to a tidal pool in the vicinity which never completely drained.

Table 5.7 Density of the individual species at Apex Transect per 4 m^2

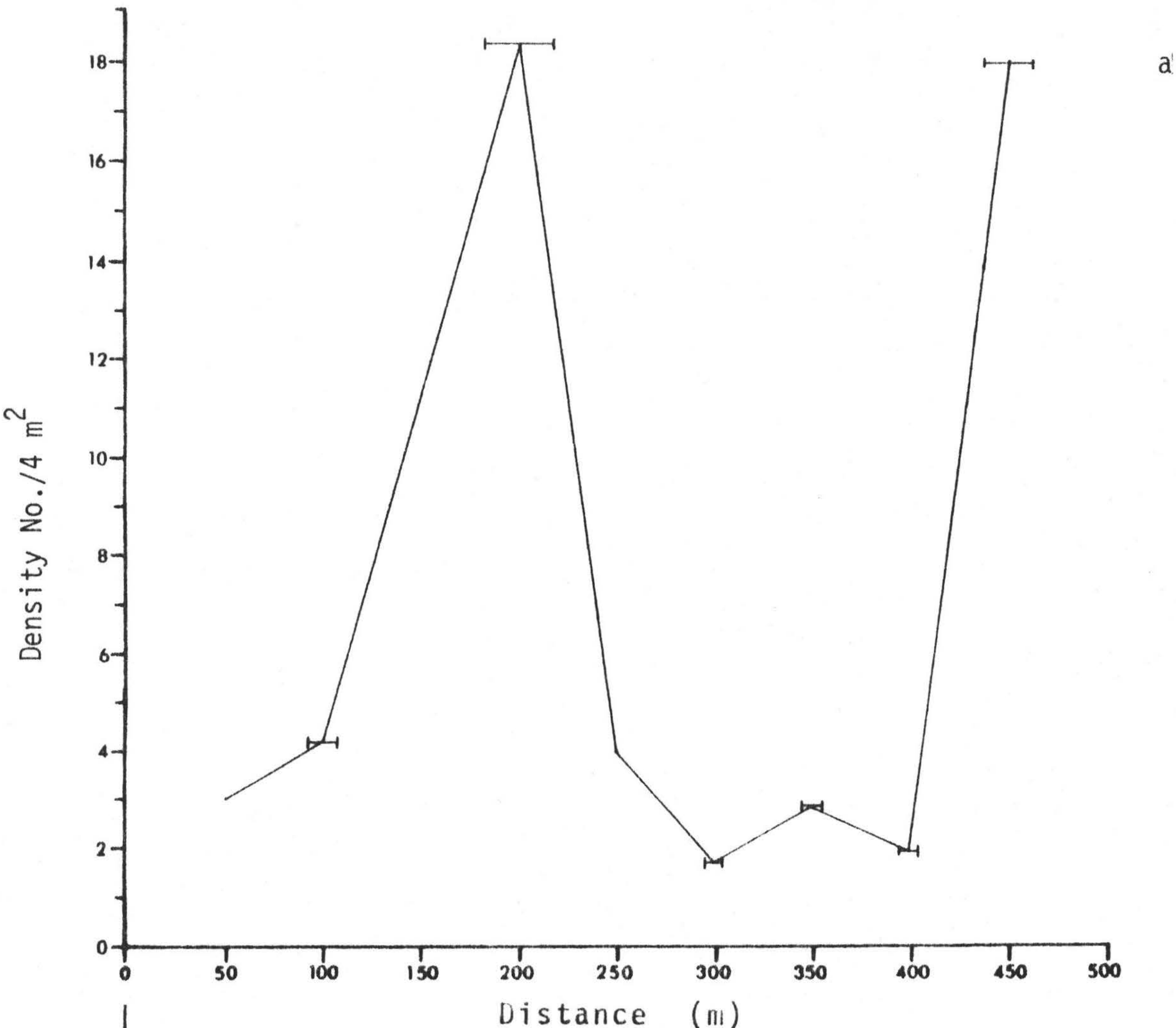
Distance (m)	Cyrtodaria kurriana	Hiatella arctica	Musculus niger (discors)	Mya truncata	Thracia myopsis	Margarites sp.	Sea Anemone	Priapulid	Echiura
50	-	-	-	1.2	-	-	3	-	-
100	-	.2	-	-	-	-	2.6	-	.6
150	-	-	-	-	-	-	-	.33	-
200	-	-	-	-	-	-	-	-	18.5
250	-	-	-	-	-	-	-	-	4
300	-	-	-	.33	-	-	1.33	-	-
350	-	-	-	-	-	-	2.0	.83	-
400	-	-	-	.7	-	-	.57	.57	-
450	-	.1	.18	.45	-	-	9.9	.64	3.1

Table 5.8 Density of the individual species at Rock Transect per 4 m^2

Distance (m)		Cyrtodaria kurriana	Hiatella arctica	Musculus niger (discors)	Mya truncata	Thracia Myopsis	Margarites	Sea Anemone	Priapulid	Echiura
25 m	L#1	-	-	-	-	-	-	-	-	-
	L#2	-	-	-	-	-	-	-	-	-
	L#3	-	-	-	-	-	-	-	-	-
150 m	L#1	-	-	-	-	-	-	.5	-	-
	L#2	-	-	-	-	-	-	.5	-	-
	L#3	-	-	-	-	-	-	-	-	-
75 m	L#1	-	-	-	-	-	-	-	-	-
	L#2	-	-	-	-	-	-	.5	-	-
	L#3	-	-	-	-	-	-	1.0	-	-
100 m	L#1	-	-	-	.333	-	.667	5.7	1.67	5.0
	L#2	-	-	-	1.4	-	-	13.43	2.1	
	L#3	-	-	-	.5	-	-	7.0	2.25	

Table 5.9 Density of the individual species at Rodgers Island per 4 m^2

Distance (m)	Cyrtodaria kurriana	Hiatella arctica	Musculus niger (discors)	Mya trauncata	Thracia myopsis	Margarites sp.	Sea Anemone	Priapulid	Echiura
35.5	-	-	-	-	-	-	3.75	-	-
50	-	-	-	-	-	-	1.6	-	-
75	51	-	-	.5	-	-	3.2	-	-
100	79.3	-	-	-	.38	-	11.4	-	.63
125	81.8	-	-	.4	.8	-	7.4	.2	8.6
150	91.4	-	-	.6	2.0	-	7.4	-	9.0
175	92.8	.75	-	1.75	2.0	-	7.5	-	4.3
200	81.7	-	-	2.3	-	-	4.3	-	1.3
225	44	-	2	2	-	-	8	-	-
250	3.5	-	-	-	-	-	14.5	-	-
275	-	-	.67	3.7	-	-	11.0	-	-



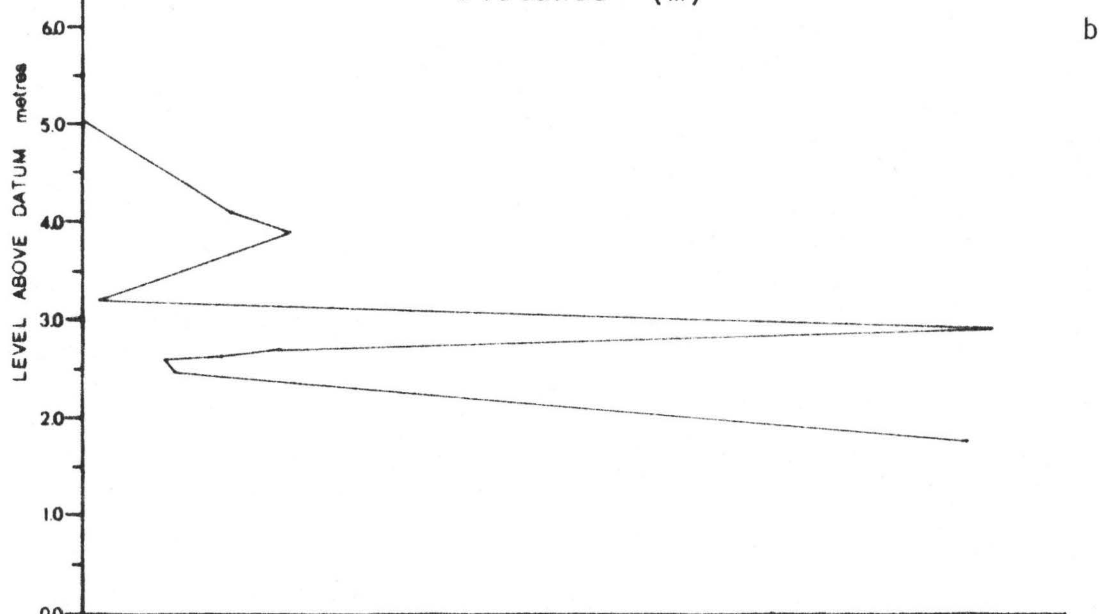


Figure 5.1a,b Apex transect macrofauna density against distances and tidal height.

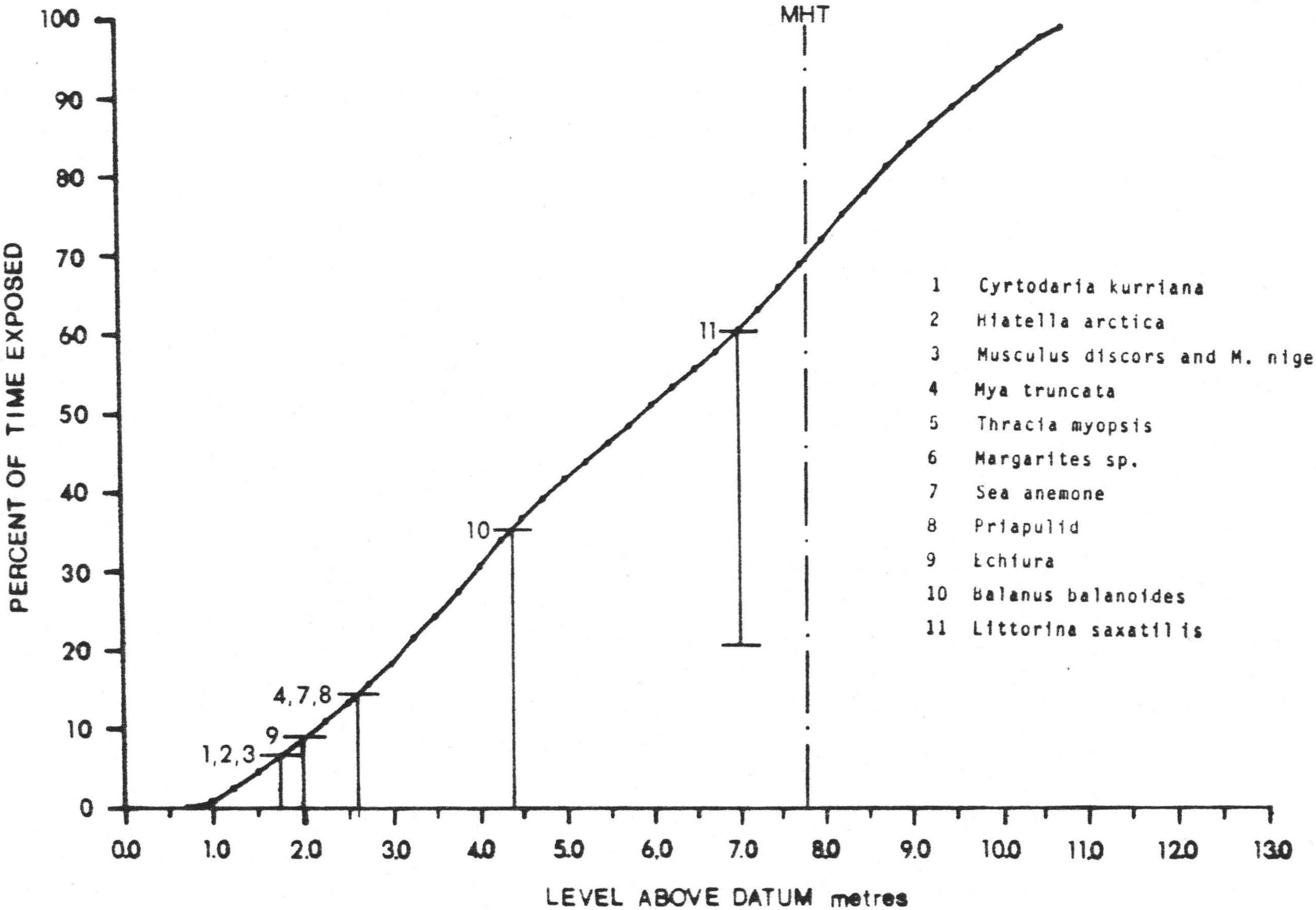


Figure 5.2 Exposure curve against the tidal range of Apex macrofauna species.

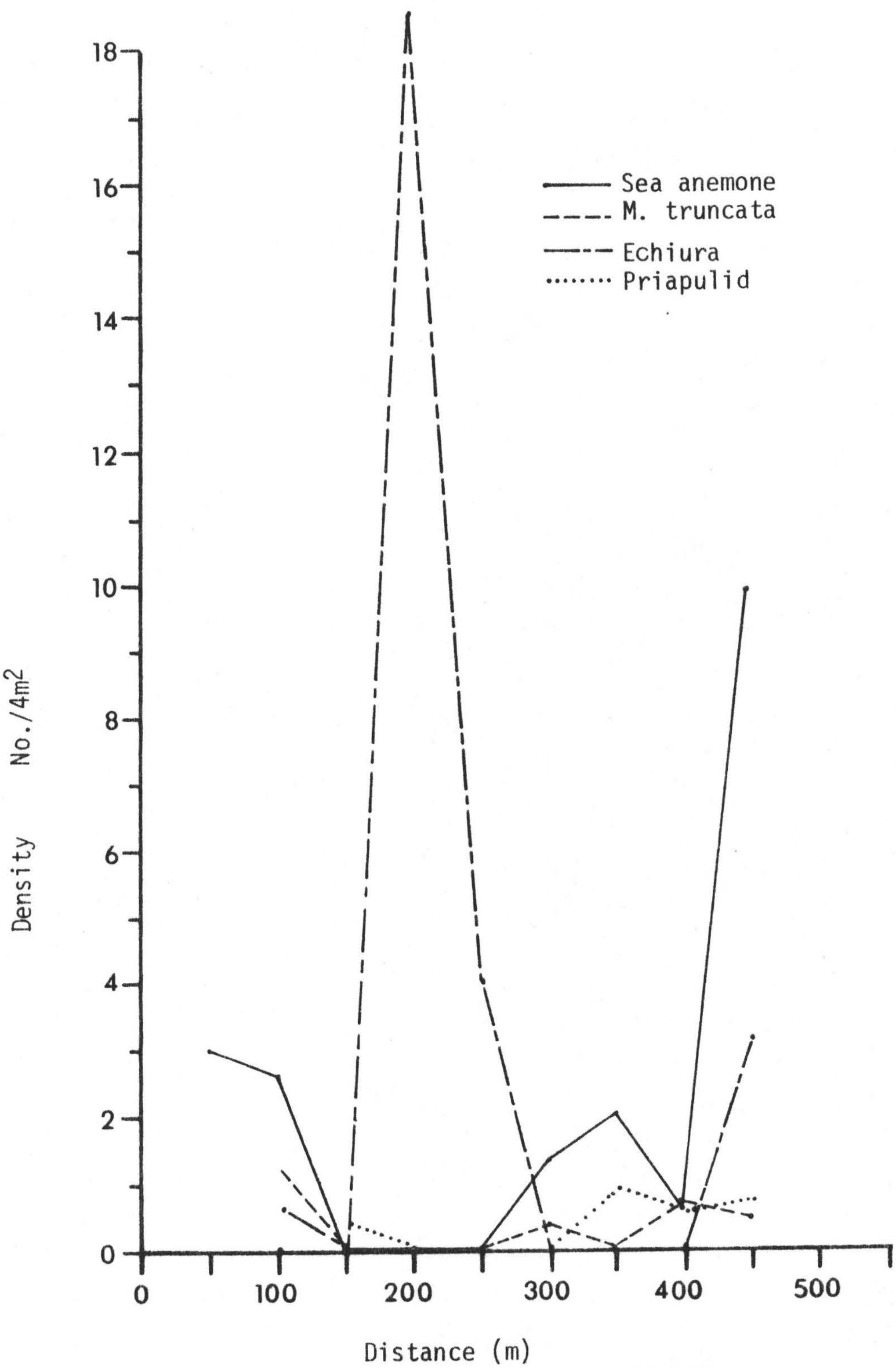


Figure 5.3 Densities (4 m^2) of macrofauna across the Apex transect.

A tidal pool behind the boulder ridges at 100 m hosted a variety of low tidal species not normally encountered so high on the flat. Mya truncata, Hiatella and echiura were all found at this site. The high numbers of echiura at 200 m were noted earlier.

5.4.3 Rock Transect

Three transects approximately 100 m apart were surveyed at the Rock Transect site (Table 5.5, 5.8). The highest total macrofauna densities were obtained approximately 100 m from shore, at 2.2 m above tidal datum. Densities of 14.7, 17 and 10.25 per 4 m^2 were obtained. These high densities were expected, given the low aerial exposure and the well sorted sands conducive to infaunal populations existing at this site (Fig. 5.4, 5.5).

The relative absence of fauna shoreward was due to higher tidal levels, less available sediment due to a high boulder coverage, and the winter ice foot which froze to the bed over most of the tidal flat. The intense ice action the area underwent was discussed in Chapter 3. The presence of the ice until late in the spring discourages larvae which require water for fertilization or for migration to new sites, such as the barnacles, M. truncata and sea anemones.

The ice foot which reached thicknesses over 3 metres, provided copious amounts of fresh water for the flat. Only fresh water tolerant species like M. truncata and the adult L. saxatilis could survive this period. Littorina were observed living on the substrate under the ice during melt.

The effect of ice on the lower margins of the Rock Transect

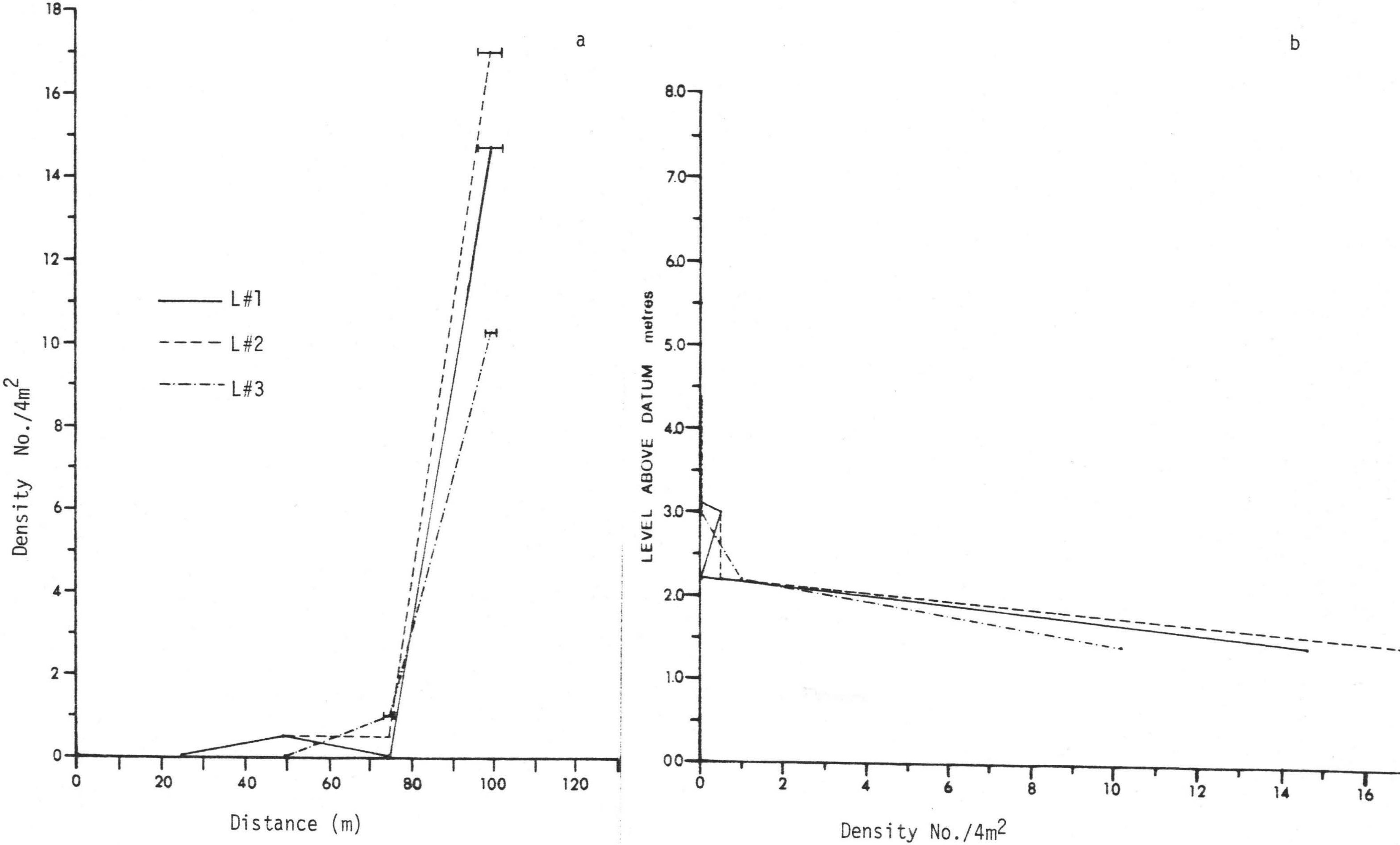


Figure 5.4a,b Rock transect macrofauna density against distances and tidal height.

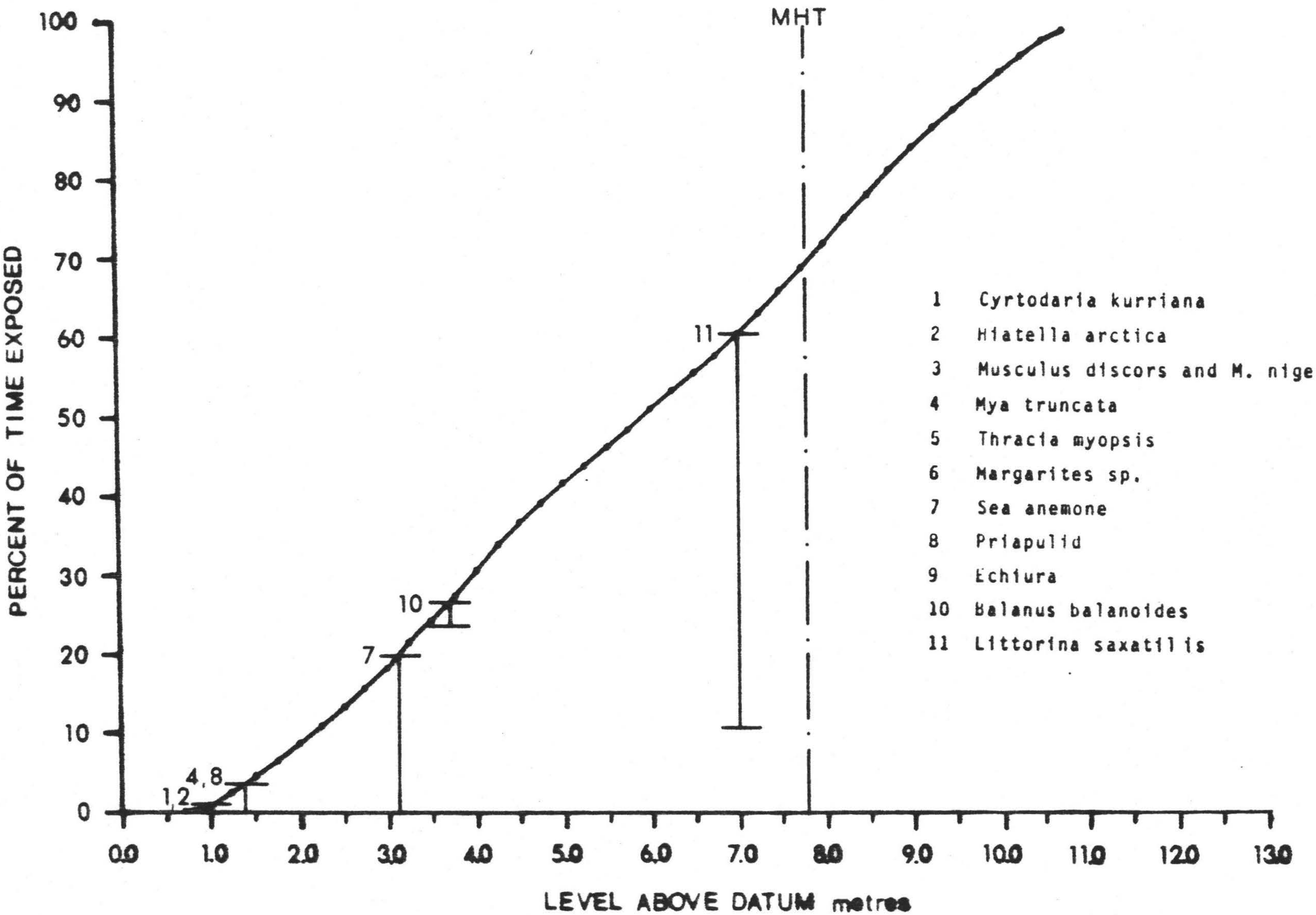


Figure 5.5 Exposure curve against the tidal range of Rock transect macrofauna species.

was discussed in Chapter 3. Ice floes stranded in the area late in the 1980 season killed the Cyrtodaria and Hiatella populations evident at low water. Neither species showed any sign of recolonizing their previous sites in 1981, thus demonstrating the slow recovery rates in this sensitive environment.

The Rock Transect had the lowest macrofaunal species diversity of any of the lines covered, due to the ice foot and the stranding of ice floes in early August 1980. Only 5 species were noted on this flat, but all were numerous (Table 5.10). Like Apex, the greatest percentage of the population was the sea anemone at 70.8%, followed by priapulids 13.9%, echiura 8.1%, Mya truncata 6.2 and Margarites 1%. Only sea anemones occurred shoreward of 100 m in small pools on the flat (Table 5.8). The tidal ranges of the macrofauna observed in 1980 and 1981 are graphed versus exposure in Figure 5.5. Sea anemones and echiura were observed to inhabit the tidal pool at 25 m in 1980, with a few sea anemones still there in 1981.

Barnacles were found in great densities on all of the other transects studied. Only 20 Balanus in total were found across the entire Rock transect. They lived in well protected cracks and overhangs, on a number of the largest boulders on the boulder ridge at 25 m. The ice foot and accompanying ice effects probably account for their unusual absence.

5.4.4 Rodgers Island Transect

A single transect was surveyed in 1981 at Rodgers Island. This area had the highest macrofaunal densities encountered in this study

Table 5.10 Percent macrofauna species at each transect

Transect	Cyrtodaria kurriana	Hiatella arctica	Musculus niger (discors)	Mya truncata	Thracia myopsis	Margarites sp.	Sea anemone	Priapulid	Echiura
Apex Transect	-	.7	.7	6.1	-	-	59.5	6.5	26.6
Rock Transect	-	-	-	6.2	-	.96	70.8	13.9	8.1
Rodgers Island	80.7	-	.13	1.4	.92	-	13.0	.03	3.7
Mean Percent	26.9	-	.3	4.6	.3	.3	47.8	6.8	12.8

(Table 5.6). Densities of 110.2 and 109.0 per 4 m^2 were obtained at 150 m (1.74 m ALLT) and 175 m (1.64 m ALLT) respectively (Fig. 5.6a b). High standard deviations at 175 m (St.D. 68.6) and 150 m (St.D. 24.0) illustrate the great variability in animal density encountered even over short distances. This variability was mainly due to the presence or absence of ponds and tidal channels where slight differences in the surface substrate were evident. It may also reflect ice gouging kill of the sedentary species.

The high densities were mainly due to the dominance of Cyrtodaria kurriana which accounted for 80.7% of the total animals found (Table 5.10, Fig. 5.7). This infaunal species burrowed into the active layer of the substrate where it was restricted from further downward movement by the clay layer. It requires long periods of inundation (80%) and needs sediments suitable for burrowing like the well sorted medium sands found at this transect. C. kurriana also appear to be sensitive to ice action and low salinities, thus the low tidal areas < 3.95 m on this flat were well suited to their growth. Although no measurements were taken, C. kurriana were a wide variety of sizes, indicating the presence of both adult and juvenile specimens.

Thracia myopsis, which made up .8% of the total species, also had its highest densities at 150 m and 175 m from shore (Fig. 5.7). M. truncata increased in density in a seaward direction as it did at the other transects. Mya is a suspension feeder, straining debris from the sea water through a siphon which it extends to the surface. Thus, it requires high inundation periods (80%). Since the animal is only capable of digging one burrow in its lifetime, it is important

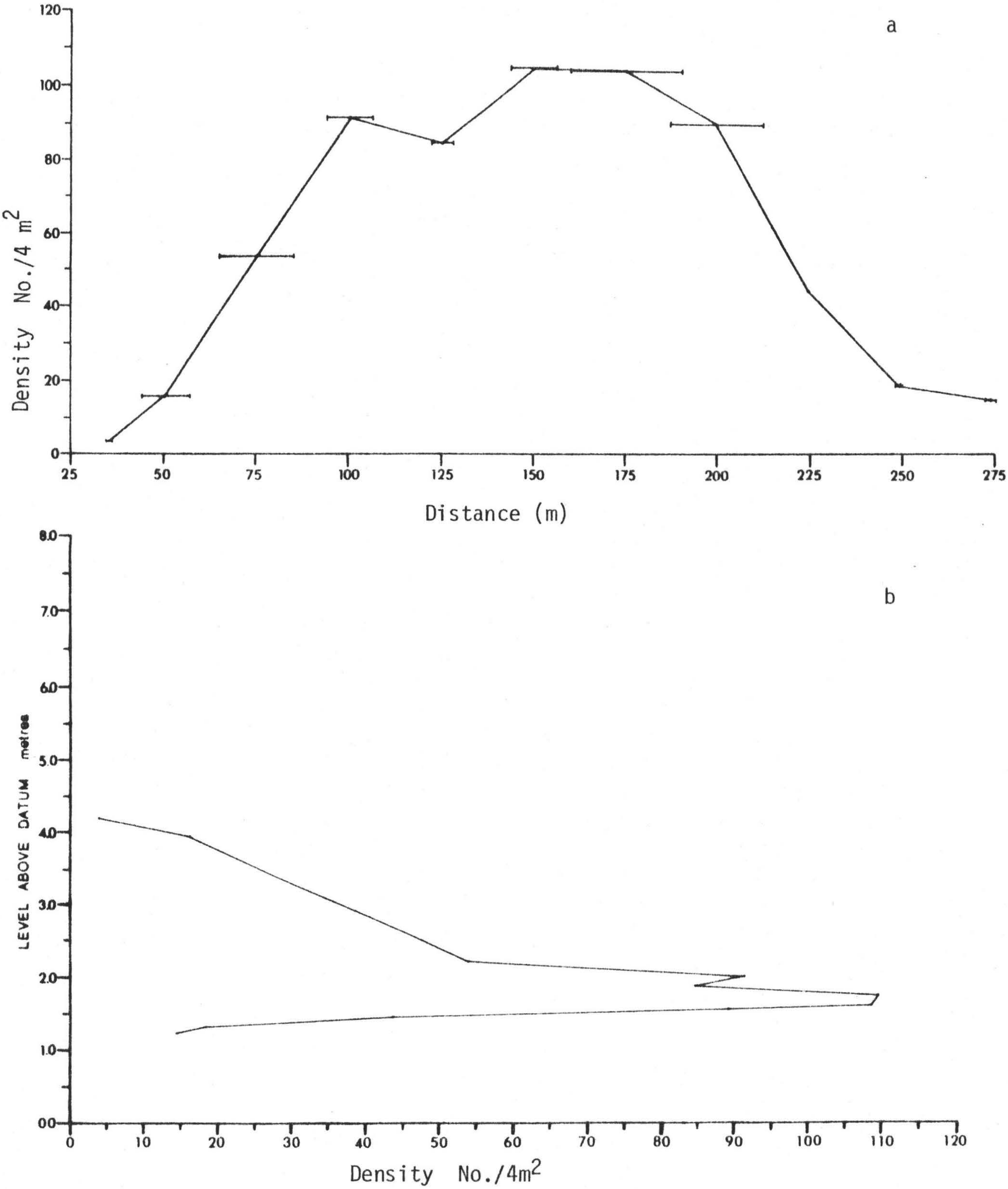


Figure 5.6a,b Rodgers Island macrofauna density against distance and tidal height.

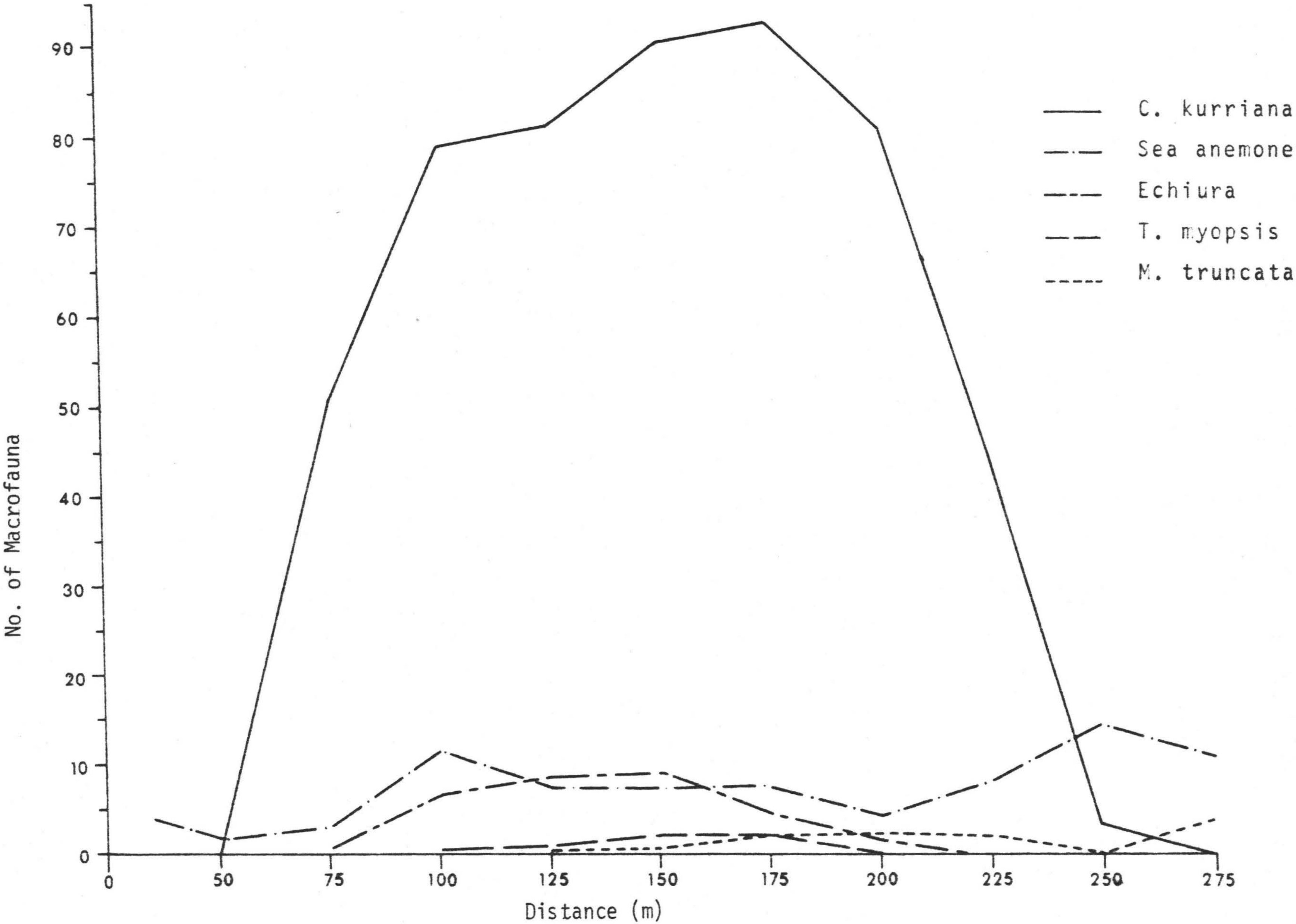


Figure 5.7 Densities ($4m^2$) of macrofauna across Rodgers Island transect.

the sediment be cohesive enough to support this burrow, like the sands on this flat. On average, Mya burrowed 21 cm into the substrate and often into the clay layer as well. One interesting phenomena noted during sampling, was the animals apparent avoidance of too much insolation During early morning low tides, the Mya siphons were evident above or at the surface. Fewer siphons were observed at the surface at low tides during the day. This probably related to higher surface temperatures and possible dessication since the animal cannot completely close its shell. Another explanation for the low water distribution of Mya relates to its value as a food source for the local people.

Echiura were found in densities between 8.6 and 9.0 per 4 m^2 between 125 m (1.87 m ALLT) and 150 m (1.74 m) from shore. As noted earlier, this animal prefers relatively fine surface sediments on which to feed, since they are surface deposit feeders. They also require cohesive sediments to support the U-shaped burrow in which they live. The area between 100 and 200 m fit these requirements. The animal was restricted past 200 m by slightly coarser sediments and lower exposure.

Of the 5 major categories, not one had its peak density at the same site (Fig. 5.7). The tidal and exposure range in which the Rodgers Island species lived is illustrated in Figure 5.8. Both Thracia and echiura appear to have a lower tidal limit of 1.5 m, 5% exposure. The relative rarity of Balanus and Littorina was also due to tidal limits. The zone preferred by these animals was the bedrock cliff at Rodgers Island which was covered by an ice foot in the

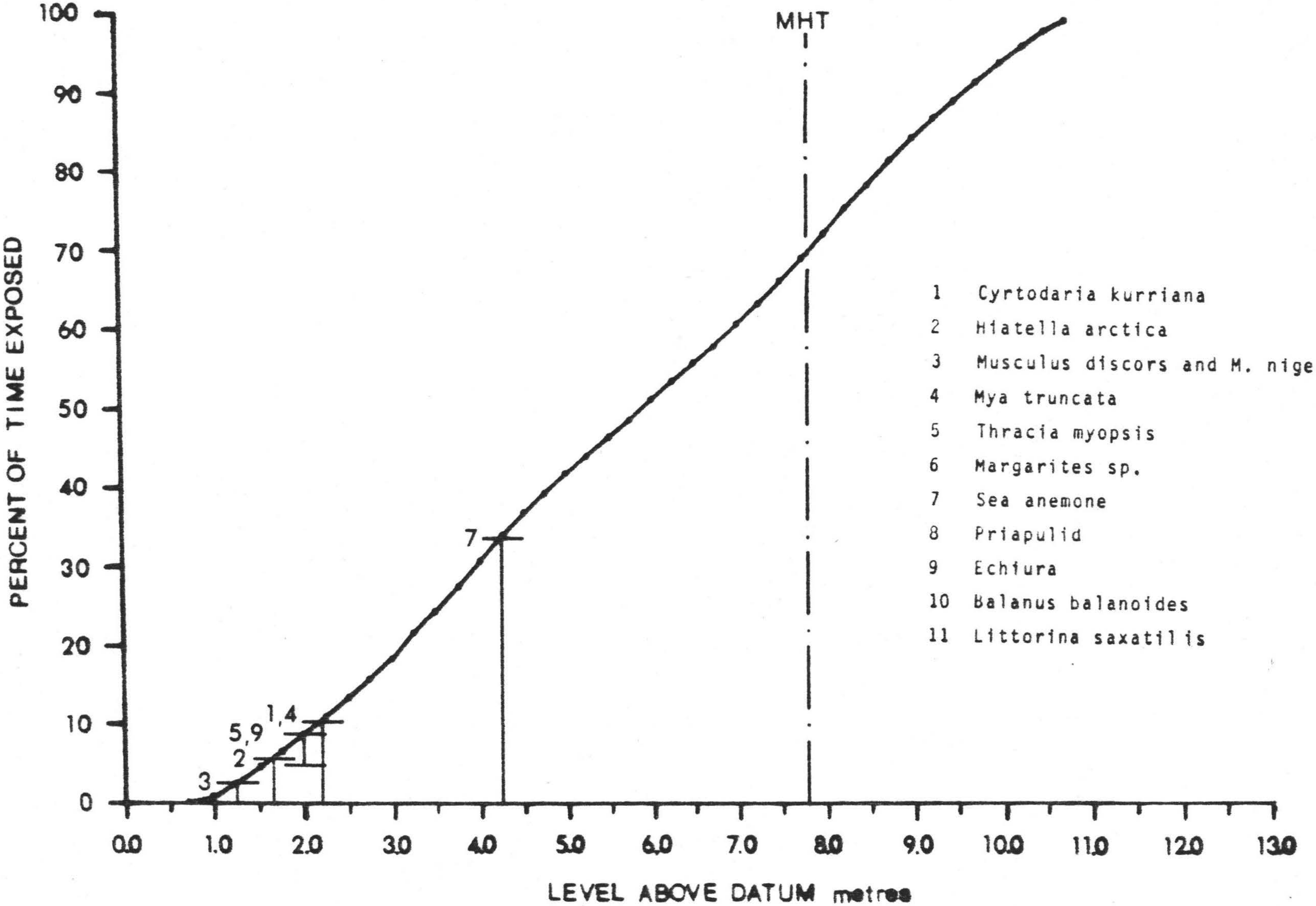


Figure 5.8 Exposure curve against the tidal range of Rodgers Island macrofauna species.

winter, thus discouraging their growth.

5.4.5 STB Transect

Quadrat studies at STB in 1980 out to 550 m (3.8 m ALLT) failed to show any infaunal macrofauna. Subsequent observations have shown that sea anemones and Crenella faba which live on the algae attached by byssal threads, were evident around the 600 m mark. A few empty Musculus, Mya and Hiatella valves were washed upshore, indicating that they may live at the lower limit of the tidal flat. Figure 5.9 illustrates the zonation across these flats from the available information.

5.4.6 Comparisons Between the Transects

Table 5.10 shows the percentages of the various species found at each of the lines. Thus, the dominant species by abundance, can be determined for each line. Sea anemones are the dominant species at both Apex and Rock transects. They are followed in importance by echiura at Apex and priapulids at Rock transect. Mya is of similar importance at both lines. At Rodgers Island, sea anemones take second place in terms of number. Approximately 80.7% of the total animals counted were C. kurriana. The low percentage values for Mya and Musculus at Rodgers Island are a result of the comparatively large number of C. Kurriana. Numerically, many more Mya and Musculus were found at Rodgers Island, than the other transects. The low density of Mya at Apex is in part due to the collection of this edible mollusc over many years. At present, an average maximum Mya density is 3.7 per 4 m^2 at Rodgers Island. Collections, such as one made in 1981,

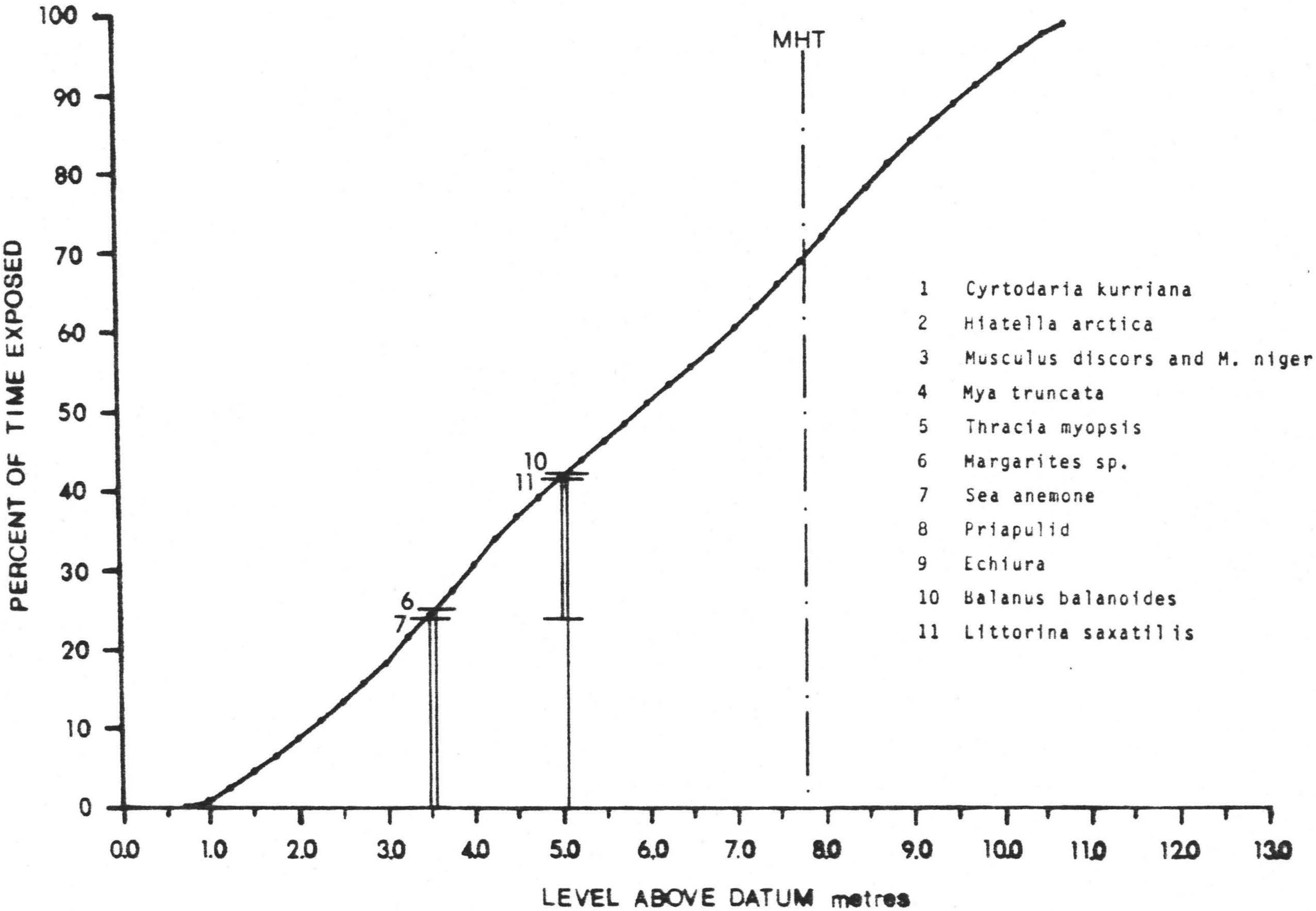


Figure 5.9 Exposure curve against the tidal range of macrofauna on STB in 1980, 1981.

which yielded 210 individuals during 2 low tides, seem likely to deplete the population over the next few years.

Figure 5.10 illustrates the relationship between tidal height and macrofaunal densities at the various transects. The highest densities occurred between 1.4 m and 2 m ALLT on all of the transects. Thus, tidal height is an important factor in the biological zonation. The greatest diversity of species also occurred within this range (Fig. 5.11). There were 9 species at 1.9 m ALLT at Rodgers Island, and 8 at Apex (1.5 m). A maximum of 5 species were found at 1.4 m ALLT at the Rock transect, however Hiatella and Cyrtodaria were eliminated there in 1980. In general, the diversity increased with depth on the tidal flats.

In Figure 5.12 the distribution of the various species with tidal height is shown for all four transects. Mya, Cyrtodaria, Hiatella and Musculus have upper tidal limits within 1.2 m of each other for all the transects, indicating some tidal control. Mya and Cyrtodaria begin around 2.5 m ALLT and Hiatella and Musculus at 1.75 m ALLT.

The echiura distribution appears to be determined by the occurrence of the proper substrate. Their upper limit was around 3.0 m ALLT, excluding tidal pools on Apex at 4.25 m above tidal datum. Their variation seaward of 3.0 m seemed dependent on the presence of fine sediment. Their limit, discussed earlier may reach 1.0 m ALLT depending on the substrate.

Sea anemones were found in tidal pools, water filled depressions or under protective algal fronds, below 4.5 m ALLT.

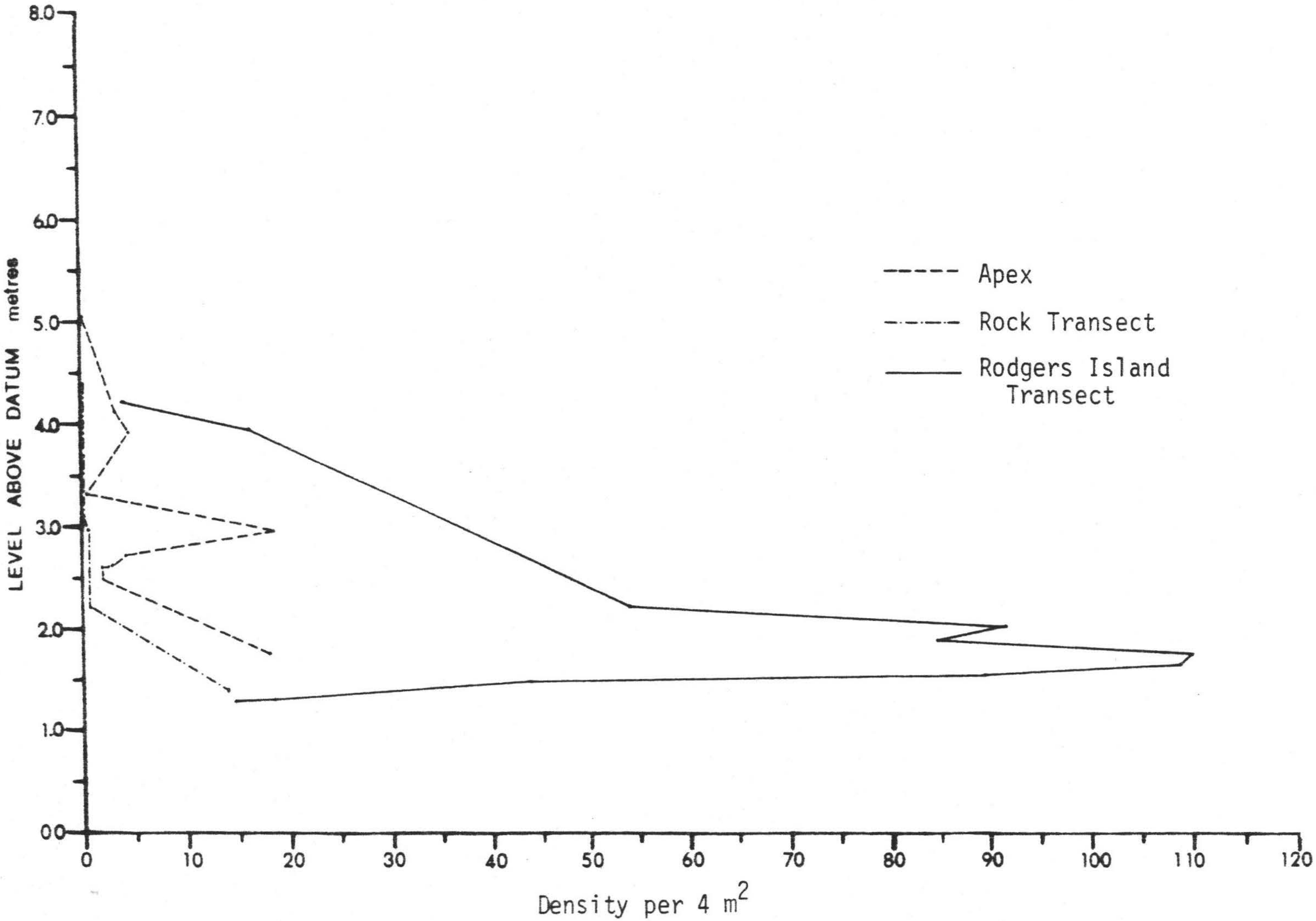


Figure 5.10 Density of macrofauna (4 m^2) on Apex, Rock and Rodgers Island transects against tidal height.

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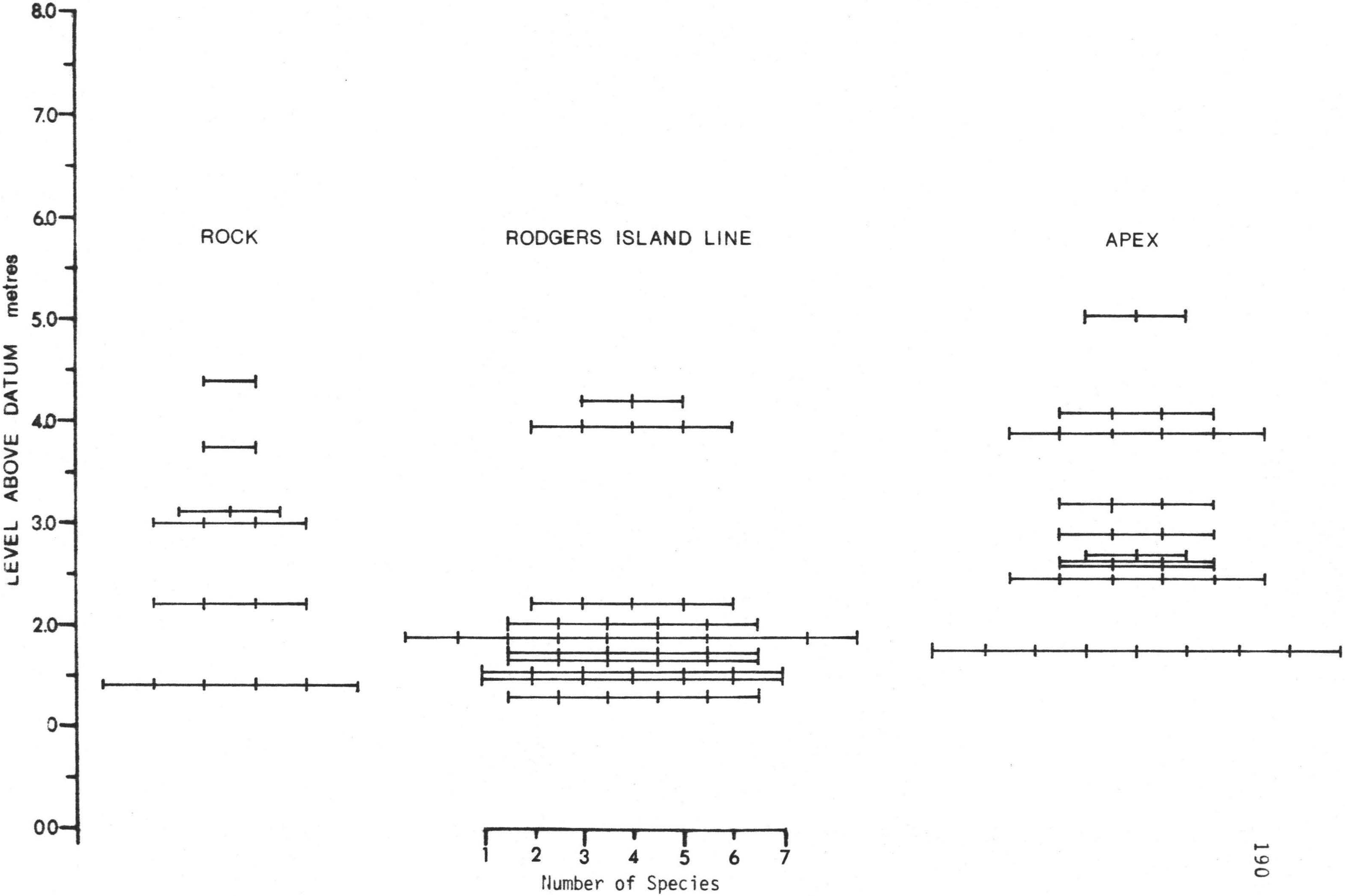
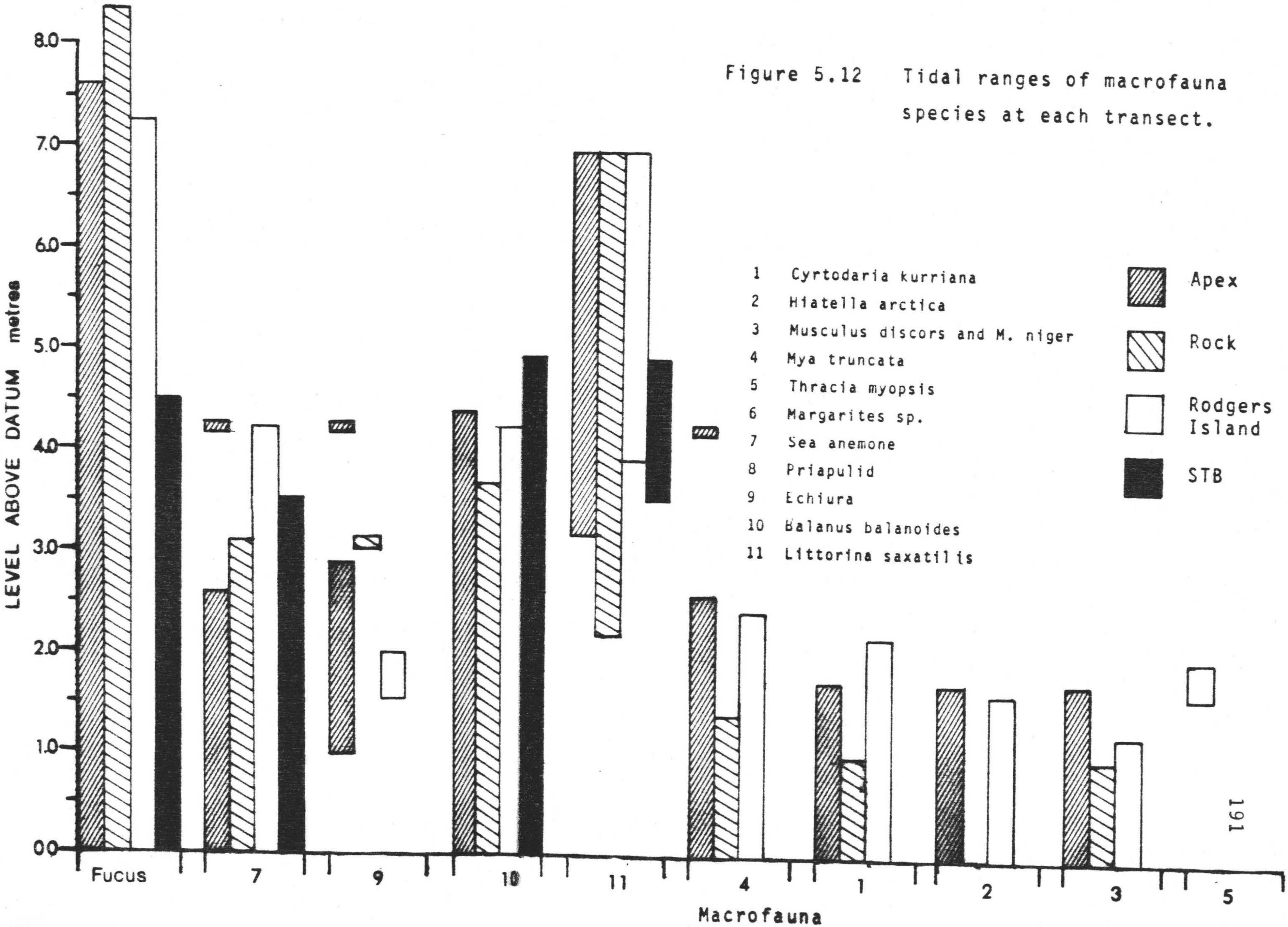


Figure 5.11 Number of macrofauna species against tidal height at each transect.

Figure 5.12 Tidal ranges of macrofauna species at each transect.



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5.5 *Littorina saxatilis*

5.5.1 *Littorina saxatilis* Distribution

The distribution of, *Littorina saxatilis* was examined over three transects Apex, Rock and STB (Fig. 5. 2 , 5. 5 , 5. 8). All three transects exhibit a great deal of similarity. The total number and density (per 50^2 m^2) of *Littorina* decrease seaward and shoreward of a central concentration - presumably this is their optimal habitat (Fig. 5.13a, 5.14a, 5.15a). This maximum concentration occurs around 4.0 m ALLT on all 3 transects. Maximum densities also occurred at this height, with 55.3 individuals per 50^2 m^2 at Apex, 87.7 at Rock transect and 17 at STB. Four m above tidal datum also marked the height of maximum boulder concentrations across these transects, which likewise influenced the number of *Littorina* at this height.

Differences in number between the lines reflect local constraints. High densities at the Rock transect were probably due to its relatively more sheltered location from wave action, than the transects on the north side of Koojesse Inlet. The boulder ridges at the Rock transect and Apex also probably provided shelter for the *Littorina* as well as sites for micro-algal growth on which they feed. Fewer, and more isolated boulders in the upper tidal range of STB, probably limited the number of *Littorina* on this transect. The lower densities at the boulder ridge at 4.0 m ALLT on STB may be due to strong tidal currents which scour around this ridge (Chapter 4).

Sparce densities of *Littorina* occur above 5 m ALLT due to increasing exposure, although they were found up to 7.0 m ALLT in crevices on the bedrock. None were found below 1.0 m ALLT.

5.5.2 Migration of *Littorina saxatilis*

The migration of *Littorina* was studied at Apex and STB during the ice free period in 1981. The results are summarized in Tables 5.11 and 5.12. At Apex, 68% of the marked *Littorina* did not move any appreciable distance from their initial location over a 24-day period. A 58% recovery was obtained for these same *Littorina* 3 days earlier. The apparent missing *Littorina* had retreated to the macroalgae, *Fucus evanescens* due to strong winds and wave action. Once environmental conditions improved, they moved back to the open rock surface. Thus, wind and wave action play a role in *Littorina* activity.

Wind and wave action may also explain why few *Littorina* were found on the upper flats of STB. Isolated boulders, with little fucal cover offered little to no protection for these animals under wave action, thus few inhabit the area. In the more seaward areas where significant numbers are found, little migration occurred in 1981. Over a 19-day period, 88% of the *Littorina* were recovered at STB. The apparent lack of large scale movement suggests that the limits of major *Littorina* concentration will not vary throughout the open water season, in response to changes in wave and tidal conditions.

5.6 *Balanus balanoides*

5.6.1 *Balanus balanoides* Growth Rates

Estimates were made on the growth rate of *Balanus balanoides* during the summer in 1981, as an indicator of the age of the population. Twenty-six barnacles were measured at 3 sites at Apex. The average increase in height was 1.32 mm and .93 mm in breadth over 24 days.

Table 5.11 Number of <u>Littorina saxatilis</u> found over time at Apex

Distance (m)	Height ALLT	July 26 1981	July 28 1981	August 15 1981	August 18 1981
0	5.1	10	6	6	6
13.3	4.7	10	7	7	7
23.5	4.4	10	8	2	5
32.1	4.1	10	9	5	5
50	4.1	10	10	4	10
74.7	3.7	10	10	10	10
89.9	4.3	10	8	3	5
100	3.9	10	10	2	7
125	3.6	10	8	6	6
140	3.5	10	10	10	
160		10	6		
% Recovery			84.4	50	67.8

Table 5.12 Number of *Littorina saxatilis* found over time at STB

Distance (m)	Height ALLT	July 26 1981	July 30 1981	August 13 1981
150	5.0	6	6	6
200	4.3	10	10	10
250	4.4	10	10	8
300	4.1	10	10	10
350	4.5	10	10	10
400	4.2	10	9	8
450	4.1	10	8	10
500	4.1	10	8	5
% Recovery			93.4	88.5

Thus, most of the barnacles on the flats are at least 1 year in age, and have successfully wintered under the ice at least once.

5.6.2 Balanus balanoides

The density of barnacles reached a maximum of 164.4 per 100 sq cm between 350 m and 400 m (4.2 to 4.5 m ALLT) at STB (Table 5.13). Seaward and shoreward the densities decreased. This was partly due to a decrease in the size and number of boulders between 0 m and 100 m and seaward of 600 m. It was also due to tidal range limits. The upper limit appears to be around 5.0 m ALLT and the lower limit may be more a function of available sites than tidal constraints.

The greatest concentrations of barnacles were found on the east facing sides of the boulders studied (Table 5.14). These large densities occurred on the east side 30% of the time. Maximum concentrations occurred on the seaward (south) facing side of the boulder 25% of the time, 18% of the time to the west and 16% facing landward (north). Greater exposure to insolation on the east and seaward facing sides of the boulders may explain the greater densities which occurred there.

Relationships between the size (volume = .065 x height (width + breadth)^2) of the barnacles and distance is not as readily apparent (Table 5.13). The smaller barnacles were found close to shore in the upper reaches of the flat. Shorter periods of inundation shortens the feeding time for the barnacle, which could account for their slightly smaller volume.

Table 5.13 <u>Balanus balanoides</u> Information

Site (m)	Height ALLT	Mean Rock Vol. sq. cm.	Density in 10 x 10 cm	Standard Deviation	Mean Vol. of Barnaclus	St. D.	No. of Sites Examined
50-100	5.9-5.2	5,770.5	.8	-	.023	0.042	1
100-150	5.2-4.95	499,701.2	57.4	46.4	.26	.132	16
150-200	4.95-4.26	2,210,503.1	115.9	28.2	.356	.163	16
200-250	4.26-4.36	2,536,836.1	104.5	16.3	.40	.123	4
250-300	4.36-4.14	1,253,495.4	126.3	22.9	.40	.14	8
300-350	4.14-4.5	448,959.8	101.8	24.4	.42	.17	16
350-400	4.5-4.2	964,599.8	164.4	47.4	.37	.17	16
400-450	4.2-4.14	350,226.8	129	32.2	.33	.13	16
450-500	4.14-4.11	900,147.98	128.4	52.5	.422	.20	8

Table 5.14 Side of Boulder with the highest *Balanus balanoides* densities

Site	Rock	Landward	Seaward	East	West
50-100	1	1	0	0	0
100-150	1	0	1	1	0
	2	1	0	0	1
	3	1	0	1	0
	4	1	1	0	0
150-200	1	0	1	1	0
	2	0	1	1	0
	3	0	0	1	1
	4	0	0	1	1
200-250	1	0	0	1	1
250-300	1	1	0	1	0
	2	0	1	1	0
300-350	1	0	0	1	1
	2	0	1	1	0
	3	0	1	1	0
	4	0	1	1	0
350-400	1	1	0	0	1
	2	0	1	1	0
	3	1	0	1	0
	4	0	1	0	1
400-450	1	0	1	1	0
	2	0	1	0	1
	3	0	1	1	0
	4	0	0	1	1
450-500	1	0	0	1	1
	2	1	0	1	0
	3	0	1	1	0
	4	1	0	1	0
Total		9	14	22	10
Percentage Occurrences		16	25	39	18

5.7 Macroalgae Distribution

Three classes of macroalgae were encountered on the flats at the head of Frobisher Bay Cholorophyceae, Phaeophyceae and Rhodophyceae. Within these classes 14 species were identified (Table 5.2). These species are most typical of the littoral and sublittoral flora found on moderately exposed coasts (Wilce 1959).

Some of the species grow under the ice throughout the winter like Neodilsea integra and Chaetomorpha melagonium. Others like Ulvaria obscurra and Pilayella littoralis live only one year. Biennials which live 1½ years or more, lose their leaves, which grow in again in the spring. Biennials are represented by Stictyosiphon tortilis, Rhodomela confervoides, Halosaccion ramentaceum, and Alaria esculenta. The remainder remain year round, some growing through the winter like Palmaria palmata or fruiting in the winter or spring like Sphacelaria arctica (Whelden 1947, Taylor 1957, Hillson 1977).

The most abundant species was the Fucus evanescens which was present on all four transect lines (Fig. 5.13). Its upper limit was near high water, whenever suitable sites were encountered. On Apex, Rock, and Rodgers Island transects, where the upper flat was bedrock, this fucus could live in the depressions and cracks on the rock surface, thereby extending its limit to 8.4 m. A few discrete individuals were found between 7.4 and 7.6 m ALLT on STB. The absence of bedrock and suitable boulders resulted in a lower upper limit on STB. This limit was 4.5 m ALLT.

Fucus vesiculosus was found between 6.5 m and 6.7 m ALLT, in small tidal pools on the bedrock at Apex. These tiny plants showed

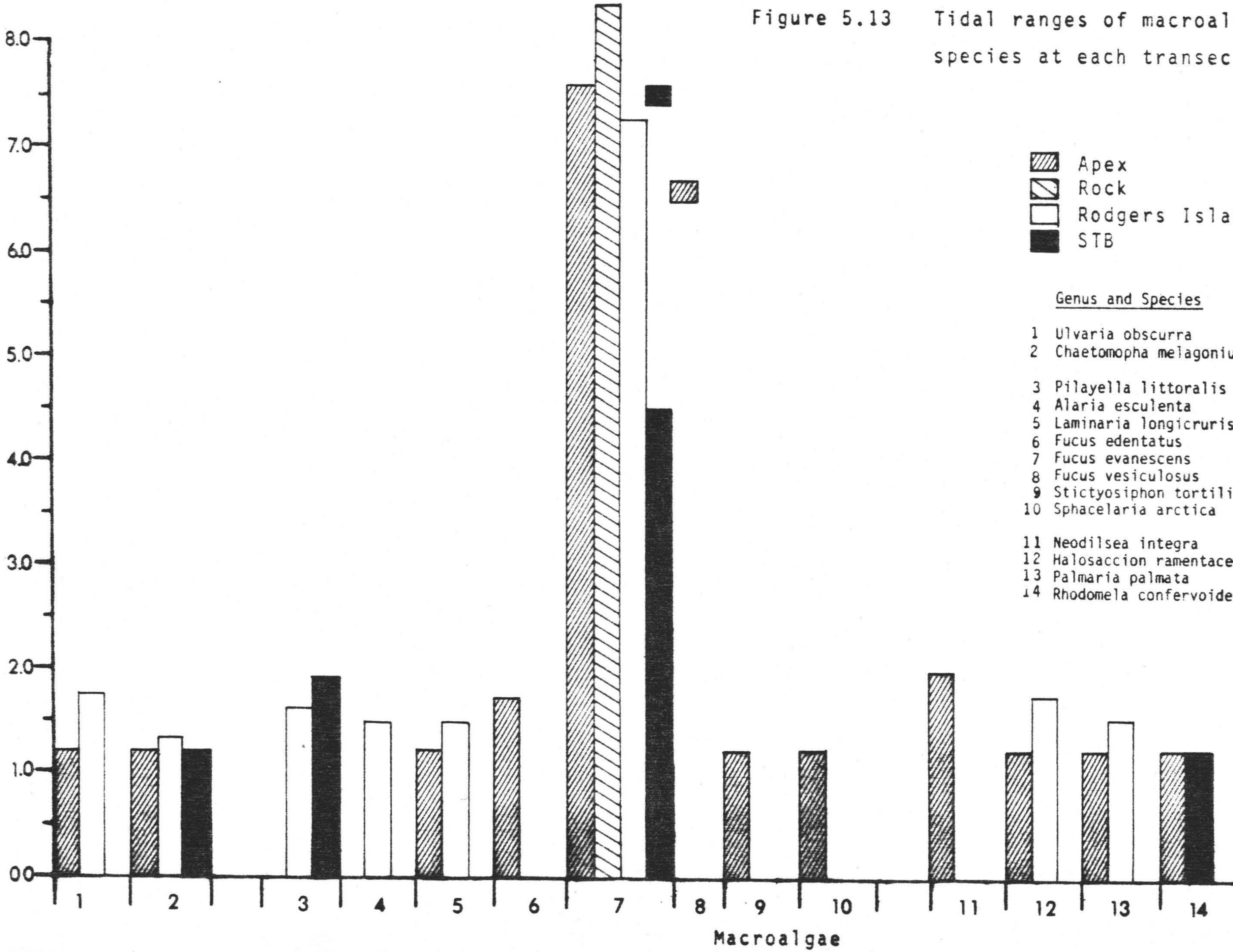


Figure 5.13 Tidal ranges of macroalgae species at each transect.

evidence of having been torn probably by the ice with subsequent regrowth. They were able to withstand abrasion and fresh water influx since the area was covered by the ice foot most of the year.

The remainder of the species occur below the 2 m ALLT mark on all of the transects. These plants are more sensitive to ice action and require less than 20% exposure to the air and direct sunlight.

5.8 Conclusions

The macrofauna and macroalgae studied at the head of Frobisher Bay, do exhibit a zonal preference from high to low tide. Figure 5.14 illustrates the tidal range against exposure for the macrofauna and macroalgae studied. Reference will be made to this figure throughout the following discussion on the major conclusion drawn in this chapter.

1. Sea anemones were the most common macrofauna encountered. They accounted for 47.8% of the total number of macrofauna counted in the quadrat analysis. Their upper limit is around 4.2 m ALLT however their range can be extended by the presence of tidal pools in the upper shore areas, such as at Apex.

2. The echiura found in Koojesse Inlet were from the bonelliidae family and had not previously been found on southeast Baffin Island. The animal requires fine, but cohesive sediments in which to burrow. It frequently burrows to the underlying clay, thereby introducing new sediments to the active layer. It lives from 3.0 m to 1.0 m ALLT and has been found in tidal pools up to 4.2 m ALLT at Apex.

3. Bivalves accounted for 32.1% of the fauna examined in the quadrat analysis. Cyrtodaria kurriana was the most numerous of the

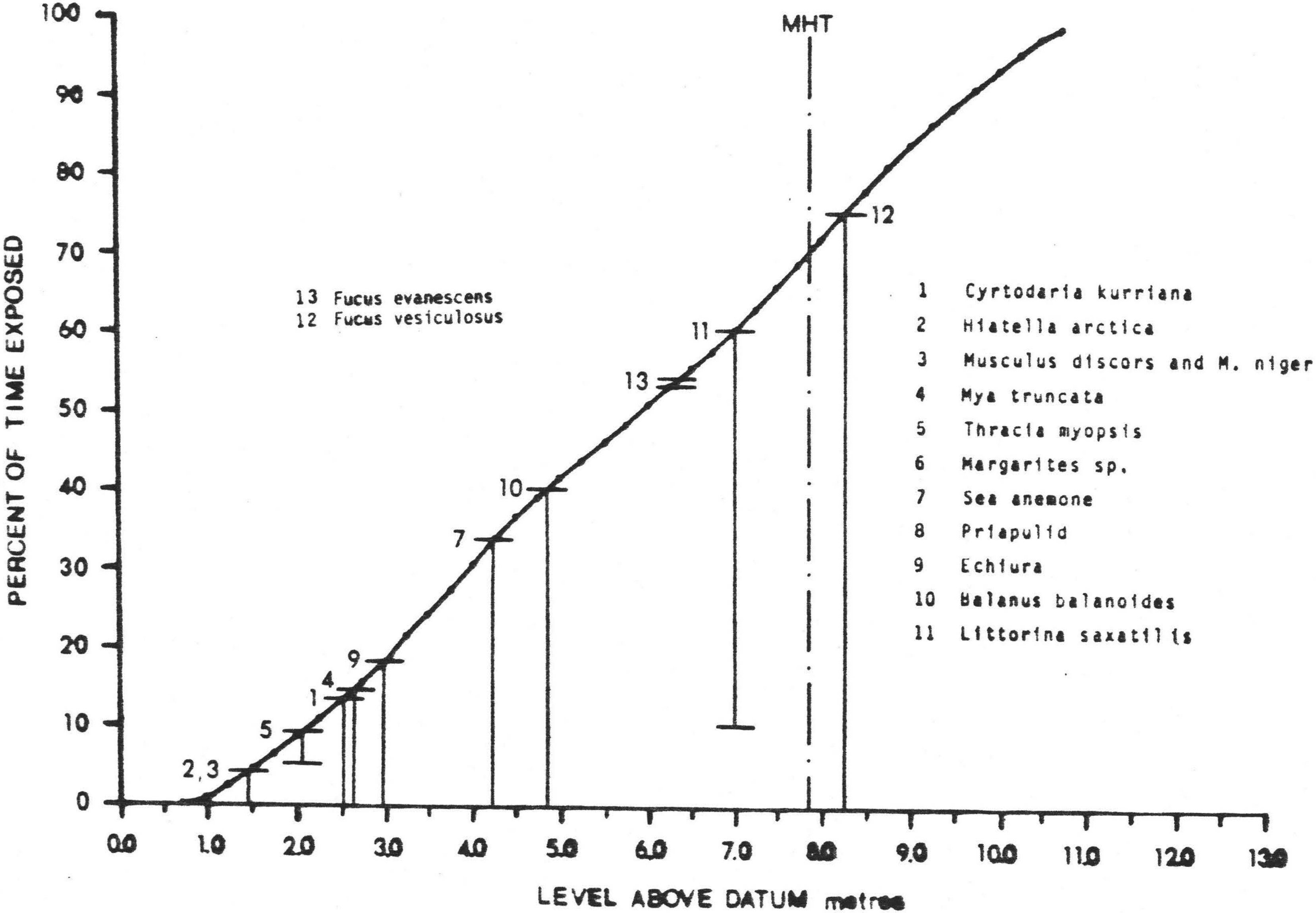


Figure 5.14 Exposure curve against the tidal range of all macrofauna and macroalgae species collected at the head of Frobisher Bay, 1980, 1981.

bivalves. This animal attained the highest densities of any of the macrofauna, reaching a density of 92.8 per 4 m^2 at 1.6 m ALLT at Rodgers Island. It requires less than 15% exposure and is very susceptible to ice gouging and fresh water. It lives buried in the upper 10 cm of the Rodgers Island flat which undergoes some ice action during breakup. While dead specimens were collected at the other transects, live specimens were only seen at Rodgers Island in 1981 and the Rock transect in 1980.

Mya truncata was the second most abundant bivalve. It was found on all of the transects except STB. It requires cohesive sediments in which to burrow, often reaching depths of 21 cm. It requires less than 15% exposure and is found below 3.0 m ALLT. This animal is currently undergoing a lot of pressure, since they are regularly harvested for human consumption. Their slow growth means that they will undergo a net decrease in number in intertidal locations over the next few years.

Thracia myopsis, Hiatella arctica, Musculus discors and M. niger require less than 10% exposure. Thracia were found living in the substrate only at Rodgers Island. The other 3 specimens were found on Apex, Rock and Rodgers Island transects (in 1980).

4. Littorina saxatilis inhabit the algal covered boulder surfaces between 1 m and 7 m above the tidal datum with maximum densities at the 4.0 m level. The greatest density was 87.7 per 50^2cm^2 on the Rock transect. The animal does not migrate during the summer but remains in the same location. Only during high wind and wave action does the animal move, seeking refuge under algal fronds.

5. *Balanus balanoides* densities were highest between 4.2 m to 4.5 m ALLT, where a maximum density of 164.4 per 100 sq cm was achieved. Their upper limit was 5.0 m ALLT and their lower limit unknown. The animal preferred east and south facing sites on boulders, probably due to increased temperatures in cool weather by the sun.

6. *Fucus evanescens* is the most common algae, inhabiting the flats to 8.0 m ALLT, in protected cracks in the bedrock. *Fucus vesiculosus* was found in tidal pools, torn by ice action from the ice foot. The remaining algal species require less than 10% exposure and live below 2.5 m ALLT.

7. The greatest total macrofauna densities and diversity occurs between 1.0 m and 2.0 m ALLT. Rodgers Island had the greatest densities due to the large number of *Cyrtodaria*. A density of 110.2 per 4 m^2 was attained at Rodgers Island.

Differences between the lines reflect substrate type, boulder cover, exposure to maximum fetch length, and gradient which affects tidal current velocities and tidal range.

CHAPTER 6

THE DISTRIBUTION OF POLYCHAETES IN THE INTERTIDAL ZONE

6.1 Introduction

This chapter examines the distribution of polychaetes across the intertidal zone at the head of Frobisher Bay. The study included all species greater than .55 mm in size, encompassing the meiofaunal to macrofaunal range. Polychaetes were found across the entire tidal flat, in such great numers, and large diversities, that they required a chapter of their own. This chapter will concentrate on the densities and locations of the various species. Specific zones of habitation can be determined from the collections made in 1980 and 1981 (Appendix 1a, Table 6.1).

Information on the life habits of the 26 polychaete species collected at Frobisher Bay, is sparse and scattered throughout the literature. For this reason, and because there has been no previously published, systematic collection in the area, information on the 26 polychaete species is provided in Appendix 1b. The reader is directed to read this appendix, since it discusses the habitat preferences and animal/substrate relationships found by other researchers, as well as this researcher, which are pertinent to this study.

6.2 Polychaete Literature Review

Until recently, the polychaeta class from the phylum Annelida was relatively ignored. Little work had been done on developing taxonomic keys nor on the life habits of many of the species in this

Table 6.1 Errant and Sedentary Polychaetes Collected in Frobisher Bay

Errantia

Nephtyidae
- *Nephtys caeca*
- *Nephtys ciliata*

Phyllodocidae
- *Eteone flava*
- *Eteone longa*
- *Phyllodoce groenlandica*

Polynoidae
- *Harmothoe imbricata*

Sedentaria

Ampharetidae
- *Ampharete acutifrons*

Capitellidae
- *Capitella* sp. "capitata group"
- *Mediomastus* sp.

Cirratulidae
- *Chaetozone setosa*

Flabelligerdae
- *Flabelligera affinis*

Maldanidae
- *Praxillella affinis*
- *Praxillella praetermissa*

Opheliidae
- *Travisia forbesii*

Orbiniidae
- *Scoloplos acutus*

Sabellidae
- *Chone* cf. *infundibuliformis*
- *Euchone analis*
- *Laonome kroyeri*
- *Sabella crassicornis*

Scalibregmidae
- *Scalibregma inflatum*

Spionidae
- *Laonice cirrata*
- *Polydora caeca*
- *Polydora quadrilobata*
- *Scolelepis* (Nerinides) sp.
- *Spio filicornis*
- *Spio goniocephala*

class. The importance of this group in the marine environment is now recognized and efforts to define and classify the various members are now underway (Fauchald 1977; Appy, Linkletter & Dadswell 1980).

Polychaetes are typically marine species and are rarely found in freshwater and terrestrial environments. They are multi-segmented worms with parapodia, and have setae arranged in distinct fasciles. They are dioecious and have simple gonad ducts. However, according to Fauchald (1977), any of the above features can be absent and are not a prerequisite to be identified as a polychaete.

Traditionally, polychaetes have been divided into two orders, errantia and sedentaria, which are based on life habits and anterior development (Table 6.1). The errantia are generally free living migrants, plundering any food source they encounter. All species with jaws are included in this group. They have few anterior appendages and a large number of equal body segments. The Sedentaria are generally more sedentary in nature, burrowing permanently into the substrate and often living within tubes which they construct. They are usually deposit or filter-feeders, with a limited number of body segments, often separated into different regions (Fauchald 1977, Hobson and Banse 1981). Some species have numerous similar anterior appendages, while on others they are absent.

Some of the earliest and most extensive keys, particularly of northern polychaetes, are from the Russian literature. Gaevskoia (1948) published taxonomic keys on many of the flora and fauna, including polychaetes, of the Russina marine areas. Ushakov (1965, 1972) has worked extensively on keys for the polychaetes of the eastern Russian waters and the Baltic Sea, also present in the Canadian Arctic (Hartmann and Schröder 1971).

A number of North American keys were used to identify the polychaetes sampled in Frobisher Bay (Pettibone 1953, 1963, Blake 1971, Banse and Hobson 1974, Fauchald 1977, Appy, Linkletter and Dadswell 1980, Hobson and Banse 1981). Pettibone's keys (1953, 1963) of the New England region also contain substantial information on polychaete life habits. The genus Polydora were identified using information on North American east coast Polydora species by Blake (1971). Many Arctic species are also found in the key from the Bay of Fundy prepared by Appy, Linkletter and Dadswell (1980), which was extensively utilized. The account of benthic errant and sedentary polychaetes of British Columbia by Banse and Hobson (1974, 1981) aided in the preliminary identification of families. The review by Fauchald (1977) supplied useful definitions and keys, of the orders, families and genera of polychaetes.

There are few studies of the life habits of many of the polychaetes. The publications by Pettibone (1963), Schafer (1972) and Fauchald and Jumars (1979) are among the most useful. The latter two provide valuable insight into the relationships between the microenvironments and the fauna.

Arctic faunal studies which provide polychaete information include Thorsen (1936) and Madsen's (1936) work on the Greenland coast. Studies closer to Frobisher Bay include Ellis (1955, 1966), Ellis and Wilce (1961), Den Beste and McCart (1978) and Wacasey (pers. comm. 1980). All of these publications were noted in greater detail in Chapter 5. Most recent work by Aitken and Gilbert (1981) in Pangnirtung

Fiord and McCann, Dale and Hale (1981) in Frobisher Bay provide information on Subarctic polychaete species.

6.3 Polychaete Collection and Preservation

A polychaete sampling scheme for 1981, was devised based on the species list compiled from collections taken in 1980. Four tube cores were taken at random locations every 50 m along the Apex and STB lines, and every 25 m along the Rodgers Island and Rock Transects. Each set of 4 cores, sampled 125 cm^2 of the sediment surface. During sampling, temperatures were taken at the sample site, at the surface and at 5 and 10 cm depths in the sediment (see Chapter 4).

In the Frobisher Bay laboratory, the cores were sieved through a 1.00 (.5 mm) sieve, to capture all of the meiofaunal specimens. The fauna were counted, then preserved in buffered 10% formalin for 24 hours, and then transferred to isopropyl alcohol. Macrofauna were handled in a similar way (Chapter 5).

6.4 Polychaete Densities and Distribution

6.4.1 Introduction

Lists of the polychaete species and their collection sites are tabulated in Appendix 1. Tables 6.2, 6.3, 6.4, 6.5 list the polychaete densities per 100 sq cm, standard deviations and substrate temperatures, where taken at each sampling site. In the following discussion, the results for each line will be dealt with separately in the following order, Apex, Rock, STB and Rodgers Island transects. The section will conclude with comparisons between the 4 lines.

Table 6.2a Apex Transect Polychaete Densities, July 20, 1981

Distance from Shore (m)	Height above tidal datum (m)	Density No/100 sq. cm.	Standard Deviation	Surface Temp. °C	Temp. at 5 cm °C	Temp. at 10 cm °C
0	5.1	25.7	5.0	3.9	2.9	2.7
50	4.1	17.6	.58	2.8	2.1	1.7
100	3.9	13.6	3.0	2.6	2.3	2.0
150	3.2	19.2	.82	2.7	2.1	1.7
200	2.9	22.5	3.8	2.4	1.6	1.5
250	2.7	16.8	2.1	1.8	1.7	1.4
300	2.6	6.4	1.4	1.6	1.4	1.0
350	2.6	10.4	1.7	1.6	1.2	.9
400	2.5	27.3	5.1	1.5	1.1	.7
450	1.8	29.7	4.9	2.0	1.6	1.0

Table 6.2b Apex Transect Polychaete Densities, July 28, 1981

Distance from Shore (m)	Height above tidal datum (m)	Density No/100 sq. cm.	Standard Deviation	No. of Species	Surface Temp.°C	Temp. at 5 cm °C	Temp. at 10 cm °C
0	5.1	483.6	209.6	1	2.9	1.75	1.4
50	4.1	52.9	2.9	3	5.7	2.4	1.6
100	3.9	98.6	19.8	5	4.2	1.9	1.3
150	3.2	73.8	8.2	6	6.4	1.8	2.6
200	2.9	24.1	6.1	5	9.5	4.9	1.8
250	2.7	10.4	2.2	4			
300	2.6	16.8	3.9				

Table 6.3 Rock Transect Polychaete Densities, July 19 and 27, 1981

Distance from Shore (m)		Height above tidal datum (m)	Density No/100 sq. cm.	Standard Deviation	No. of Species	Surface Temp.°C	Temp. at 5 cm °C	Temp. at 10 cm °C
Line #1	0	3.5	176.5	43.5	5	7.8	5.6	4.2
	12.5	3.1	82.6	8.7	6			
	25	3.7	35.3	4.5	4	7.7	6.0	5.1
	50	3.0	12.0	2.8	3	7.4	5.3	3.7
	75	2.2	17.6	.58	3	6.1	3.8	2.7
	100	1.4	23.3	3.3	2			
Line #2	0	≃ 3.5	87.4	12.8		7.0	4.6	3.5
	12.5	≃ 3.1	254.3	47.4				
	25	≃ 3.7	30.5	7.3		7.1	6.2	4.2
	50	≃ 3.0	11.2	3.0		8.4	6.3	5.0
	75	≃ 2.2	28.1	2.6		6.3	4.8	3.0
	130	≃ 1.0	38.5	9.9				
Line #3	0	≃ 3.5	44.9	2.6		7.5	4.4	2.9
	12.5	≃ 3.1	108.3	22.4		6.8	3.6	2.8
	25	≃ 3.7	57.7	14.1		6.9	3.9	2.7
	50	≃ 3.0	19.2	3.2		4.7	2.3	1.9
	75	≃ 2.2	36.9	.58				
	100	≃ 1.4	9.6	4.0				

Table 6.4 STB Transect Polychaete Densities, August 11, 1981

Distance from Shore (m)	Height above tidal datum (m)	Density No/100 sq. cm	Standard Deviation	Number of Species
0	7.5	628.0	37.5	1
50	5.9	473.2	56.8	1
100	5.2	506.9	48.4	2
150	5.0	727.5	46.3	3
200	4.3	149.2	11.1	5
250	4.4	64.2	9.9	3
300	4.1	44.1	3.4	5
350	4.5	36.9	7.4	5
400	4.2	41.7	6.7	5

Table 6.5 Rodgers Island Transect Polychaete Densities, August 2, 1981

Distance from Shore (m)	Height above tidal datum (m)	Density No/100 sq. cm.	Standard Deviation	No. of Species	Surface Temp. °C	Temp. at 5 cm °C	Temp. at 10 cm °C	No. of Juvenile Molluscs
50	3.9	30.5	5.3	4	-	-	-	0
75	2.2	22.5	1.9	5	1.8	1.6	1.6	4
100	2.0	39.3	6.3	4	1.9	1.5	1.6	1
125	1.9	28.1	.96	3	2.1	1.0	.9	6
150	1.7	32.1	5.0	5	1.7	1.9	1.7	3
175	1.6	36.1	2.9	7	2.3	1.7	1.4	2
200	1.5	52.9	3.0	10	2.4	2.3	2.3	13
225	1.5	66.6	3.4	9	3.1	2.5	2.3	2
250	1.3	81.0	9.7	9	2.8	2.4	2.1	5
275	1.3	93.0	11.9	9	2.9	3.5	3.3	12
300	1.0	78.6	4.8	10				2

6.4.2 Apex Transect

Polychaetes were sampled twice at Apex transect, on July 20 and July 28, 1981 (Table 6.2a, b). Polychaete densities were noticeably higher on the second occasion, with a maximum of 483.6 specimens per 100 sq cm, compared to 297 per 100 sq cm obtained earlier. The highest densities achieved on July 20, occurred at 1.5 m and 4.5 m ALLT. A similar peak was noted at 4.5 m on July 28, samples were not taken at the lower tidal level.

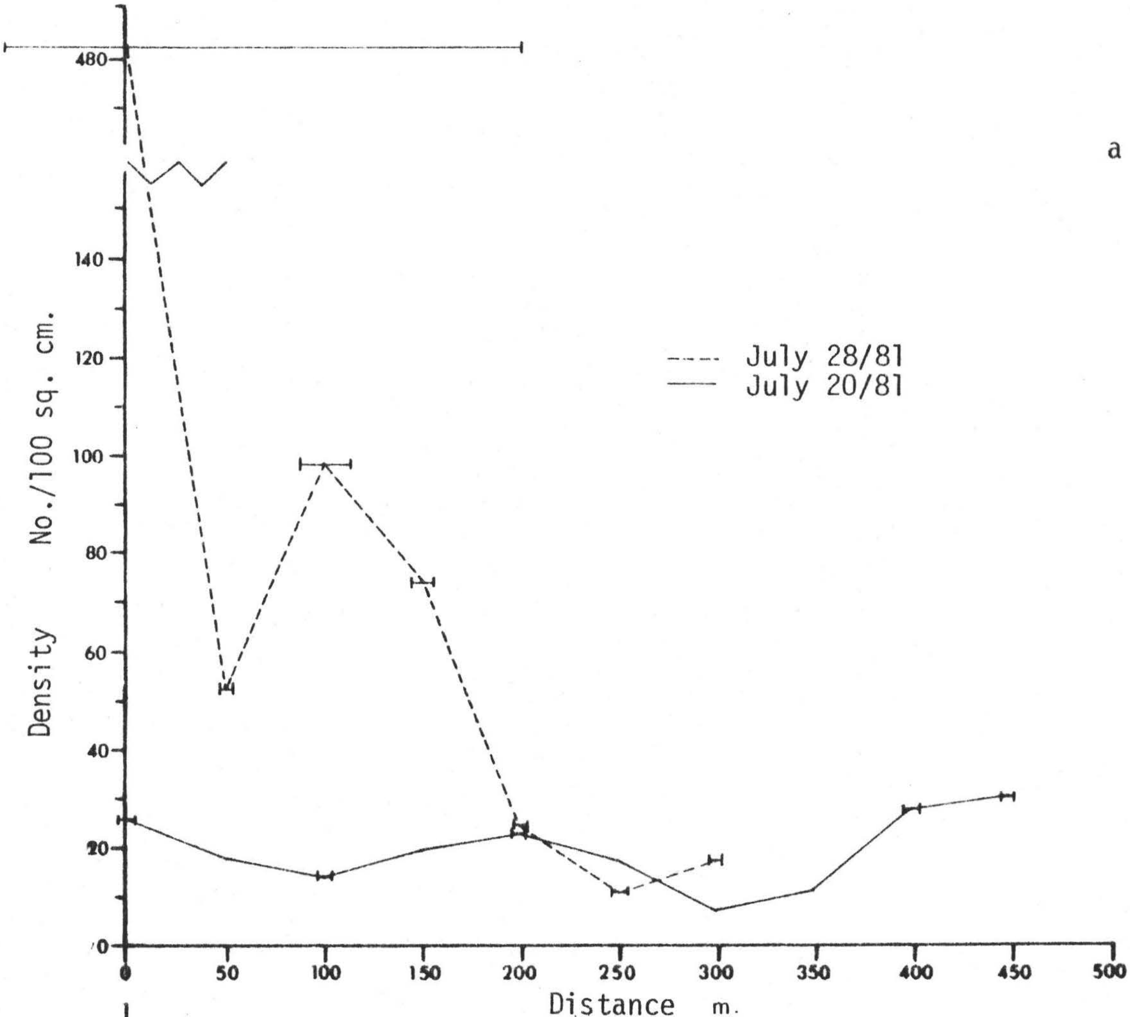
The differences appear to reflect a "polychaete bloom". After ice breakup, conditions were conducive for the reproduction of many of the polychaetes. As environmental conditions improved with time, more and more of the new polychaetes became apparent. Many of the worms in the earlier sample, were larger, more mature worms and many had expired (a prominent feature after reproduction for some species). In the later sample, the worms were smaller and appeared to be juveniles.

The bloom,later in the season,reflected the migration of species with pelagic larvae from low water to higher flats, such as Eteone and Phyllodoce, and some of the spionids. In fact, the greatest change occurred due to the sudden influx of the spionid, which dominated the population, accounting for 84% of the total number of polychaetes found. This species appears to recolonize the flat every year. This species has not been previously described nor identified in any previous research in Arctic or temperate locales.

Improving environmental conditions could also explain the appearance of polychaetes roused from winter dormancy, or newly hatched from eggs in the substrate. The sea water regained its normal salinity profile after breakup. Water and substrate temperatures gradually rose, and wave and current action helped sort the sediment surface, providing suitable sites for polychaete settlement. Substrate temperatures at 5 and 10 cm depths were only slightly warmer on July 28 than July 20, both periods had highly variable temperatures. However, surficial temperatures were significantly warmer on July 28. Thus, illustrating the effect of insolation and warmer air temperatures on the substrate, which no doubt influenced polychaete larvæ. Both sampling periods were approximately 2.0^{o}C warmer at the 5 and 10 cm depths, than earlier in the season when ice still existed on the flats. The lower densities obtained July 20, 1981 are due to the few number of perennial worm species present on the tidal flats. _Capitella "capitata"_, _Eteone longa_ and _E. flava_ are present year round and accounted for most of the animals collected.

On July 28, 1981 densities decreased in a seaward direction towards lower tidal levels (Fig. 6.1a, b). This was mainly due to the sudden appearance of _Scolelepis_ which dominated the upper tidal flats (Fig. 6.2). _Scolelepis_ could tolerate the coarser sediments at 100 m as well as the fine muds at 0 m where they reached a maximum number of 603 per 125 cm^2. A decrease in their number at 50 m, probably reflected slightly less favourable conditions due to the extensive coverage of the sediment by fucus and boulders, under which many carnivorous amphipods resided. These amphipods were observed feeding on the _Scolelepis_, which probably accounted for their fewer numbers. The sudden decrease in number at 150 m (3.2 m ALLT) may reflect an approaching lower tidal limit. _Scolelepis_ were encountered at great

Figure 6.1a,b Apex transect polychaete density against distance and tidal height.



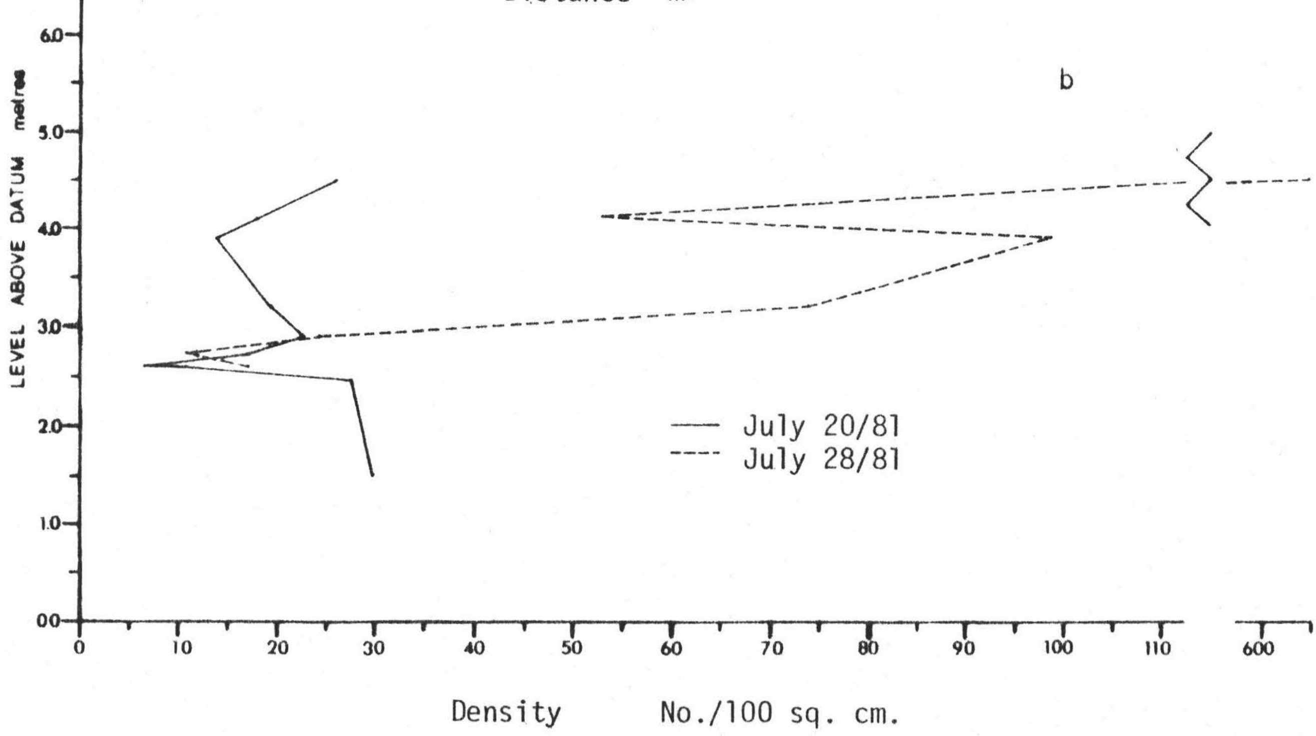
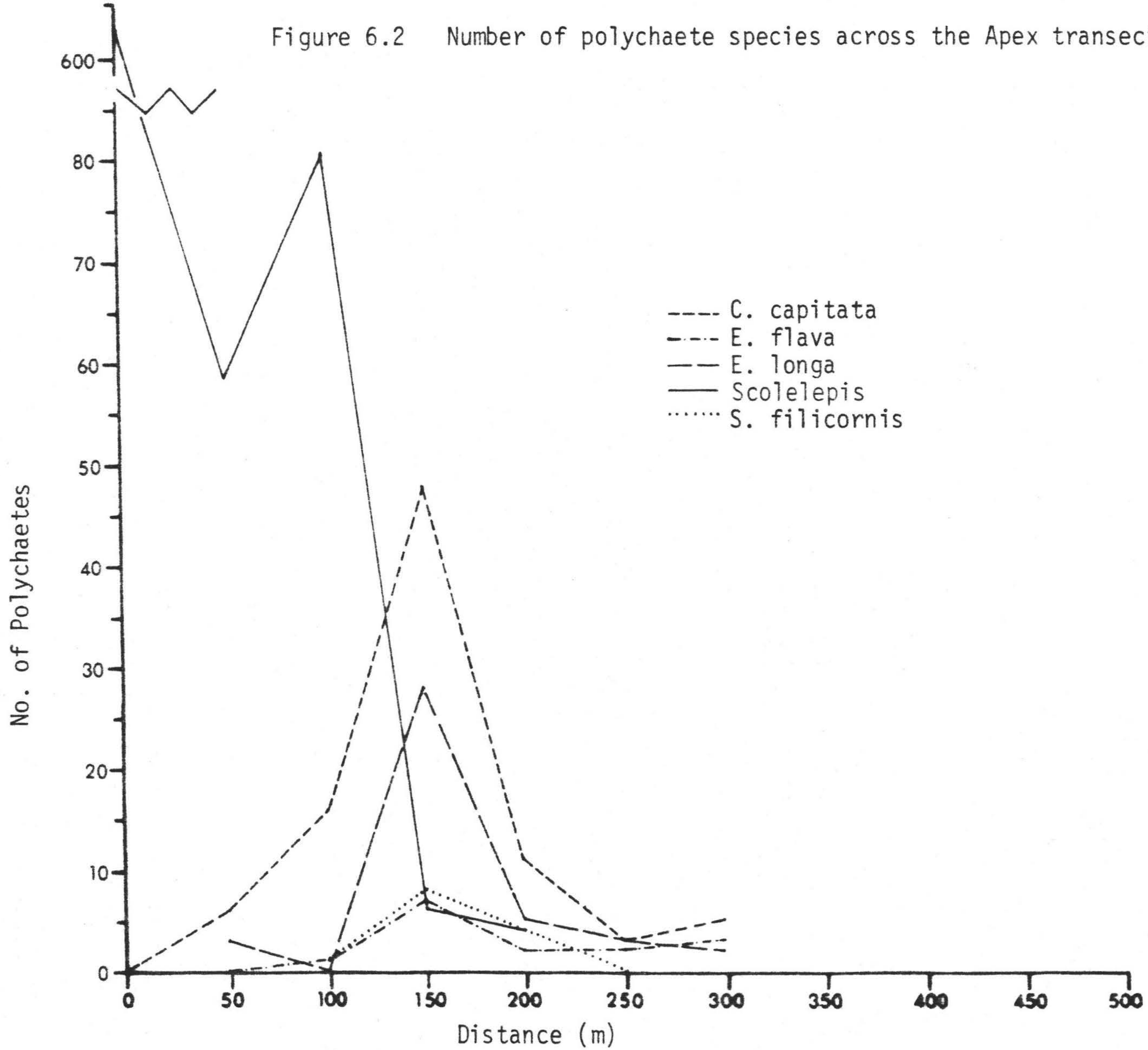


Figure 6.2 Number of polychaete species across the Apex transect.



number at similar depths on other lines but only when in tidal pools. It also seems likely that this area marks the presence of competitive species such as Capitella, E. flava and E. longa and Spio filicornis, which reached their greatest number at this position. The site had an admixture of fine and coarse sediments and was exposed approximately 20% of the time (Fig. 6.2).

The tidal ranges occupied by the polychaetes found at Apex are graphed against tidal exposure in Figure 6.3. E. longa, E. flava and Capitella occurred in areas with at least 35% exposure. Scolelepis were encountered between 4.5 and 2.9 m ALLT with 35 to 19% exposure. The remainder of the species were encountered below 19% exposure.

6.4.3 Rock Transect

Initial samples were taken at sites 100, 75, 50 and 12.5 m on Line #3 on July 19, 1981. Later collections were made on July 27, 1981 from 0 to 25 m. Comparisons between the 12.5 m site on Line #3 from the two sampling dates reveals little difference in the numbers of the perennial Eteone and Capitella population. Significant differences were observed with the number of Scolelepis, which numbered 13 on July 19 and 101 on July 27. The same population explosion noted for Apex Transect occurred at this site as well. Thus, the lines graphed in Figure 6.4a, 6.4b from the 2 sampling periods will be treated separately.

As at Apex, the highest denities occur close to shore between 3.0 to 3.5 m ALLT, reaching 254.3 per 4 m^2 at 12.5 m (Table 6.3, Fig. 6.4a, b). Fine sediments, in a tidal pool from 10 to 25 m from shore

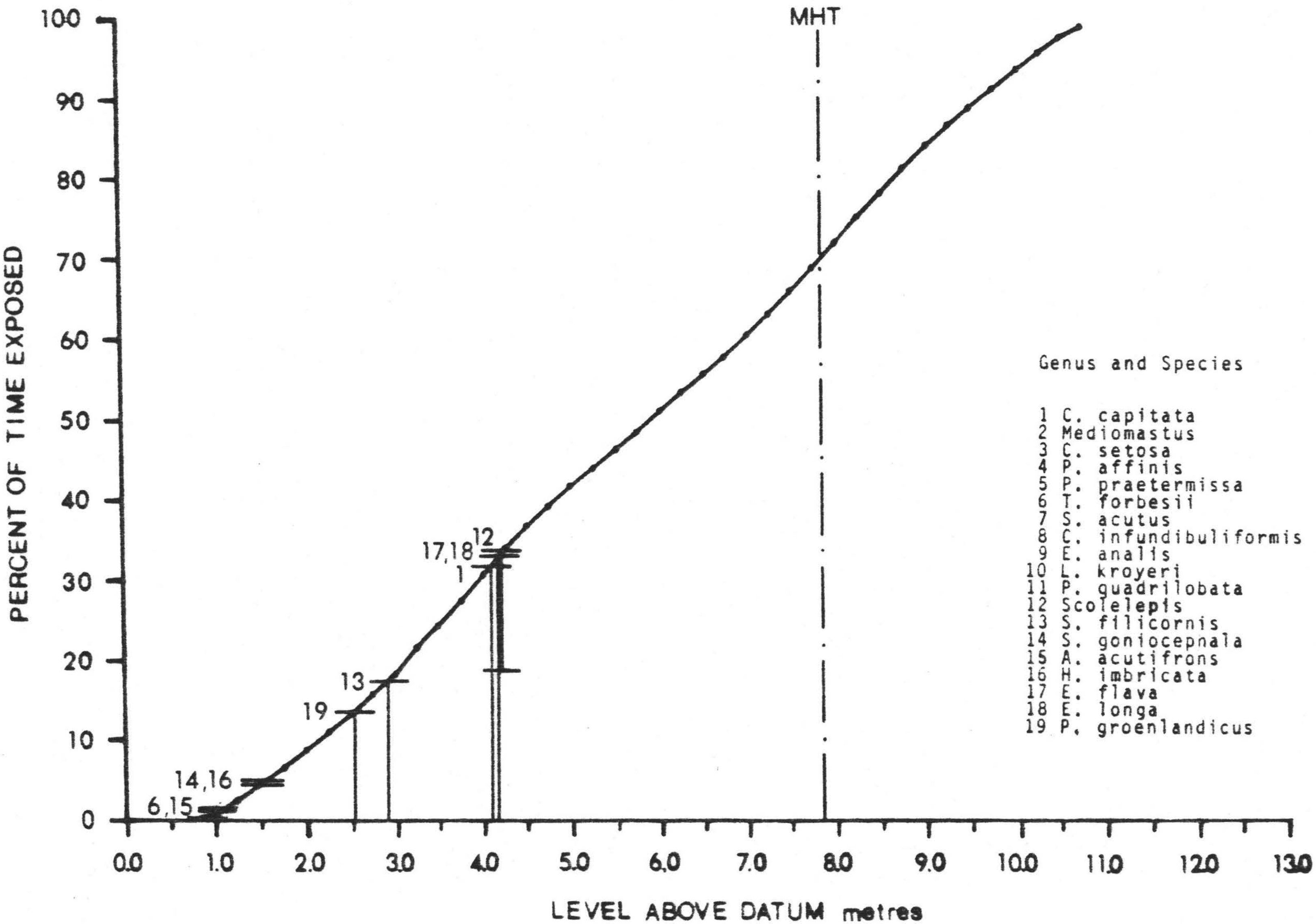


Figure 6.3 Exposure curve against the tidal range of Apex polychaete species.

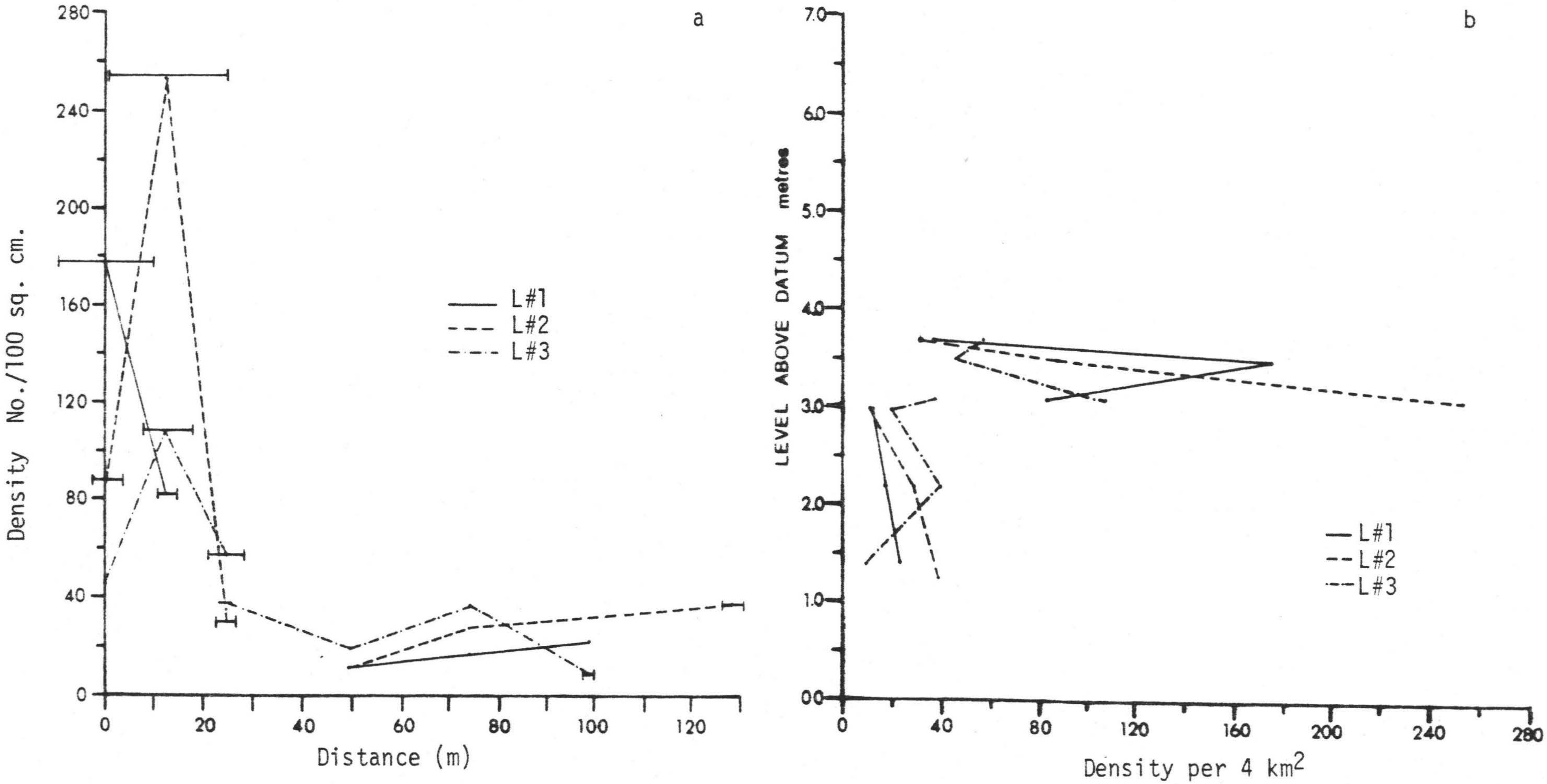


Figure 6.4a,b Rock transect polychaete density against distance and tidal height, Lines #1,2,3.

account for the large number of Scolelepis which caused the high densities (Fig. 6.5).

The lower densities experienced from 25 m seaward were due to the time of sampling and the presence of suitable habitats. Like Apex, the Rock transects were well covered with fucus, boulders and carnivorous amphipods. There were also numerous tidal drainage areas with coarse, gravel deposits, that discouraged those polychaetes which preferred finer sediments. At the low water edge (2.2 m ALLT), well sorted sand patches supported large numbers of Harmothoe imbricata and some maldanids, although none were collected in the tube coring analysis.

Samples from July 19, 1981 have small standard deviations, proving that little variation existed between the sites sampled. However, on July 27, large standard deviations were obtained. Thus, a great deal of variation in densities occurred between sites close to shore. This accounts for the variation observed between the three lines at similar tidal heights (Fig. 6.4a, b). Variations were due to subtle substrate differences and the presence/absence of the tidal pool.

Polychaetes collected from Line #3 were analysed in detail (Fig. 6.5). As noted earlier Scolelepis are greatest in number between 3.5 m and 3.0 m ALLT, in the tidal pool. Their numbers dropped off significantly at lower levels past 3.0 m as they had past 3.2 m ALLT at Apex. As the numbers of Scolelepis decreased at 50 m, the number of Eteone increased. Eteone are known to feed on Scolelepis, thus a predator/prey relationship appears to exist. In turn, the number of Eteone decreased at 75 m where large numbers of Capitella were collected. Both are motile animals although Capitella often builds tubes

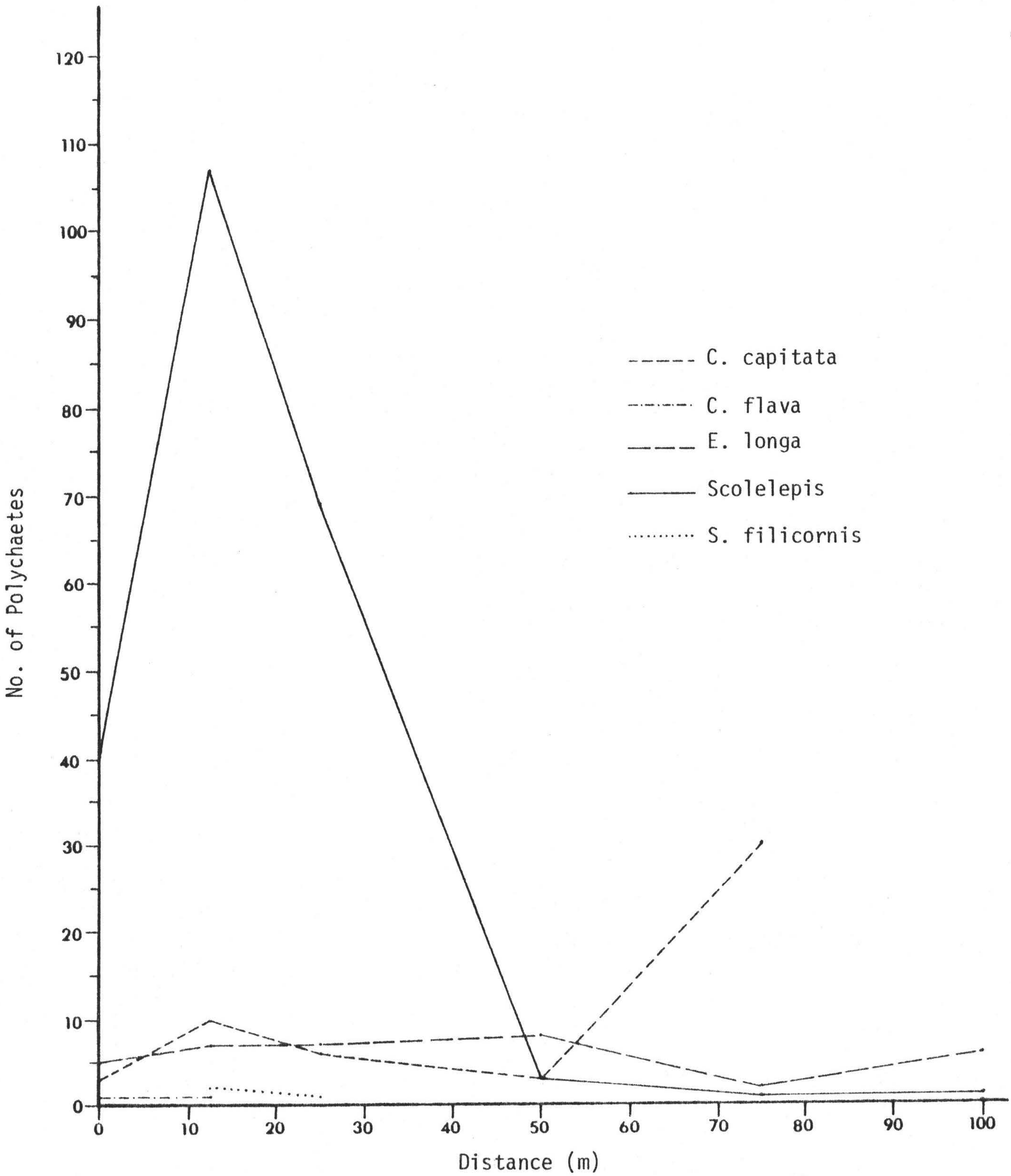


Figure 6.5 Number of polychaete species across the Rock transect, Line #1.

throughout the sand. Large numbers of these tubes could discourage Eteone.

Five polychaete species, E. flava, E. longa, Capitella, Scolelepis and Spio filicornis lived in the tidal pool on the Rock transect. This pool never drained, and thus extended the tidal limit of S. filicornis which fed on the Scolelepis. On the exposure curve in Figure 6.6 the tidal position of the polychaetes collected in 1980 and 1981 has been illustrated. A few species not previously noted, were encountered at 1.7 m ALLT in the well sorted sands at the low exposure end (< 8%) of the flat. Harmothoe imbricata a common Arctic intertidal species and Ampharete acutifrons were both collected at low water. Polydora quadrilobata and Spio goniocephla were also identified in the tidal pool.

6.4.4. STB Transect

Like Apex and Rock transect, densities decreased with distance from shore and depth at STB (Fig. 6.7 a, b). As noted previously, this is largely the result of the great number of Scolelepis, which lived up to 7.5 m ALLT on this flat (Fig. 6.8). The highest density occurred at 150 m (4.9 m ALLT) 727.5 per 100 sq sm and dropped off sharply to 149.2 per 100 sq cm at 200 m (4.3 m ALLT). Shoreward of 200 m, the flats are dominated by sediment mounds, a few discrete boulders, fine sediments and numerous pools. Coarser sediments, and more and larger boulders, begin about 200 m from shore and increase to the boulder ridge at 350 m. Favourable conditions for the settlement of Scolelepis occur shoreward of 200 m. Although large standard

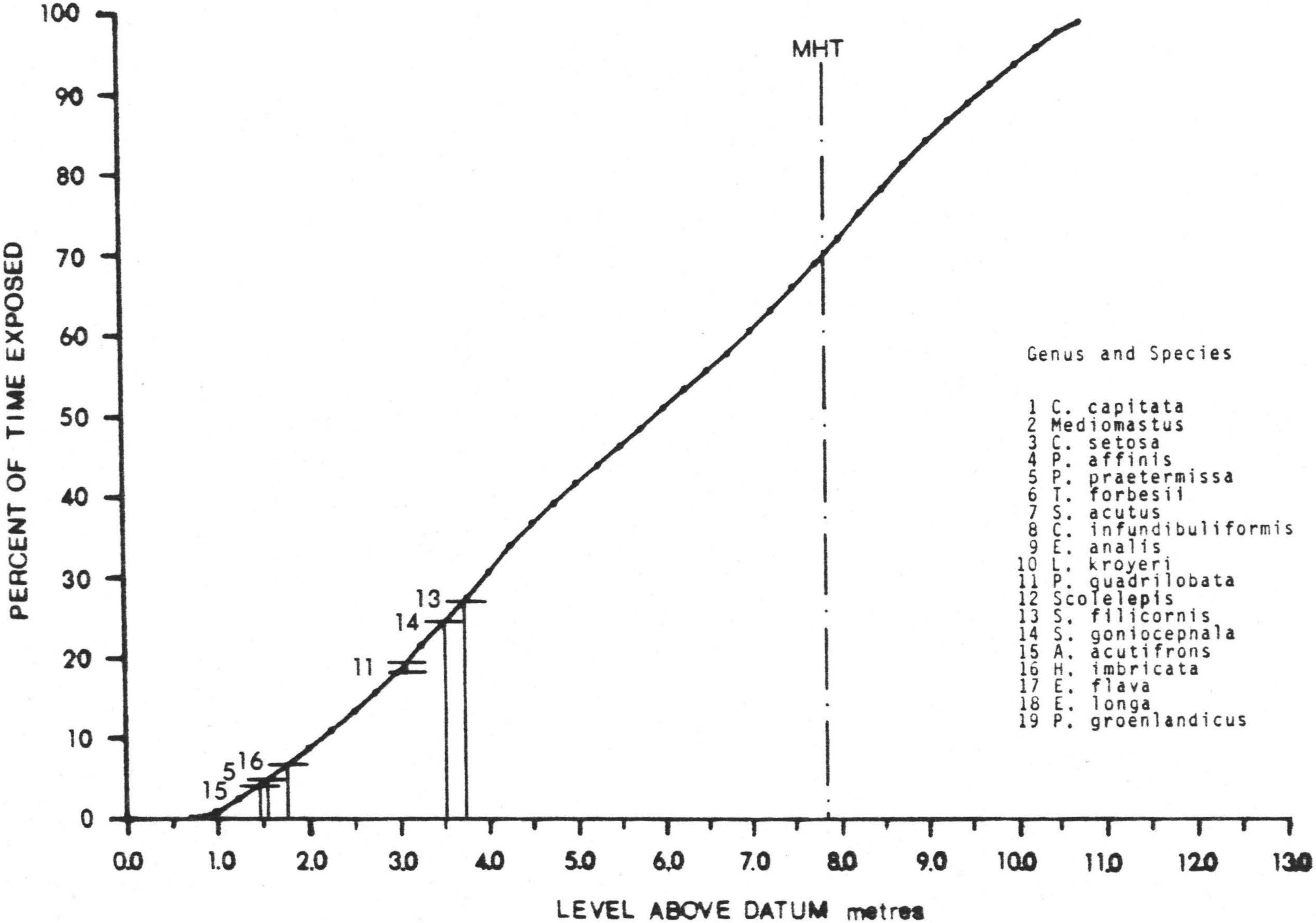
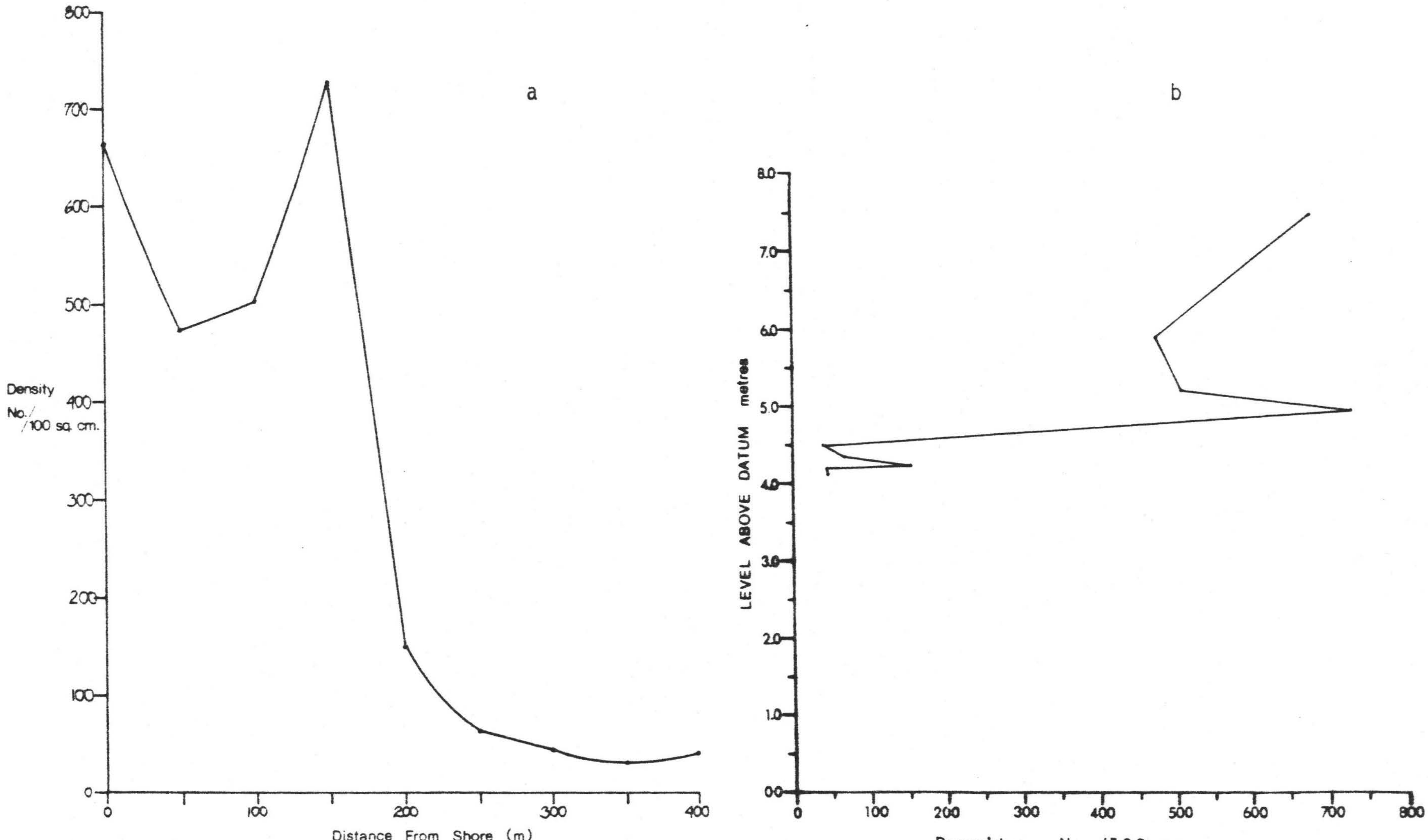


Figure 6.6 Exposure curve against the tidal range of Rock transect polychaete species, Line #1.

Figure 6.7 a,b STB transect polychaete density against distance and tidal height.



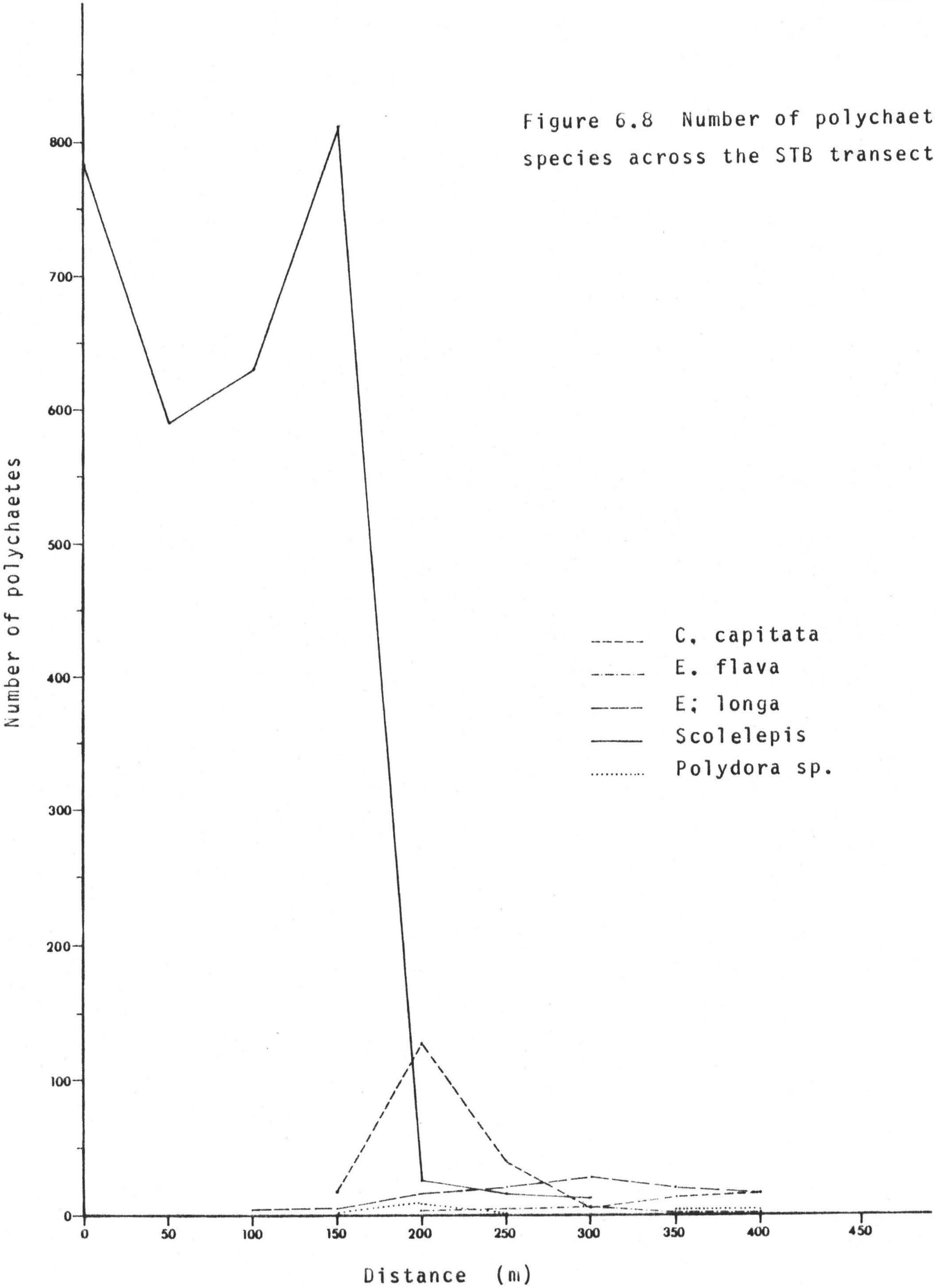


Figure 6.8 Number of polychaete species across the STB transect.

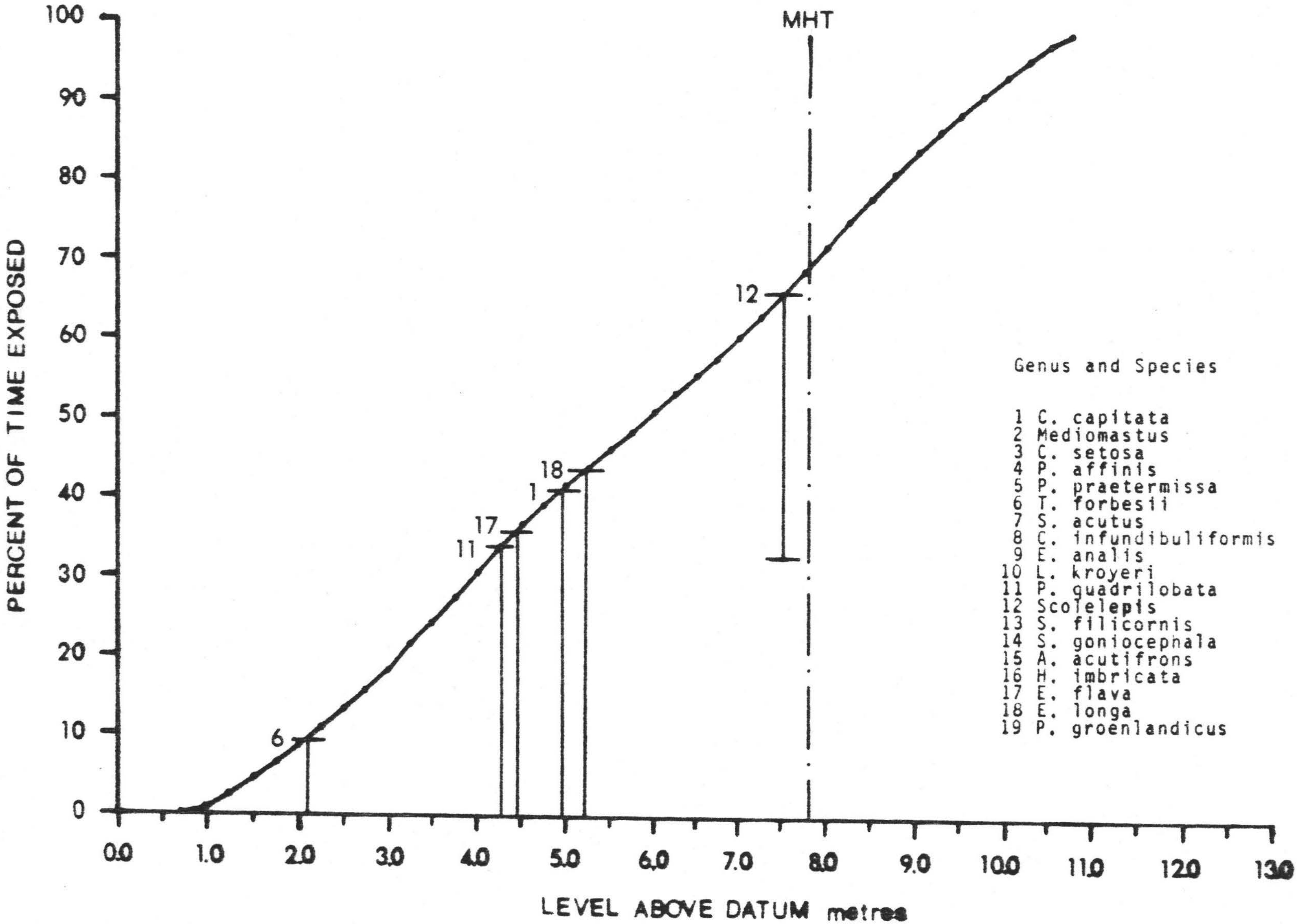


Figure 6.9 Exposure curve against the tidal range of STB transect polychaete species.

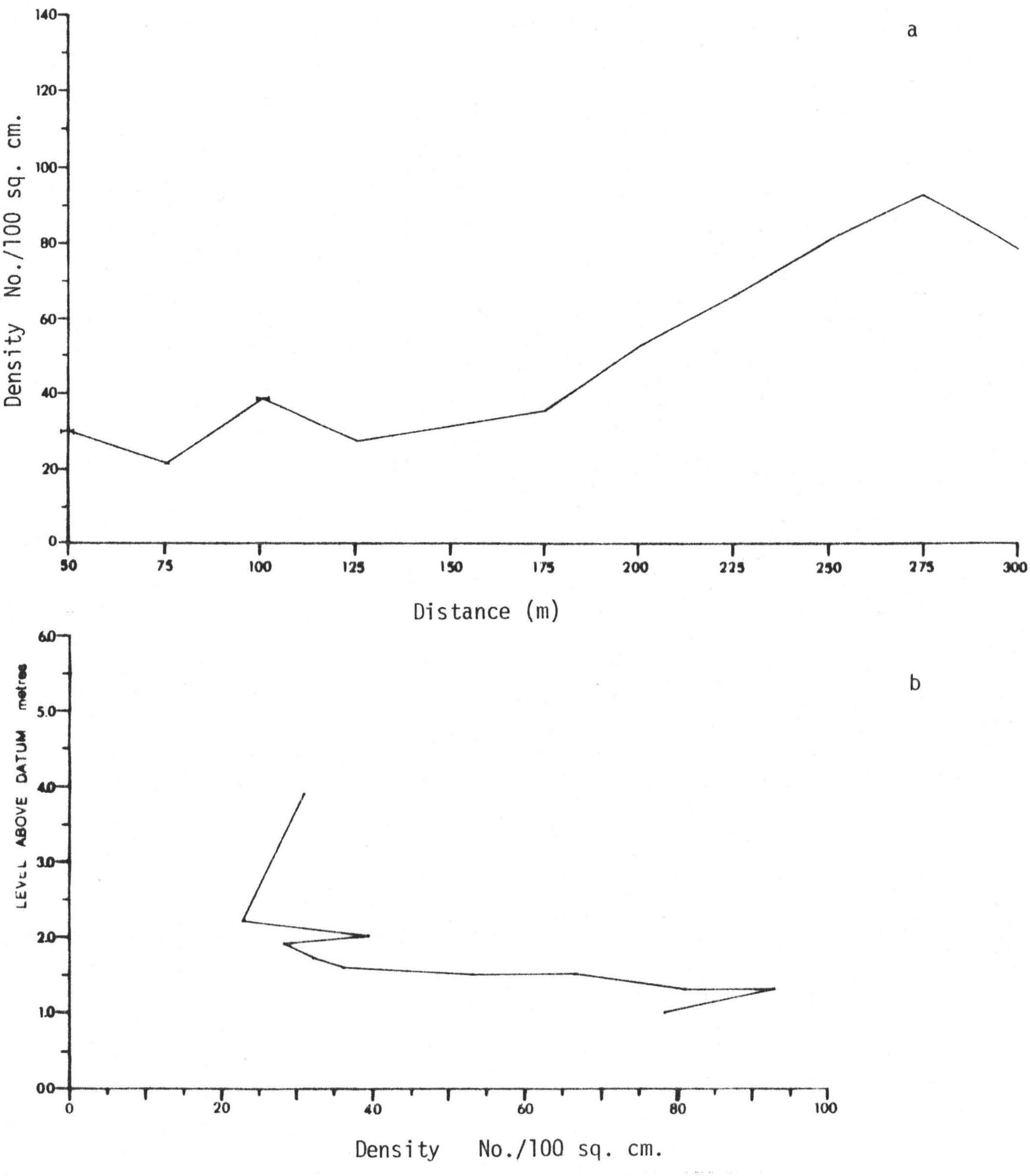


Figure 6.10a,b Rodgers Island transect polychaete density against distance and tidal height.

deviations shoreward of 200 m indicate that highly variable densities are still encountered in this region. The concentration of boulders at 350 m to 400 m effectively reduces the available polychaete sites. The area also has a fairly coarse thin active layer which is scoured by tidal currents and effectively limits the spionids. Substrate differences and the absence of tidal pools are the primary reasons for the changes in density across the flat. Changes in tidal height play a less important role at STB, since similar tidal heights on Apex, and the Rock transect encountered maximum densities in the range where STB had the lowest (< 4.5 m ALLT).

Again, possible relationships may exist between the decrease in Scolelepis and the rise in the number of motile polychaetes such as Eteone, Polydora and Capitella (Fig. 6.8) (See earlier discussion for Rock transect). The errant polychaetes dominate the lower reaches of STB which were sampled. Strong tidal currents generated during flood and ebb tides, due to the low gradient (See Chapter 5), caused high mobility of the active layer. This along with the lower number of boulders beyond 600 m offered little protection to sedentary polychaetes. Thus, only the free moving errant polychaetes could adjust to this environment (Fig 6.9).

6.4.5 Rodgers Island

The flats at Rodgers Island illustrate the change in polychaete species and densities in the sediment below 2.2 m ALLT. Polychaete densities increase with distance from shore (Fig. 6.10ab) and decreasing tidal height. In general the substrate is well sorted medium sand, with a few small boulders. Gravels only occur in the large tidal channels, east of the line. Thus, tidal height, exposure and faunal competition probably play the major role in the polychaete distribution on these tidal flats.

The highest density was 116 per 100 sq m at the 275 m site (1.3 m ALLT) (Fig. 6.10 a,b). This is largely due to a great number of Sabellidae mainly Euchone analis and Capitella capitata (Fig. 6.11a, 6.11b). Sabellids were not encountered in any great numbers on any other line. A few were observed in tidal pools at Apex at 100 m from shore, and at a low, low water. These sedentary suspension feeders require maximum amounts of inundation for their survival. Thus, tidal pools and levels < 2.0 m ALLT with < 10% exposure (Fig. 6.12) are required. In great concentrations, the sandy tubes of the sabellids (Chone infundibuliformis, E. analis, Laonome kröyeri) help consolidate the active layer and prevent mobilization of the sediment. Sabellid tubes are long and frequently extend 10 cm into the substrate. During low tide the animals retreat to the lower part of the tube. Amphipods were observed nipping at sabellid tentacles while the tubiculous worms were feeding. Thus, sabellids prefer open locations with fewer algal fronds, which would disrupt water circulation and affect the feeding pattern of the worms. Secondly, less fucus usually means fewer amphipods.

Capitella accounted for 48% of the total number of animals sampled, usurping the usual dominant species Scolelepis (Fig. 6.11a). Capitella exhibit a marked decrease in number at 80 m, 175 m, 250 and 300 m and an increase in the points in between. Similarly Mediomastus sp. and Praxillella praetermissa were fewer in number at 200,250 and

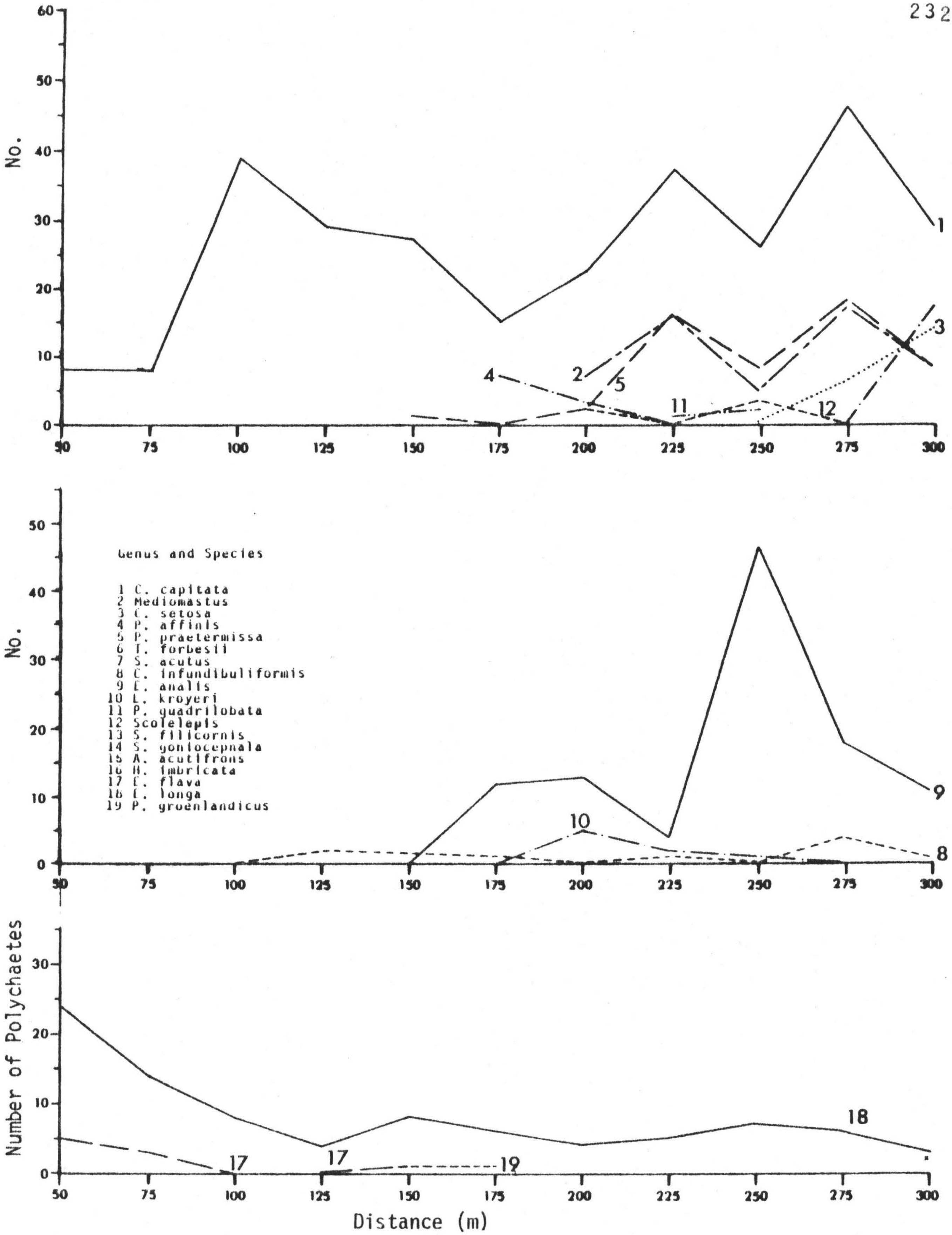


Figure 6.11 Number of polychaete species across the Rodgers Island transect.

300 m. Coincidently at 175 m , 250 m and 300 m the greatest number of carnivorous, errant polychaetes were collected (Fig. 6.11c). E. flava, E. longa, and Phyllodoce groenlandicus account for 14% of the total population. H. imbricata another carnivore was found at 300 m A predator/prey relationship probably exists between these animals.

Scolelepis and Polydora were collected at very low tidal levels, 1.3 m to 1.5 m ALLT. This adds further credence to the claim that their lower limit is influenced by substrate and faunal competition as opposed to exposure.

The majority of the species encountered at Rodgers Island prefer areas with less than 10% exposure (Fig. 6.12). Only Capitella and the 2 errant polychaetes E. longa and E. flava lived above 2.0 m ALLT, tolerating 30% exposure at their upper limit.

6.4.6 Comparisons Between the Transects

Trends in polychaete distribution across the tidal flats can be determined by comparing the 4 transects. Using the total number of polychaetes collected on each transect, the percent occurrence of each family has been calculated to show the dominant families (Table 6.6). Spionidae (mainly Scolelepis) dominate Apex, Rock and STB transects accounting for 84%, 70% and 89.5% respectively of the total animals sampled. At Rodgers Island, the dominant family was the capitellidae at 48.4%. This family was the second most dominant group for the other three lines. The errant Phyllodocidae occupy the third position, except at Rodgers Island. On this low tidal transect the importance of the sedentary tube worms, Sabellidae, was apparent.

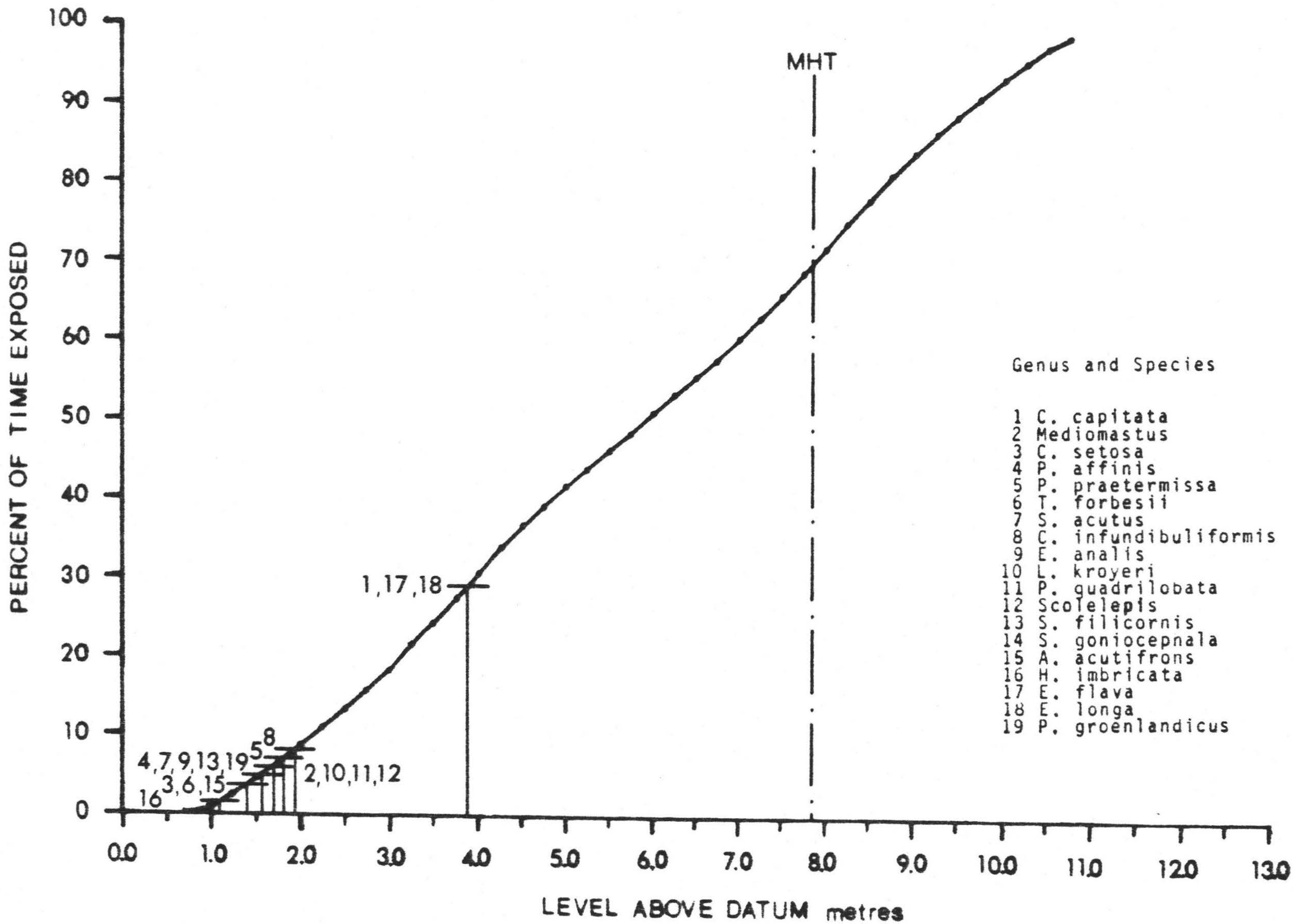


Figure 6.12 Exposure curve against the tidal range of Rodgers Island polychaete species.

Table 6.6 Percent Polychaetes in each Family collected at each Transect

Family	Apex Transect % Collected	Rock Transect % Collected	Rodgers Island % Collected	STB Transect % Collected
Ampharetidae	-	-	-	-
Capitellidae	9.7	18.8	48.4	6.8
Cirratulidae	-	-	2.9	-
Flabelligeridae	-	-	-	-
Maldanidae	-	-	11.7	-
Nephtyidae	-	-	-	-
Opheliidae	.1	-	-	-
Orbiniidae	-	-	.1	-
Polynoidae	-	-	.3	-
Phyllodocidae	6.1	11.3	14.3	3.7
Sabellidae	-	-	17.3	-
Scalibregmidae	-	-	-	-
Spionidae	84	69.9	4.2	89.6

These animals dominated the fine well sorted sands at the lower parts of the flats. Other families like the maldanidae also exhibited high numbers on this flat encouraged by a soft substrate and low exposure.

The importance of the low tidal areas on the polychaete diversity is evident in Figure 6.13, which shows the number of different species encountered at each tidal level for every transect. The average number of species found between tidal heights, 2 to 1 m ALLT, 3 m to 2 m, 3 m to 4 m etc. was calculated and also illustrated. From this last diagram, it is evident that the number of species increase with increasing depth. On average 7 polychaete species were encountered between 1 and 2 m ALLT and 1 species between 6 and 8 m ALLT. Thus, tidal height, and exposure play a fundamental role in the existence and development of the polychaetes. In general, the majority of polychaete species are encountered below 5 m ALLT (Fig. 6.14). This is due to the large number of sedentary polychaetes like Capitellidae and Sabellidae. Secondly, it reflects feeding patterns with many suspension feeders requiring $< 40\%$ exposure (Fig. 6.15). Thirdly, the mode of settlement and growth of the polychaete species influences their distribution.

Few infaunal species are present above 5 m ALLT since this area is heavily scoured by ice floes during breakup and its upper layers which may contain polychaetes and eggs are removed during freezeup. Species which inhabit this area must recolonize it every year. This may be by pelagic larvae during breakup like the phyllodocidae and some spionids or movement by motile polychaetes which migrate through the sediment in the spring, like the Phyllodocidae and some of the

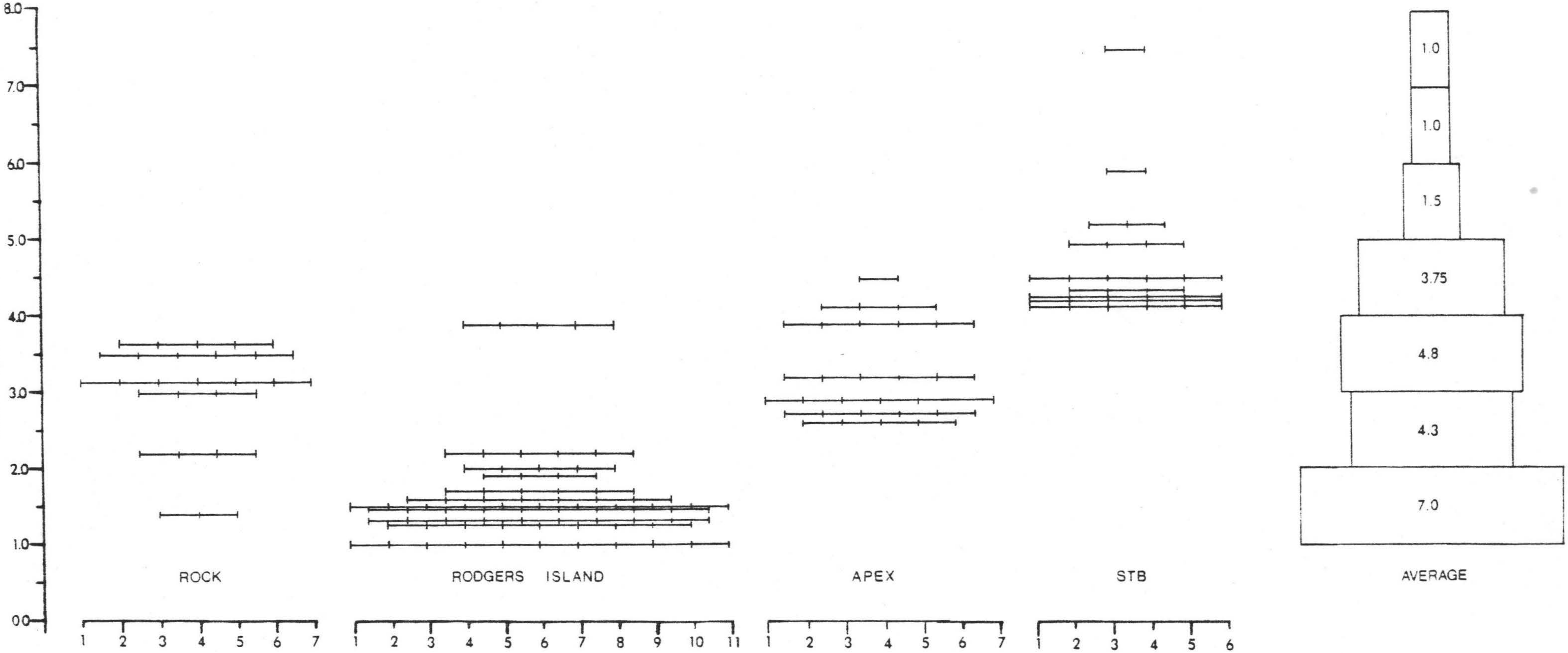


Figure 6.13 Number of polychaete and meiofauna species against tidal height at each transect

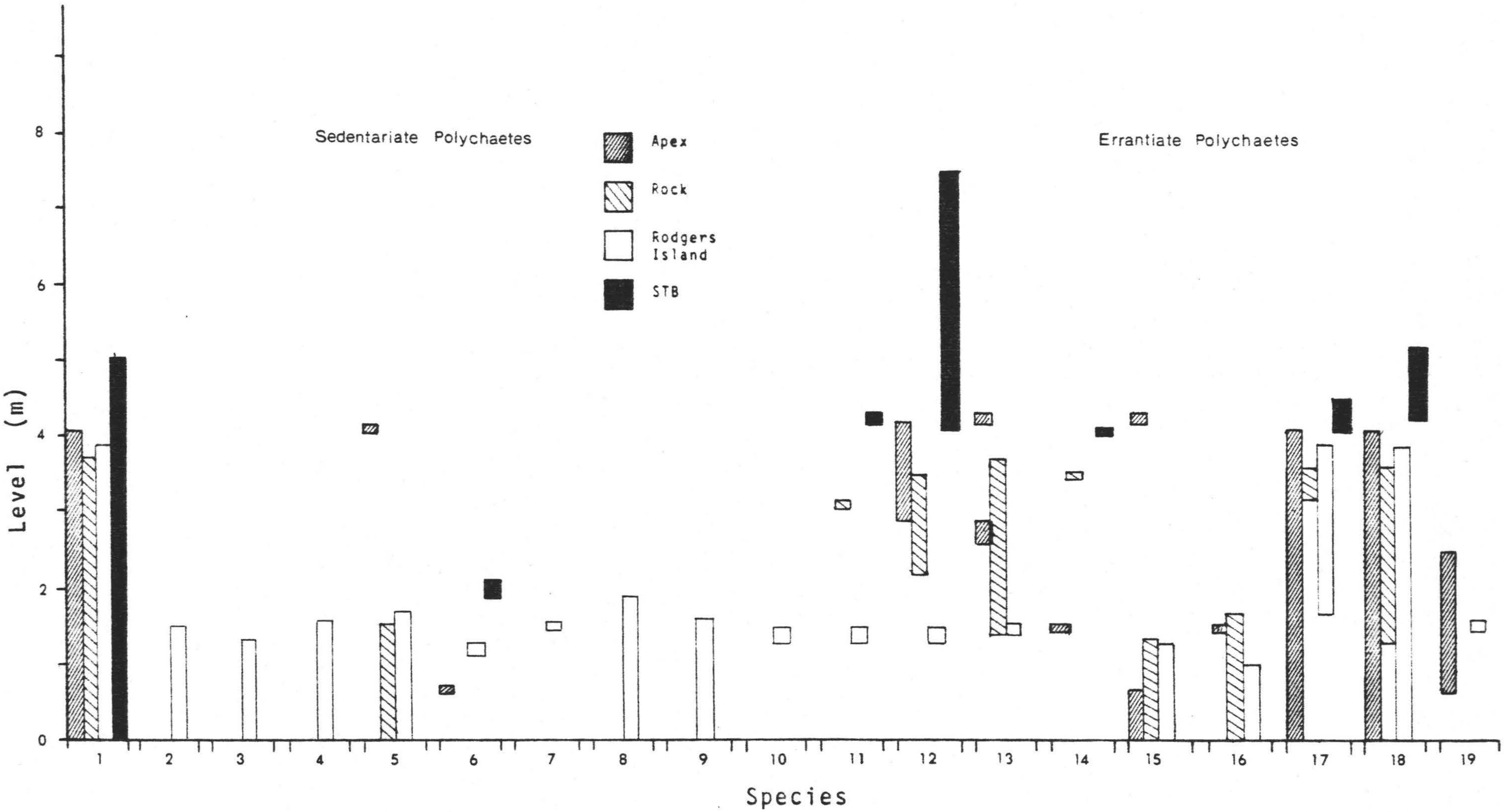


Figure 6.14 Tidal ranges of the polychaete species at each transect.

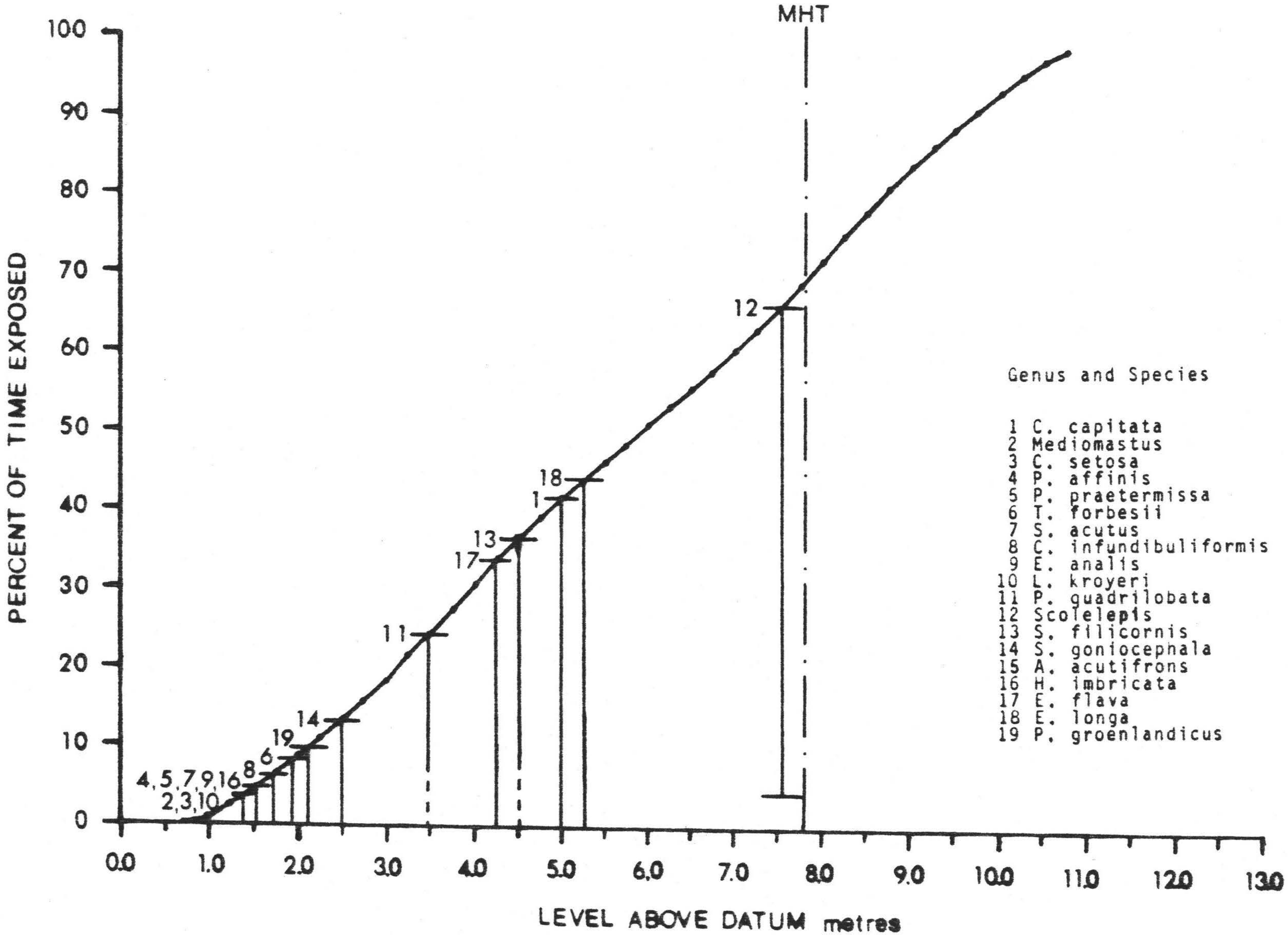


Figure 6.15 Exposure curve against the tidal range of all polychaete species.

capitellidae (Capitella sp.). The upward limit of these species is affected by substrate, exposure limits, and low salinities during breakup. Temperature changes may also affect them, since the upper sediment surface can go from 2.0°C to 10.0°C within a few hours of insolation. Wave and current action can also mobilize sediments which affect sedentary tube dwellers. Spionids appear to be particularly well adapted to shifting sands as they can remake their burrows numerous times.

In Figure 6.14 the tidal limits of all the polychaete species collected on the transect lines are illustrated. Scolelepis existed up to 7.5 m ALLT. There appeared to be lower limits to its distribution its lowest occurrence was at 1.3 m ALLT. As noted earlier, the increase in Eteone coincided with the decrease in Scolelepis. There is probably a relationship, since E. longa has been reported to feed on the (Spio filicornis and Scolelepis squamata) Spionidae. 5.0 m ALLT at 40% exposure, is the upper limit for Capitella sp. S. filicornis, and the errant polychaetes E. flava and E. longa. Capitella populations are generally more dense at 4.0 m ALLT and again at 2.0 m ALLT at Rodgers Island. Their lower limit is not known. E. flava generally occurs at 4.5 m ALLT and E. longa 5.2 m. The E. flava are less common and may have a lower limit due to competition and coarser sediments as observed on the Rock transect and Rodgers Island. The E. longa are more ubiquitous across the tidal flats.

The remainder of the species begin occurring around 2.0 m ALLT, with 10% exposure. It is felt that many of these infaunal species live for a number of years. In contrast are the species which must recolonize the upper levels of the flat every spring, like the Spionidae. These species likely only live for one summer season.

A number of tubiculous species were found in the tidal pools at Apex Transect, 4.4 m ALLT. Ampharete acutifrons, and Praxillella praetermissa were found living in these pools. Suitable substrate and 0% exposure allow their growth. However, the area underwent heavy ice action, during freezeup when ballycatters formed and during break-up when ice floes were frequently stranded on the pools. These species must have somehow escaped the ice action and must be fairly tolerant of fresh water. It is not known how they survived the freezing temperatures and the sea ice which must have frozen to the bed.

6.6 Other Meiofauna

During the sieving exercise, a number of meiofaunal species were encountered which were not polychaetes. Shell meiofauana were collected in the fine substrates from Rodgers Island (Table 6.5). The abundance of adult molluscs likely contributed to their existence. Many of the juveniles were too small and immature to be identified. Species identified were Cylichna alba, Hiatella arctica (juvenile) Cyrtodaria kurriana (juvenile), Cingula castanea, Oenopota bicarinata and Thyasira flexuosa. Crenella faba was observed living on fucal fronds on most flats.

Nemertines were found below 2.0 m ALLT. They can live on a wide variety of substrates in the sediment or twined around mussel byssal threads or algae. Procephalothrix spiralis (Coe 1930) was one of the species encountered. It is often associated with decaying organic matter and lives off invertebrate eggs, larvae and other soft bodied prey (Coe 1943).

6.6. Conclusions

Polychaetes exhibit distinct locational preferences and this has resulted in a relatively well defined zonation across the tidal flats. The exposure curve in Figure 6.15 shows the zones occupied by the species, collected at the head of Frobisher Bay in 1980 and 1981. The following major conclusions were made in this chapter.

1. The Spionidae are the most abundant polychaete family present in Koojesse Inlet. Scolelepis sp. was the most common species in this family. This unknown species has never been recorded nor identified in previous Arctic&temperate publications. It alone attained the highest densities of polychaetes anywhere on the transects 727.5 per 100 sq cm at 4.9 m ALLT at STB. Scolelepis dominate the upper parts of the flat to 5.0 m ALLT and are the only species found above 5.2 m ALLT. They must recolonize the upper tidal flat every spring since the area undergoes heavy ice action.

2. Capitellidae are the second most numerous family. Capitella sp. appears at 5.0 m ALLT. The animal is motile and constructs numerous tubes which maintain a link with oxygen above ground. Accordingly they can tolerate, and prefer, muddy substrates.

3. The errant polychaetes dominate the midflat region although they are found from 5.0 m to the low, low tidal datum. These species can migrate through the substrate, their upper tidal limit set by

substrate, exposure limits and low salinities during breakup. Eteone are carnivorous and have been observed feeding on spionids, accordingly they appear to control the lower limit of distribution of Scolelepis.

4. The midflat region between 2.0 m and 5.0 m ALLT has E. flava, E. longa, Capitella, Polydora, S. filicornis and S. goniocephala as well as Scolelepis. The area has between 25 and 45% exposure with densities ranging from 15 to over 700 species per 100 sq cm. The high densities only occur when Scolelepis are encountered.

5. Below 2.0 m ALLT the tubiculous polychaetes dominate the substrate. Sabellids such as Euchone analis, Chone infundibuliformis and Laonome kröyeri dominate the lower parts of the tidal flats, where their sand tubes help stabilize the substrate from wave and current erosion. These animals are filter feeders and require at least 90% inundation to survive. Other tubiculous worms are from the fragile maldanidae family which actively burrow the sediment causing a great deal of bioturbation.

Carnivorous, mobile worms which inhabit the lower flats include H. imbricata and Phyllodoce groenlandicus. Mobile deposit feeders like Travisia forbesii and Chaetozone setosa are also common to area with < 10% exposure.

6. In general, it appears that low tidal species live over a number of season, whereas, in the upper flats, recolonization must occur every year. The species usually only survive one season due to freezing temperatures and the removal of the upper layers of sediment by ice.

7. Tubiculous polychaetes, such as the sabellidae and

ampharetidae help stabilize the sediments. Active burrowing by _Maldanidae, Capitella_ and _Scalibregma inflatum_ help mix the upper layers of sediment. Aeration of the top 4 cm of sediment is mainly due to these motile species, particularly _Scolelepis_ in the upper flat tidal pools. Some deep burrowing species enhance the breakdown of the grey clay layer, thereby introducing new material to the tidal flat system. Finally, sorting of the sediments can occur by the selective feeding preferences of certain deposit feeders like _Travisia forbesii_, _Chaetozone setosa_, and some spionids.

CHAPTER 7

CONCLUSIONS

7.1 Conclusions

Results of the research, described in the preceding pages, have been summarized at the end of each chapter (Sections 2.6, 3.7, 4.5, 5.8 and 6.6). It remains for this chapter to summarize these findings, and recount the salient details, which are as follows.

1. Average ice conditions in Frobisher Bay vary only in timing and duration from year to year. The sequences of ice freezeup and breakup remain the same. Ice begins to form in late October and is usually complete by mid-November. Sediments, including fines and boulders, are incorporated in the ice and experience some horizontal movement during ice formation. Thaw is initiated, on average, by June 14 and is followed by a sequence of ice breakup events which conclude with ice-free conditions by July 17. The ice breakup sequence experienced at the headward reaches of Frobisher Bay (Table 2.5), is influenced by local environmental and morphologic features. Tidal flats by river mouths are the first intertidal areas to breakup. Thus, throughout most of the breakup period, tidal flats, more than any other coastal environment are subject to the erosional and depositional effects from drift ice.

2. Ice action plays an important role in the biological and physical zonation of the tidal flat. In the Upper Flat zone in

Koojesse Inlet, some 22,450,000 kg of sediment from the active layer can be incorporated in the fast ice. This disrupts the normal grain size distribution and bedforms, and destroys the infaunal populations, established in the ice-free period. Ice formed micro-relief developed in the Upper Flat zone from the removal of sediment from ice freezeup.

Boulders up to 1 m in diameter and larger are regularly transported by the ice during the winter. Data suggest that boulder movement during freezeup is as important as during breakup. Boulders are most likely to be incorporated in the ice if they are small, isolated and lying loosely on the substrate surface. Many of the transported boulders were deposited around 5.0 m ALLT in 1980-81.

The ice is very active around the ice foot/fast ice boundary, especially during breakup. Ice push boulder ridges, boulder pavement, and sediment ridges commonly form in this region. Ice action is strong from approximtely 4.0 m ALLT and up. Numerous large boulder ridges, at Apex, Rock transect and a minor ridge at STB have formed between 4.0 and 4.5 m ALLT.

The ice foot protects the rock shoreline from ice erosion and then erodes the surface itself during breakup. It also acts as a sediment trap from ice floes stranding on its surface.

The influx of fresh water during melt restricts the movement of polychaete, mollusc and barnacle larvae. Fresh water, later in the season, has a devastating effect, particularly on shell creatures like Cyrtodaria kurriana and Hiatella arctica which cannot close their shells. Significant numbers of these animals were killed in 1980 from a rare influx of drift ice at the beginning of August.

Drift ice creates many short lived features which are quickly destroyed once normal wave action resumes, like ice gouges, striations and imprints. Drift ice is also responsible for the transport of sediments and boulders during breakup.

3. Tidal action has two important roles on the tidal flats. First, varying tidal levels expose different parts of the tidal flat at different times and for varying lengths of time. Thus, marine processes cannot act consistently at different tidal levels. Also, flora and fauna have specific requirements on the amount of time they are covered by water. Many are sensitive to dessication by the sun and others rely on the presence of water for reproduction and feeding. Thus, exposure levels restrict flora and fauna to specific tidal heights (zones).

Secondly, the tides influence the chemical and physical (temperature and velocity) properties of the water. These properties affect wave and current action on bedforms and the grain size distribution. At Koojesse Inlet, the highest currents are generated during ebb tide, but the highest average velocities occur at flood tide. Thus, a mixture of ebb and flood dominant, ripples, sand waves and deltas exist on the flats. In general flood dominant features were common on the upper parts of the tidal flat and ebb dominant at the lower part.

From the exposure curve calculated for Frobisher Bay, 4.0 m ALLT and 7.5 m ALLT signify the position of abrupt changes in the number & duration of exposures. Four metres above the tidal datum, marks the boundary between the bouldery and very bouldery tidal flats and the position of boulder ridges (Fig. 7.1). Secondly, it delineates the upper tidal limit of perennial, sedentary infaunal species (Fig. 7.2). At 7.5 m ALLT, sand beaches occasionally develop. Scolelepis can live up to this tidal height, which is just short of the mean tidal height of 7.8 m ALLT. Only Fucus evanescens is encountered past 7.5 m ALLT.

4. The tidal flats in Koojesse Inlet and around Rodgers Island are erosional flats. The rarity of large scale depositional forms, the thin active layer and net erosion over two summers of study supports this view. The flats are presently eroding into a glacio-lacustrine deposit which supplies the flats with sediments for its active layer.

5. The tidal flats at the head of Frobisher Bay exhibit physical zonation. In Figure 7.1, a typical Frobisher Bay profile has been drawn, its exposure curve is shown above. The tidal flat is divided into 6 morphological zones: beach , fines flat, bouldery flat, very bouldery flat, boulder ridges and graded flat. In more general terms, beach and fines flat are part of the upper flat, bouldery flat, very bouldery flat and boulder ridges are characteristic of the middle flat, and the graded flat is found on the lower flat. The zones are based upon sediment characteristics, boulder distribution, drainage patterns, surface morphology, gradient, and tidal height (See, section 4. 4.3).

Using maps and aerial photos this simple scheme can be extended to all of the tidal flats in Frobisher Bay. Thus, indirectly, information can be obtained on the effects of ice, wave and tidal

Figure 7.1 The morphological and biological zonation of the typical Frobisher Bay tidal flat.

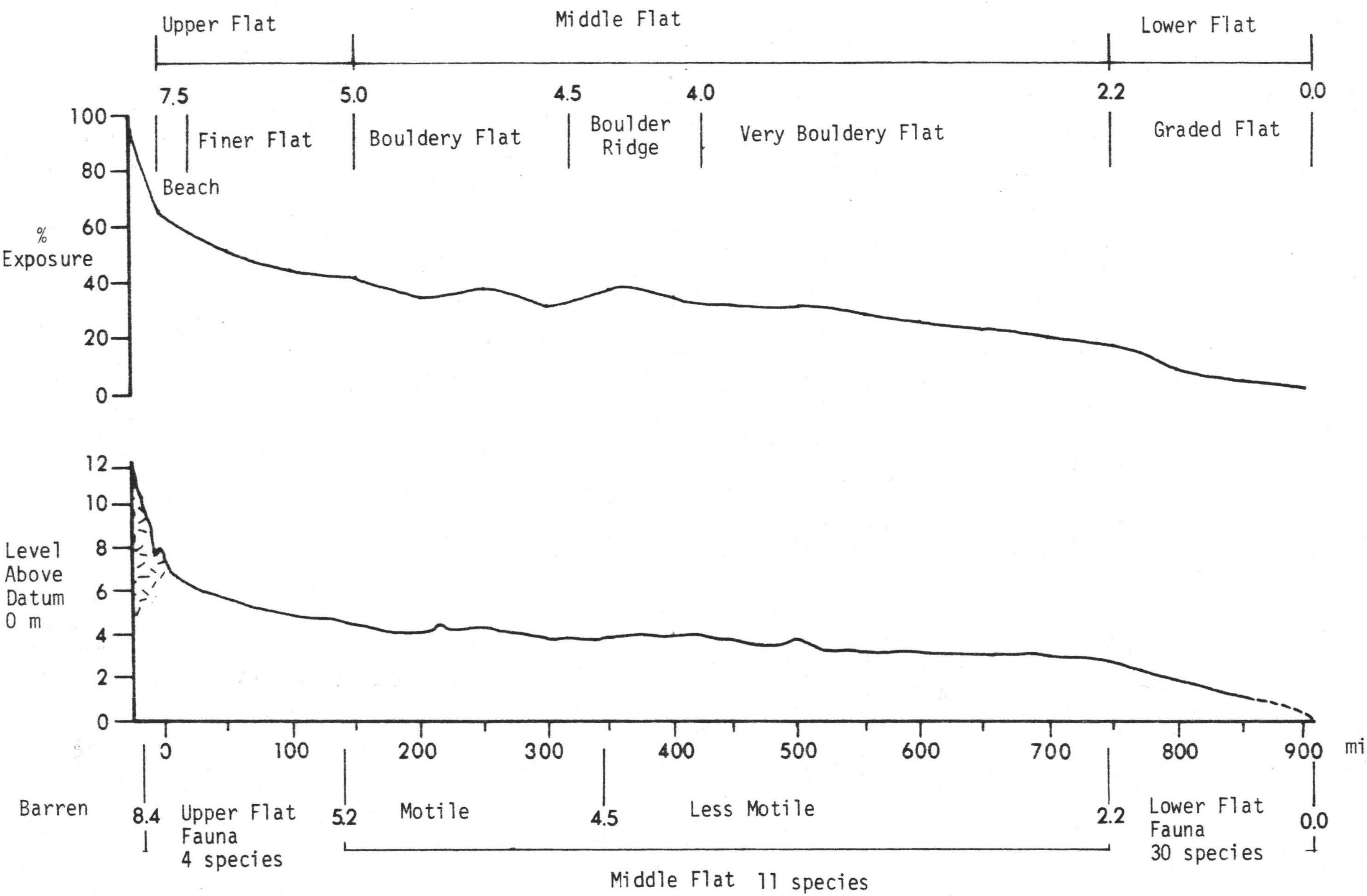


Figure 7.2b Species Legend for Figure 7.2a and Tidal Ranges

Number	Species	Tidal Range m ALLT	Biotic Community
1	√Fucus evanescens	8.4	High Flat
2	√Scolelepis (nerinides) sp.	7.5	"
3	√Littorina saxatilis	7.0-2.2	"
4	√Fucus vesiculosus	6.5-6.0	"
5	√Eteone longa	5.2	Motile Middle
6	√Capitella "capitata" sp.	5.0	Flat
7	√Balanus balanoides	4.95	"
8	√Eteone flava	4.5	"
9	√Sea anemone	4.25	Less Motile
10	Spio goniocephala	4.1 1.5	Middle Flat
11	Spio filicornis	3.7 1.4	"
12	Polydora quadrilobata	3.1 1.3	"
13	√Echiuris	3.1 1.0	"
14	√Mya truncata	2.6	"
15	Priapulia	2.6	"
16	Phyllodoce groenlandicus	2.5 .7	Lower Flat
17	Crenella faba	2.2	"
18	Margarites sp.	2.2	"
19	√Cyrtodaria kurriana	2.2	"
20	Travisia forbesii	2.1 .6	"
21	√Thracia myopsis	2.0 1.7	"
22	Neodilsea integra	1.95	"
23	√Chone infundibuliformis	1.9	"
24	√Pilayella littoralis	1.9	"
25	Ulvaria obscurra	1.75	"
26	√Hiatella arctica	1.75	"
27	Musculus discors	1.75	"
28	Musculus niger	1.75	"
29	√Praxillella praetermissa	1.7	"
30	Harmothoe imbricata	1.7	"
31	Halosaccion ramentaceum	1.7	"
32	√Fucus edentatus	1.7	"
33	√Euchone analis	1.6	"
34	√Praxillella affinis	1.6	"
35	Scoloplos acutus	1.5	"
36	Mediomastus sp.	1.5	"
37	√Laonome kröyeri	1.5-1.3	"
38	Palmaria palmata	1.5	"
39	√Laminaria longicruris	1.5	"
40	√Alaria esculenta	1.5	"
41	Ampharete acutifrons	1.4	"
42	Chaetozone setosa	1.3	"
43	Chaetomorpha melagonium	1.3	"
44	Stictyosiphon melagonium	1.3	"
45	Sphacelaria arctica	1.2	"
46	Rhodomela confervoides	1.2	"

Tidal Range refers to the upper tidal limit, the lower limit is at least to the 0m datum unless otherwise noted.

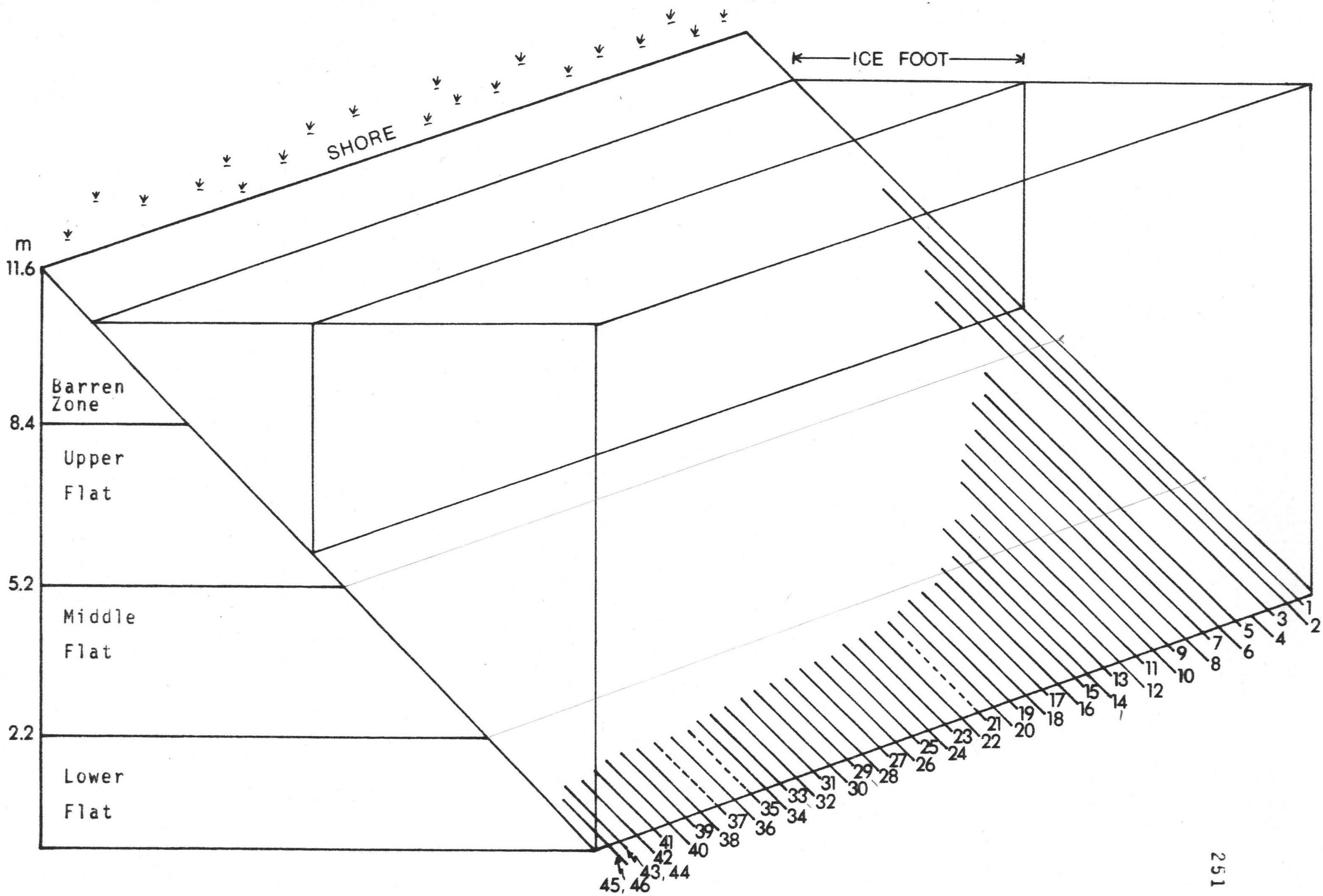


Figure 7.2a Tidal Ranges for the Biota at Frobisher Bay

action over a broader area without the necessity of further fieldwork. Approximate tidal heights can also be inferred.

6. Also of great importance is the fact that floral and faunal communities correspond to essentially the same tidal heights as the physical zonation (Fig. 7.1). In Figure 7.2a all of the flora and fauna collected in this study have been graphed according to the tidal ranges in which they were found, and are listed in Figure 7.2b. From this diagram three biological communities are evident. In the first community, from 8.4 to 5.2 m ALLT only 4 species exist, two macroalgae, Fucus evanescens and Fucus vesiculosus and two fauna, L. saxatilis and Scolelepis. This zone is usually covered by an ice foot in the winter months. The algae and the L. saxatilis can survive being frozen in ice and can tolerate low saline conditions. Scolelepis recolonizes this upper flat region every year after the ice has left.

There are 12 species in the middle flat biota which can be further divided into 2 subsections, motile and less motile middle flat biota. The motile subsection extends from 5.2 m to 4.5 m and introduces 4 new species. Balanus balanoides are tolerant of ice and fairly fresh water, so they can survive in this zone with little problem. Both E. longa and E. flava are very motile creatures which can migrate through the sediment to new sites and to great depths thus escaping unfavourable environments.

Below 4. 5 m ALLT perennial sedentary infauna appear, such as the sea anemones, and echiuris. The spionids probably recolonize each year and the Phyllodoce has motility similar to Eteone.

This zone marks the appearance of the first bivalve, Mya truncata which was recorded in burrows to depths of 26 cm. It too can escape unfavourable conditions by descending to the bottom of its chamber.

On the lower flats, below 2.2 m ALLT additional floral and faunal species appear. They require less than 10% exposure. Many of them are intolerant of freezing temperatures and low saline conditions. Most of the bivalves appear in this zone, as do most of the macroalgae species collected.

The above findings illustrate that the biological zonation characteristic of temperate flats is also present in the Subarctic flats of Frobisher Bay. While competition, substrate, salinity and protection play important roles in the resultant zonation, exposure appears to be the primary cause of zonation across these flats.

7. Sea anemones were the most common infaunal species collected. The second most abundant animal was the bivalve Cyrtodaria kurriana which lived in great abundance in limited locales. They were found in densities as high as 92.8 per 4 m^2 at 1.6 m ALLT at Rodgers Island. Mya truncata was the second most abundant bivalve. The numbers of this edible animal will probably decrease in the intertidal zone over the next few years. This is in response to the large numbers which are harvested every year for local consumption. The slow growth rate of the Mya will not allow it to maintain its population against continued harvesting in the intertidal zone.

8. Echiura found in this study, are from the bonelliidae family, and have never been previously recorded for Frobisher Bay, nor to this researchers knowledge Southeast Baffin Island. The animal

lives in fine but cohesive sediments below 3.1 m ALLT. Its U-shaped burrow often reaches down into the clay layer.

9. The highest macrofaunal densities and diversities occurred between 1.0 m and 2.0 m ALLT on Rodgers Island, where 10 species reached a density of 110.2 per 4 m^2. Including all of the flora and fauna, the greatest diversity occurs in the lower flat zone.

10. The most abundant polychaete at Frobisher Bay was Scolelepis (nerinides) sp. This worm reached a maximum density of 727.5 per 100 sq. cm.

Scolelepis sp. did not fit into any of the taxonomic keys available. Nor were there any reports about this species. It appears that it might be a previously undocumented species (J. Fournier pers. comm.)

11. Polychaetes in the upper flat areas usually do not live longer than a year. Freezing temperatures and the removal of sediments account for this trend. However, on the lower flats many species, particularly the tubiculous worms, appear to live a number of years. More favourable conditions contribute to this phenomenon.

12. Tubiculous polychaetes such as the sabellidae and ampharetidae, help stabilize the active layer of the tidal flats. Continual burrowing by Scolelepis, Capitella and Eteone help aerate the upper part of the active layer. Selective feeding by surface deposit feeders such as echiura, Travisia forbesii and Chaetozone setosa help sort the upper surface sediments, while other burrowers mix it. Deep burrowing into the clay layer supplies new fines for the tidal flat active layer. Mya truncata, echiura and some of the sabellids are responsible for introducing new sediments to the flat in this way.

Thus, there are relationships between biological and physical components and physical processes across the Subarctic macrotidal tidal flats, at the head of Frobisher Bay. These relationships have resulted in distinct morphological and biological zonation. Biological inputs into the system are still not well understood mainly due to the lack of information on the life habits of many of the species.

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APPENDIX 1a Polychaete collections from Frobisher Bay 1981

Apex transect

Location Ht. above 0 datum Family	0m A26A + 4.2 m July 28, 1981	50 m A27A + 4.1 m July 28, 1981	100 m A28A + 3.9 m July 28, 1981	150 m A29A + 3.2 m July 28, 1981	200 m A30A + 2.9 m July 28, 1981	250 m A31A + 2.7 m July 28, 1981	300 m A32A + 2.6 m July 28, 1981
Ampharetidae							
Capitellidae		6 Capitella sp. "capitata group"	16 Capitella sp.	48 Capitella sp.	11 Capitella sp.	3 Capitella sp.	5 Capitella sp.
Cirratulidae							
Flabelligeridae							
Maldanidae							
Nephtyidae							
Opheliidae						1 Travisia forbesii	
Orbiniidae							
Phyllodocidae		3 Eteone longa 1 Eteone flava	1 E. flava	28 E. longa 7 E. longa	5 E. longa 2 E. flava	3 E. longa 2 E. flava	2 E. longa 3 E. flava
Polynoidae							
Sabellidae							
Scalibregmidae							
Spionidae	603 Scolelepis (Nerinides) sp.	59 Scolelepis sp.	97 Scolelepis sp. 1 Spio filicornis 1 Spio goniocephala	6 Scolelepis sp. 8 S. filicrnis	4 Scolelepis sp. 4 S. filicornis 4 Spionid (unknown)	1 Spio goniocephala	1 spionid (unknown)

APPENDIX 1a continued

Rock transect

Location Ht. above 0 datum Family	Om R18A + 3.5 m July 27, 1981	12.5 m R21A + 3.1 m July 27, 1981	12.5 m R6A + 3.1 m July 19, 1981	25 m R24A + 3.7 m July 27, 1981	50 m R11A + 3.0 m July 19, 1981	75 m R5A + 2.2 m July 19, 1981	100 m R12A + 1.4 m July 19, 1981
Ampharetidae							
Capitellidae	3 Capitella sp. "capitata group"	10 Capitella sp.	13 Capitella sp.	6 Capitella sp.	3 Capitella sp.	30 Capitella sp.	
Cirratulidae							
Flabelligeridae							
Maldanidae							
Nephtyidae							
Opheliidae							
Orbiniidae							
Phyllodocidae	1 Eteone flava 5 Eteone longa	1 E. flava 7 E. longa	2 E. longa	7 E. longa	8 E. longa	2 E. longa	6 E. longa
Polynoidae							
Sabellidae							
Scalibregmidae							
Spionidae	41 Scolelepis (Nerinides) sp. 1 Spio goniocephala	107 Scolelepis sp. 2 Spio filicornis 1 Polydora quadrilobata	13 Scolelepis sp.	69 Scolelepis sp. 1 S. filicornis	3 Scolelepis sp.	1 Scolelepis sp.	1 Scolelepis c.f. sp.

APPENDIX 1a continued

Rodgers Island

Location Ht. above 0m datum Family	50 m RI38A + 3.9 m Aug. 3, 1981	75 m RI37A + 2.2 m Aug. 3, 1981	100 m RI36A + 2.0 m Aug. 3, 1981	125 m RI35A + 1.9 m Aug. 3, 1981	150 m RI35A + 1.7 m Aug. 3, 1981	RI29A 175 m RI30A RI31A + 1.6 m Aug. 3, 1981	RI27A 200 m RI28A RI33A + 1.5 Aug. 3, 1981	RI25A 225 m RI26A RI32A + 1.5 m Aug. 3, 1981	RI22A 250 m RI23A RI24A + 1.3 m Aug. 3, 1981	RI16A 275 m RI20A RI21A + 1.3 m Aug. 3, 1981	RI17A 300 m RI18A RI19A + 1.0 m Aug. 3, 1981
Ampharetidae		1 Ampharete acutifrons									
Capitellidae	8 Capitella sp. "capitata group"	8 Capitella sp.	39 Capitella sp.	29 Capitella sp.	27 Capitella sp.	15 Capitella sp.	25 Capitella sp. 7 Mediomastus cf. sp.	37 Capitella sp. 16 Mediomastus cf. sp.	26 Capitella sp. 5 Mediomastus	46 Capitella sp. 17 Medomastus	29 Capitella sp. 8 Mediomastus
Cirratulidae											
Flabelligeridae											
Maldanidae					1 Praxillella praetermissa	9 Praxillella affinis	3 P. affinis 2 P. praeter-missa	16 P. praetermissa	8 P. praetermissa	18 P. praetermissa	17 P. affinis 8 P. pratermiss
Nephtyidae											
Opheliidae											
Orbiniidae							1 Scoloplos acutus				
Phyllodociade	5 Eteone flava 25 Eteone longs	3 E. flava 14 E. longa	8 E. longa	4 E. longa	1 E. flava 8 E. longa	6 E. longa 1 Phyllodoce groenlandicus	4 E. longa 1 P. groenlandicus	1 E. longa	7 E. longa	6 E. longa	3 E. longa
Polynoidae											2 Harmothoe imbricata
Sabellidae			2 Chone infundibuliformis			1 C. infundibuliformis 12 Euchone analis	13 E. analis 5 Laonome Kroyeri	1 C. infundibuliformis 4 E. analis 2 L. kroyeri	46 E. analis 1 L. Kroyeri	4 C. infundibuliformis 18 E. analis	1 C. infundibuliformis 11E. analis
Scalibregmidae											
Spionidae	1 unknown	2 unknown			3 unknown	1 unknown	2 Scelelepis (Nerinides) sp. 1 Spio fili-cornis	1 Polydora quadrilobata 1 unknown	2 p. quadrilobata 3 Scolelepis sp. 4 unknown	1 unknown	4 unknown

APPENDIX 1a continued

STB transect

Location Ht. above 0 datum Family	0m STB5A + 7.5 m Aug. 11, 1981	50 m STB6A + 5.9 m Aug. 11, 1981	100 m STB7A + 5.2 m Aug. 11, 1981	150 m STB8A + 5.0 m Aug. 11, 1981	200 m STB9A + 4.3 m Aug. 11, 1981	250 m STB10A + 4.4 m Aug. 11, 1981	300 m STB11A + 4.1 m Aug. 11, 1981	350 m STB12A + 4.5 m Aug. 11, 1981	400 m STB13A + 4.2 m Aug. 11, 1981
Ampharetidae									
Capitellidae				18 Capitella sp. "capitata group"	128 Capitella sp.	40 Capitella sp.	4 Capitella sp.	13 Capitella sp.	15 Capitella sp.
Cirratulidae									
Flabelligeridae									
Maldanidae									
Nephtyidae									
Opheliidae									
Orbiniidae									
Phyllodocidae			3 Eteone longa	4 E. longa	3 Eteone flava 16 E. longa	21 E. longa	6 E. flava 28 E. longa	1 E. flava 20 E. longa	2 E. flava 16 E. longa
Polynoidae									
Sabellidae									
Scalibregmidae									
Spionidae	783 Scolelepis (Nerinides) sp.	590 Scolelepis sp.	629 Scolelepis sp.	885 Scolelepis sp.	8 Polydora quadrilobata 26 Scolelepis sp.	16 Scolelepis sp.	13 Scolelepis sp. 4 Spio goniocephala	3 Polydora cf. quadrilobata	1 Spio filicornis 3 Polydora cf. quadrilobata

APPENDIX 1b

Life Habits of Arctic Polychaetes Present in Frobisher Bay

Errantia

Order Phyllodocida
Suborder Phyllodociformia
Family Phyllodocidae

Eteone flava, (Fabricius 1780)
Eteone longa, (Fabricius 1780)
Phyllodoce groenlandica, (Oersted 1842)

Phyllodocidae are generally carnivorous, moving freely over the surface, burrowing in the substrate or swimming. *Eteone flava* and *Eteone longa* are characteristically burrowing forms found from intertidal to deep subtidal locations. *E. flava* can be found among rocks, gravelly sands and combinations of mud, gravel, rock and shells. *E. longa* can be found in higher intertidal locations, and appears to prefer slightly finer sediments although it too can tolerate gravels, pebbles, rocks, shells and other worm tubes. *E. longa* spawns in April and May, and its larvae have a relatively short planktonic existence (Pettibone 1963). Many *E. longa* were found near river mouths in West Greenland (Madsen 1936), indicating an apparent tolerance to fresh water.

E. longa exhibited a wide variety of eating preferences. They can live on ingested sediments, practise cannibalism and hunt other invertebrates, often following the mucous trail left by their prey. *E. longa* have been observed feeding on *Spio filicornis* and *Scolelepis* squamata (Khlebovich 1959, Michaelis 1971 from Fauchald and Jumars 1977), two genera found on the Frobisher Flats.

Phyllodoce groenlandica is also carnivorous. It lives in sands, on algae holdfasts a combinations of mud, gravel, stones etc. similar to Eteone. They lay eggs which are attached to the substrate and algae by short staffs. Larvae are present from March to September and have a relatively long pelagic life (Pettibone 1963), an uncommon occurrence for most Arctic polychaetes (Thorson 1936).

Order Phyllodocida
Suborder Aphroditiformia
Family Polynoidae

Harmothoe imbricata (Linné 1767)

Harmothoe imbricata is a very common and abundant Arctic species (Madsen 1936, Thorson 1936, Pettibone 1963) living to great depths, but preferring intertidal positions (Fauchald and Jumars 1977). It is found on substrates of mud, sand, rock, gravels, clinging to holdfasts and fronds of algae, like Laminaria, and living in rock cracks, tidal pools and among barnacles, mussels, tunicates and old worm tubes.

H. imbricata belongs to the carnivorous, motile, jawed (CMJ) feeding guild as proposed by Fauchold and Jumars (1970). It has adopted a 'sit-and-wait' prey capture technique, attacking live prey only, such as amphipods and other polychaetes. They may also eat some algae to supplement their diet (Fauchald and Jumars 1979).

H. imbricata spawns towards the end of May to June and is complete before August in Northeast Greenland. Thorson (1936 found that the species had adapted to the environmental conditions thereby eliminating its larval, pelagic stage, observed in boreal climates. The eggs and developing trochophores are protected by the female under its elytra until mature enough to survive on the substrate alone (Pettibone 1963). Small H. imbricata specimens which had not yet developed eyes or elytra were found in the upper parts of the substrate by Thorson (1936).

The animal is euryhaline, capable of withstanding "rather fresh water" and can tolerate great ranges in temperature (Pettibone 1963). They can also tolerate oxygen deficiences for up to 7 days and the presence of H_2S for 3 to 6 days (Ushakov 1965).

Order Phylledocida
Family Nephytyidae
Nephtys caeca
Nephtys ciliata

These species were not common in Koojesse Inlet and preferred low tidal locations. Nephtys ciliata are commonly found in mud, muddy sand, gravelly mud or sand (Pettibone 1963). Schäfer (1972) found N. ciliata to live exclusively in mud as can N. caeca, but it prefers sand. N. caeca tolerates coarser substrates like shifting sand, muddy and gravelly sands, mud with rocks and gravel (Pettibone 1963). They are free-living burrowers which have been observed to form poorly agglutinated burrows which are frequently deserted (Schafer 1972).

Nephtyidae are carnivorous, highly mobile species with jaws, which subsist on small invertebrates and ingested sediments (Fauchald and Jumars 1979).

Sedentaria

Order Orbiniida
Family Orbiniidae

Scoloplos acutus, (Verrill 1873)

This family, orbiniidae, is considered midway between errant and sedentary polychaetes. They are burrowers and are highly motile living from the littoral zone to 98 fa. Scoloplos acutus has been found in sticky and soft muds to fine to coarse sands, and combinations of pebbles, rocks, gravel shells etc (Pettibone 1963). Some were found by the Sylvia Grinnell River. The animal secretes mucous which lines the inside of its burrowing trails but does not consolidate the walls into a tube (Schäefer 1972). The S. acutus is a non-selective deposit feeder, which may feed on organic debris or small organisms in the sediment (Pettibone 1963, Fauchald & Jumars 1979).

Its yolked coral-pink eggs are visible in the summer in temperate locations. The eggs are usually deposited near where the adults live attached to the substrate. It is thought that the pelagic larval stage is lacking (Pettibone 1963).

Order Spionida
Suborder Spioniformia
Family Spionidae

Laonice cirrata (Sars 1951)
Polydora caeca
Polydora quadrilobata (Jacobi 1883)
Scolelepis (Nerinides) sp.
Spio filicornis (O.F. Muller 1976)
Spio goniocephala (Thulin 1957)

Spionids are usually tubicolous worms frequently found in abundant numbers on all substrates in shallow waters. All of the spionids except the *Polydora* are capable of leaving their tubes and building new ones when necessary (Fauchald and Jumars 1979). Certain *Scolelepis* live in shifting sands, and build loose burrows or are entirely free living (Hartmann-Schröder,1971). Muddy sandy areas and sites with well-sorted fine sands are densely populated by these worms.

Polydora quadrilobata settle in fine sands or muds on the tidal flats. They construct well consolidated U-shaped tubes 3 to 5 cm in depth (Schäfer 1972). *Scolelepis* have similar tubes in Frobisher Bay which often protrude above the sediment surface following removal of the surrounding substrate. These tubes help bend the surficial sediments and restrict erosion.

Spionidae were assigned to the burrowing motile, tentaculate feeding guild by Fauchald and Jumars (1979). They are surface deposit feeders capable of selecting the size and content of food particles. The animal sits with its head at the opening of its tube and stirs the water with its tentacles to catch plankton. It also runs its tentacles across the bed picking up surficial debris (Schäfer 1972, Fauchald and Jumars 1979).

Spio filicornis was prominent on clay shores(Madsen 1936) and sandy substrates (Thorson 1936) along Northeast Greenland. *S. filicornis* develop in two ways. In the autumn it develops without any pelagic stage by nurse eggs. This occurs when only a few of the eggs deposited in a capsule develop, they obtain nutrients by eating the rest of the eggs. In the spring pelagic larvae develop without nurse eggs (Thorson 1936).

Spio filicornis can tolerate salinities as low as 5% making them a good northern intertidal inhabitant (Hartmann-Schröder 1971).

Order Spionida
Suborder Cirratuliformia
Family Cirratulidae

Chaetozone setoas (Malmgren 1866)

These simple polychaetes live in shallow water to 2600 m (Appy et al 1980). Most species are free living, often settling in small collections of mud in rock crevices, under rocks or on algae holdfasts. Some build mud covered tubes. Chaetozone setosa are considered to be selective surface deposit feeders, using their palps to collect their food. This particle selectivity has been observed to change the particle composition of sediments immediately next to the animal (Fauchald and Jumars 1979).

Order Capitellida
Family Capitellidae

Capitella sp. "capitata group"
Mediomastus sp.

Capitellidae are mainly motile deposit feeders, although some like Capitella capitata build tubes at or near the sediment surface. Through these tubes they maintain a link with the oxygen above ground by irrigation and thus can tolerate liquid slime and other black anoxic muds near anaerobic conditions for long periods (Ushakov 1965). They appear to prefer muddy substrates, apparently feeding non-selectively on algae and sediment detritus (Fauchald,1979).The large mobile forms are capable of marking the sediment permanently through feeding and locomotion activities (Schäfer 1972). Capitella has pelagic larvae in boreal conditions but little is known in the Arctic environment.

Order Capitellida
Family Maldanidae

Praxillella affinis
Praxillella praetermissa (Malmgren 1866)

Maldanidae (bamboo-worms) are often found on slimy and loamy facies (Ushakov 1965) and soft substrates at all depths. They are mainly tubiculous, possessing a variety of tube types. Praxillella affinis and P. praetermissa collected in Koojesse Inlet constructed stiff mucous tubes with sand grains on the outside. These animals are capable of tube building throughout life, and burrowing from one location to another. Fauchald and Jumars(1979) postulated that these animals would discontinue extensive tube construction in nutrient rich environments. They are listed under the burrowing, jawless, sessile feeding guild. Their burrowing activities cause great bioturbation of the upper sediments (Schäfer 1972).

Order Opheliida
Family Opheliidae

Travisia forbesii (Johnston 1840)

Opheliids burrow into sandy or sandy muddy sediments (Ellis 1960). They are probably more selective deposit feeders than has been previously believed (Fauchald & Jumars 1979), ingesting organic material in the substrate like diatoms and detritus. For defense T. forbesii emits a disagreeable H_2S odor. It is an arctic-boreal circumpolar species which prefers shallow, littoral areas (Ushakov 1965).

Order Opheliida
Family Scalibregmidae

Scalibregma inflatum (Rathke 1843)

Scalibregma inflatum live in mud and silt and are distributed widely over the mud surfaces of the North Sea. According to Caspers (1950a see Schäfer 1972), four hundred animals per sq. metre are not uncommon in the summer. They can live at great depth, 30-60 cm below the surface in galleries excavated in the sediment. Fine feeding burrows which frequently change position radiate out from the main galley. The animal moves into its fecal tube to discharge fecal pellets at the surface (Schäfer 1972).

S. inflatum is an active burrower, feeding on sediment detritus a depth and occasionally at the surface (Fauchald and Jumars 1972).

Order Flabelligerida
Family Flabelligera

Flabelligera affinis (Sars 1829)

Flabelligera affinis was collected on the tidal flat during low tide after a storm. This species is subtidal and not found in the intertidal area. It is a motile surface deposit feeder which ingests algae and detritus. Its body was covered with a thick layer of mucous.

Order Terrebellida
Family Ampharetidae

Ampharete acutifrons (Grube 1860)

Ampharate species live in both mud and silt habitats where they build mucous burrows. These tubes are frequently longer than the animal and help bind the upper sediment layers when in great densities. The animal is a surface deposit feeder which extends retractable ciliated tentacles to indiscriminately pick up surface detritus (Schäfer 1972, Fauchald and Jumars 1979).

Order Sabellida
Family Sabellidae

Chone ef. infundibiliformis (Kröyer 1856)
Euchone analis (Kröyer 1856)
Laonome kröyeri (Malmgren 1866)
Sabella crassicornis (Sars 1851)

The sabellidae are sessile, filter feeders living in their tubes for life. They filter pelagic diatoms unicellular algae, dinoflagellates larvae, and small invertebrates. Ellis (1960) found Euchone analis preferred sand, and muddy sand substrates. In general, sabellidae occur in the tidal zone but prefer deeper parts of it (Schäfer 1972). They build tubes with two openings, made of elastic, stringy mucous encrusted with mud. E. analis had its tubes covered with fine sand grains which varied in colour in Frobisher Bay. Dark, grey grains were located where the tentacles rested, and a red, oxidized colour began by the mouth. This halo of oxidized iron hydroxide helps consolidate the tube walls (Schäfer 1972).

In great concentrations, these Sabellids help stabilize the surface of the sediment, preventing erosion by wave and current action.

APPENDIX 2

Methodology Employed

Surveying

Most of the research concentrated on the 4 transect lines. A stadia rod and a Kern level was used to survey boulder positions, surface topography and tidal heights. Slopes across the tidal flats were calculated from the surveys. Tidal height above low low tide was determined from surveyed benchmarks and actual tidal levels obtained from the tidal recorder in Koojesse Inlet (C.T. O'Reilly, Tidal Officer pers. comm.). Horizontal surveying accuracy was within 1.8 m S.D = 1.4 m and vertical heights within .2 m.

Shoreline and Coverage Measurements

Horizontal distances were measured on the maps using an opisometer to within .5 km. Percent coverage of ice and other aerial measurements were made with a planimetre accurate to within .1%.

Sediment and Boulder Measurements

Sediment depths and boulder measurements were taken with a standard metre stick and rounded to the nearest centimetre.

The movement of surficial sediments was monitored using depth of disturbance rods (DOD). Steel rods, 3/16 inch in diameter were inserted at 50 m intervals down the flats in clusters of 5, 2 metres apart. Washers were placed on the rods resting at the sediment surface. Measurementswere taken at various times, to the washer from the top of the rod in millimetres. The washer dropped with the substrate surface during erosion and was covered with sediment which was measured during net deposition. An overall average was obtained from each cluster of 5 rods to determine the value of net erosion or deposition at each site.

Water Analyses

Multiple 12-hour tidal cycles were monitored for tidal current velocities, temperatures and salinities. Two sites were chosen and relocated for repeat monitoring using an East Berks Boat Co. Sextant. Current velocities were obtained using a Price 622AA current metre which was calibrated at CCIW in 1980.

A YSI Model 33 specific conductivity meter was used to measure salinities below $4^{\circ}C$ to ± 0.9% at 20% and ± 1.1% at 40%. Water temperatures were obtained using YS1 44006 precision thermistors and a Beckman Tech 300 multimeter which is accurate to within ± 0.025%. The thermistors were calibrated with the multimeter using a Lauda K-4/RD oil bath.

Sediment Analyses

Rough grain size estimates were made in the field using sample grain size charts. In the laboratory standard dry sieving (< 4.00) and pipette techniques (> 4.00) outlined by Folk (1974) were used.

The sediment was first put in a centrifuge for 10 minutes to remove salts. Organic material was removed using 10% hydrogen peroxide. The Wentworth grain size scale was used and Folks statistics calculated.

Foram analyses on the clay layer followed procedures used by Terasmae (Western University, Geology 441 Techniques). The sample was first treated with 50 ml of 25% H_2O_2 which was boiled off. After cooling, the sample was sieved using a 60 mesh (2.00) sieve. The material retained on the sieve was then examined for forams through a microscope .

Visual Techniques

Field measurements and observations were supported by a number of visual aids. Colour video films taken during the ice breakup sequence also provided information on the regional geomorphology (See Chapter 2). Aerial photographs Flight A 25553, 1980 from the Remote Sensing Library in Ottawa were used to denote surficial zones and tidal channels.

A Minolta Super 8 movie camera was used to document the direction of ebb and flood tides at Apex and STB. Time lapse photos were taken at 40 second intervals over a 12-hour period.

Exposure Index

The exposure index and current velocity calculations were obtained from values from the predicted tide table for Frobisher Bay (Canadian Hydrographic Service) utilizing a computer program by C. Smart and P.B Hale (pers. comm.). The primary assumption of the program is that a simple cosine function describes the tide behaviour between high and low tide. The program computes the time between up and down water crossing at particular tidal heights. The summation of these crossings at each height for a month gives exposure indices for that month.

Vertical instantaneous velocities were calculated from the slope of the tidal curve. The program solves for the steepest slope where the maximum rate of vertical water height changes over time. Assuming a low gradient, horizontal velocities could be calculated from the vertical velocities using the following equation.

$$\text{Horizontal Velocity} = \frac{dz}{dt} = \frac{dy/dt}{dy/dx}$$

where $\frac{dy}{dt}$ = vertical velocity in m/hr

$\frac{dy}{dx}$ = tidal flat gradient m/m