OBSERVATIONS OF THE BEACH ENVIRONMENT OF SOUTHWEST DEVON ISLAND, NORTHWEST TERRITORIES WITH SPECIAL REFERENCE TO THE ROLE OF ICE

OBSERVATIONS OF THE BEACH ENVIRONMENT OF SOUTHWEST DEVON ISLAND, NORTHWEST TERRITORIES WITH SPECIAL REFERENCE TO THE ROLE OF ICE

by

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SCOPE AND CONTENTS:

The open water season of Radstock Bay is less than three months long and varies considerably from year to year. The break-up and ablation sequence of the bay is regular and systematic, commencing with a period of snow melt and run off and continuing until the dramatic evacuation of the ice. This evacuation is dependent on the ice coverage of Lancaster Sound. The ice foot, a feature found often on arctic beaches was found to be larger in areas of more shallow sloping beaches. A sediment size analysis revealed a trend of diminuation of grain size from S. to N. reflecting net sediment transport in that direction. The two major geomorphic events of the 1971 open water, were two storms, both of which had winds from the S.E. that generated 1.0 meter waves which moved sediment from S. to N. The importance of a small pack of ice in the nearshore zone in inhibiting wave action was noted during one of these events. The freeze-up sequence progressed slowly after the advent of sub-freezing temperatures until the temperature of the seawater reached its freezing point, whereupon the rapid covering of the bay with ice ensued.

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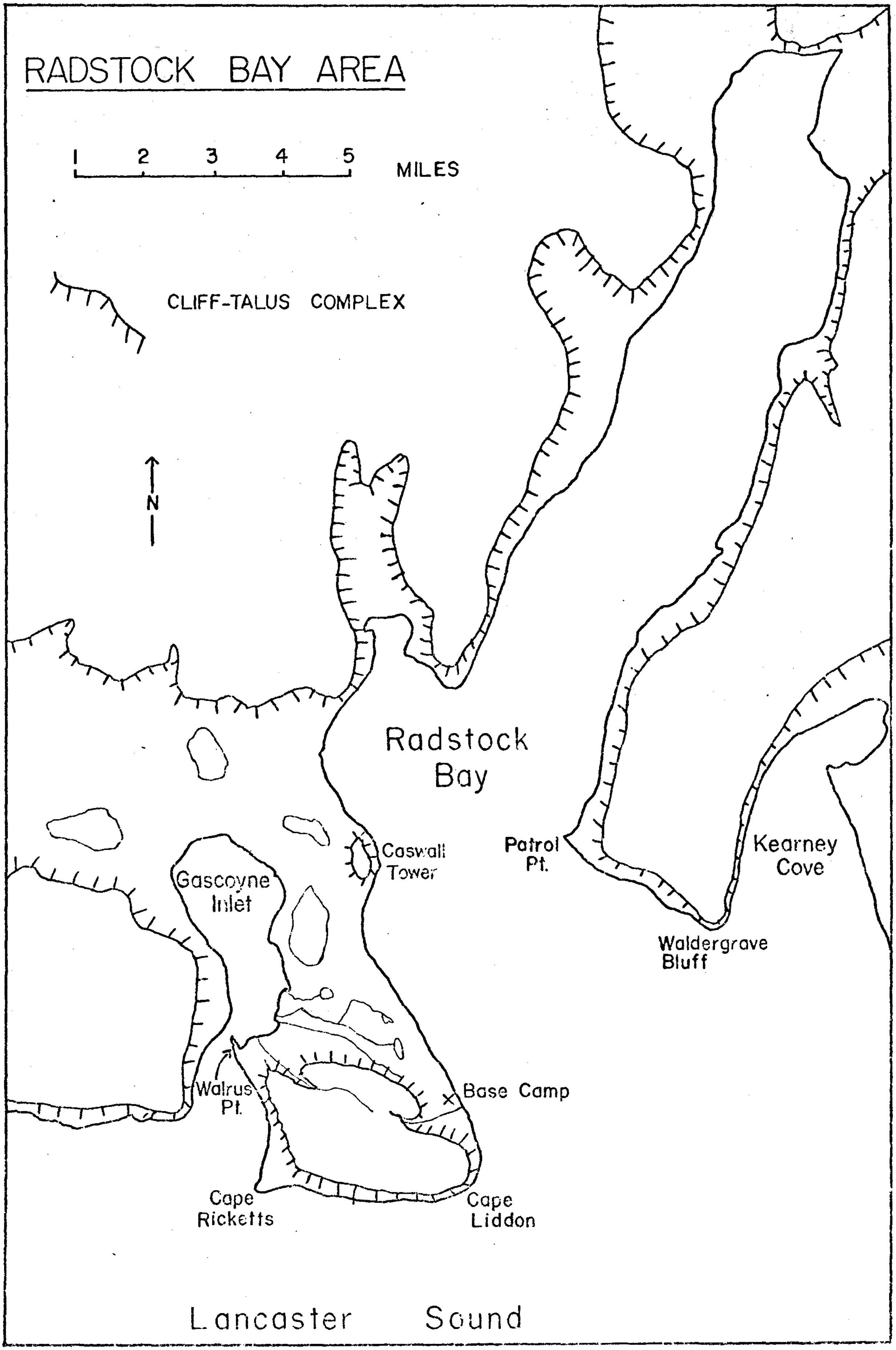

RADSTOCK BAY AREA
1 2 3 4 5 MILES
CLIFF-TALUS COMPLEX
N
Radstock Bay
Caswall Tower
Gascoyne Inlet
Patrol Pt.
Kearney Cove
Waldergrave Bluff
Walrus Pt.
Base Camp
Cape Ricketts
Cape Liddon
Lancaster Sound

CHAPTER I

INTRODUCTION

There is little work on the active beaches of the arctic recorded in the literature. Exceptions to this generalization are in the series of investigations at Pt. Barrow, Alaska (MacCarthy 1953, Rex 1955 and 1964, Hume and Schalk 1964a, 1964b and 1967) in the Cape Thompson area (Moore 1960 and 1966 and Greene 1970) and on Southwest Devon Island (McCann and Owens 1969, 1970 and Owens and McCann 1970).

This thesis results from the continued investigations of the beaches in the Radstock Bay-Cape Ricketts area of Southwest Devon Island and focuses in detail upon the role of ice. The break-up and ablation cycle, and the freeze-up cycle, were both documented and, as well, a detailed study was made of the ice foot. The break-up and freeze-up characteristics of this area and three other areas of the Southern Queen Elizabeth Islands over a period of years were tabulated and compared on the basis of unpublished ice reconnaissance maps of the Ice Reconnaissance Division, Meteorology Branch, Department of Transport, in order to provide a broader picture. Further study of the sediment of the beaches of Radstock Bay was undertaken to verify the findings of McCann and Owens (1969) by the use of more detailed sampling.

It may be said that arctic beaches in general are different to beaches of temperate climates but not fundamentally different. The major morphogenetic process is wave action as in other beaches, but arctic beaches are in a comparatively low energy environment. This is due to the inhibiting effects of ice. Generally the beaches are locked in ice for 80% of the year with up to 25% of the coasts getting no open water in any one year. Also, during open water conditions floating pack ice reduces wave action. Ice can have a positive effect on the beaches under certain conditions creating such features as ice push ridges but generally these are of minor importance. For beaches located in the Archipelago, the island nature of the coasts limits fetches further.

Radstock Bay (74°40' north, 91°21' west) is a 13 mile long, 5 mile wide bay which is entered from Lancaster Sound between Wallis Point and Cape Liddon (Fig. 1.1). The outer portions of this Bay are a fairly uniform 80 to 90 meters in depth. It has an Eastern arm, Kearney Cove, which is of no interest to this study, and a Western arm which proceeds due north then trails a further 9 miles to the northeast. The western shore of the outer section of the Bay, the important area for this study, consists of a 300 meter high plateau fringed by a cliff-talus complex in the south, with a series of raised and active beaches in a spit-like configuration towards the north. It was on the southern extremity of these beaches that the base camp was located. The 4 miles of beach north of the base camp, terminating at Caswall Tower, an isolated plateau peak, was the location of the most intensive investigations that were undertaken during the 2 field seasons.

The coast and beaches of this area are described in an M.Sc. thesis (Owens 1969) and a series of papers by McMaster geomorphologists (McCann and Owens 1969, Owens and McCann 1970, McCann and Owens 1970, McCann 1970, McCann and Hannell 1971 and McCann and Carlisle 1972). Other aspects of the physical landscape of the study area are described in 3 other M.Sc. theses (Jackson 1970, Bones 1971, Cogley 1971).

The beaches of this area are subject to mixed semidiurnal tides, that is, two complete oscillations of water level a day with inequalities in both height and time of arrival of maximum values. They are in the mesotidal range with a mean range of approximately 20 meters. The maximum fetch is 175 kilometers out of the Southeast.

The first investigations of Southwest Devon Island commenced during the spring of 1968 at Cape Ricketts, when plan and profile configuration and sediment size and shape were determined. The summer of 1969 saw the work concentrated on Radstock Bay and the recording of one large event, a major storm, in August of that year. The original conception of this present study was to monitor the break up and ablation sequence on Radstock Bay during the spring and summer of 1970. Also, the nature of the ice foot and range of beach sediments were to be measured and analysed in detail. Field work commenced June 17, 1970 and ceased August 20, 1970. Plans to study the freeze-up sequence and so have a complete record of conditions throughout the open water period were devised but had to be postponed for financial reasons until the following year. Opportunity for this work availed itself during autumn of 1971 and field work recommenced August 20, 1971 on Radstock Bay and continued until October 6, 1971 when all wave action on the shore had ceased and the beach face slope had frozen.

This thesis commences with an analysis of the break-up and freeze-up characteristics of Southwest Devon and three other locations in the Southern Queen Elizabeth Islands through the 10 years 1959 to 1968. Next the break-up and ablation sequence of Radstock Bay in 1970 is documented and this is followed by an analysis of the well developed ice foot as it appeared in that year. The results and discussion of the sediment size analysis follow these first three ice oriented chapters. Consideration of the open water conditions of 1971,including discussion of the results of two storms, and the nature of the freeze-up cycle, precede the final chapter of conclusions. The thesis is intended to be a case study, observing the small scale break-up characteristics, large scale ablation sequence, the ice foot and sediments locally, the effects of storms during open water conditions and the freeze-up sequence of Radstock Bay, N.W.T., through spring, summer and fall conditions.

CHAPTER II

ICE CONDITIONS IN THE SOUTHERN QUEEN ELIZABETH ISLANDS, BASED ON ICE RECONNAISSANCE MAPS: 1960 - 1971

Any discussion of beaches in the Arctic or Antarctic must always concern itself with ice. Beaches north of the Arctic Circle are frozen for most of the year, generally, and in the Queen Elizabeth Islands are frozen for 75% of the year. When they are frozen the beaches are completely immobile and not affected by any process agents. Thus the effect of the ice is inhibiting and negative, reducing the time through which wave action can work on the beaches but generally not affecting the sediments positively. It is true that there are evidences of positive ice action in the form of ice push ridges but Hume and Schalk (1964) suggest that only 1 or 2% of the local beach material is involved in this process in the Point Barrow area and McCann and Owens (1970) concur for the Southwest Devon area. Notwithstanding all of this, ice is the major difference between Arctic beaches and beaches of lower latitudes.

A discussion of the nature and distribution of ice in the arctic can be presented by many different methods and at many different scales. This study commences with a discussion of the nature of the break-up over the Southern Queen Elizabeth Islands through 12 seasons in this chapter and is followed by a documentation of the break-up of one season, 1970, in Chapter 3.

The break-up and freeze-up dates for any one location may indicate a long or short active season on a beach. By tabulating these through time, some measure of the regularity or lack of regularity in the length of open season can be ascertained. In order to investigate differences in length of open season throughout the Southern Queen Elizabeth Islands, 4 stations were selected and data about them gathered. The four locations were 1) Radstock Bay, Devon Island, because it is the study area, 2) Resolute Bay, Cornwallis Island, because it has the most data available and represents a more closed ice situation, 3) Philpot's Island, which actually is not an island but a peninsula on the eastern end of Devon Island, because it represents a location with a large fetch over the more ice free Baffin Bay and 4) Gull Head, on the south shore of Ellesmere Island because it is on an enclosed sea from which and into which little ice moves (Fig. 2.1).

The source of the data tabulated is the Canadian Department of Transport, Meteorological Branch, Ice Reconnaissance Division unpublished maps. Each year from April until December the Ice Reconnaissance Division flies reconnaissance flights throughout the arctic recording ice distribution. The Canadian forces and the Polar Continental Shelf project (Canada Department of Energy, Mines and Resource Management) also fly reconnaissance flights over the arctic, and their data too, was consulted, though the flights were less frequent and the ice conditions recorded less accurately.

The major insufficiency of this data is its lack of frequency. Figure 2.1 shows the area covered by the first 3 recorded flights after March 1, 1964 that penetrated the area of Lancaster Sound-Barrow Strait,

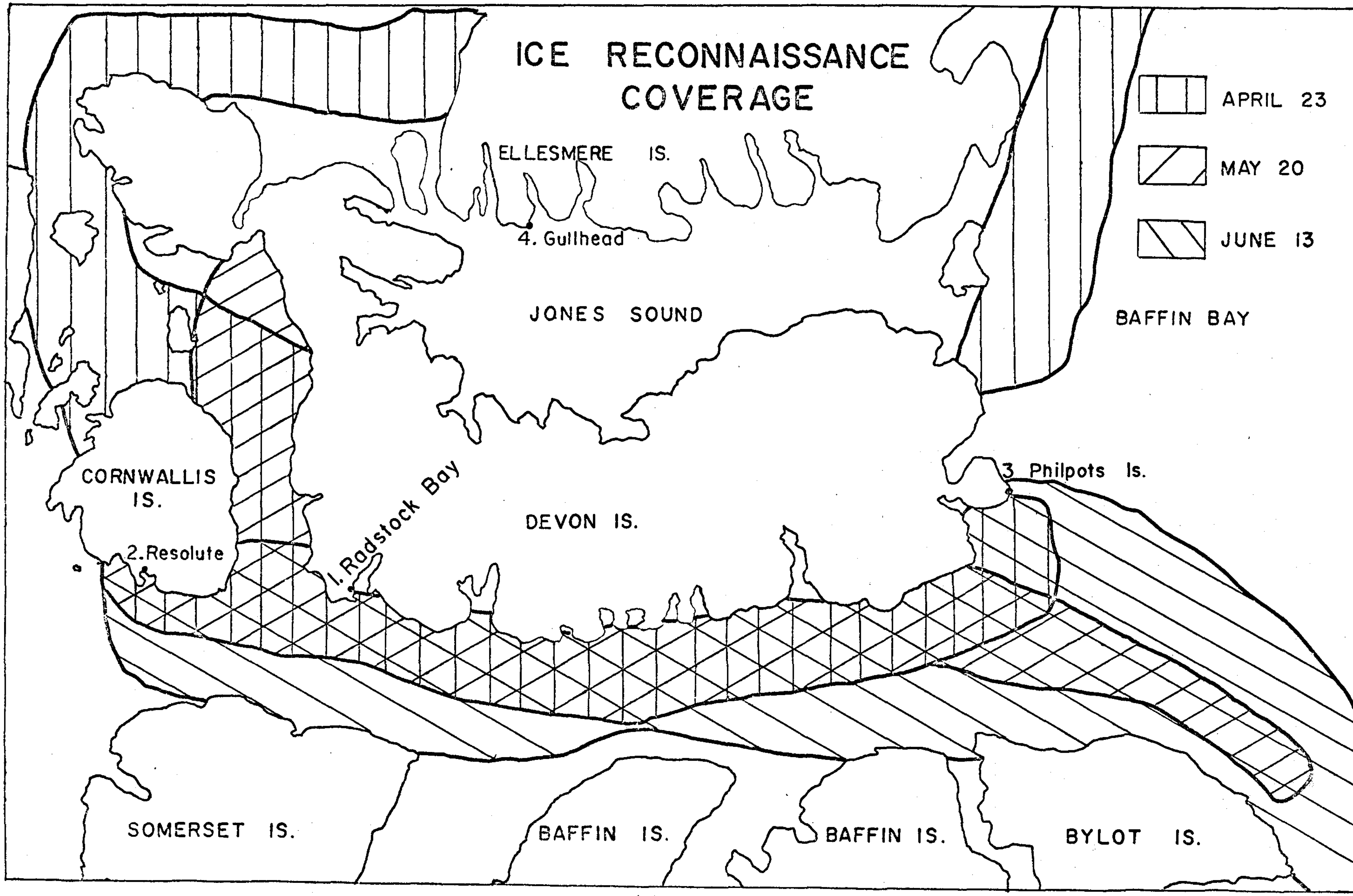

ICE RECONNAISSANCE
COVERAGE
APRIL 23
MAY 20
JUNE 13
ELLESMERE IS.
4. Gullhead
JONES SOUND
BAFFIN BAY
CORNWALLIS IS.
2. Resolute
1. Radstock Bay
DEVON IS.
3 Philpots Is.
SOMERSET IS.
BAFFIN IS.
BAFFIN IS.
BYLOT IS.

FIG. 2.1

near Radstock Bay. One can see from this that in a period of 51 days between April 23, and June 13, there was only one flight. This infrequency is by no means rare. In some areas observations were not carried out due to inclement weather. An example of this is Philpots Island in 1966, when only once was an observation made, in the whole season. Another shortcoming of the data is the fact that the major use of the reconnaissance is as a navigation aid. For this reason, flights are seldom sent along coastlines but nearly always along mid-channel. This is observed in Figure 2.1 where the flights along Barrow Strait and Lancaster Sound do not cover the upper parts of the inlets on the southern shore of Devon Island.

A note should also be made concerning the reliability of the data. Because the inlets are of little concern to navigators, little attention is paid to them, resulting in errors. Most often these consisted of a series of observations on successive flights which showed in the first instance foot ice in an inlet, in the second instance open water, and finally fast ice again. Fast ice is defined as ice that is in the position in which it was frozen and therefore would not be expected to be in evidence after open water conditions obtain, before freeze-up.

While it is noted that mid-channel conditions can seriously effect break-up characteristics in coastal areas, this is often only in the form of a negative control. Inlet ice cannot escape into a sound that is itself locked in but remains trapped until the break-up of the larger body. Thus inlet observations cannot be inferred from mid-channel conditions after the initial break-up. These facts make the reconnaissance data immensely less valuable a tool to probe the problems of ice break-up and freeze-up on arctic beaches, than first it appears.

The problem with dealing with intermittent observations is of course that there is no information whatever for the time between observations. For this reason, workers in this field have had to augment this data with heresay from eskimo hunters, ice island information, and records of explorers who wintered in the Arctic. All of this evidence was cited by Lindsay (1968) in his discussion of ice distribution in the Queen Elizabeth Islands. Though concerned more with ice strength in relation to aircraft weight, navigation, and other practical ends, he does describe very carefully what he thinks is a typical break-up pattern. He describes how Jones Sound breaks-up, starting at its east and west extremities and advances towards the centre of the sound, with little transport either way. He describes Lancaster Sound-Barrow Straits as having the earliest break-up, often in May for the northeastern section, advancing from east to west until by the last week of July in most years it has all broken as far west as Resolute. There is no mention of the Baffin Bay coast in this otherwise fairly exhaustive study. Another calculation which he computes for all of these areas is the amount of import and export of ice. Of interest to this study he noted imports into Lancaster Sound from Barrow Strait and in Barrow Strait from Wellington Channel and Viscount Melville Sound but no exports at all from Lancaster Sound. This means that Lancaster Sound is the site of more melting than the amount of ice that freezes there each year. This analysis also points out that there is no importing or exporting of ice from Jones Sound. He discussed variations in break-up pattern from year to year and picked out years that he designated as good, bad and average (1962, 1964, 1966, respectively).

In the good year, or year of early break-up, the ice cleared off the channels before usual. In the bad year it did not clear off many channels at all. In his conclusion, Lindsay notes that long range ice break-up forecasting can only give a general picture, lacking in the important specific details. An example of an important specific detail would probably be the expected characteristics of break-up in the inlets. In this discussion Lindsay obviously took advantage of previous work, Markham and Hill (1963), Markham (1963), and Hill, Cooper and Markham (1965); papers in which the break-up and distribution of ice during specific years was discussed. For that reason these papers will not be discussed here.

For the purposes of this study a number of assumptions and rules had to be made. One-tenth ice cover was assumed to be open water. This contingency was employed for two reasons. At time of break-up there are often many widely scattered bergy bits and growlers that constitute considerably less than one-tenth ice cover, that are by convention recorded by the ice reconnaissance team as one-tenth, because of their danger to navigation. Also, it is considered that one-tenth sea ice cover will not effect wave generation and transmission characteristics to a significant degree. Similarly, all shore fast ice is considered to be ten-tenths cover because of its absolute control over wave action.

It must again be noted that the data collected by ice reconnaissance flights is always static. One cannot discern from those maps the date that the ice broke or left a specific area, but only whether or not that area was open or closed on the date of the flights. The dates of opening and closing of season for a study such as this must be computed. In order to do this calculation, a set of simple assumptions must be made as follows.

An event which occurred during the time between two observation dates is deemed to have occurred midway between them. If two events occurred during the time between two observation dates, then one-third of the time is deemed to have elapsed between the first observation date and the first event, a further one-third of the time is deemed to have elapsed between the two events, and the final one-third of the time is deemed to have elapsed between the second event and the second observation date.

For the years 1960 to 1971, a set of data was tabulated (Tables 2.1, 2.2, 2.3, and 2.4). The dates listed are break-up, open water, reclosure (including conditions of less than ten-tenth ice cover), re-opening, final reclosure, and other dates of events if any. In addition the number of days of open water season is listed. It is important to note that this refers to the number of days between first open water (and not just break-up) and reclosure, minus any midseason closed periods. The plus sign in evidence in some of the length of season values means that the season is open ended; that is, there is no final date of closure and therefore the computed season length value is a minimum.

The results for Radstock Bay reveal a mean length of season in excess of 55 days. Out of the 10 years for which there are results, 5 of those years have open ended seasons (that is, reconnaissance flights do not cover the entire open season) so this figure is obviously too low. The longest mean open season length is Philpots Island at 62 with 5 years out of the 11 being open ended. Resolute Bay had a relatively short open season mean of 43.9 followed closely by Gull Head which had 42.3. Resolute had more data available for it with only 2 seasons out of 11 being open ended. Gull Head, on the other hand, had 7 out of 11 open ended.

The greatest variation from year to year according to these calculations was Radstock Bay. This is reflected in a standard deviation of 29.5 days. The other three locations are relatively the same in variability with Resolute Bay having the lowest standard deviation of 18.7 days and Philpots Island and Gull Head having 20.4 and 20.1 days respectively.

The previously expressed notion (Lindsay 1968) that the Queen Elizabeth Islands open from east to west seems corroborated by this evidence. Beyond this, the dearth of hard data makes further generalizations spurious. The length of open season varies considerably both from place to place and from year to year quite markedly.

TABLE 2.1

BREAK-UP AND FREEZE-UP DATES FOR RADSTOCK BAY, DEVON ISLAND

YEAR	BREAK-UP	OPEN WATER	RECLOSURE	REOPENING	RECLOSURE	OTHER	SEASON LENGTH IN DAYS
1960	May 1	No Data	No Data	No Data	No Data		No Data
1961	June 13	July 6	No Data	No Data	No Data	Sept 13(open)	98+
1962	June 14	July 5	Oct 11$(\frac{9}{10})$	No Data	No Data		98
1963	June 7	Aug 26	Sept. 16$(\frac{10}{10})$	Sept 28	Sept 24		20+
1964	May 7	Aug 9	Oct 14$(\frac{10}{10})$	Aug 27	No Data	Sept 30$(\frac{8}{10})$	52
1965	July 22	July 27	Aug 8$(\frac{10}{10})$	Aug 15	Oct 16	Sept 29$(\frac{9}{10})$	64
1966	Aug 1	Aug 7	Aug 26$(\frac{7}{10})$	No Data	No Data		No Data
1967	July 11	Aug 17	Aug 22$(\frac{9}{10})$	Aug 26	No Data	Aug 26(open)	5+
1968	July 11	July 14	No Data	No Data	No Data	Sept 20(open)	68+
1969	July 20	Aug 2	Sept 28	No Data	No Data		57
1970	July 31	Aug 9	Aug 15(4)	Aug 12	Sept 23		43
1971	July 18	July 22	No Data	No Data	No Data	Sept 21(open)	61+

$\bar{x} = 55.6$ $\sigma = 29.5$ $\sigma^2 = 871.1$

TABLE 2.2

BREAK-UP AND FREEZE-UP DATES FOR RESOLUTE BAY, CORNWALLIS ISLAND

YEAR	BREAK-UP	OPEN WATER	RECLOSURE	REOPEN	RECLOSURE	OTHERS	SEASON LENGTH IN DAYS
1960	May 15	June 15	July 7$(\frac{7}{10})$	Aug. 18	Aug. 22$(\frac{4}{10})$	Aug. 28(open)	26+
1961	July 5	July 15	Aug 2$(\frac{5}{10})$	Aug. 6	No Data		No Data
1962	July 10	July 14	Oct 2$(\frac{6}{10})$	No Data	Oct 26		80
1963	July 15	Aug 22	Sept 6$(\frac{7}{10})$	Sept 8	Sept 12		17
1964	May 25	May 29	June 6$(\frac{10}{10})$	July 4	Aug 11		46
1965	No Data	Before July 17	July 19$(\frac{10}{10})$	Aug 10	Sept 29		50+
1966	Aug 2	Aug 3	Aug 11$(\frac{10}{10})$	Sept 3	Oct 9$(\frac{9}{10})$		43
1967	Aug 2	Aug 9	Aug 12$(\frac{7}{10})$	Aug 15	Sept 22$(\frac{8}{10})$	Aug 30-Sept 14 (open)	26
1968	July 24	July 26	Aug 5$(\frac{8}{10})$	Aug 17	Aug 30	Sept 15-27(open)	55
1969	July 16	July 20	July 27	Aug 15	Aug 17	Aug 19-Oct 10 (open)	61
1970	July 16	Aug 8	Aug 9	Aug 14	Aug 22	Sept 1-24(open)	32
1971	Before July 11	July 24	July 28(4)	Aug 10	Aug 11	Sept 1-24(open)	29

$\bar{x} = 43.9$ $\sigma = 18.7$ $\sigma^2 = 352.$

TABLE 2.3

BREAK-UP AND FREEZE-UP DATES FOR PHILPOT'S ISLAND, DEVON ISLAND

YEAR	BREAK-UP	OPEN WATER	RECLOSURE	REOPEN	RECLOSURE	OTHER	SEASON LENGTH IN DAYS
1960	No Data	Before July 5	No Data	July 5	Sept 2		59+
1961	July 14	July 4	No Data	No Data	Sept 4		62
1962	No Data	July 18	Sept 19 ($\frac{7}{10}$)	No Data	No Data		100
1963	June 25	June 25	Aug 27 ($\frac{7}{10}$)	No Data	Oct 11		63+
1964	Before May 20	July 22	Aug 6 ($\frac{3}{10}$)	Aug 18	No Data		48+
1965	No Data	Before July 24	Oct 4 ($\frac{9}{10}$)	No Data	No Data		72
1966	No Data	Before July 27	No Data	No Data	No Data		No Data
1967	No Data	July 26	Sept 29 ($\frac{9}{10}$)	No Data	No Data		65+
1968	No Data	Before May 1	June 15 ($\frac{10}{10}$)	No Data	No Data		46+
1969	No Data	Before Aug 1	Sept 15 ($\frac{10}{10}$)	No Data	No Data		45
1970	May 27	June 17	Aug 19 ($\frac{6}{10}$)	No Data	No Data		33
1971	Before July 16	July 18	Oct 13	No Data	No Data		87

$\bar{x} = 62.$ $\sigma = 20.4$ $\sigma^2 = 417.9$

TABLE 2.4

BREAK-UP AND FREEZE-UP AT GULL HEAD, ELLESMERE ISLAND

YEAR	BREAK UP	OPEN WATER	RECLOSURE	REOPENING	RECLOSURE	OTHER	SEASON LENGTH IN DAYS
1960	May 1	May 28	Aug 20($\frac{7}{10}$)	Sept 9	No Data	Sept 31(open)	75+
1961	June 13	July 6	No Data	No Data	No Data	Aug 30(open)	55+
1962	No Data	Before Aug 3	Aug 16($\frac{5}{10}$)	Aug 20	Sept 12 (6)	Oct 15($\frac{10}{10}$)	36+
1963	June 11	July 1	Aug 24($\frac{7}{10}$)	No Data	No Data		86
1964	June 18	Aug 29	No Data	No Data	No Data		No Data
1965	July 24	Aug 15	No Data	No Data	No Data	Sept 23(open)	39+
1966	Aug 1	Aug 8	No Data	No Data	No Data	Sept 7(open)	30+
1967	July 1	Aug 18	No Data	No Data	No Data	Sept 1(open)	13+
1968	May 25	June 20	Aug 27($\frac{9}{10}$)	Sept 1	Sept 15($\frac{10}{10}$)		51
1969	No Data	Before July 20	July 26($\frac{8}{10}$)	Aug 20	Sept 26		43
1970	July 29	Aug 3	Aug 25($\frac{6}{10}$)	No Data	No Data		22+
1971	Before July 12	Aug 16	Oct 3($\frac{8}{10}$)	No Data	No Data		48

$\bar{x} = 42.3$ $\sigma = 20.1$ $\sigma^2 = 405.8$

CHAPTER III

BREAK-UP AND ABLATION SEQUENCE ON RADSTOCK BAY DURING 1970

Essentially this chapter documents the break-up and ablation of the fast ice and ground ice of Radstock Bay and nearby Lancaster Sound in 1970. No previous study has involved such a complete documentation of ablation and break-up of the ice, in relation to beach processes from late winter conditions to complete open water conditions. It is essential that one understands the sequence of events that leads to break-up in order to gain a fuller knowledge of beaches in the Arctic. One should also know how the break-up and ablation characteristics of inshore areas differ from the offshore, strait, and open sea areas. This chapter follows logically from Chapter 2 as it discusses the characteristics and variations of break-up in the inshore and offshore areas of Radstock Bay and Lancaster Sound during the spring and summer of 1970.

Ablation of ice and snow can commence as soon as the sun returns in the late winter, in the form of sublimation, but generally this is of minimal importance. The time of maximum ablation is usually after the beginning of the climatic summer (defined by Thompson 1967, as the first day that the mean daily temperature rises above 32°F). This date is of more significance in the High Arctic than in lower latitudes because there is a very small diurnal temperature range in the north, due to the

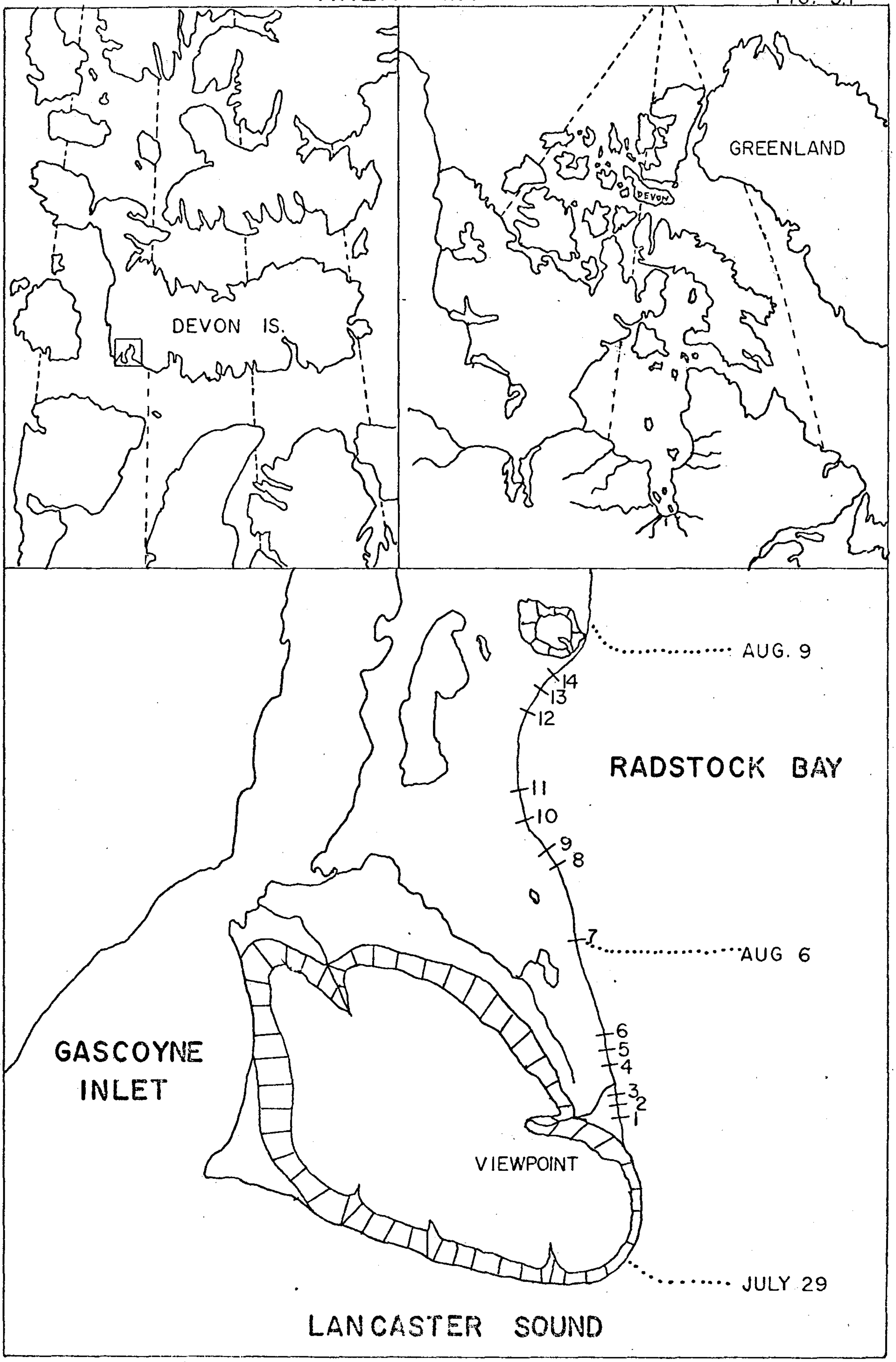
24 hours of daylight. In the south the pattern of ablation usually includes a long period of daytime melting and nightime freezing. This differs markedly from the pattern of the north, where generally the land remains frozen until sometime in late spring, when the daily mean temperature reaches 32°F whereupon melting proceeds quickly for most of the 24 hours of the day. This marked, rapid change of season is often noted by travellers and researchers in the north. In 1970 this date was June 21.

Observations in the field consisted of accurate field notes and surveyed profiles. The profiles were surveyed by the precise levelling method from beach marks established on the raised beaches. They were all linked to a common datum later in the season by the establishment and levelling in of temporary bench marks at the mean lower high water marks at each profile location. While it was safe the profiles were extended out onto the sea ice and the ice thickness was measured.

The 14 profile locations (Fig. 3.1) are all along the southern portion of the western shore of Radstock Bay. They are taken across beaches that face in directions in the quadrant east through south. All the beaches are similar in nearshore bathymetry. Usually 50 meters or so from the shoreline in 5 meters of water the bottom of surface is 95% free of active beach sediment and consists of boulders or rock ledge. The depth at 100 meters from shore was a fairly consistent 10 meters. The active or intertidal zones on all beaches were similar too, in that they all were roughly planar and shallow sloping (5-10°). The profile locations varied considerably in aspect, as is observed in Figure 3.1. The backshores of the profiles also differed from one another. Profiles #1, #2, #3, #4, #5, and #6 are backed by a series of steeply sloping raised

AREA MAP

FIG. 3.1



beaches that rise to a height of 100 meters that are themselves backed by the 10 meter high talus slopes of the plateau. Profile #7 is located at the base of a small erosion face (2 meters high) and about 100 meters from the bulk of the raised beaches which here are less steeply sloping than further south. A shallow sloping, marshy area is here between the plateau ? and the raised beaches. Profiles #8 and #9 are located on a headland again at the base of a 2 meter high erosion cliff. Behind them is a 100 meter wide section of shallow sloping, raised beach followed by a series of 3 erosion faces, each 10 or 15 meters in height. Behind profiles #10 and #11 is a shorter, 20 to 30 meter wide, flat section of raised beach, in front of the series of erosion faces analogous to those behind profiles #8 and #9. The three remaining profiles #12 #13 and #14 are located on a wide, very shallowly sloping stretch of raised beaches that rises gradually and uninterrupted back some hundreds of meters. Behind these is a complex of old raised beach remnants, areas of solifluction and intermittent streams and behind all this is the Devon Island Plateau.

The party took to the field on June 17, 1970 and after establishing a base of operations, observations commenced June 19. The dates on which profiles were surveyed throughout the summer are listed in Appendix I.

The ablation sequence appeared to follow a regular pattern throughout in all locations, but the sequence commenced and finished earlier in more favourable locations than in less favourable environs. In the study area, it was in the area of profiles #12, #13 and #14, (that is, the beaches with the most southerly exposure) that the sequence first started. This discussion commences with a documentation of the sequence as it occurred at all locations and continues with a discussion of local variations.

As of June 19 there was everywhere a complete cover of fast ice blanketed with soft blown snow. Parallel to the shore,5 or 6 discontinuous cracks or shore tidal leads, often roofed over with snow, were in evidence. Immediately shoreword and seaward of the zone of ice that later became visible as the ice foot, there were lees, or areas protected somewhat from the wind, in which snow accumulated. Because of this the ice foot itself (also snow covered) and the active beach could not be immediately located. Also the aforementioned tidal leads were observed in places. Generally, the snow was only 0.1 to 0.2 meters deep out on the ice proper, but drifts of over a meter in depth were not uncommon in the nearshore zone. After probing the ice immediately shorewards of the most landward tidal lead, it was discovered that the ice foot was present continuously along the entire length of the shore. The sea-ice thickness ascertained by probing down the leads varied little between 2.2 m and 2.4 m. On the raised beaches, the snow cover primarily in the swales varied considerably from 100% cover in the area of the base camp in the protected south, to 10% cover in the wind blown northern beaches near Caswall Tower. The snow depth varied considerably up to 2 m, owing to its blown nature. Nowhere was there any running water.

The first notable change in this condition came on June 21. (precisely the date of the start of the climatic summer), when water was observed in puddles on the ice subsequent to a rainstorm. Again it is noted that this occurred first in the Caswall Tower area and the following is an account of conditions there. During the time between June 21 and June 26 the puddling increased with the excess water running off down the leads. Because of the differences in melting points between the sea ice

(28.5°F) and snow (32°F) it seems clear that the surface runoff (on the ice) is the result of melting snow, and also the ablation of sea ice.

Previous to June 26 the area of the beaches that was covered in snow markedly decreased but nowhere was there surface runoff. Though evaporation and sublimation do play a role in this ablation, it is a minor one, since at low temperatures the saturation vapour pressure of the air is diminished and the air cannot hold very much water vapour. Also, close observation of the beaches revealed that most of the water flowed away underground over the surface of the permafrost. Several dye tests were undertaken to establish the nature of this flow. In several locations shallow pits were dug in order to observe the flow. Dye was injected in a section immediately downslope of snow patches in two locations, and the trace was observed and timed. In all cases the plume was less than one meter wide over 10 meters of travel. The rate of flow was often greater than one meter per minute. The net result of all of this flow was a ponding of fresh water up against the ice foot in the lee that was previously described as a zone of drifting. June 26 was the first date on which this was observed.

June 27 was the date of the first observation of running surface water. This was sighted at the base of a large snow patch situated in the small stream. It emerged from the snow bank only to percolate below the surface after one meter. Also, at Caswall Tower, some surface runoff was observed flowing out of a talus cone. Again this percolated below the surface, this time into a frost wedge. All of this water began to enlarge the aforementioned ponds, which were caused by the damming effect of the ice foot.

During all this time, the snow on the ice itself melted almost completely into water or slush. Following a considerable amount of ponding landward of the ice foot, some of the water found routes to the first lead over low sections. Once this lead occurred, the draining water rapidly ablated a channel or lead feeder through the ice foot and within 3 days had cut through to the beach shingle. This condition obtained for the Caswall Tower area by June 30 and progressed rapidly in other areas shortly after. By July 8 all of the lead feeders were debris filled and abandoned after having drained all of the available surface runoff and virtually all the snow being ablated. All along the shore, from profile location #1 through #14 these channels divided the ice foot up into 20 to 30 meter long sections.

By July 2 there was a 95% water coverage on the ice, rapidly draining into the tidal leads and seal holes and thus widening them. By July 17 the ice surface was 95% free of water and appeared to consist of firm, white, first year ice. The rapidity of the spring thaw is observed in the fact that June 27 was the date of the first running water observation and by July 17 virtually all of the snow and water on the ice surface was removed.

During the first few days of July, the water in the two streams flowed rapidly. When this water reached the ice foot it ponded up then breached as in other locations, the only difference being the rapidity with which it breached (because of the amount of water). The reason that this water could easily breach the ice foot dam, is that the stream water was fresh and by definition above 32°F, whereas the ice foot was saline and therefore melted at 28.5°F.

Previous to July 12 the ice in Radstock Bay, Gascoyne Inlet and Lancaster Sound, as far as the eye could see, was ten-tenths fast ice; that is,it was in the same position that it was frozen in during the previous autumn's freeze-up. On July 12,for the first time, open water was sighted to the east on Lancaster Sound. It appeared as a band of sea stretching the width of the Sound from a point several miles east of Cape Liddon, to Prince Leopold Island. This open sea was at least several hundred meters in width. Beyond the open patch the ice was broken, about eight-tenths or nine-tenths and the break-up appeared to be proceding towards the west. The ice broke from the mouth of Radstock Bay on July 17. On that date a band of open sea approximately 300 meters in width was observed between the fast ice of Radstock Bay, and the nine-tenths broken ice of Lancaster Sound.

A southerly wind between July 19 and July 29 jammed the broken pack ice of Lancaster Sound against the southern shore of Devon Island. Between Cape Liddon and Cape Ricketts there were several instances of ice push. This pressure from the south held the fast ice in Radstock Bay intact, not allowing it to break out. The only noticable changes in the ice of Radstock Bay was a continuation of the process of interlead ice, separating into floating blocks of ice. This process began first in the Caswall Tower area July 13 and rapidly more and more blocks became free to float, drifting back and forth parallel to the shore until July 23 when there was a zone of floating blocks between the fast ice of the Bay and the ice foot in all locations.

The major process of ablation after the removal of the snow from the beaches and ice surface, is the less visible process of sea ice candling. This is the process whereby the ice is melted from below, pitting the bottom surface in a manner suggesting the shape of candles. This melting from below makes a block of ice top heavy and if the block is small enough, can cause it to flip over. In areas where seal breathing holes abounded (maintained all winter long by the seals) the surface of the ice became pitted. By August 5 the sea ice had been reduced to 0.5 meters in thickness or 21% of its maximum extent. The affect that candling has of pitting the lower surface and thus reducing volume faster than it reduces the thickness means that more than 80% of the volume of the ice was gone as of August 5. This is compared to the ice foot, which rests on the beach face, which was reduced to 55% of its maximum magnitude as of August 8. This shows quite clearly the importance of sea water in sea ice ablation (Fig. 3.2).

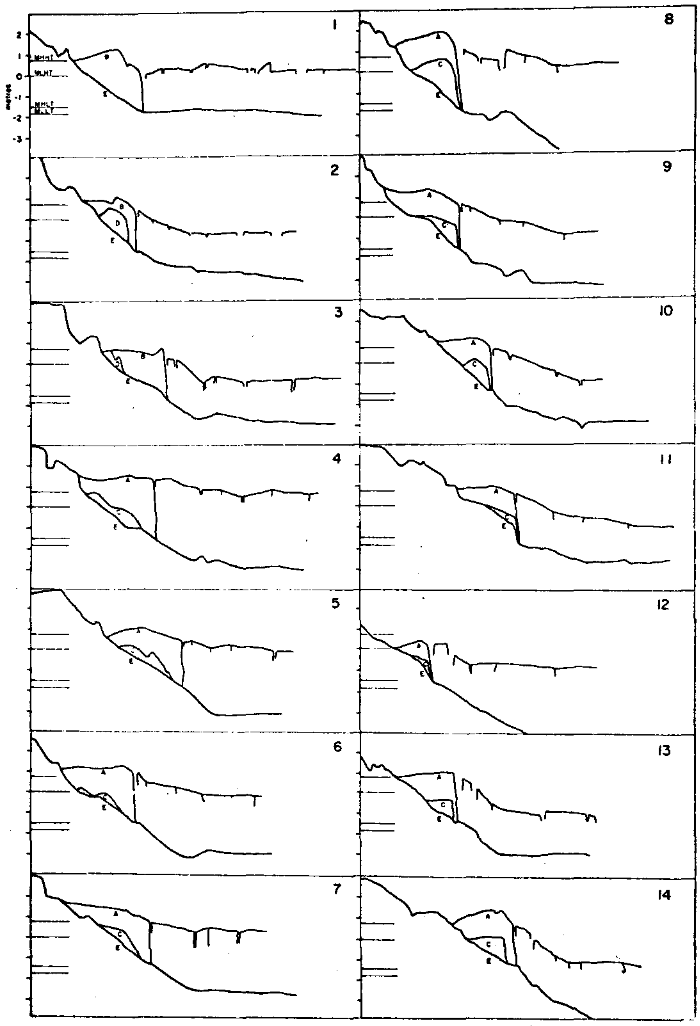
August 6 marked the date of the first movement in the close ice of Radstock Bay. The large floe situated between the lead across the Bay at profile #7 and the open water at the mouth of the Bay began to move under the influence of brisk 10-12 knot north-westerly winds. It moved at a rate in excess of 50 meters per hour. For a half a day this large floe, estimated at 30,000 meters^3 of ice, remained wedged in the Bay, jammed in against the headland south of profile #7. By 0600 hours on August 7 this entire block had cleared the Bay.

The next block to evacuate the Bay began to move southward from the lead, across the Bay that had formed at Caswall Tower. This floe began to move August 8 and completely evacuated the Bay on August 9.

On August 15 the remaining fast ice in the Bay, an estimated 50,000,000 meters^3 of ice, moved en masse clear of the Bay in less than

FIG. 3.2

PROFILES



A - July 2

B - July 12

C - Aug. 8

D - Aug. 12

E - Aug. 15

12 hours, under the influence of a 15 knot north-easterly wind. The only remnant of ice that remained was the ice foot. This was completely removed in less than a week (described in Chapter 4).

The series of events of the ablation sequence described above proceeded similarly in all areas. The only difference, from place to place, as noted before was that these events obtained in the Caswall area first. The ponding prevalent on the ice foot occurred here June 29, but did not occur in all locations for another 6 days. The first chunks of interlead ice that were freely afloat were in the Caswall area July 13. It was not until July 23 that this obtained for all sections of the beach. The Caswall Tower beaches (#12, #13 and #14) were the most southerly in aspect and the most open and windswept. For these reasons it was assumed that more retarded beaches did ablate more slowly because 1) they faced a more northerly direction 2) they were in the lee of a steep raised beach erosional bluff or 3) both. All other locations are less favourable in both categories. The only break in the sequence occurred in the final stages during the ablation of the ice foot (Chapter 4). Because the major factor in the ablation of the ice foot appeared to be the presence of open water, and because the more retarded (southerly) sections of beach happened to attain open water conditions earlier than the Caswall beaches, the ice foot was ablated in the Caswall Tower area last. This occurred in spite of the fact that the strongest, highest sections of ice foot were observed in these protected areas. The section of beach described earlier as obtaining open water on August 7, had no ice foot remaining by August 13. The Caswall Tower area cleared of sea ice on August 9 but did not see the complete ablation of the ice foot until August 15. From this latter date onwards until freeze-up, the beaches of Radstock Bay were open to wave action.

In other locations in the area the break-up proceeded in a similar fashion, with a few differences. Offshore of Cape Liddon, approximately 100 meters, was a group of grounded bergy-bits, 20-40 meters long by 5 meters above sea level,that were frozen in the fast ice and remained some time after the general break-up of Lancaster Sound. These were visibly resting along the seaward edge of a shelf or rock ledge forming a line roughly parallel to the shore. After the ice of the Sound broke, these grounded ice features held ice against the shore of Cape Liddon for a few days, but eventually, as a few of them became smaller and floated away at high tide, they ceased to be a barrier. Once they became unprotected from wave action, they rapidly ablated and floated away.

At the tip of Cape Ricketts, bergy bits of the same general magnitude and probably of the same origin as those just described were grounded immediately offshore. These were gone, presumed to have floated away by August 5, but were replaced by a similar set of ice blocks on August 7. These were still in evidence on August 17 but were severely undercut by wave action along the waterline and would probably not remain until freeze-up. Indeed, they were not in evidence during 1971 at all.

Thus the pattern of break-up along the beach in the Arctic, at least in the southern Queen Elizabeth Islands can follow a regular pattern, varying in time of events because of aspect or local relief. This pattern is affected by the weather of course, but also by the state of the break-up in adjacent areas. Radstock Bay, for example, could possibly have broken any time after July 19, but it was forced closed for some time by wind driven ice from the south. The previous year's freeze-up is important in that it dictates the amount, constituents and configuration of the ice that will be melted the following spring. It seems logical that older, thicker, stronger ice, drifted in from another area and frozen into the back in this area would seriously retard the break-up. Also, it is important to note that probably the most important agent of sea ice ablation is the sea water itself. This statement is amplified in connection with the ice foot in Chapter 4.

CHAPTER IV

DETAILED ANALYSIS OF THE ICE FOOT

In this chapter a more detailed analysis of ground ice will be undertaken, commencing with a discussion of the literature followed by an analysis of the data collected during the 1970 field season.

The ice foot is a phenomenon that is recorded often by researchers doing different kinds of work in the Arctic and Antarctic. This is partly the result of the fact that for part of the year it is the only viable route of transportation for the eskimo sleds. It was defined by Wright and Priestley(1922) as the ice formation which joins the sea and land between high and low tide marks. Bentham (1937) defines it as that part of the sea ice which is frozen to the shore and is therefore unaffected by tidal movements. This is reiterated by Koch (1928) who writes "... the ice foot [is] a belt of sea ice adhering to the coast, unaffected by tides". In areas of low tidal range, there is an analogous feature, that is "... a flat rampart of alternating layers of beach sediment and ice called a kaimoo" (Moore 1968, p. 21).

Generally the ice foot may be described as a rampart of ice that lies above low water mark, is frozen to the beach face slope and therefore is independent of the sea ice and tides. Its lower surface is frozen to the sediment surface and therefore takes on the shape of the beach face slope. The seaward edge is usually vertical or near vertical due to abrasion against the sea ice moving up and down with the tides. The shape of the upper surface may be hummocky if sea ice is incorporated in it or mound-like if it formed during times of considerable wave action and generally is a function of wind, waves and tides at the time of freeze-up. Petersen (1962) reported on an ice foot developed along the steep rock shores of N.W. Greenland that formed a ledge with a flat bottom between mean water mark and low water mark. This form of ice foot has a flat bottom because the steep angle of the beach face prevents ice from adhering along the full width of the feature.

The ice foot may be affected by tides, waves, and ice during its formation, with resultant differing shapes. In their 1922 classic work on Antarctic glaciology, Wright and Priestley classified the ice foot as follows:

1. The tidal platform ice foot, formed by tide action between high and low water marks.

2. The storm ice foot, built up above still high water mark by spray from breaking waves.

3. The drift ice foot, fabricated from drift and consolidated by sea water which surges through tidal cracks.

4. The pressure ice foot, formed by over-riding slabs of sea ice emplaced by an on shore movement of the sea ice.

5. The stranded floe ice foot, incorporating beached bergy bits.

Joyce (1950) added to this classification two additional types of ice foot as follows:

1. The false ice foot, resulting from regelation of melt water from snow on the beach.

2. Wash and stream ice foot, a feature resulting from swell, not sea, appearing only on 'shelving' beaches.

Rex (1964) differentiated between a storm caused ice foot and a frozen spray caused ice foot. He noted that the former may exeed 2 meters in height and 10 meters in breadth. The frozen spray phenomenon is different in size and shape, he noted, being only a maximum of about 0.5 meters thick in places, more often less than 0.1 meters thick, but up to 30 meters across beach breadth. Also he would change the name of the storm ice foot to 'gravel and sand ice foot' in the Pt. Barrow area because of the large amount of sediment incorporated in it there. This could simply be the result of the availability of sediment in the lower amplitude tidal regime at Pt. Barrow. In areas of greater tidal range, the beach face sediment becomes frozen and immobile, but at Barrow, the offshore sediment is constantly submerged and mobile until freeze-up.

The most recent reviews of the ice foot are those of E. H. Owens and S. B. McCann (1970) and H. G. Greene (1970). The former paper is a result of investigations in the S.W. Devon Island study area during the summer of 1968. Besides noting its existence during that year, they reported that it reduced the relevance of the conventional freeze-up and break-up dates but they did not discuss ice foot genesis. Greene's discussion results from two and one-half months field work near Nome, Alaska. Here the small tidal range is almost insignificant. He attempted to define the kaimoo "... a bed of ice and frozen sand and gravel extending seaward from the waterline" (p. 421). This is not consistent with other definitions in the literature and is not clarified in his paper.

It is suggested here that this confusion of name could be clarified by the use of the term ice foot as an all inclusive term covering all the associated features. The term kaimoo appears to refer to a micro-tidal ice foot. The ice foot is a ground ice feature that varies areally (because of tide variations) and from year to year (because of climatic and ice variations) in size, shape and sediment content. This statement would make the term sand and gravel ice foot unnecessary.

Essentially, "the formation of the ice foot begins as soon as the air temperature falls below -1.7°C for an extended period" (Petersen, 1962, p. 36). This was earlier stated by Bentham (1937) as a condition of ice foot development. This condition obtains for large areas of the Arctic and Antarctic in autumn just prior to the sea ice freeze-up. It seems that the ground ice can be formed from frozen spray or from storm waves or from the rise and fall of tidal waters or from the grounding of sea ice upon the frozen or unfrozen beach face slope or any combination of these processes.

The ablation of the ice foot usually occurs subsequent to the sea ice break-up in the spring as a result of warmer weather, but as Petersen (1962, p. 40) points out "it is however the sea water which makes the ice foot melt away, not the higher air temperatures". The sea ice more easily affects the ice foot after break-up and this explains the rapid, post break-up ablation noted in Chapter 3, p. 27.

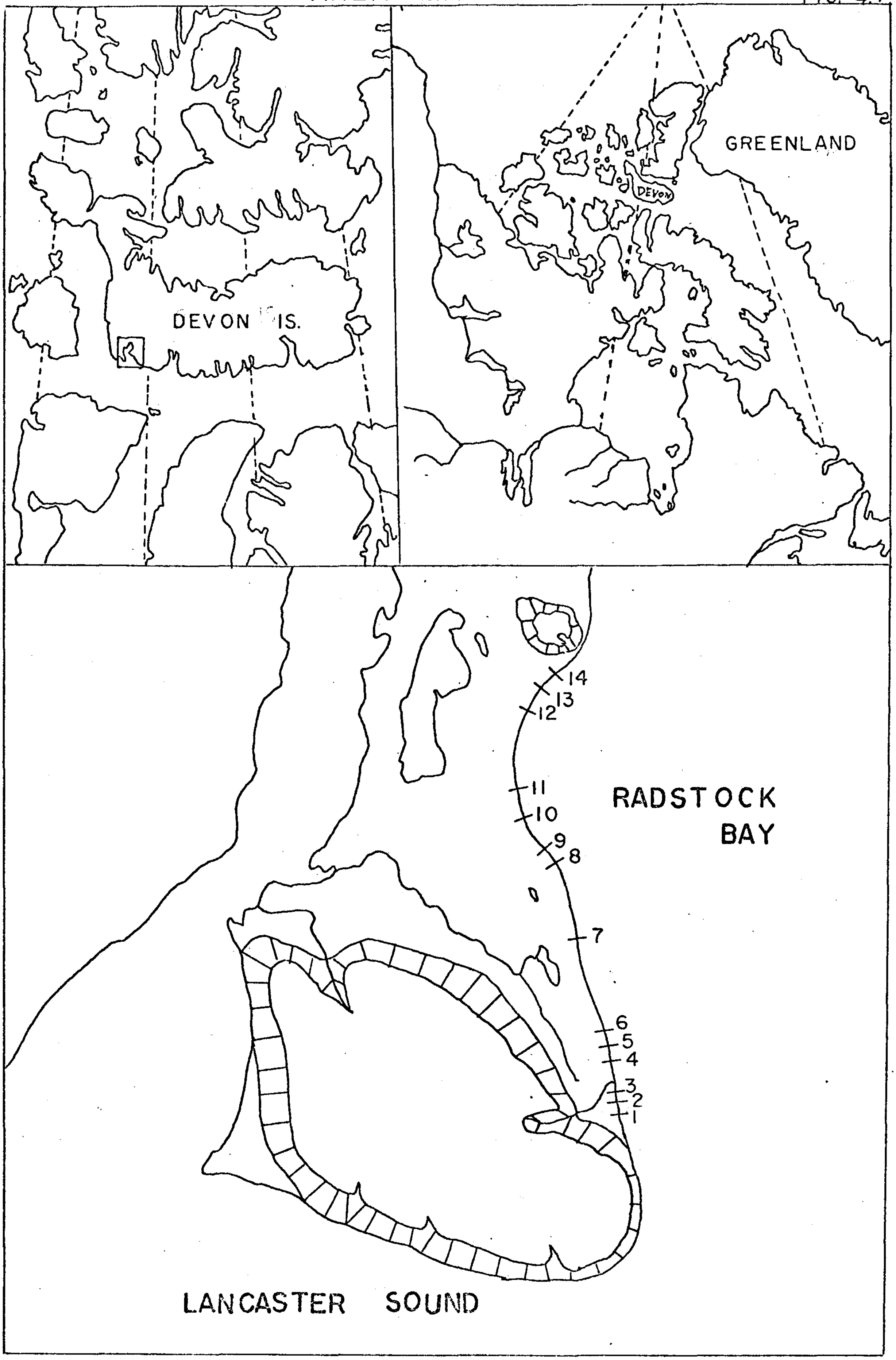
During the summer of 1970, the field party recorded many profiles across the beach. There was in mid-June an ice foot formation along the study beach continuously in all locations. It was assumed to have been present from the preceding autumn (1969). During early July it became divided into sections by the forementioned lead feeders, Chapter 2, p. 23.

Profiles were recorded on all profile locations on July 23, July 8, July 13, and August 15. In addition most profiles were surveyed June 24, July 24, and August 8. The locations of these profiles is recorded on the map (Fig. 4.1) and the profiles themselves are shown on Figure 3.2. In order to reduce each profile line to a common datum, the temporary bench mark established at each of the 14 locations were tied into one system by levelling from each to the high tide water mark of August 15, a day with very small waves.

The profiles were surveyed over beaches that differed in many respects. Some beaches, notably those in the Caswall Tower area, profiles #12, #13 and #14, were backed by a shallow sloping backshore of smooth raised beaches. They are exposed to the south, southeast, with a maximum fetch of 120 kilometers. Immediately east of this is the small remnant plateau peak Caswall Tower and 9 kilometers to the north is the main Devon Island Plateau. A fairly narrow section (less than 50 meters wide) of shallow sloping raised beaches backed by a 10-15 meter high erosional bluff is the location of profiles #10 and #11. These beaches are exposed across Radstock Bay to the north, northeast. The fetch is 15 kilometers up the valley to the northeast and 9 kilometers to the southeast across the Bay. The large plateau remnant is 3 kilometers to the southwest. Profiles #8 and #9 are located immediately at the base of a 2 to 3 m high erosional bluff. 150 m behind these to the west is an extension of the same large erosional bluff present behind #10 and #11. The large plateau remnant is located 2.3 kilometers to the southwest. These beaches face slightly northeast and have the same fetch as #10 and #11. At the base of the small erosion cliff in the area of profile #7, is found an

AREA MAP

FIG. 4.1



exposed bed of till, but otherwise the area is identical to the area adjacent to profile #8 and #9. Profile #7 faces south-east with a fetch of 9 kilometers across Radstock Bay. Also, profiles #4, #5 and #6 are backed by a small 2 meter high erosional cliff that is analogous to the small bluffs at profile #7, #8 and #9. 100 meters behind that is a 30 meter high erosional bluff analogous to the higher raised beach bluffs of profile #10 and #11. Behind this rises a large sequence of raised beaches to a height of 100 meters backed by the large remnant plateau. Even closer to the plateau are profiles #1, #2 and #3 which have even steeper, higher sequences of raised beaches behind them. Both of these last two beaches face due east with a fetch of 9-15 kilometers, but with a fetch to the southeast of hundreds of kilometers.

Also plotted (Fig. 3.2) is a set of generalized profiles for the 14 profile locations of the ice foot at maximum development (July 2,3), just before complete ablation (August 8) and after ablation (August 15). This gives a simple representation of cross-sectional shape of the ice foot. It may be noted that the form of the feature in this area is very consistent. Its seaward edge is in each case a near vertical face along the most shoreward tidal crack or lead. Shoreward of this is a mound, usually within 5 meters of the first lead, that is the highest point above sea level on the ice foot. Immediately shoreward of this mound in almost every case was a small crack or furrow of inexplicable origin running the length of the feature, usually less than 0.5 meters deep. This feature was invariably frozen closed and cannot be seen on the surveyed profiles. The rest of the ice foot consisted of debris filled ice levelled up against a moderate beach slope of 5°-11°.

From these surveyed profiles several measurements were obtained. The maximum thickness and width were recorded from the profiles surveyed July 2,3. It should be noted that the thickness measurement differs from heights of the top of the mound and the bottom of the ice foot measurements, which were also taken, in that thickness is here defined as the maximum vertical thickness (not extent). The last record of the 1970 ice foot was seen in the August 8 profiles, as the August 15 surveying was subsequent to final ablation. The same maximum thickness and width and height measurements were recorded from these later profiling dates.

The measurements taken of the ice foot from the surveyed profiles revealed a mean maximum width of 16.2 meters with a standard deviation of 3.01 (that is, 95% of the ice foot widths would be expected to fall between 10 and 22 meters). The mean maximum recorded ice foot thickness was 2.21 meters with a standard deviation of 0.43 (that is, 95% of the ice foot thicknesses would be expected to fall between 1.40 and 3.00 meters).

The heights of the top and bottom of the ice foot at each profile line in relation to the various tidal heights are shown in Figure 4.3 From this it may be observed that the top of the mound is, in each case higher than the small tide high water mark, and in all but 2 cases is above the large tide mean high water mark. The lower limit mean of the ice foot was found to be between the large tide low water mark and the small tide low water mark. The mean height of the higher limit of the ice foot is 3.12 meters above mean lower low tide, and the mean height of the lower limit is 0.23 meters above that same plane. The upper limit is somewhat more variable with a standard deviation of 0.5 compared to 0.37 for the

FIG. 4.3

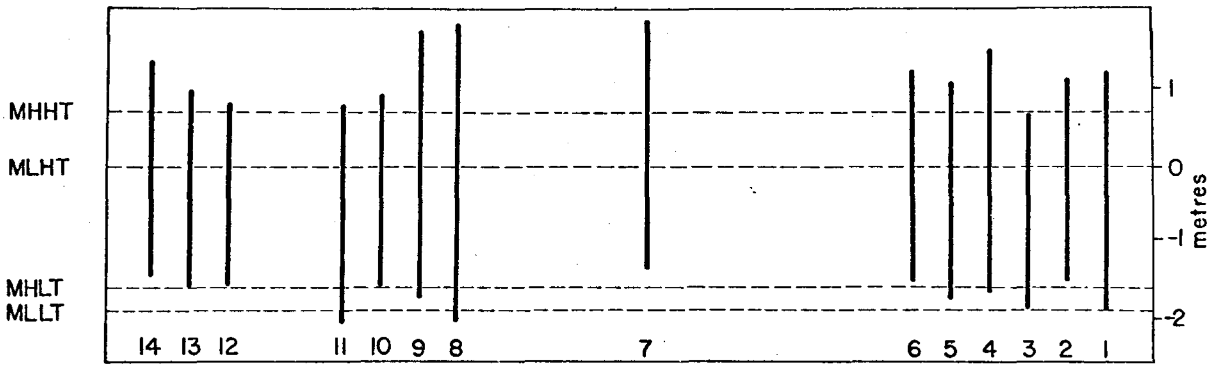
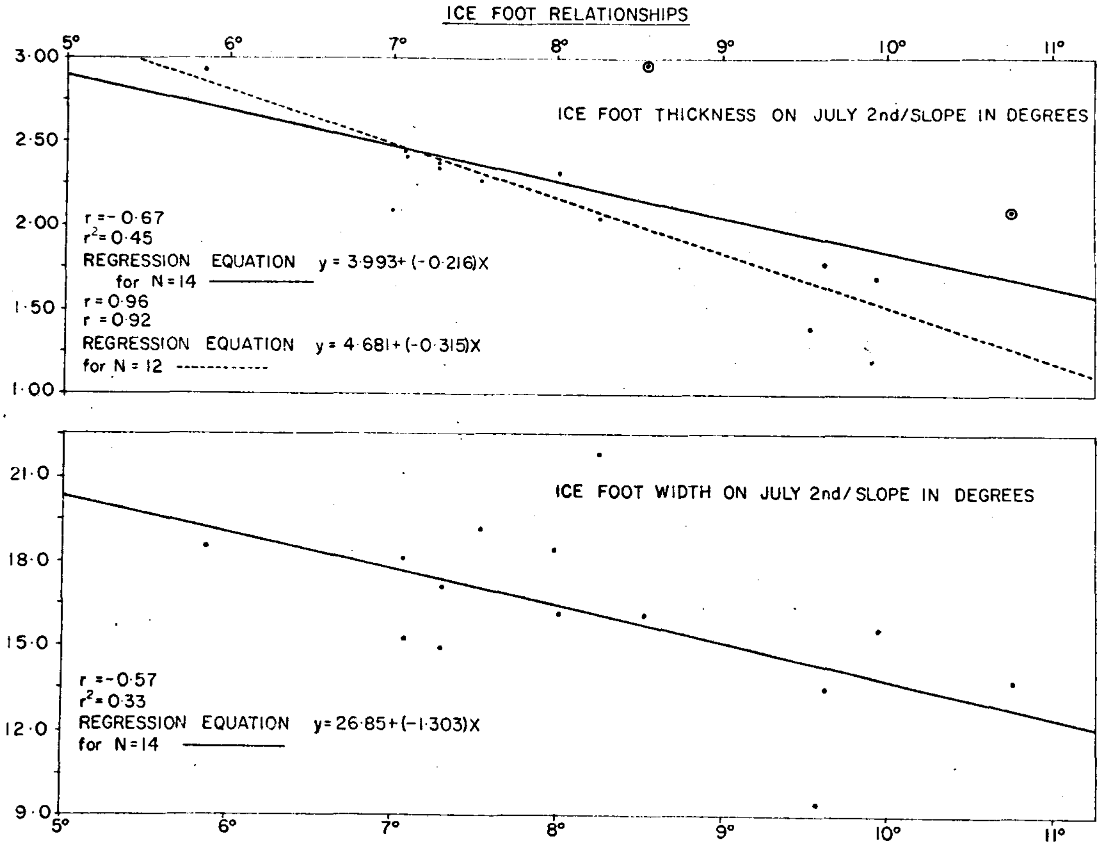

MHHT
MLHT
MHLT
MLLT
14 13 12 11 10 9 8 7 6 5 4 3 2 1
1
0
-1
-2
metres

FIG. 4.4


ICE FOOT RELATIONSHIPS
ICE FOOT THICKNESS ON JULY 2nd/SLOPE IN DEGREES
r = -0·67
r² = 0·45
REGRESSION EQUATION y = 3·993+ (-0·216)X
for N = 14
r = 0·96
r = 0·92
REGRESSION EQUATION y = 4·681+(-0·315)X
for N = 12
3·00
2·50
2·00
1·50
1·00
ICE FOOT WIDTH ON JULY 2nd/ SLOPE IN DEGREES
r = -0·57
r² = 0·33
REGRESSION EQUATION y = 26·85+(-1·303)X
for N = 14
21·0
18·0
15·0
12·0
9·0
5° 6° 7° 8° 9° 10° 11°

lower limit.

A study of Figure 4.3 reveals no trends in height of the top or bottom limits along the beach. The highest 3 values for the top parameter come from headland locations (profiles #7, #8 and #9) and may be assumed to have resulted from some ice movement or push during the formulative period. The next 4 highest values are not from headland locations but are situated on relatively straight sections of beach. Thus, there appears to be little regularity of trend. The lower limit values are less variable and show no trends whatever.

In order to investigate relationships between the beach zone environment and the ice foot, it was felt that some indicator of beach slope would be of value. Upon viewing the profiles, it seemed clear that the intertidal beach was fairly planar and therefore amenable to a simple, meaningful, mean slope calculation. This was done between the points on the beach face slope designated as mean large tide mark and mean small tide mark. The upper mark was chosen as it was the datum for all profiles. The lower was chosen as it was the lower limit of accurate surveying. This results from the fact that the lower tidal zone is almost always water covered after the ice foot ablated and therefore inaccessible and by definition inaccessible before that.

It was found from this that the beach face slope was quite consistently gently sloping. The range of slopes was from 5.86° (tan·103) to 10.75° (tan ·190) with a mean slope of 8.19° and a variance of 1.831. In order to test for a general trend of slope change along the beach, a regression was performed between distance down the beach, and the slope. The co-relation coefficient was sufficiently low (0.26) that it was not significant and the slope was indistinguishable with only 14 observations.

In order to determine whether beach slope had any effect upon ice foot parameters, several relationships were plotted. To test whether slope would to any degree affect the ice foot maximum width, these two values were plotted on Fig. 4.4. It appeared that a condition of increasing ice foot width with decreasing beach slope was in evidence. A subsequent regression analysis revealed a co-relation coefficient of 0.57 (32.5% explained variance).

Another relationship investigated was that between maximum thickness and slope. Thickness here refers to maximum vertical thickness and not to the difference between the height of the top of the mound and the bottom of the ice foot. This is plotted on Figure 4.4. It appears from this distribution that 12 of the 14 data points align quite rigidly. The two that deviate are #9 and #10. These points have the steepest slope and the greatest thickness, respectively, of all the points. Using all the data a regression analysis was conducted yielding a coefficient of co-relation of -0.67 with an explained variance of 45%.

Both of the co-relation coefficients are sufficiently high that there was less than 1% probability that the co-relations were due to chance. Also, a Student's t test showed that there was less than 1% probability of making errors in choosing the alternative hypotheses that the slopes of both regression lines were not equal to zero.

The beach slope/ice foot thickness relationship is more conclusive than the beach slope/ice foot width relationship. The stronger linear relationship is revealed by the higher co-relation coefficient of 0.67 (compared to 0.57). There is an even stronger relationship if the two errant points circled on Figure 4.4 are omitted. It is reasonable to omit these two values (profiles #8 and #10) because they both reflect ice foot thicknesses exceeding that expected. This is probably the result of pack ice pushing on shore at these two locations and is therefore not fundamental to the beach slope/ice foot thickness relationship, but superimposed upon it. The co-relation coefficient calculated for the 12 data points was 0.96. This means that 92% of the variation in ice foot thickness for these 12 locations can be explained by change in the beach slope.

It appeared after viewing the distributions that utilization of a linear regression was valid but a power curve and an exponential curve were also fitted to the data. In both cases the co-relation coefficients were lower than that calculated by the linear methods. Thus, it is argued that the relationship depicted in the distribution is better described as a linear function than as a power curve or exponential function.

The intuitively pleasing notion that the slope of the beach would significantly affect the size parameters of an ice foot resting upon it seems to be corroborated by the evidence discussed above. On a shallowly sloping beach any given height of the tide or wave crest will affect a greater swash zone area than on a steeply sloping beach. This relationship of increasing width of ice foot with decreasing slope can explain 45% of the variability in ice foot width. The rest of the variation could be due to partly random factors such as grounding ice blocks or locally variable factors such as fetch differences.

There is also a high strength linear relationship between the beach slope and ice foot thickness that agrees with what one would expect. On a shallow beach face slope, swash would be expected to travel further horizontally with given conditions than swash on a steeply sloping beach. The backwash would be expected to remain up the beach longer and the water depth be less on a shallow sloping beach than on a steep one. During the freezing, yet open water conditions, such as are generally believed to be conducive to ice foot development, this backwash would allow more opportunity for freezing and build-up on the beach face.

Generally, these results show, as would be expected, that at least within the range of slopes examined here, a shallower slope would tend to be associated with ice foot development of greater magnitude.

The notion that the beach with the most southerly aspect would have the highest ablation rate was investigated. In Figure 4.7 the horizontal and vertical ablation rates in meters per day are plotted against relative aspect in degrees. The scatter of data points clearly to the lack of a relationship. There are no trends in evidence here either. The only regularity seems to be that profiles #1, #2 and #3 have the highest ablation rates of any profiles on the beach. The vertical and horizontal ablation rates are also plotted on Figure 4.5. The conclusion is that aspect has no bearing on ablation rates of the ice foot, at least for beaches facing directions from only one quadrant. This leads to the question; what is the major process in the ablation of the ice foot? As noted previously, Petersen (1962) and others believe that sea water is the prime source of heat for the ablation of the ice foot. The following is an attempt to verify this on Radstock Bay.

The only possible process agents available for the ablation of the

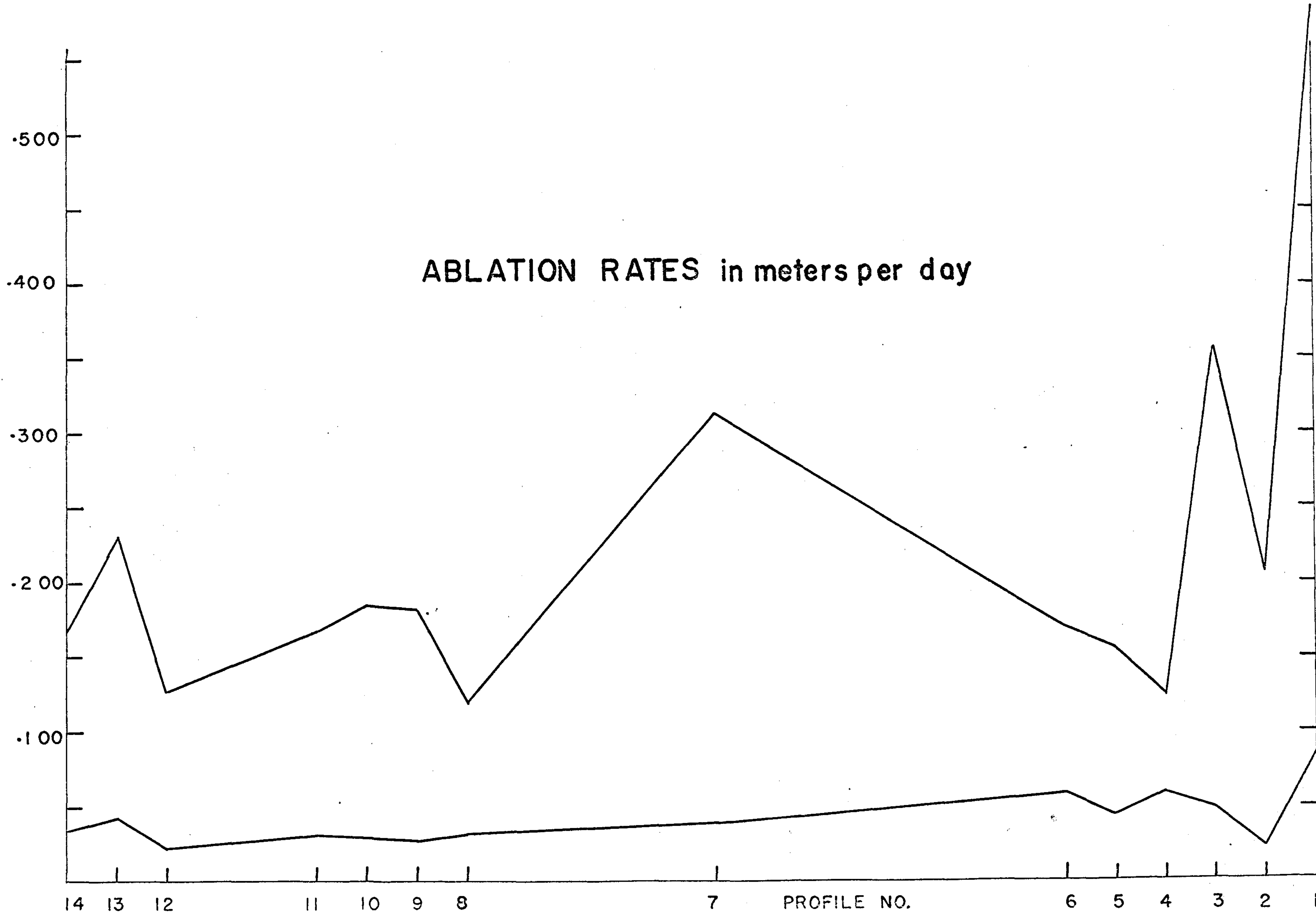
TABLE 4.1

ICE FOOT ABLATION RATES FOR RADSTOCK BAY 1970

IN METERS PER DAY BETWEEN TWO SETS OF DATES, FOR WIDTH AND THICKNESS

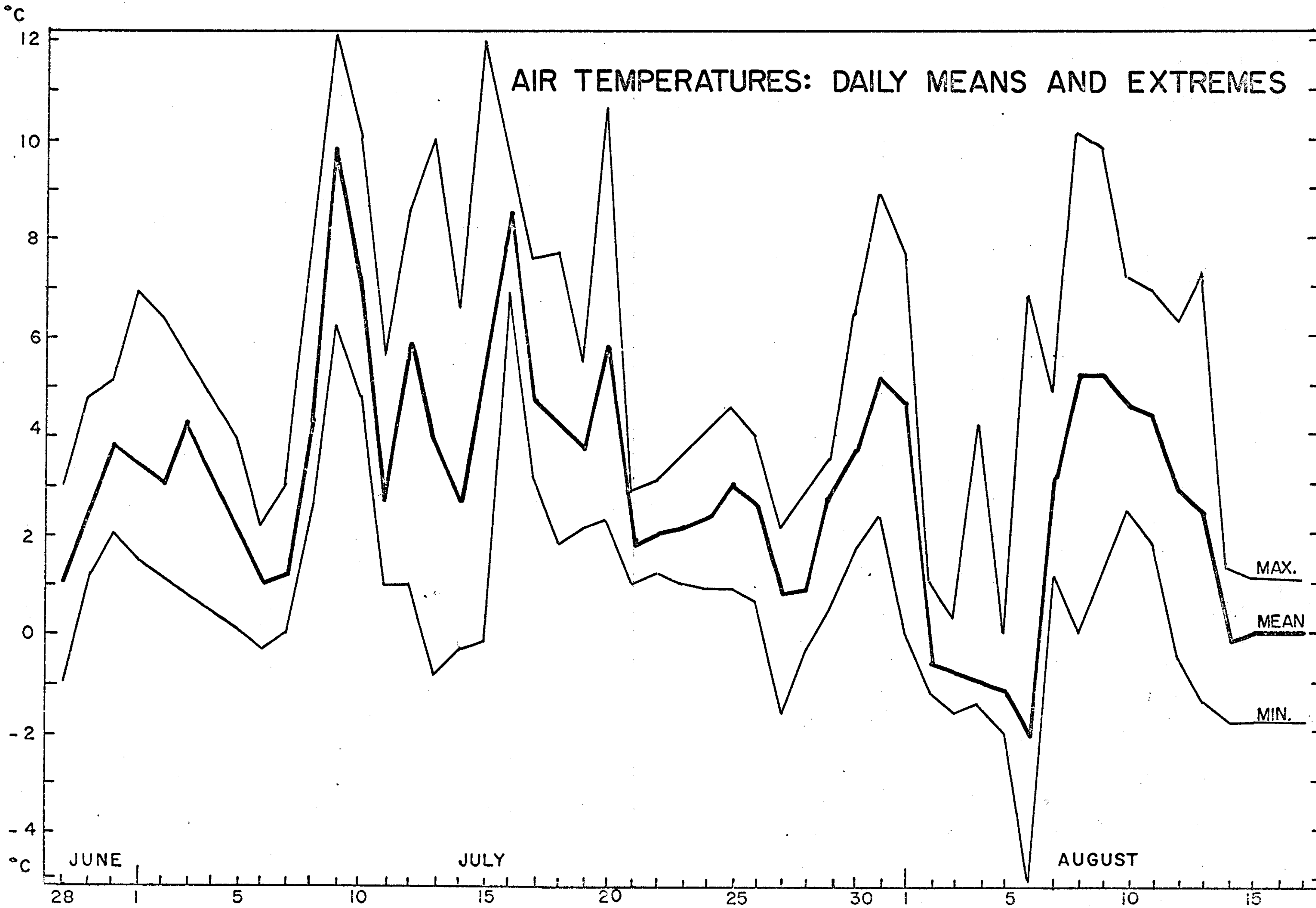
PROFILE NUMBER	WIDTH July2,3-Aug.8	WIDTH Aug.8-Aug.15	THICKNESS July2,3-Aug.15	THICKNESS Aug.8-Aug.15
1	0.590	0.000	0.049	0.000*
2	0.207	2.500	0.023	0.367
3	0.355	1.900	0.081	0.240
4	0.125	2.000	0.058	0.117
5	0.156	1.929	0.042	0.109
6	0.169	0.171	0.058	0.057
7	0.314	1.500	0.038	0.100
8	0.121	1.750	0.032	0.260
9	0.181	1.700	0.028	0.154
10	0.185	1.007	0.030	0.143
11	0.167	1.264	0.031	0.829
12	0.128	0.700	0.023	0.079
13	0.229	0.943	0.042	0.121
14	0.167	1.321	0.034	0.169

*Values here are zero because the ice foot had completely ablated before August 8 at that location.



ABLATION RATES in meters per day
·500
·400
·300
·200
·100
14
13
12
11
10
9
8
7
PROFILE NO.
6
5
4
3
2
1

FIG. 4.5



AIR TEMPERATURES: DAILY MEANS AND EXTREMES
°C
12
10
8
6
4
2
0
-2
-4
°C
MAX.
MEAN
MIN.
JUNE
JULY
AUGUST
28
1
5
10
15
20
25
30
1
5
10
15

FIG. 4.6

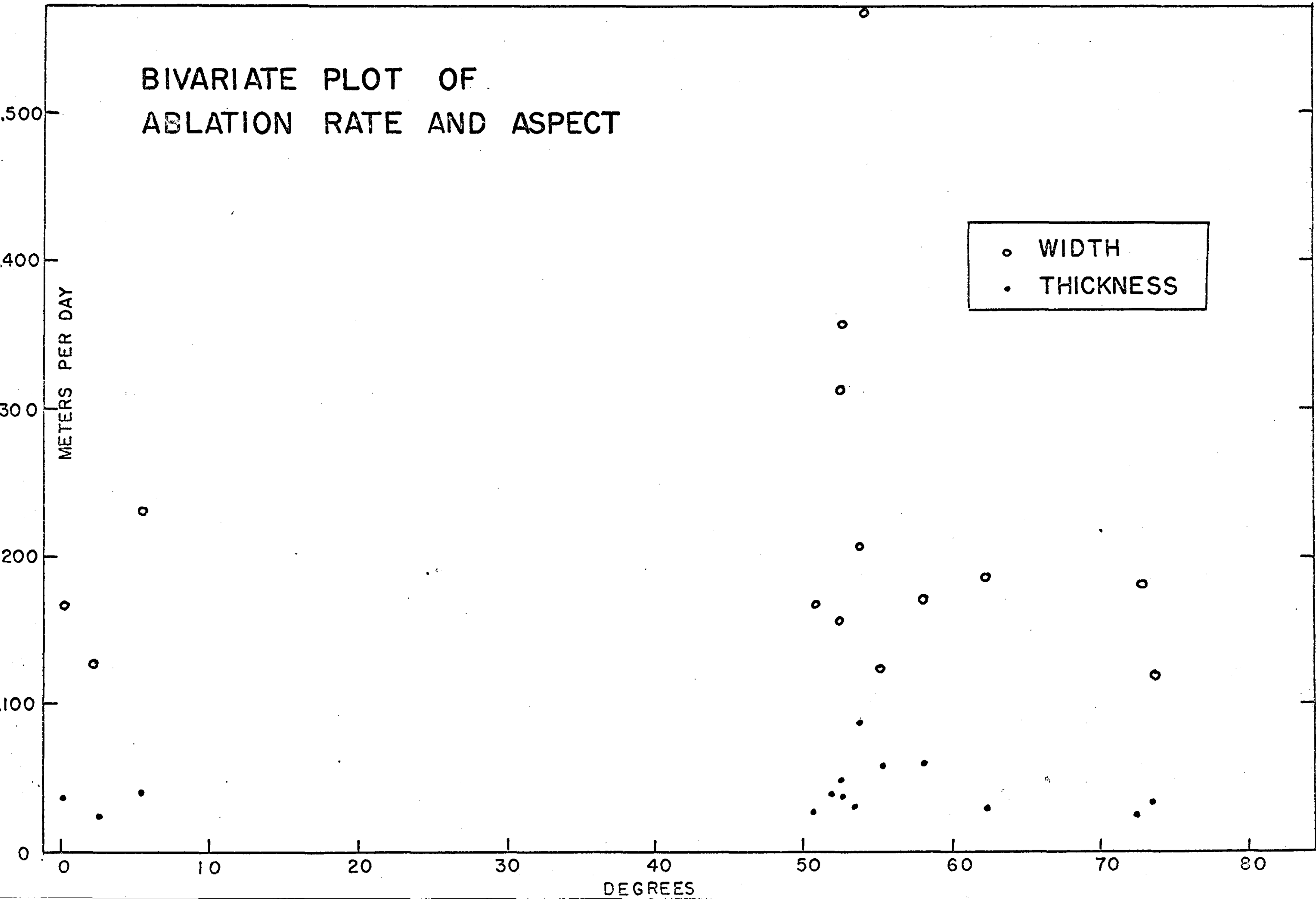

BIVARIATE PLOT OF
ABLATION RATE AND ASPECT
WIDTH
THICKNESS
METERS PER DAY
.500
.400
.300
.200
.100
0
0
10
20
30
40
50
60
70
80
DEGREES

FIG. 4.7

ice foot are from direct solar radiation, from a sensible heat flux from the atmosphere, and from a negative heat storage from the sea water to the ice foot.

In order to determine which of these processes is dominant, some simple ablation rates were calculated. The values for the ablation rates for each profile were derived from the surveyed ice foot width and thickness. The differences in these measurements between surveying dates was divided by the number of intervening days to give simple ablation rate values. The values obtained for profiles #1, #2 and #3 were derived from the intervals July 14 to August 12 and August 12 to August 15. The values for all other profiles were derived from the intervals July 2 to August 8 and August 8 to August 15. These are tabulated in Table 4.1.

Except for the values denoted by an asterisk, these appeared to be a step level increase in the ice foot ablation rate in the order of a factor of 5 between the two periods. A comparison of these rates and net radiation on Radstock Bay was impossible as the only radiation instrument available in the field was an actinograph and this recorded insufficient observations to be of use. Information on net radiation was available for Resolute Bay, N.W.T. but this was not utilized because of the high variability of weather characteristics between the two locations 125 kilometers apart. It is sufficient to say that due to the decreasing angle of inclination and corresponding increasing air mass (radiation travel distance through the atmosphere), radiation values will generally decrease after June 20. Moreover a review of the cloud statistics (mean quarter daily cloud tenths) for Resolute Bay, N.W.T. (Thompson 1967) reveal a slight increase in cloud cover in August which should reinforce the decreasing radiation values. Even if this were not so, an increase in net radiation would probably not be a step level change of such magnitude but rather a gradual one.

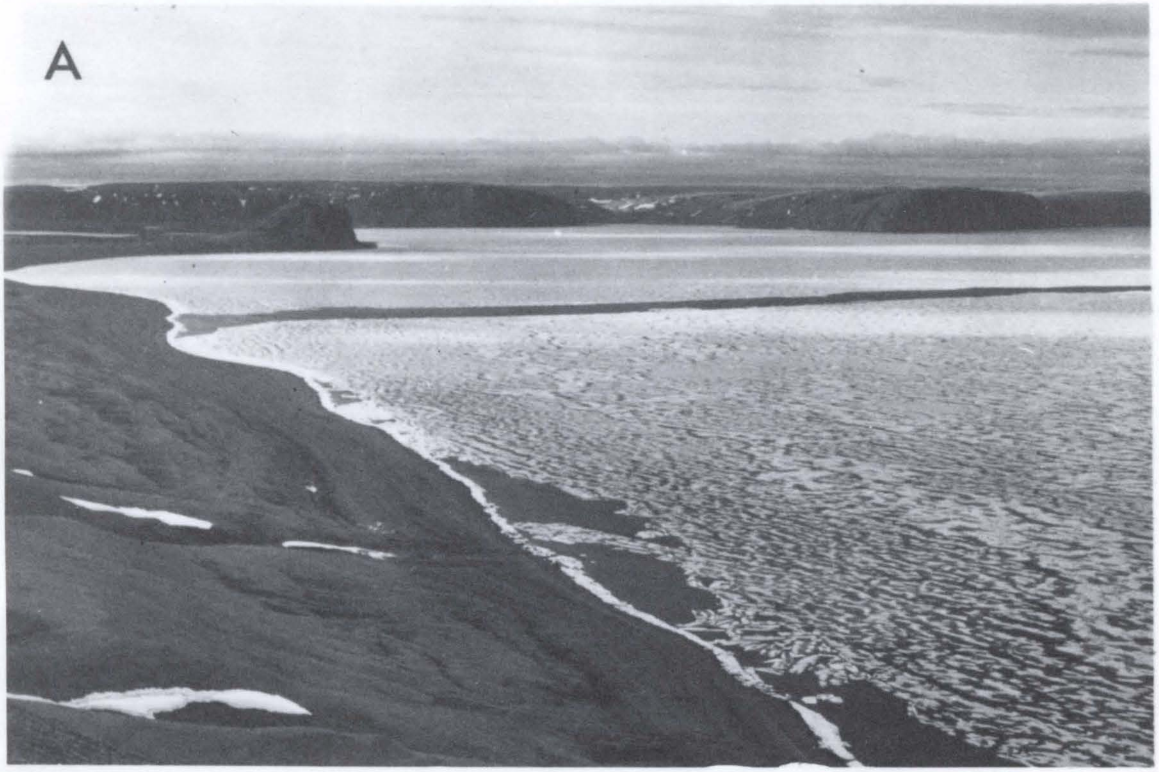
In order to compare ablation rates to sensible heat (air temperature is a good approximation or indicator of sensible heat flux) a graph of maximum, minimum and mean daily air temperatures recorded in a Stevenson Screen at Radstock Bay is shown in Figure 4.6. It may be observed from this that temperatures generally decline from mid July through mid August with much variability and specifically decline from August 8 through August 15. This would rule out sensible heat as a major energy source.

Sea water was the obvious major energy source in the ablation of the ice foot. The ice foot on Radstock Bay ablated visibly more rapidly after the sea ice had broken and allowed the sea to freely affect the foot. The ice cleared out of the Bay in the area of profiles #1 through #6 as of August 7. At this time the ice foot that remained along the whole beach was 55% of its maximum extent as observed on July 2-3. But August 13 the ice foot in the profiles #1 through #6 had completely ablated. The ice in the area of profiles #7 through #14 had cleared the Bay by August 9. Similarly the ice foot in this area had completely ablated by August 15. It is noted that through this time wave action was minimal and nowhere was there erosion of the foot save by ablation. Thus, in spite of the fact (previously stated), that the presence of the ice foot renders conventional break-up dates useless as an indicator of the initiation of wave action on sediment; it is observed that, at least during this one year, the break-up date immediately precedes this initiation by one or two days.

Plate 1A shows the condition of the fast ice of Radstock Bay, July 16 as seen from the viewpoint indicated in Figure 4.1. Plate 1B shows the shore on July 16 showing the ice foot, the series of free floating floes in the tidal leads and the sea ice. Figure 2A is a general view of the outer part of Radstock Bay taken from the viewpoint indicated on Figure 4.1. The mass of ice in the right foreground is moving out of the bay, leaving a fringe of beach fast ice in the form of an ice foot along the shore. Figure 2B shows the shore on August 7, with the ice foot and in the background the ice margin across the bay as it remained August 6-August 9.

A

B


A


B

CHAPTER V

ANALYSIS OF SEDIMENTS

INTRODUCTION

Processes affecting beach sediments in the Arctic environment include waves, tides, winds, ice push and rivers. Most authorities on Arctic beaches agree, however, that form and regime of the beaches are primarily the result of wave action.

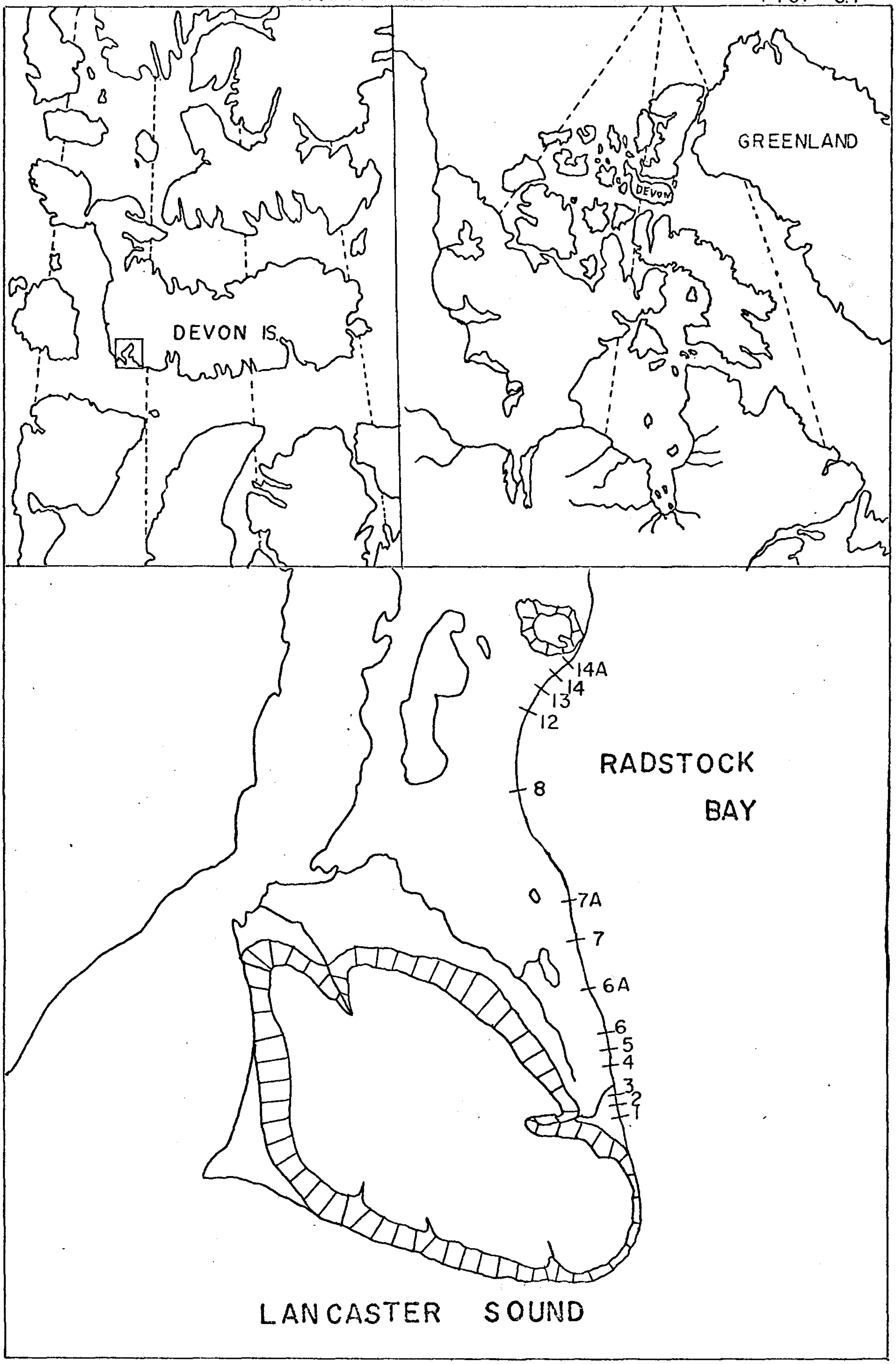
Moving ice is known to have a positive effect upon the beaches in the form of ice push ridges and other grounded ice phenomena; but, Hulme and Schalk (1964b) suggest that this affects only 1 or 2 per cent of the active sediment in the Point Barrow area of Alaska and Owens and McCann (1970) agree that the Radstock Bay area is comparable in this respect. Primarily the presence of ice is a negative factor, a constraint upon wave energy systems. Floating pack ice can alter the wave generation characteristics of an area by reducing and in winter eliminating the fetch length and can also diminish the size of waves already generated. Ice, frozen to the shore as an ice foot or kaimoo, can completely eliminate the effect of waves even when the water is open. The presence of ice and temperatures which may range from +12°C to -45°C obviously make Arctic beaches different from temperate beaches in a number of ways. Nonetheless, if wave action remains the most important process of sediment transport and the most important control of beach form, then beach sediments should show similar size grading and sorting relationships along and across beach in the Arctic as in other environments. Arctic beaches may be studied in the same basic manner as beaches in other areas.

The important parameters of waves are wave height, and wave length ignoring wave period as it may be taken as a simple function of wave length. C. A. M. King (1959, p. 8) states, "It is on the relationship between the two fundamental dimensions of the waves, the length and the height, that the effect on the beach ultimately depends". The energy of waves determines the amount of work that can be done on a beach and is a function of the two paramount parameters. These in turn are functions of speed and duration of wind and the length of open water fetch over which it flows. Waves from areas of longer fetch and/or higher speed, longer duration winds obtain longer wave lengths and higher wave heights, and therefore higher energy values than waves from shorter fetches and less strong wind systems. Thus the amount of material moved and abraded on a beach, being a function of wave energy, varies with the alignment of that beach with respect to fetch and the direction of dominant winds.

The constituent material of a beach is moved by process of beach drifting. This can be described as the process whereby sediment is pushed up the beach by swash at an angle corresponding to the angle of incidence of the waves, modified by refraction, then is moved back down the beach face by backwash in response to gravity with the lateral momentum of the water diminishing due to bottom friction. A net movement of sediment for any set of wave conditions results from a sustained difference between the angle that the swash takes across the beach face and the angle the backwash water takes return.

AREA MAP

FIG. 5.1



If material of gravel size is moved in one direction away from a source area it is commonly expected that the mean grain size will decrease as a result of abrasion, with the added possibility that the sediment will be better sorted, though the arguments for this expectation are less cogent.

In the Radstock Bay situation, with large talus aprons below high cliffs at the south end of the beach and the greatest fetch by far to the southeast (Figure 5.1) the rapid movement of material along the beach from south to north would appear to be most important. In addition wind conditions in this area point to a south to north direction of net sediment transport. This wind data is taken from the nearest Department of Transport, Meteorological Branch weather stations at Resolute Bay on Cornwallis Island 120 kilometers to the west and Dundas Harbour 250 kilometers to the east on Devon Island. These records show that on average 22% of August winds at Resolute and close to 50% of August winds at Dundas Harbour emanate from the southeast (Thompson 1970). Indeed at Radstock Bay in August 1970 the two major octants of wind direction were northwest (or offshore) and southeast. In fact, only once was there any even minor deviation from these directions. It is further noted that the ice in Lancaster Sound usually breaks up previous to the break-up of Radstock Bay. This means that there is a high probability that after break-up of Radstock Bay there normally will be open water conditions across the most important southeast fetch. These facts substantiate the expectation of south to north net sediment transport and therefore the build-up of the beaches through time. Indeed this is observed in the large raised beach complex which backs the modern beach zone.

The obvious sediment size response expected from these environmental factors is a diminuation of grain size along the west shore of Radstock Bay from south to north. Also, one might expect to see greater sorting along the beach as expressed by the smaller values for standard deviation in the north than in the south. Another commonly accepted beach form-sediment size relationship is between cross-sectional gradient and mean particle size. This is expressed by C. A. M. King (1959, p. 327), "The slope (of the beach) becomes steeper as the material becomes coarser ...". All of these relationships were tested for the beach of the western shore of Radstock Bay.

PREVIOUS WORK

Very little has been written on Arctic beach sediment. A review of references in the papers that do deal directly with this topic (McCann and Owens 1969, and Moore 1966) reveals this paucity. These references invariably relate to temperate sedimentological studies, techniques of analysis manuals or work dealing with morphology of beaches or some other geomorphological phenomenon.

Even in the papers written on the subject there is a dearth of hard data. Nicholls (1961), in the paper entitled, "Characteristics of Beaches Found in Polar Climates", nowhere refers to particle size save by the use of the word gravel. This description of some glacial-beach phenomena found in the Antarctic appears to be purely qualitative. Rex (1964) published a discussion of beach sediment in the Pt. Barrow, Alaska situation apparently on the strength of two samples taken from disparate areas. His samples were taken from the Pt. Barrow spit which is aligned

N.W.-S.E. and also from a tombolo which is aligned at right angles to the spit. He found that the materials that composed the samples were 85-90% chert, 7-14% quartzite, quartz or sandstone and less than 3% limestone. The mean grain size for the two samples was found to be -1.23 phi (2.3 mm) and -0.05 phi (1.1 mm). The standard deviations or second moment measure about the mean, taken by Rex and most others to be an adequate description of sorting were calculated to be 1.07 phi (2.05 mm) and 0.97 phi (1.93 mm) respectively. Rex followed this listing of results with a qualitative description of sediment in the various zones of his beach area. It is evident from his description that he found the wave break zone to be composed of coarser material than either the foreshore or backshore zones. Unfortunately he confined his description of particle size to the use of the word gravel.

In contrast to earlier work, extensive sampling was undertaken by Moore (1966) in the Cape Thompson, Alaska area. He noted that the material composing the modal range of his samples were as follows: 53% chert, 38% sandstones and mudstones, 7% limestone and 2% vein quartz. The samples varied in median diameter from phi 3 (0.2 mm) to phi -5 (32.5 mm) with a mean median of -2 phi (4.0 mm). Also he noted that very few limestone grains smaller than phi 0 (1 mm) were found and concluded that they were removed by solution.

Interestingly, Moore found that the concentration of limestone pebbles was higher near the limestone cliffs of Cape Thompson. This obviously leads to the conclusion that the cliffs may be a source of material for the beach. To verify this hypothesis he discussed many possible sources of materials, precluding the two rivers of the area as a major source because they carried primarily silt size material, a size range almost non-existent on the beaches. Because of former sub-aerial extension of a present day creek had not been filled with beach sediment as would have been expected if a beach system like the present had been in existence during the post-glacial sea level use, Moore concluded that material comprising the present day beaches probably did not originate as older beach sediments. Sampling revealed organism encrusted angular stones on submarine outcrops and yet none were found on the beaches even after storms. This led to the conclusion that the offshore areas did not significantly contribute to the active beach sediments. Evidence such as the destruction and removal of some sod houses, known to have been occupied some centuries ago indicated to Moore that erosion of sea cliffs and older deposits were in some areas contributing material. He also corroborated this with observations of rock falls and fresh debris piles along the base of the 100 meter high cliffs. By citing the work of Kidson, Carr and Smith (1956) and others, and making use of observations on spits in the area and some energy transport relationship, Moore concluded that the beach sediment of his area probably originated from cliff material and moved alongshore unhindered by rivers resulting in a net sediment movement in the order of 28,000 cubic meters in a year. The nature of the movement was such, that with one day of wave action by waves exceeding 3.6 meters in height, the entire years movement could be reversed.

The paper that is the latest and most directly revelant to his discussion is, "The Size and Shape of Sediments in Three Arctic Beaches, Southwest Devon Island, N.W.T., Canada" by S. B. McCann and E. H. Owens

(1969). It is most relevant because one of the three beaches studied is the Radstock Bay beach sampled in this thesis and also it deals directly and exclusively with hard data on beach sediment. This research undertaken during the summer of 1968 consisted of sediment size and sediment shape analyses of 66 samples taken from three beaches that faced west, east and south on S.W. Devon Island. They systematically collected samples from 1) above high water 2) at high water 3) mean high water (presumably at the small tide high water mark) and 4) mean sea level on each of 7 profiles of the west facing beach (Cape Ricketts) and on each of the 6 east facing profiles (Radstock Bay) and on each of the 5 south facing profiles (Walrus Bay). The samples were sieved using a one phi unit interval, with the fines (smaller tran -1 phi (2 mm)) resieved and weighed in the laboratory. A computer program (SEDANL) was used to calculate the first four moment measures about the mean. It was noted that all of their samples consisted of very close to 100% limestone or shalely limestone.

Their results of sampling at Cape Ricketts showed a range of mean particle size between phi -0.95 (1.93 mm) and phi -5.33 (41 mm). The standard deviation range computed for this beach was between phi 1.73 and phi 0.42. Mean particle size and standard deviation values for the Radstock Bay samples ranged from phi -3.24 (9.5 mm) to phi -5.00 (32 mm) and phi 0.67 to phi 1.30 respectively. The values for Walrus Bay ranged from phi -3.51 (13 mm) to phi -5.43 (43 mm) and from phi 0.46 to phi 1.47 respectively for these first two moment measures.

In their analysis the authors found evidence of decreasing particle size, improved sorting and increased rounding of sediment on Radstock Bay from south to north. They concluded that material from the talus apron cliff complex in the south was the source of the beach sediment as a result of sediment movement from south to north. They also discovered a trend in mean pebble size across the beaches with coarser sediment found higher up the beaches.

The sorting (or standard deviation) values calculated on the Radstock Bay profiles showed three sites poorly sorted, 2 sites moderately well sorted and the remaining 15 moderately sorted. These terms are from the commonly used categories where standard deviations less than phi 0.50 were deemed well sorted, between phi 0.50 and phi 0.71 moderately well sorted, between phi 0.71 and phi 1.00 moderately sorted and greater than 1.00 poorly sorted. The uniformity of the Radstock Bay samples was pointed up by the authors. The authors also calculated skewness and kurtosis values for each sample but for reasons outlined later they will not be discussed.

The summary of results of sampling of the sediment of Southwest Devon Island bears repetition and verification. Repetition is warrented and verification possible because of coinciding object areas. The summary is repeated as follows:

1) Most of the material falls in the pebble range.

2) The majority of the samples indicate moderate or poor sorting of beach sediments.

3) The data for Radstock Bay ... suggest longshore movement of beach material ...

4) (There was) ... a variation in the mean particle size across the beach with the fine material occurring in the lower parts of the active zone.

DATA COLLECTION AND ANALYSIS

For the collection of sediment samples on Radstock Bay, a new sampling grid was established for the present study (Figure 5.1). The 14 profile lines utilized were chosen in order to examine the sediment from beaches of different slopes and ice environments along the 4 miles of the western shore of Radstock Bay. In order to ease collection and conserve information, some of the profile lines previously described in connection with the ice foot were chosen as collection lines. In order to test the hypothesis that samples taken from different locations on a beach profile will yield different but internally consistent mean particle size trends, three sites for sample collection were chosen on each profile line.

The most seaward of these three sites was the estimated mid tide mark which was chosen to reveal the size characteristics of the active beach zone. It was found to be impracticable to utilize a site more seaward as it would be inaccessible for subsequent surveying under most tidal conditions. The next sampling site chosen was the mean large tide mark and was assumed to be at the base of the small ridge previously referred to as the high tide ridge. This was taken in order to reveal the sediment size characteristics of the highest regularly active beach zone. The third sampling site was at the base of the first large ridge, just beyond the highest regularly active zone. This site was the least consistent of of the three as the storm ridges often merged, diverged and changed in character between the profile locations. This was chosen to reveal the sediment size characteristics of sediment in a zone that is a relic of storm conditions of the past but would probably be moved again in an extremely low frequency, high magnitude storm.

The 14 profile locations are outlined below from south to north. The first size profile lines were the previously described profiles #'s 1, 2, 3, 4, 5, 6, (Fig. 3.1). The next location, labelled #6A(Fig. 5.1) was taken from a headland location approximately equidistant from profile #6 and the next profile location, the previously described (Fig. 4.1) profile #7. The next profile, labelled #7A was taken in a zone of relic raised ice push scars, again halfway between #7 and #8. The four profiles sampled next were profiles #'s 8, 12, 13, 14 (Fig. 4.1). The most northerly profile location was immediately adjacent to profile #14 and was labelled #14A.

Thus, the sampling grid described above is in the form of a 14 by 3 matrix with 42 sampling points.

At each of the 42 sampling sites, the same collection procedure was followed. Once the general area from which the sample was to be taken had been chosen, the collector chose an arbitrary sampling point (by dropping a stone). Pebbles were collected by hand from the surface of the .30 m radius sampling point until the sample bag contained 2 or 3 kilograms.

All of the samples were sieved in the field with Tyler sieves. The mesh sizes chosen were the Wentworth phi size categories phi -6, phi -5, phi -4, phi -3, phi -2, phi -1 and phi 0. According to this scheme,pebbles larger than 64 mm in "b"-axis diameter will sit on the phi -6 sieve and particles smaller than 1 mm in "b"-axis diameter will fall through the phi 0 sieve and rest on the holding pan beneath.

The residue on the sieves was weighed on the field with an Ohaus triple beam balance (2610 gm capacity). This method was deemed acceptable since virtually 100% of the sample pebbles consisted of limestone or shalely limestone of the same or nearly the same density.

Once the sieving and weighing was done, there was a choice to be made as to computational methods. The alternatives were, the use of a computer and moment measure statistics or the use of graphs and simple intercept statistics. A problem often cited with the use of graphic statistics is, as R. A. Baker (1968, p. 679) pointed out "graphic statistics are a function of only selected points and ignore the data between those points ...". But, as he later notes, "this weakness is seldom serious ...". The graph and intercept statistics method was chosen finally for its speed and facility in the field.

The measured weight values for each phi category were first transformed into percentages of the weight of the total sample. These were accumulated to obtain cumulative percentages. These were in turn plotted on percentage probability paper. The formula chosen to calculate the statistical mean particle size for each sample was that derived by McCammon (1962). It was chosen because it included more intercept values in its calculation and therefore loses less information. It is as follows:

$$M_Z = \frac{(\theta\ 10\ \text{phi} + \theta\ 30\ \text{phi} + \theta\ 50\ \text{phi} + \theta\ 70\ \text{phi} + \theta\ 90\ \text{phi})}{5}$$

where θ represents the percentile intercept. The phi unit intercept values for each of these intercepts were extrapolated and employed in the formula for each sample.

To ascertain a sorting value, the inclusive graphic standard deviation devised by Folk and Ward (1957) was used. It is as follows:

$$\sigma = \frac{\theta\ 84\ \text{phi} - \theta\ 16\ \text{phi}}{4} + \frac{\theta\ 95\ \text{phi} - \theta\ 5\ \text{phi}}{6.6}$$

where θ represents the percentile intercept. Each of these percentiles were extrapolated to find the phi unit intercept and employed in the formula for each sample.

The calculation of skewness was neglected for several reasons. The major useful ness of the skewness parameter as used in the literature was in distinguishing between sediment from different environments. Obviously, this capability would serve no purpose in this study. Also, due to the necessity and realities of working in the field, a whole phi unit interval sieve system had to be employed. In this regard R. L. Folk (1962, p. 145) pointed out "... a whole phi unit spacing is virtually useless ... if one is trying to study (the) subtleties of (the) tail ...". Since skewness is essentially a parameter which describes the configuration of the tails, its calculation in this instance did not seem valid.

The results of analysis are tabulated in Table 5.1. They are shown in histogram form in Figure 5.2

The analysis revealed all mean size values to be in the range phi -5.85 to phi -3.10 (i.e., all in the pebble range). The mean of the mid tide man particle size values was calculated at phi -4.34. The high tide mean was phi -4.91 and storm phi -4.97. That is the mid tide particle size mean was the finest of the three. This concurs with McCann and

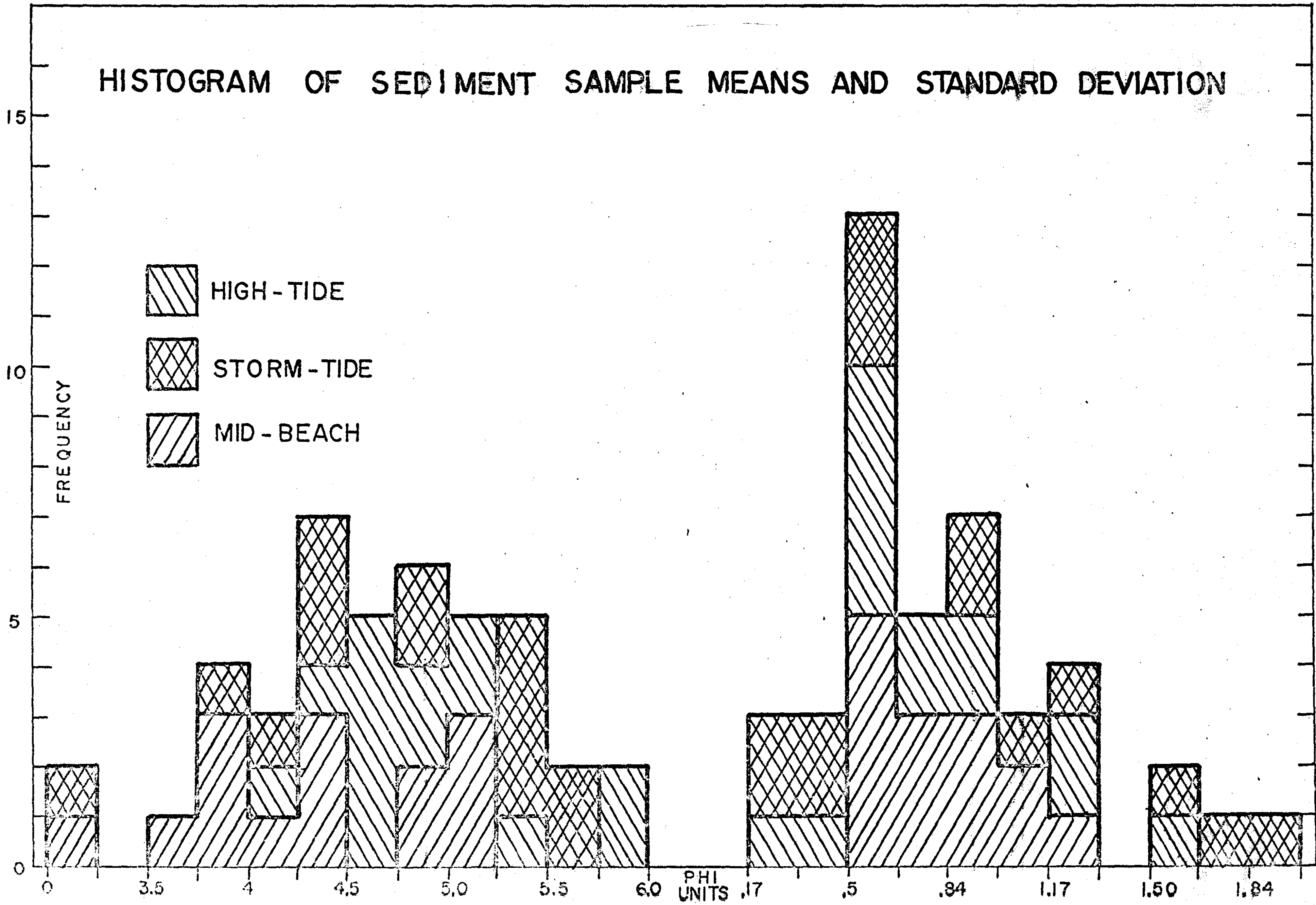

HISTOGRAM OF SEDIMENT SAMPLE MEANS AND STANDARD DEVIATION
HIGH-TIDE
STORM-TIDE
MID-BEACH
FREQUENCY
0
5
10
15
PHI UNITS
0
3.5
4
4.5
5.0
5.5
6.0
.17
.5
.84
1.17
1.50
1.84

FIG. 5.2

Owens (1969) fourth summary statement but the significances of the find will be reviewed later. The second finest value for mean particle size was that calculated for the means in the storm environment. It appears to some degree that possibly the action of waves in the active zone does result in coarser sediment being found higher up the beach. A possible reason for the lack of a distinct and consistent difference in pebble grade across the beach as McCann and Owens (1969) observed could be that the present samples were taken immediately after the ablation of the ice and before even the first set of open water tides allowed wave action over the entire beach face slope. The McCann and Owens (1969) samples were taken far later in the season.

To test whether the differences between the means were due to chance or whether they were actually the result of significant consistent differences in size at different sampling points, a simple Student's "t" test was performed. The null hypothesis was that the means of the sampling distributions of mean particle size were the same. When testing the mean of sediment in the mid-tide zone against those of the high tide zone a "t" value of 2.47 was calculated. This value exceeded the critical value of "t" at the 0.95 confidence level. This means that the null hypothesis of equivalence can be rejected at 0.95 confidence. This could not be said at the 0.99 confidence level. The "t" values calculated for the differences between high and storm tidal regimes and the mid and storm tide regimes were (0.562 and (1.583) respectively. The null hypothesis that these sets of compared means were equal cannot be rejected with 0.95 or 0.99 confidence as they fail to exceed the critical value of "t" as obtained from the statistics tables.

In process terms this means that there was a significant difference between mid and high tide sediments in that the mid tide sediment was finer, but, the storm tide level sediment, outside of wave action except during severe and infrequent storms (1:10 or 1:100 years) could not be distinguished as distinctly different from the other two samples at 0.95 confidence level. The storm tide level sediment however was significantly coarser than the mid tide level samples at the 0.80 confidence level. This reveals that the expected process of wave action throwing up coarser material to higher levels on the beach (observed on temperate beaches by many and in the Arctic by McCann and Owens (1969)) did not appear.

McCann and Owens noted a trend of diminishing particle size from south to north on Radstock Bay. To systematically check whether there was any significance to this possible stochastic result, the sample means were plotted against a distance function (Fig. 5.3). The respective regression lines were passed through the data for each of the three regimes. This revealed the trend of diminishing particle size from south to north in all cases. The co-relation coefficients obtained for the regression's were tested against the critical value of r for 14 data points (at 0.95 confidence) and found to be significant. These values appear on Table 5.2

Next a simple slope "t" test was undertaken to test whether the slopes of these three regression lines differed significantly from zero. This was done because the slopes were quite shallow. This test would reveal whether mean particle size significantly changed with distance away from the southern supply cliffs or was randomly distributed and happened by chance to have the observed trend. The results of the Student's "t" test showed that there was less than 0.01 probability of

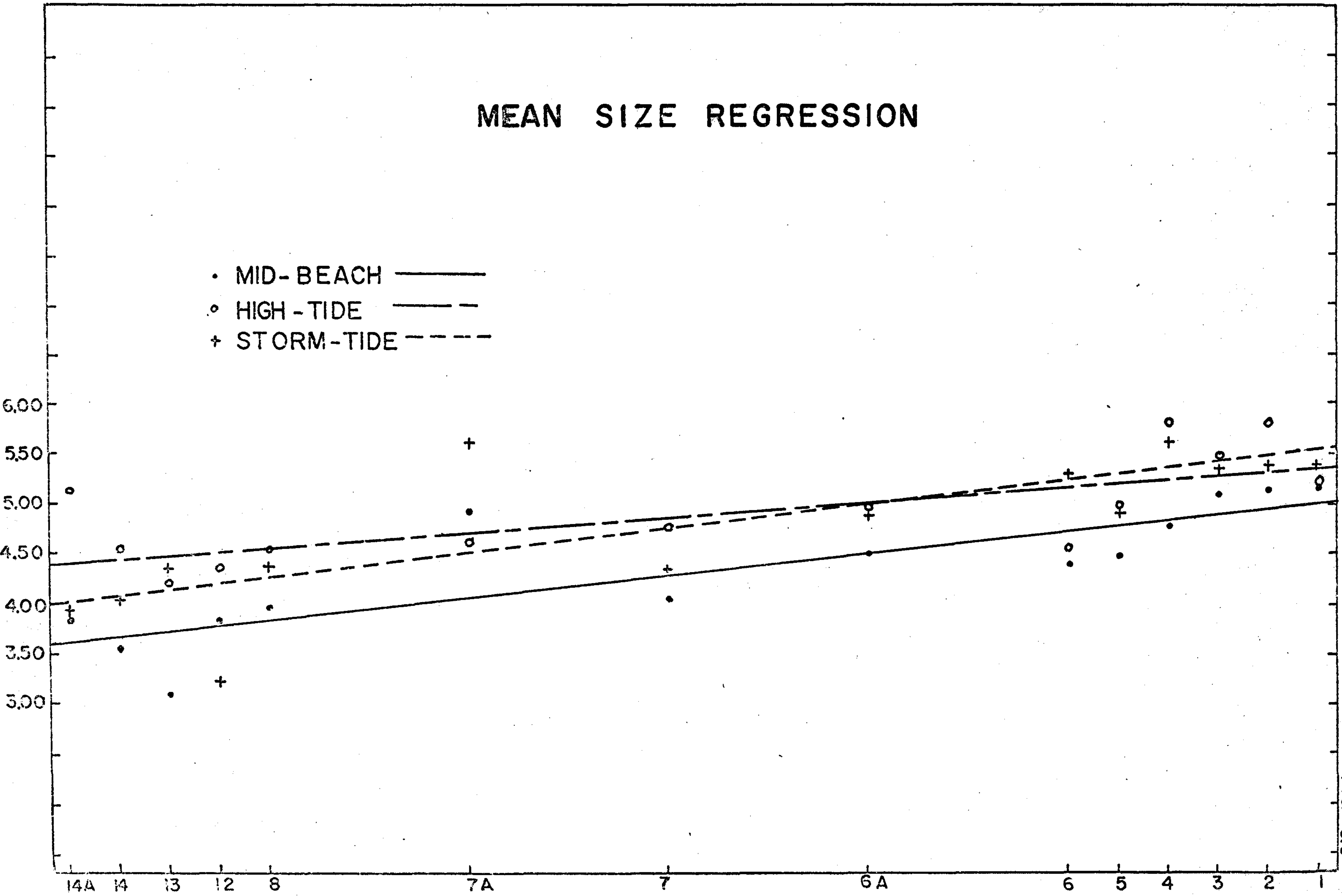

MEAN SIZE REGRESSION
MID-BEACH
HIGH-TIDE
STORM-TIDE
6.00
5.50
5.00
4.50
4.00
3.50
3.00
14A
14
13
12
8
7A
7
6A
6
5
4
3
2
1

FIG. 5.3

error in accepting the alternative hypothesis that the slopes were not equal to zero.

The regression lines of the respective regimes appear to be following similar trends. The high and storm tide height regression lines cross one another at a very acute angle and the mid-tide zone line is nearly parallel to them. The closeness of the slopes of these lines suggested the use of another "t" test to test whether the slopes of these were significantly different. The results of this test showed that the null hypothesis of equivalence of slopes could not be rejected at every 0.99 confidence limits. This means in process terms that the rate of decay of particle size from south to north along the western shore of Radstock Bay was the same for all regimes. This also makes fairly conclusive the notion that the cliff and talus apron complex to the south are indeed the source of material from which these beaches were formed.

Subjectively the distance, particle size,decay function appeared to be best described by a linear function, hence the linear regression was performed. But, in case a power curve or exponential regression curve might have better described the distribution, these types of regression were undertaken. The co-relation coefficients for all three methods for all three regimes were tabulated on Table 5.2. It is observed that the highest co-relation coefficient were invariably calculated for the linear regression. Thus it seemed reasonable to say that the distance decay function of particle size was best described by a linear function.

To test whether a relationship between beach slope and particle size existed, a linear regression was performed. In order to do this a value for slope was determined from the surveyed profiles and was here defined as the tan of the angle between the plane of a section of beach 1.5 meters above and 1.5 meters below the mid-tide line of the beach, and horizontal. The co-relation coefficients calculated between the beach face slope, and the particle size for all three environments were low ($\sim$ 0.20). They were moreover not significantly high enough for 14 data points even at the 0.90 confidence level. This lack of significance was also true for a regression of standard deviation and slope. This is not what was expected and was possibly the result of the narrow range of values encountered in this example. Bascom (1951) working at Half Moon Bay, California plotted values of particle size against beach slope. What he discovered (in the sand range at least) was a limiting "minimum probable slope", but not a discreet function of size and slope. The range of location of his data points, in any small area of his regression, appears to fit into an envelope but are arranged randomly within this envelope. That is, within the range of some mechanical limits the points may vary. With shingle, a different limiting function would be expected. This may be expected to vary with flatness or sphericity or roughness or density or attain variable of the constituent beach material. Within the small range of slopes on Radstock Bay (5° to 11°) only the randomness could be seen. The limiting function was not observed because the range of values of either axis was so small. It is reasonable to expect that had a wider range of slopes and material sizes been included, the data points would have appeared as near random, within definite limits. However, it appears that the beach slope and mean sediment size for all three regimes of this example were not related directly.

The other moment measure about the mean that was useful in

TABLE 5.1

DISTRIBUTION OF STANDARD DEVIATION VALUES

	WELL SORTED < 0.50 Ø	MODERATELY WELL 0.50 Ø-0.70 Ø	MODERATELY 0.70 Ø-1.00 Ø	POORLY > 1.00 Ø
MID TIDE	0	4	7	3
HIGH TIDE	2	4	5	3
STORM TIDE	4	3	2	5
TOTAL	6	11	14	11

describing sediment size distributions was the second, the standard deviation. The distribution of this parameter for all sites appears on Fig. 5.2 next to the distribution of the means of sediment size. A qualitative analysis of this distribution showed it to be a fairly normal distribution withan overall mean of 0.828 (in the moderately sorted range). The values for the means of the second moment measure about the particle size means, for each environment is as follows. The mid-tide 0.810, the high-tide 0.790 and the storm-tide 0.883. All of these values fell in the range of moderately sorted sediment. When all 42 sample standard deviations were counted, they were distributed as seen on Table 5.1.

A "t" test to determine if the means of the sampling distributions of the standard deviations were significantly different were performed. This showed that in no case could the null hypothesis that the means were equalbe rejected at the 0.99 level (or at 0.95 or even 0.60). Obviously the conclusion to be drawn from this is that since the means of the standard deviations of each environment were not significantly different, therefore the sorting of material in each regime was not significantly different.

In order to determine whether this sorting varied systematically along the beach, the standard deviations were plotted against distance (Fig. 5.4). To facilitate observation and help in viewing the trends, the range of standard deviations was traced across the graph. It was noted that the limiting values, both higher and lower, on any profile were from all three regimes with no real consistency as to which was larger or smaller. There appeared no obvious trends other than the fact that at each location the range of standard deviations appeared to be

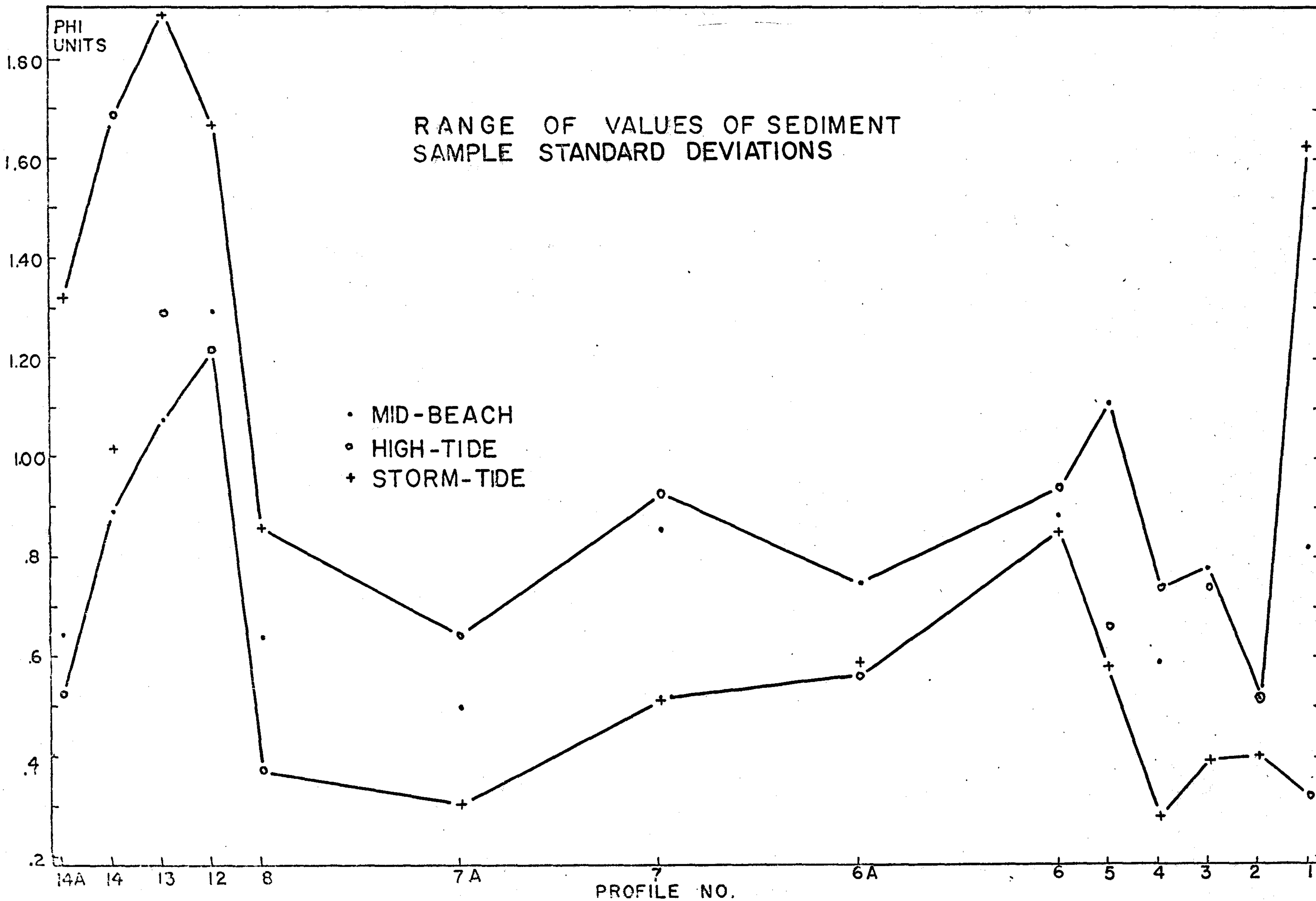

PHI UNITS
1.80
1.60
1.40
1.20
1.00
.8
.6
.4
.2
RANGE OF VALUES OF SEDIMENT SAMPLE STANDARD DEVIATIONS
• MID-BEACH
o HIGH-TIDE
+ STORM-TIDE
14A
14
13
12
8
7A
7
6A
6
5
4
3
2
1
PROFILE NO.

FIG. 5.4

relatively small. That is, if at one site, one of the sample standard deviations was small, there was a high probability that the other two sites on that profile would also be small. To test the significance of this, a Chi-square test was done on all of the distributions. It must be noted that this test technique was employed using actual standard deviation values (hence decimal) and not count data, but this should not invalidate the technique. The calculated X^2 value for the three distriubtions was 2.89. This was far exceeded by the critical value at 0.99 confidence levels. This means that the null hypothesis and the distributions were indistinguishable and could not be rejected. A process conclusion from this would have to be that the sorting value on any one profile for any of the three regimes would be more a function of the location of the profile rather than the location of the regime. It appeared that each profile location had a wave environment (surely the dominant sorting process) which determined the sorting capability of that location for active and rarely active beaches.

A linear regression was performed on these sorting distributions for the mid, high and storm regimes against distance with resultant co-relation coefficients of -0.22, -0.49 and -0.49 respectively. These were not high enough to be significantly different from zero statistically at the 0.99 confidence levels (or 0.95). That means that the sorting did not vary in a linear manner along the beach. In order to see if exponential and power curve regression functions might better have described the distribution, those regressions were performed and co-relation coefficients calculated (Table 5.2). Again it appeared that the linear function best described the standard deviation distribution as well as the distribution

TABLE 5.2

CORRELATION COEFFICIENTS

MEANS

	MID TIDE	HIGH TIDE	STORM TIDE
Linear regression	0.842	0.697	0.787
Power curve regression	0.802	0.523	0.769
Exponential regression	0.803	0.520	0.781

Linear regression for combined data n = 42, r = 0.722

STANDARD DEVIATIONS

	MID TIDE	HIGH TIDE	STORM TIDE
Linear regression	0.23	0.49	0.49
Power curve regression	0.20	0.56	0.31
Exponential regression	0.20	0.43	0.50

Linear regression for combined data n = 42, r = 0.42

of sample means.

As can be seen in Figure 5.4 the range of values of standard deviations are high and rising in the area of profile #14A through profile #12. The values drop markedly to a fairly low level at profile #8 from which they slowly rise along the beach to the north at profile #6. Here again the values diminish from south to north from profile #6 through profile #2. Values for profile #1 appear anomolous. The range of values and lack of a consistent trend along the beach make this distribution markedly different from the distribution of mean sediment size (Fig. 5.3). The conclusion to be drawn from this was that the mean particle size would probably be a function of distance that the material had travelled from what is obviously its source in the south, but the sorting of these same particles was probably a function of the aspect, fetch, local protective surroundings offshore bathymetry, or other parameter for each location. The three sites on any profile varied little in values of either mean size or standard deviation. This infers that present conditions in the active mid-tide zone were in existence when the high and storm tide zones were last influenced. To visually show this, a bivariate plot of standard deviations and mean particle sizes was drawn (Fig. 5.5). It is obvious that the environments for the three regimes were indistinguishable. A full one-third of the data points fell in the intersection of all three zones and a further near one-third were in the intersection of at least two zones.

In order to test whether the slope of the beach was related to the standard deviations of the mean particle size, a regression similar to that done previously for particle size was performed. The co-relation

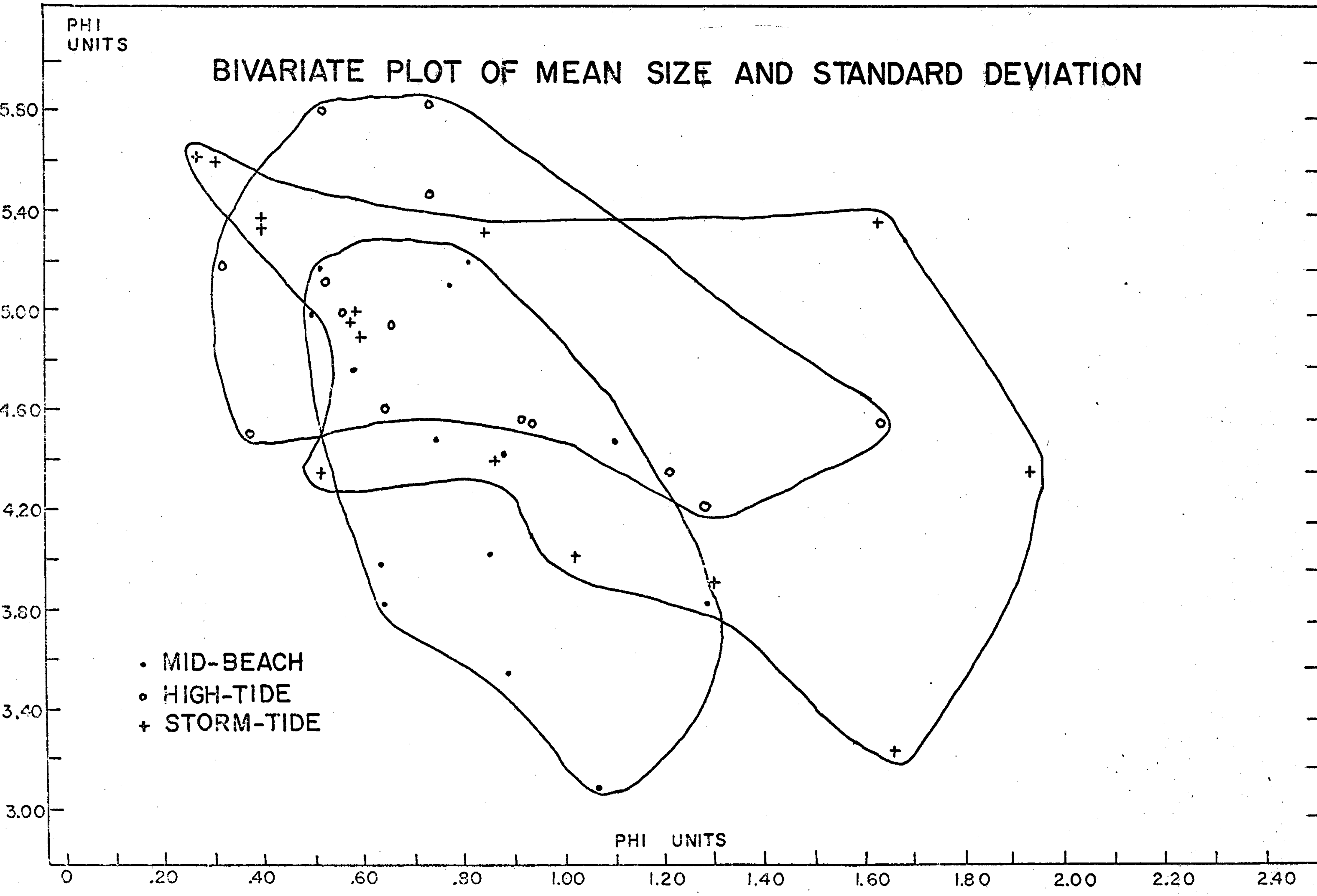

BIVARIATE PLOT OF MEAN SIZE AND STANDARD DEVIATION
PHI UNITS
5.80
5.40
5.00
4.60
4.20
3.80
3.40
3.00
0
.20
.40
.60
.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
PHI UNITS
MID-BEACH
HIGH-TIDE
STORM-TIDE

FIG. 5.5

coefficients for these three environments were so low (< 0.20) that they were not statistically significant (at 0.95 confidence levels).

The conclusions of these investigations are as follows:

1. Sediments along Radstock Bay's western shore fall into the pebble range and are moderately sorted.

2. The sediments systematically and significantly diminished in size from south to north.

3. The sorting along the beach appeared to be of a function of local fetch, local aspect and bathymetry or other local factors, rather than the distance from the source areas.

4. The slope of the beach, at least in the narrow band of sediment sizes found here, did not appear to be a function of mean sediment size or mean sorting values.

5. The sediment in the storm high and mid-tide zones did not appear to indicate distinct environments, but rather were indistinguishable and the result of the same processes and/or the same process rates.

CHAPTER VI

OPEN WATER CONDITIONS AND FREEZE-UP SEQUENCE

INTRODUCTION

This chapter deals with open water conditions, including two important geomorphic events, and the subsequent freeze-up sequence on Radstock Bay as observed during the late field season of 1971. Obviously a full seasons observations from winter conditions through to the freeze-up during one year would have been ideal, but this was impossible for financial reasons. Instead, the 1970 field season included the times of break-up and the early few days of open water conditions. August 20, 1971, one year to the day from the date of departure from the field in 1970, marked the date of the first observations of open water conditions.

It is important to learn about the characteristics of the beaches during the short open water season because, as previously stated, waves are still the dominant process agent affecting arctic beaches.

OPEN WATER CONDITIONS

Observation of the beaches of Radstock Bay during the latter part of the open water season of 1971 consisted basically of the precise levelling of the profiles (the previously described 14 profiles) on six occasions and careful note taking. All wind speeds and directions were estimated and later compared to the windspeeds for Resolute Bay. Also two sets of marked pebbles were placed in the mobile sediment system and retrieved at a later date. This chapter commences with a discussion of the general characteristics of this beach as it changed under the affects of waves and tides. This is followed by a description of what happened during the autumn of 1971, from August 20 until October 8, especially during the days of strong winds and large waves. This incorporates a discussion of the profile changes as revealed in the surveys and in a discussion of alongshore sediment transport as revealed in the marked pebble experiments. The chapter concludes with a documentation of the freeze-up sequence as observed in 1971 on Radstock Bay.

The essential fact about shingle beaches in areas like this study area, is that they change constantly during open water conditions under the influence of waves and tides. Basically of course it is the waves that affect change or transport on a beach, but the tides are a control upon the level or height on the shore along which waves can work. It is essential then to understand the tides before one can fully know the characteristics of a beach. Tides of this area of the Arctic are mixed semidiurnal with inequalities in both maximum height and times of apogee and perogee. This means that the tides reach a zenith twice a day, but the maximum are of differing magnitudes. The range of amplitides of tides in this area is approximately 2.5 meters, varying of course throughout the year, and through the month.

As a tide approaches its zenith, the rate of rise of the water level diminishes until it reaches zero at the crest of the high tide. Similarly the rate at which the water level drops from its maximum increases until mid-tide, whereupon the rate begins to diminish until at the minimum level it has reached zero. The curve that describes this function is a simple sin curve.

Under low energy conditions, this characteristic change in water levels causes a characteristic beach face ridge system. Generally the system appears to have a small beach ridge formed immediately above the water level in the early stages of an advancing tide. As the tide rises, the small ridge, often only 0.1 of a meter high, will be pushed up slope. As the tide begins to recede again, the small ridge will remain intact, abandoned. When the tide is dropping there is only the opportunity for small micro relief ridges because the tide level changes are most rapid around the mid-tide level and there is no opportunity for the accumulation of debris being pushed up slope that there is on a rising tide. When the tide approaches low water mark and the rate of change of water level diminishes and stops, there is time for the formation of a small ridge. If the wave action on that particular day is moderately strong, this lower ridge will be removed by waves. If the waves are very small, this ridge will remain. If the rising tide in any instance is a lower high tide, the previous high tide must have been a higher high tide. In these cases the higher high tide ridge will remain untouched by the formation of the lower one. When the situations are reversed, and the larger high tide follows the smaller one, most often the lower high tide ridge will become incorporated into the higher tidal ridge. After the retreat of the tide in the former case two ridges will be visible, representing higher high tide conditions and lower high tide conditions. In the second instance the retreat of the tides will reveal only one ridge representing higher high tide conditions. It is reiterated that in all cases it is the waves that do all of the work, and the tides merely control the plane through which the work is carried out.

All of the above occurs simply as described only with waves of approximately the same small height and length. During periods of large waves over high tides, shingle will be thrown up beyond normal active beach levels. Also the phenomenon of storm surge, or the piling up of water by the wind during storms to cause abnormally high tides will be superimposed on the larger wave system. Even more basically, waves of different periods and steepnesses will tend to cause differing beach slope relationships and therefore differing beach ridge configurations. It is known for example that very steep waves tend to be destructive, combing down beaches while less steep waves tend to be constructive generally. Even these generalizations are oversimplifications of very complex relationships not fully understood.

Another subjective observation of the Radstock Bay beaches concerns the sorting of the beach material. It appeared that the beach face was better sorted immediately following a storm, than at any other time. After a storm, often there was a wide planar beach face with well sorted sediments on the surface. As subsequent tides rise and fall over this beach face, they cause ridges to form, superimposing sorting characteristics that relate to the lower energy regime. These low energy ridges most often are not as well sorted as high energy systems observed on Radstock Bay.

In any case it is obvious from the preceding discussion that the beaches of Radstock Bay, during open water conditions constantly undergo a complex system of changes. This will be discussed again later in this chapter.

It is agreed by most authorities that the infrequent events that are of high magnitude do more work than more frequent low magnitude events. For example, Hume and Schalk (1967) point out that one storm at Pt. Barrow caused a transport of sediment that exceeded the net sediment transport of the entire remainder of the year. It appears that the beaches of Radstock Bay are in a state of equilibrium that consists of constant change within certain limits that correspond to and are in response to energy inputs. For this reason the monitoring of storm events during open water periods is an important way of gaining an insight into the amplitudes of this system.

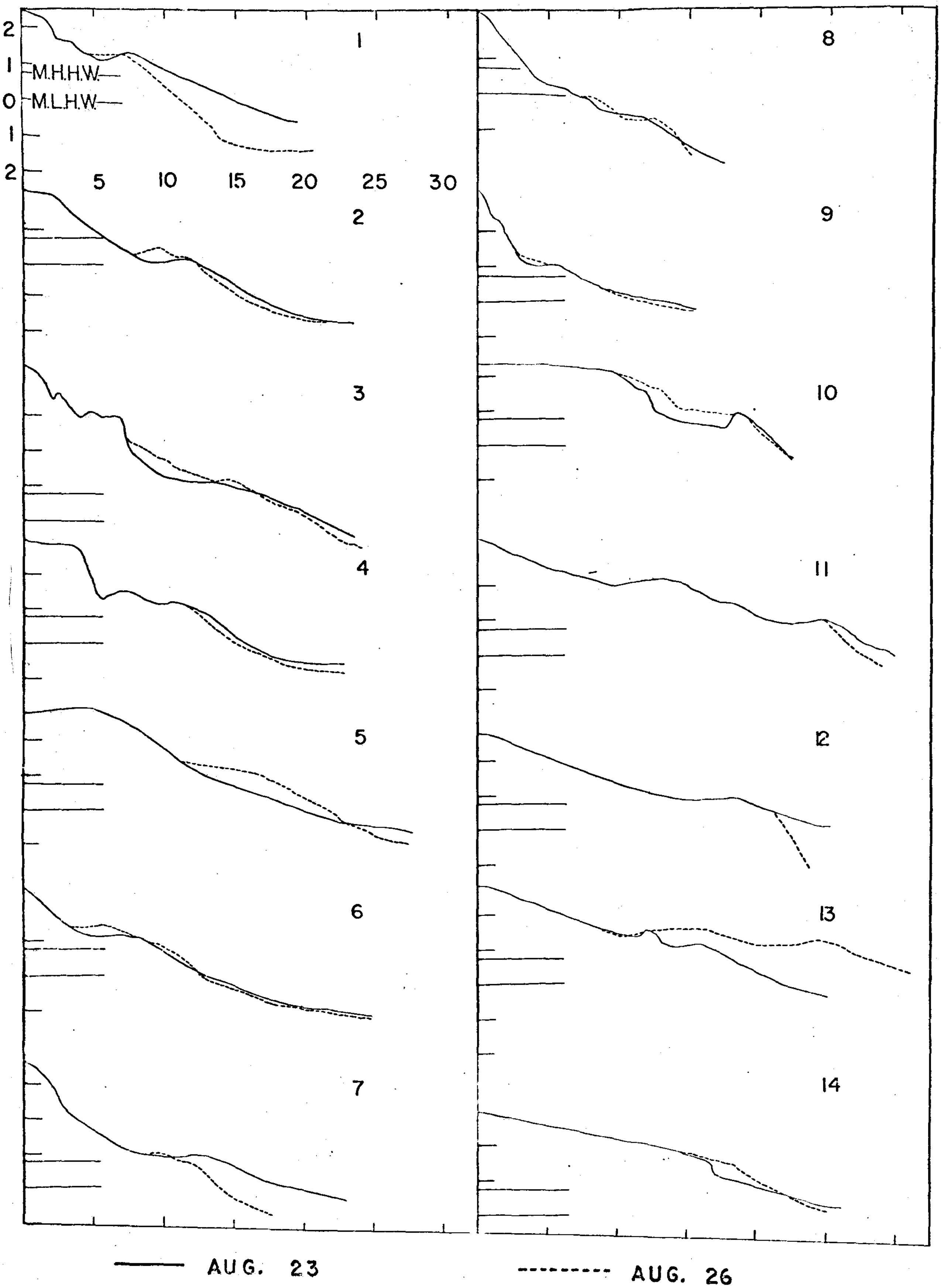
The first 3 days of observations August 20, 21 and 22 saw winds slowly rising from almost calm to moderate. The winds recorded at Resolute Bay had daily mean values of 3.4 m.p.h., 12.1 m.p.h. and 16.1 m.p.h. in a month (August) with a mean velocity of 14.5 m.p.h. The entire Radstock Bay at this time was free of ice. During the late hours of August 22 the winds speed began to rise from the southeast to the mid 20's (23 m.p.h. in Resolute). The speeds continued to rise during the morning of August 23, but with this change came a large amount of pace ice with up to five-tenths cover that lay alongshore in a band 20 meters to 100 meters wide by 1300 hours. For the rest of that day the winds blew in an estimated range of 35 to 40 m.p.h. (corroborated by the data from Resolute Bay where the daily mean for August 23 was 35.5 m.p.h.). These winds blowing over the long fetch to the southeast that was at that time virtually free of ice generated fairly large waves approximately 1.0 to 1.5 meters in height and 6.0 seconds in period. In spite of this large input of energy, virtually no waves reached shore because of the barrier of pack ice. By

2300 hours of August 23, much of the barrier ice had been pounded into brash and/or ablated but it appeared that the winds were diminishing to the mid 20's (this is not seen in the hourly wind speed values for Resolute but is entirely feasible considering the 125 kilometer distance between Radstock Bay and Resolute, plus the differences in local topography). By 1100 of August 24 over 50% of the beach was ice free and most of brash had been thrown up beyond normal high tide levels on the overnight high tide whereupon it was buried partially in shingle. By 1300 most of the remaining ice had shifted further up into the Bay to leave the shore mostly open to wave action. The winds during the day for the most part were estimated to be in the upper 30's and lower 40's (Resolutes daily mean velocity was 36.8 m.p.h.) diminishing in the late afternoon and evening. At Cape Liddon, an area open to the most direct assaults of the waves had some talus undercutting, and everywhere it was obvious that sediment was rapidly moving alongshore from south to north.

The beaches were profiled during the days of August 23 and August 26. These profiles are reproduced in Figure 6.1. The profiles surveyed on August 23 in most cases reveal a fairly smooth beach face slope, resulting from the erosion of previous small ridges by the rising waves immediately prior to the entrance of the ice into the Bay. The profiles surveyed on August 26 show a different but characteristic form. In 11 cases of the 14, there is deposition up on the upper portions of the slope and in 12 of the 14 cases there is erosion downslope. The lower zone of erosion appeared to the observer in the field to be the upper part of a general flattening or diminishing of beach face slope, the lower part of which could not be surveyed as it was submerged. The upper

FIG. 6.1

COMPARISON OF PROFILES AUGUST 23 - 26



zone of deposition is the result of shingle and brash ice being thrown up at the height of the storm. It is obvious that there are considerable differences from place to place as would be expected in a system of net transport in one direction. There are locations where erosion has taken place to such an extent that the surface of the beach face on August 26 was over one meter lower than on August 23 (profile #1). The opposite is true for other locations (profile #13).

It is interesting to note that for several hours a quantity of ice alongshore in places only 20 meters wide, was enough to virtually eliminate wave action. It is also interesting to note that in slightly over 24 hours the bulk of that ice (mostly first year ice) had been ablated. This adds strength to the notion that sea water is the major agent of ablation sea ice.

During the time from the cessation of the storm on the evening of August 24 until early on the morning of September 9, the winds were for the most part from the north, northeast or northwest octants, and varied in speed from calm to approximately 15 m.p.h. This time was one of low wave energy and correspondingly little change. It was during this time that an experiment was undertaken to mark pebbles to gain some simple idea of sediment transport characteristics and capabilities. A careful search of the area near profiles #1 through #6 revealed only 2 pebbles that had previously been painted for a similar experiment during 1970. Both were along profile #4, the point of their injection into the active beach zone but they were both well above the zone of normal active sediment. On August 26 at 1160 hours, 300 pebbles painted bright red (a different colour to the pebbles of 1970) were placed at the estimated mid-tide level at a time when the tide had just passed a low water level and was commencing to rise. These were placed along in a line one meter long perpendicular to the shoreline on the shallow sloping beach face slope. The pebbles were left to be moved by the small waves from the north for 6 days (or 12 tides) until September 1. The retrieval took the form of a careful search and gave a recovery rate of slightly more than 5%. The maximum distance travelled by only one of the recovered pebbles was about 170 meters to the south. There was no real pattern to the distribution of the pebbles, but rather they were randomly distributed between the injection point and the point to the south attained by the furthest moved pebble. There were no pebbles found beyond the injection point to the north. This demonstrates the obvious notion that waves from the north will cause a sediment transport towards the south. The fact that the 16 recovered pebbles were found over the short 170 meter long range in a rather random pattern probably means that the bulk of the pebbles were buried, and not lost out of either end of the search area.

The second experiment with coloured pebbles was performed under much different wave conditions. In this case the large waves were from the south as will be described later. On September 10 at 1030 hours 300 pebbles were placed on the estimated mid-tide mark and as in the previous experiment the tide was at the low water mark. Unlike the previous experiment the estimated height of the waves was approximately 1.0 meters with some of 1.5 meters observed later in the day. The large waves, from the south this time, subsided during the evening and morning of September 10-September 11 after two high tides had elapsed. The recovery rate for the stones injected into the sediment transport system September 10 was

7 out of 300, or just over 2%. These were found 70, 155, 200, 228, 235, 245 and 450 meters down range towards the north. It is interesting that 5 of the 7 pebbles recovered had travelled further over the 2 tides with large waves driving them, than the furthest moved pebble of the first experiment which moved through 12 tides with much smaller waves driving it.

Also, on September 11 five pebbles from the August 26 injection were found along the range, rather evenly spaced. There were none of these found south of the injection point. 3 pebbles from the batch that were employed in the 1970 experiment were also discovered along the beach. It seems clear that the obvious response to waves out of the south is sediment net transport to the north. The fact that one storm of one days duration could reverse the net sediment transport of 16 days of continuous waves from the opposite direction clearly shows the importance of the higher magnitude event. The fact that more marked pebbles were discovered that belonged to the two previous experiments, 16 days and over one year earlier, shows that over the past year there has been net sediment transport towards the north, but this has not been very marked. This is revealed in the fact that 450 meters was the maximum distance alongshore that any pebbles moved. The spit-like configuration of portions of the raised beaches, and the overwhelming importance of the southeast as a major fetch makes net sediment transport from south to north the expected condition. Though this is borne out by the tracer study, the magnitude of the transport is smaller than would have been expected. This leads again to the notion that the really large magnitude low frequency event not observed in 1971 is of paramount importance in the transport of beach sediments.

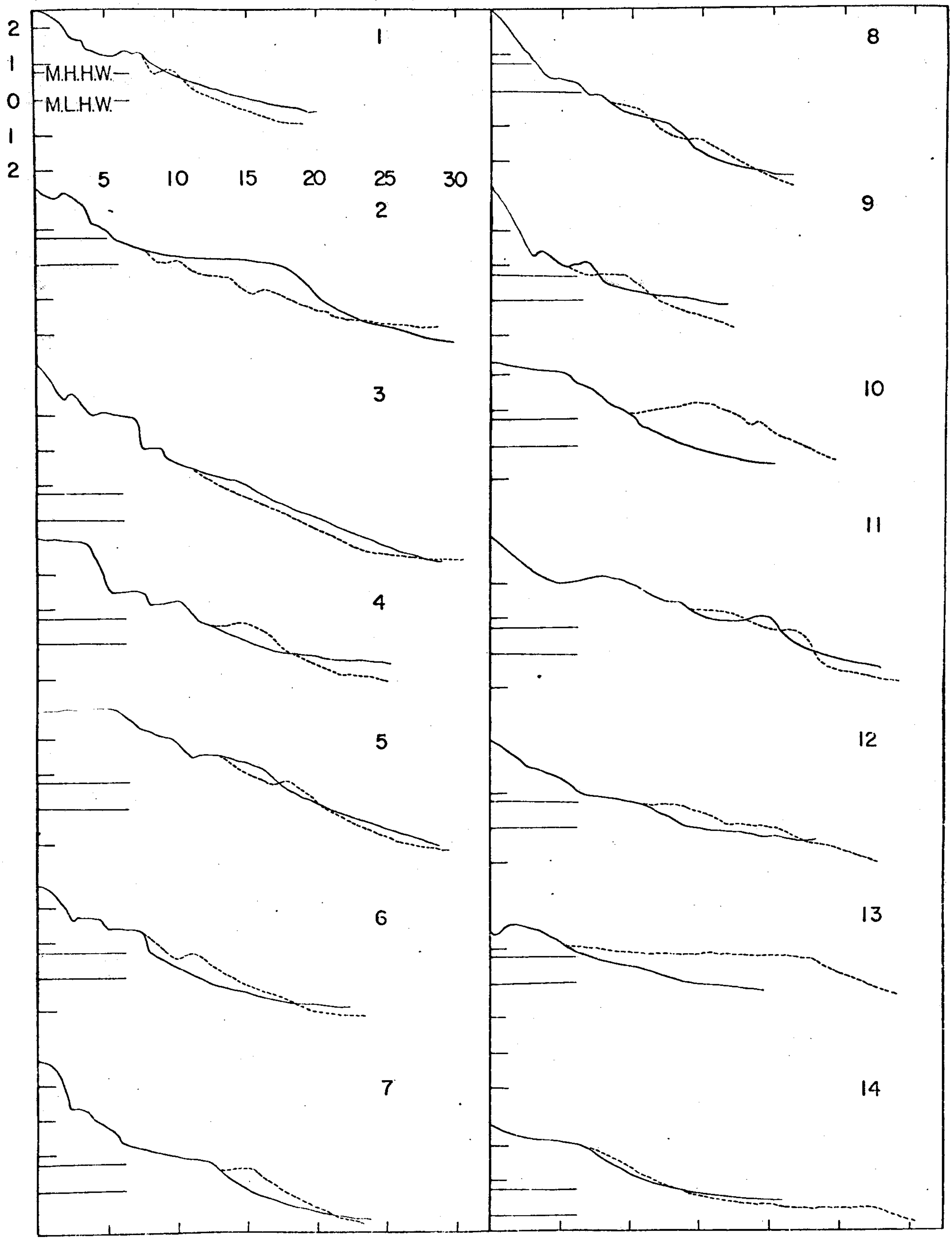
The southerly and easterly winds of September 9 marked the first departure from northerly winds since August 24. These winds were for the most part only 5 to 10 m.p.h. Through the early morning hours of September 10 the wind speed at Resolute Bay increased from about 25 m.p.h. at 0000 hours to 32 m.p.h. at 0600 hours. During the rest of the day it varied between a low of 27 m.p.h. and a gust of 41 m.p.h., all out of the S.E. This seems to relate quite well to the estimated wind speeds and direction observed on Radstock Bay for this date. These winds drove up waves that appeared to be between 0.75 meters and 1.0 meters in height. The period measured for them varied between 4.0 and 6.0 seconds. The longer wave periods were observed, as expected, later in the afternoon. Winds diminished steadily during the morning of September 11 from 27 m.p.h. at midnight until by 1600 the speed was 14 m.p.h. The wave height diminished steadily through this time too, but not as rapidly as the wind.

The profiles were surveyed on the morning and early afternoon of September 10. Because of the cold and strong wind most of the lower portion of the beach face slope could not be surveyed for fear of getting wet and suffering from exposure. This makes the profiles a less useful device for studying changes in beach face form, but it still is the best method of accurately recording across beach shape. In spite of this disadvantage, the shape of the beach face of September 10 is quite clear as revealed in Figure 6.2. In each case the beach face slope is very smooth and slightly concave.

The next time the profiles were surveyed was September 14. During the intervening days between surveys, the wind had diminished in speed but remained out of the south for 2 days, and then shifted to north at 5 to 15 m.p.h. the last 2 days. These profiles appear to be much more

FIG. 6.2

COMPARISON OF PROFILES SEPTEMBER 10 - 14



SEPT 10 ——— SEPT 14 - - - - -

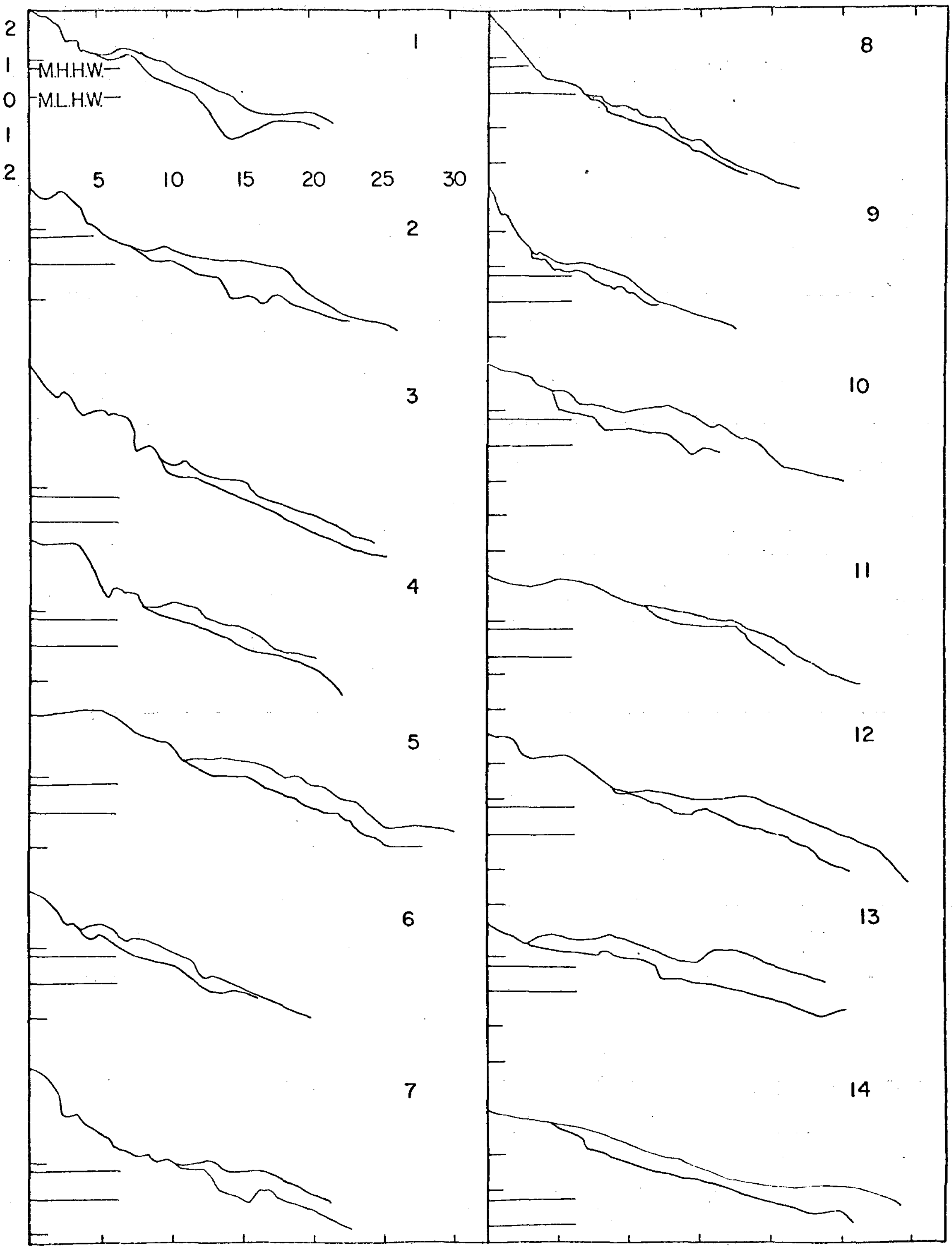
undulating and uneven. Clearly this is a result of the formation of small ridges by the smaller waves, over the 8 or so tides that elapsed between survey dates.

Apart from the individual interpretations of each profile not too much can be said about the changes. Most profiles reveal an erosion in the lower parts of the beach face. In some places, notably profiles #6, #7, #10, #12 and #13, there has been a marked deposition mostly above the high tide level. This is probably shingle thrown up on September 10 subsequent to the surveying, as this was the only time where waves were large enough to move debris any distance above high tide levels. Also clear on all profiles except #3, #7, #13 and #14 is a small ridge at about mean higher high tide level. This is probably a ridge formed subsequent to the storm on a later high tide. Generally the profiles reveal a combination of erosion on the lower parts of the slope as the shingle is combed down, and a ridge on the upper portion resulting from shingle thrown up. It is noted that since the lower portions of the beach were not accessible to survey, the shape of the rest of the slope that had been combed down, could not be decerned. Superimposed on this is a more recent smaller high tide ridge.

In the earlier discussion of the general characteristics of these beaches mention was made that the normal condition was one of change. In order to ascertain an idea of the variability of this change,the highest points on all of the profiles were joined by a curve (Fig. 6.3). Similarly all of the lowest points are joined. The area between these two curves has been described by King (1959, p. 199) as follows, "The zone between the two curves may be termed the 'sweep' zone, and may be defined as

FIG. 6.3

SWEEP ZONES 1971



that portion of the vertical plane perpendicular to the coastline within which movement of material may take place by wave action". Clearly, the longer the time over which profiles have been taken regularly, the more representative will be the 'sweep' zone of the limits of the change in beach shape. More correctly, the construction of a 'sweep' zone shows the zone in which movement of beach material has taken place rather than the zone in which movement may take place. In this example the sweep zone of Figure 6.3 represents the limits of movement of beach material on Radstock Bay over the open water season of 1971. This season had two major events but the winds generally did not exceed force 8 or force 9 on the Beaufort Scale (force 8 is 35 m.p.h.). During the summer of 1969 (August 11-12) S. B. McCann documented a storm event in which wave heights reached 1.3 m, (McCann 1972). This storm strength he points out could be expected to obtain at least once per year during July, August or September, and further it could be expected to coincide with open water conditions in one out of two years. Thus we see that the events of 1971 are by no means extraordinary. The sweep zone of Figure 6.3 then cannot take into account the high magnitude event which could severely alter beach morphology, but is a good indicator of normal conditions. Under 1971 conditions the mean maximum vertical extent of sweep zone was 0.677 meters and the standard deviation was 0.10. Thus, for this beach any movement of beach materials, either erosion or deposition which results in less than this 0.677 meters of profile change can be regarded as normal.

FREEZE-UP SEQUENCE

The process by which the sea ice and ground ice form during the autumn is one of continued outgoing radiation by the water with diminishing incoming radiation. Also there is cooling by conduction through contact with the air which is cooling in the fall and cooling by the loss of latent heat when snow lands in the water and melts. It must again be noted that seawater is saline and therefore freezes at a colder temperature than freshwater.

When observations commenced August 20, 1971, the seawater was ice-free and the air temperature was in the mid 40's F. The sun was above the horizon for approximately 22 hours a day and there was zero snow cover. There was some precipitation previous to August 30 but it was all in the form of rain or mist. On August 30 snow fell for the first time and by 1500 had covered 95% of the ground surface. The snow stayed on the ground from that day on and will probably stay until the summer of 1972. Where the winds had blown the snow on the inter-tidal zone, and the rising tide had inundated it, the snow completely melted. At the high tide level, a zone of slush formed, but never did it freeze. This phenomenon repeated itself many times between the first snow and September 4 when the slush was observed frozen at night. The air temperature dropped below 32°F on September 2, but the salt content of the slush prevented it from freezing until the temperature dropped further. Also, on September 4, the creeks of the area had all ceased to flow and all but the one largest lake had frozen over.

The first ice seen on the beach face was observed at 1600 hours September 6 at Walrus Point in a location that was shaded nearly all day long. This took the form of a surface layer of soft ice surrounding the surface pebbles on the active beach. By 2100 on the same day it was observed on Radstock Bay. September 7 saw the rising tide melt this surface layer of ice completely, but the frozen slush at the high tide level remained.

September 9 was a very warm day (36°F) and this caused the slush, and much of the snow immediately above the high tide level to melt and drain away. September 10 saw much sediment movement with large waves. This succeeded in eroding the zone of the beach where some brash had previously been buried. The high air temperatures of September 11 ablated these pieces of bash leaving the beach free of ice. September 12 was very cold again (mid twenties) and saw a recurrance of the pebbles of the active beach freezing at the surface. This recurred nightly for the next week, but nowhere did the sea water freeze on the surface. During the day of September 19 it was very cold (17°F) and snowing. This had occurred on other dates earlier but this time the snow did not melt when it landed in the sea. Clearly the sea temperature was between the freezing points of seawater and freshwater. In some areas, notably in Gascoyne Inlet the wind drove the surface slush, as the unmelted snow soon became, into the shore where it collected. As the tide dropped this slush was washed ashore, stranded and frozen into an incipient ice foot. On Radstock Bay the snow did not melt either but the wind from the northwest was blowing offshore. The next few days saw the consolidation of this incipient ice foot by seaward surface refreezing and beach face freezing. During these days wave action was insignificant and the temperature in the lower 20's and below. September 22 for the first time ice was observed on the sea-ice in the form of thin sheets of a type of hard slush, the characteristic texture of freezing seawater. Also at this time the incipient ice foot was observed submerged at high tide in places, but it was not being ablated. Generally by now the surface freezing of the beach face extended down to a few centimeters from the low water mark when the tide had dropped. This frozen state of the surface of the beach face was not substantial enough to restrict in any significant way the movement of beach sediments when the wave heights exceeded 0.2 m.

On September 23 strong winds (20-25k) combined with open seas and relatively warm temperatures 28°-30°F succeeded in completely overruning and ablating the incipient ice foot formation of the previous few days. Also some shingle and kelp was thrown up over the drift snow above normal higher high water mark. This change in the freezing pattern however was shortlived for on the next day the slush was refrozen into an incipient ice foot and the beach face surface began again to freeze during times of low water. From September 24 until September 30 it did not snow, therefore there was little slush available to augment the rampart on the beach, but the surface of the beach froze regularly on each low tide. September 29 saw some pack ice enter the western side of Radstock Bay and come aground in a band 10 to 50 meters wide along the entire shore. September 30 saw large waves, sometimes up to 1.5 meters high or higher but this didn't affect the sediments of the beach because of the protecting effect of the pack of ice described previously. Instead the pack ice was attacked and in many cases broken down into brash that was pushed on shore by the wind and weak waves that could penetrate the ice barrier. In places this ice and spray froze _in situ_, only to be overridden by later high tides laden with brash. By early October when the wind and waves had subsided, the frozen brash had formed a rampart 0.3 to 0.4 meters high on the beach face, with the same characteristic shape as the ice foot. Offshore there was a zone grounded growlers and bergy-bits with some floating brash in the still water between them.

The final freezing that appeared to lock the beach for the rest of the season seemed to follow a dramatic drop in temperature on October 2 when the temperature dropped to around 0°F at 1800 hours. The morning of October 3 saw over 50% of the surface of Radstock Bay frozen over. Along shore this was observed to be 1 or 2 cm thick. The weather continued to be very cold until the day that the party left the field October 7. Throughout the remaining days the ice on the Bay thickened and covered a greater area. October 4 saw it covering 90% of the surface with a thickness of 2.5 to 4.0 cm. By October 6 over 95% of Radstock Bay was frozen. Along shore the ice was 7.5 cm thick and the sediment of the beach was covered in a rampart of ice 0.2 to 0.4 m thick. It appeared that unless a very large storm,larger than any observed during 1971, hit the area, the sediments of the beach would be immobile probably until sometime after early July 1972.

Generally there seems to be a system of freeze-up that follows a simple pattern of events. There is a period where the sea water temperature drops, but there is no freezing. During this time the air temperature is generally below the freezing point and freshwater sources freeze. If snow falls during this period it will be melted on the beach face by the seawater but sometimes it will freeze above the high tide mark. A period follows this when the snow that falls will not melt in the sea water, and the beach face begins to freeze, first at night only, then later any time when the tide falls. The specific date on which the sea water reaches its freezing point may vary greatly from year to year, but when that day arrives, the surface of the sea will freeze over rapidly, increasing in thickness rapidly as long as the temperatures remain low enough. Anytime during this systematic freeze-up, a storm event may occur, agitating the water and bringing the warmer subsurface water upwards. Waves breaking on shore then can ablate any ice frozen to the sediment both by physical removal and by melting. After a storm the pattern of events quickly carried on until the surface is frozen thickly enough to resist all further winds. From this point onwards the sea ice will grow thicker _in situ_, incorporating all residual pack ice, and the ice foot can for some time continue to grow as, being incremented with water on successive high tides.

CHAPTER VII

CONCLUSIONS

There are basically 2 methods of studying an arctic beach. First, one can use secondary and remotely sensed data. This method which has been utilized in Chapter 2, made use of the ice reconnaissance maps but has some severe drawbacks. Primarily, the data collected by any agency is collected for a purpose that is often not related to the purpose the researcher has. The reconnaissance maps, for instance, were compiled as a navigational aid and therefore often do not indicate ice cover over inshore areas. More fundamentally, in the Arctic, reliable data from secondary sources is relatively scarce because of the vastness of the area and the scarcity of people. The second method entails going into the field and making both qualitative and quantitative observations of beach form, beach changes and some of the processes operating on the beaches. The major measuring technique utilized during 1970 and 1971 was the surveying of profiles by the use of the precise levelling method. This was a time consuming task, taking many days, but proved to be the most accurate and efficient method of measuring the form and form changes of the beaches. During conditions of fast ice cover on Radstock Bay it was possible to level in the bottom of the inshore zone and measure the sea ice thickness. This method was also the major tool utilized to study the ice foot, a feature often recorded along Arctic coastlines. Another well tried and indispensable technique used was that of sediment size analysis. Because of costs of transport, all of samples had to be seived in the field. The technique of dye tracing currents is simple and effective as is the emplacement and tracing of marked pebbles to determine the direction of movement of beach sediment.

All of the above methods have proved suitable to study the beaches of Radstock Bay. More sophisticated analyses which are utilized on lower latitude beaches cannot be employed in the Arctic because of the very large physical problems. The use of a small boat, for instance, for inshore work is virtually out of the question because of the dangers of ice, and the complete lack of search and rescue facilities.

The data gathered throughout the field seasons of 1970 and 1971 have yielded some very interesting results. The reconnaissance of the ice conditions of the southern Queen Elizabeth Islands revealed the differences in length of open water season to be expected, both from place to place, and from year to year. The documentation of the break-up on Radstock Bay during 1970 revealed the systematic nature of ablation and the suddenness of the evacuation of ice, contingent upon wind and weather conditions. The analysis of the ice foot exposed a strong relationship of increasing ice foot magnitude with decreasing beach face slope. A trend of diminishing mean particle size from south to north was the major result found in the sediment analysis. This is compatible with the spit-like configuration of the beaches which points to net south to north sediment transport and therefore, because the beach is composed basically of pebbles, the diminution of mean grain size. The observation of the open water season of 1971 revealed a trend of erosion downslope with a shingle ridge thrown up often above the high tide level during storms. It also showed the inhibiting potential that a relatively small amount of pack ice along shore has over wave action. A sweep zone, recording the limits of sediment movement on the beaches, was constructed and showed a zone of movement in most cases exceeding 0.5 m vertically. Finally, the documentation of the freeze-up of 1971 on Radstock Bay saw a regular sequence of events that could easily be broken by the advent of a storm event.

Future analysis of the beach environment, carried out in the Arctic could do well to utilize some of the methods outlined in the thesis in other areas of the Archipelago. It is the opinion of the author that more research of a reconnaissance nature needs to be done in many different locations in the Arctic, in order to gain a general basic knowledge of the different types of beaches and their different environments before any really intensive work is carried out again at one particular locale.

APPENDIX I

PROFILE DATES

1970

June 22	12,13,14 Reconnaissance and bench mark establishment
June 26	4,5,6 " " " " "
June 30	10 " " " " "
July 2-3	4,5,6,7,8,9,10,11,12,13,14
July 8	4,5,6,7,8,9,10,11,12,13,14
July 13	1,2,3,4,5,6,7,8,9,10,11,12,13,14
July 19	1,2,3,4,5,6
Aug. 8	4,5,6,7,8,9,10,11,12,13,14
Aug. 12	1,2,3
Aug. 15	1,2,3,4,5,6,7,8,9,10,11,12,13,14

1971

Aug. 23	1,2,3,4,5,6,7,8,9,10,11,12,13,14
Aug. 26	1,2,3,4,5,6,7,8,9,10,11,12,13,14
Sept. 10	1,2,3,4,5,6,7,8,9,10,11,12,13,14
Sept. 14	1,2,3,4,5,6,7,8,9,10,11,12,13,14
Sept. 23	1,2,3,4,5,6
Sept. 24	7,8,9,10,11,12,13,14
Oct. 1	1,2,3,4,5,6
Oct. 3	7,8,9,10,11,12,13,14

APPENDIX II

ICE FOOT

BEACH SLOPE IN DEGREES	ICE FOOT THICKNESS IN METERS	ICE FOOT WIDTH IN METERS
9.95	1.69	14.55
10.75	2.09*	13.70
7.99	2.10	18.40
8.54	2.98*	16.25
9.58	1.39	9.05
7.28	2.35	14.85
7.07	2.42	15.25
8.01	2.13	16.10
9.62	1.77	13.50
7.28	2.35	17.10
5.86	2.92	18.50
7.53	2.27	19.10
7.07	2.42	19.10
8.25	2.07	21.80

*These values were the ones that were removed for the second regression N = 12.

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