Environmental Assessment of the Alaskan Continental Shelf

Interim Synthesis: Beaufort/Chukchi

August 1978

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

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OUTER

CONTINENTAL

SHELF

ENVIRONMENTAL

ASSESSMENT

PROGRAM

INTERIM SYNTHESIS REPORT: BEAUFORT/CHUKCHI

PREPARED UNDER SUPERVISION OF

THE ARCTIC PROJECT OFFICE

AUGUST 1978

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

ENVIRONMENTAL RESEARCH LABORATORIES

Boulder, Colorado 80303

Foreword

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) has as its underlying objective the protection of the Alaskan environment compatible with the oil and gas development essential to our country's needs. Four types of information are needed to meet this objective:

1) Location of the critical wildlife habitats that must be protected.
2) Prediction of the effects from any release of oil or from other insult.
3) Identification and development of new monitoring techniques.
4) Definition of stresses that the environment places on man-made structures, to reduce the number of incidents affecting pollution or safety.

The Alaskan program, managed by the National Oceanic and Atmospheric Administration (NOAA), is systemically developing all four classes of information in each of nine areas proposed for leasing in the Alaskan OCS under sponsorship of the Bureau of Land Management (BLM) and NOAA. This effort is described in OCSEAP's Program Development Plan, Technical Development Plans, and in the many reports generated by the program. They are available from the OCSEAP Editor, Rx4, NOAA, Boulder, CO 80303 or from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

A major part of the OCSEAP effort involves "synthesis" of information pertinent to OCS decisions and presentation of it in reports of maximum usefulness to decision makers. It is OCSEAP policy to distribute information as quickly as possible. Successive synthesis reports will update preceding "interim" syntheses for each lease area by incorporating the new findings from ongoing studies. OCSEAP's methods of achieving such synthesis and specialized reports are still experimental. Clearly, the research scientists must be involved in the effort, but an external impetus of some kind is needed to facilitate "synthesis" by bringing people together from many disciplines, to generate and then to publish the final document. The Arctic Project Office of OCSEAP (see Preface) has provided the leadership and climate to achieve this synthesis document for the Beaufort Sea; final editing and publication were accomplished by the OCSEAP office in Boulder.

The reader should recognize that this is a report from the scientists; it does not necessarily represent BLM, NOAA, OCSEAP or other governmental positions on any issue. For a given area, it presents in one document the bulk of the Beaufort Sea environmental information needed for decision making. Publication has been scheduled so as to make this document available for wide distribution well in advance of the joint State-Federal Beaufort Sea Sale pending for December 1979.

OCSEAP is pleased to provide this report to potential users and also to provide the most direct avenue possible between scientists and decision makers.

Rudolf J. Engelmann
Director, OCSEAP

September 1978

Preface

On 7-11 February 1977, OCSEAP investigators and other invited scientists working in the Arctic met with BLM and NOAA management personnel at the Naval Arctic Research Laboratory, Barrow, Alaska. The purpose of the meeting was to "synthesize" knowledge of the Beaufort Sea as it relates to the proposed leasing of the outer continental shelf, to assess the likely impacts of petroleum development of the shelf, and to review the adequacy of ongoing OCSEAP studies addressing these impacts. The Chukchi Sea was also discussed, but only where biological and physical processes had close links with the Beaufort Sea. Meetings of disciplinary groups, which provided overviews and identified information gaps, were followed by interdisciplinary discussions which directly addressed expected OCS impacts.*

A followup synthesis meeting was held at Barrow, 23-27 January 1978. Participants included invited representatives from the local community and the oil industry. One of the sessions was held in the building of the North Slope Borough at Barrow and broadcast live by Barrow radio. The presence of representatives from the petroleum industry was helpful in projecting demands for resources such as gravel and fresh water, assessing environmental hazards to offshore structures as caused by sea ice and permafrost, and conveying a picture of the nature of the development to be expected on the outer continental shelf.

The results of these discussions are presented in the present document. The text was written by the individual session chairmen with assistance from group members. Despite efforts by the Arctic Project Office to make the final product more uniform, differences may still exist in the way data are presented, and some inconsistencies may remain. Any remaining errors of this kind are the responsibility of the Arctic Project Office.

This document represents the best available assessment of what is known in relation to the arctic outer continental shelf and is the most realistic attempt to project the consequences of petroleum development. It is clear that many questions remain unanswered and that the report should not in any way be considered a definitive work on the impact of such development on the marine environment of the Arctic. Nevertheless, it poses a number of interesting and relevant questions and raises problems that will undoubtedly stimulate further thinking and studies. The detailed studies on which conclusions are based can be found in the individual annual and quarterly reports of the OCSEAP investigators, as well as in other references cited.

*The proceedings of this conference were distributed as a special 200-page edition of the quarterly Arctic Project Bulletin, (No. 15, 1 June 1977) published by OCSEAP's Arctic Project Office in Fairbanks. This bulletin is out of print and replaced by the present document.

Acknowledgments

Our sincere thanks go to the session chairmen and the members of the various disciplinary groups. Without their hard work this report would have been less than satisfactory. Although it is OCSEAP scientists who are listed as authors and assume the responsibility for the contents of the various chapters, the many other attendees of the meeting, from the villages along the Beaufort Sea coast, from Federal and State governments, from industry and from universities, contributed to this effort and deserve credit. We also thank the staff of the Naval Arctic Research Laboratory for their hospitality and for providing a meeting place which was unanimously agreed upon as ideal for the project. We thank Donna Becker from the Arctic Project Office for typing the draft, and Susan Rothschild, Rosalie Redmond, and Alice Bowden of the Boulder office for typing the final copy. They spent many hours and we appreciate their dedication.

This study was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaskan continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) Office.

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CONTENTS

PART I DISCIPLINARY OVERVIEWS AND IDENTIFICATION OF INFORMATION GAPS

Page No.

Page No.

PART I

DISCIPLINARY OVERVIEWS AND IDENTIFICATION OF INFORMATION GAPS

1. THE SEA ICE ENVIRONMENT

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Introduction

The influence of sea ice pervades the Arctic environment, requiring that its role in any physical or biologic process active in the area be considered. The interaction of the atmosphere and the ocean is coupled through the ice cover. The life histories of many of the organisms indigenous to the Arctic, from plankton to whales, are determined in some respects by the character and distribution of sea ice in space and time. Through the years, the Eskimo people who reside in the area have developed activities in the ice environment with which they must contend. Such information is required both for minimizing disturbance to the environment and for engineering applications. The present interest in exploiting resources in the offshore areas of the Arctic now dictates the need to develop a similar understanding of the influence of the sea ice cover on exploration and development and further requires that the influence of these activities on the environment in general, through utilization and disturbance of the ice, be understood so that it can be minimized.

With the exception of a narrow band of ice along the shore, the ice cover of the Beaufort Sea is in a nearly constant state of motion or potential motion. This motion occurs in response to forces imparted to the ice by meteorological and oceanographic influences. However, the ability of the ice to transmit these forces over long distances means that the motion in any area cannot necessarily be understood or predicted in terms of the local conditions alone; rather the state of the ice in areas far removed must be considered. In effect, the movement of the ice in the nearshore areas of the Beaufort Sea coast can often depend upon natural events occurring hundreds of kilometers away in the Arctic Ocean.

Because the ice can be mobile even in very shallow areas, operations in the Beaufort Sea are faced with significantly greater degrees of hazard from the environment than are present in other parts of the continental shelf of the United States. The movement of the ice, together with its composition, temperature and structure, largely determines the hazards to operations, and thus dictates the choice of technologies to be used to overcome them. Therefore, it is the availability of the required technology which perhaps should determine the rate at which development proceeds, rather than schedules developed for offshore leasing, exploration and development in other OCS areas.

Detailed consideration of the hazards related to the effects of sea ice are considered elsewhere in this report. In this section, a general description of the ice environment along the Beaufort Sea coast is presented, with emphasis on the proposed lease area. Next, problems that are specifically associated with sea ice, such as the interrelation between oil and ice, are discussed. Finally, data gaps and information needs are identified and recommendations for additional studies are described.

Our objective is to present and synthesize the results of sea ice studies undertaken under the OCSEA Program. Thus, references to the annual reports of various projects conducted under this program appear throughout the report in conjunction with the conclusions presented. Detailed documentation and supporting citations appear in these reports, and are generally not repeated here unless specific data or results are used in the discussion. The reader is referred to the reports for a more complete bibliography.

Ice Environment of the Beaufort Sea

The objective of this section is to present a brief discussion of the annual cycle of sea ice in the Beaufort Sea off the northern coast of Alaska. First, a description is given of the cycle of growth and decay of sea ice as it might be observed at any locality; then the changes in the areal extent of the ice cover with the seasons are discussed. It should be emphasized that the descriptions are intended to illustrate generalizations of these processes, and that variability, both from year to year and between localities in any one year, is the rule rather than the exception.

Annual Cycle of First Year Ice

Sea ice formed from still water commonly begins its growth as small, randomly-oriented crystals which freeze together to form a flat sheet. If the surface of the water is agitated during freezing these small crystals develop into a slush layer which may be up to 0.3 m thick. However, once an adequate thickness of the slush layer is reached the agitation of the surface is suppressed, and growth continues in the same manner as for the thin ice sheet formed in still water. That is, growth proceeds downward in the form of progressively larger crystals, elongated in the vertical direction, and with the c-axes of the crystals tending to align in the horizontal plane as the ice sheet thickens. At the bottom of the ice sheet is a 50-100 mm thick zone called the skeleton layer, in which spaces are still present between the growing crystals, so that the layer is porous and of negligible strength.

Salt is not incorporated directly into the solid crystal structure of ice. Instead, it is rejected by the growing crystals and is captured in the ice in the form of small inclusions of high salinity called brine pockets. In the initial stages of growth, some of the salt is rejected upwards, collecting on the surface and sometimes forming "salt flowers". Ultimately it is incorporated into a layer of porous "snow ice" which may be up to 40 mm thick, resting directly on the ice surface.

After the initial growth stage, the salt is entirely rejected downward, draining primarily through a series of brine channels. These are approximately vertical tubes with diameters of 1-10 mm, which form and are distributed about 0.1 m apart, with smaller feeder tubes branching from them. As the ice cools and grows through the fall, part of the brine within the ice slowly migrates down and out of the ice sheet. The resulting salinity profile of the ice thus shows a high salinity at the surface, which is sealed from draining to the remainder of the ice sheet by the cold surface ice. Below this, most of the ice sheet has a fairly uniform salinity, increasing values approaching the salinity of sea water in the skeleton layer.

As winter progresses, the ice continues to increase in thickness and snow drifts form on the surface. These drifts act as insulators and decrease the rate of growth of the ice below them so that by March typical thickness differences between the ice beneath a snow drift and an adjacent snow-free area, can be as much as 0.3 m for an ice sheet 1.5 m thick.

As the ice surface warms in April, melting begins at the surface, because of the high residual salt content, and the surface ice becomes porous. The brines formed at this time begin to drain away through the ice, resulting in the formation of top-to-bottom brine channels and air-filled cavities in the part of the ice above sea level. Then, with increased warming, the brines trapped in brine pockets are also released, further increasing the porosity of the ice into the range of 2-5% by the end of May. At this time ice growth ceases and water-filled melt ponds appear at the surface. These are nearly fresh, because of the earlier drainage of salt, and are used as a source of drinking water by birds.

As summer continues, the melt ponds increase in area and depth. Some eventually extend completely through the ice sheet, releasing salt water to the surface, and speeding the melting process. Any ice which survives through the summer will have had its salt largely flushed out and will start the next growing season at much lower salinity than the first year ice. This ice, called multi-year ice, is almost fresh and is much stronger than first year ice.

Distribution of the Ice Cover in Space and Time

The distribution of the sea ice cover varies through the year, but in winter the ice can be divided into two major categories. The first, called landfast or shorefast ice, consists of ice that is attached to the shore and extends for variable distances offshore. The second, the pack ice, occupies the remainder of the Arctic Ocean and drifts under the influence of wind and ocean currents. In the eastern Arctic the ice circulation is in a clockwise pattern called the Beaufort Gyre.

In summer, the landfast ice usually disappears as a recognizable entity by a combination of melting in place and breaking up. The remnants are absorbed into the pack ice with the result that only the pack ice remains over the summer. This does not imply that the area occupied by landfast ice during winter is necessarily ice-free during the summer. The reverse is often the case, as when the edge of the pack ice is close to shore. Also, even when the pack ice is some distance offshore, summer storms can rapidly drive it into shallow water areas, overriding barrier islands and depositing large masses of ice along the shoreline.

As described below, ice conditions vary from year to year and place to place, so that the description of the annual ice cycle given here must be considered as representative, rather than absolute.

Barry (1977) has determined a scenario for the annual ice cycle within the nearshore area, which appears (with minor modifications) as Table 1.1. The comparable cycle for the pack ice is more variable because of the wider range of latitudes which it occupies, but it is likely that new pack ice begins to form during October. Subsequently, the edge of the pack ice approaches the landfast ice by a combination of expansion in freezing and drift of older ice shoreward under the influence of wind and currents. If the latter condition is significant in any particular year, then masses of older ice will probably be incorporated into the landfast ice. If this does not occur, or if the shallow area is protected by remnants of ice from the previous year, the landfast ice will form as a relatively smooth sheet, possibly including ridges formed by movement of the thin, fall ice cover.

In the fall, when the ice cover is nearly continuous, a zone of interaction is established between the drifting pack ice and the relatively stable landfast ice. This zone generally forms between water depths of 15 and 20 m (although this varies along the boundary) and is usually dominated by a complex of shear and pressure ridges developed by impact of the pack ice on the edge of the landfast ice. This zone of ridges, constituting the grounded ridge zone described below, can continue to grow and expand seaward through the winter. In addition, large expanses of ice can become temporarily attached to the seaward side of this zone, thus temporarily expanding the area of ice which is contiguous with the shore, with an accompanying seaward shift of the zone of interaction between drifting and "stable" ice. However, the ridge complex is generally grounded along much of its length and thus marks the outer boundary of the stable landfast ice.

With the initiation of break-up in summer, the pack ice also decays, so that by the time the landfast ice sheet has disintegrated, the southern margin of the the pack ice consists of broken floes rather than continuous ice, and open water separates the shore from the pack ice. The position of the ice edge varies throughout the summer, but on the average it retreats to the north with the exception of storm-driven excursions toward the coast. Fig. 1.1 gives absolute maximum and minimum retreats of the pack ice. A possible method for predicting the extent of pack ice withdrawal during summer begins on page 46.

Ice Characteristics by Zone

The major divisions of the sea ice cover of the nearshore area along the Beaufort Sea coast, which were defined in the last section, can be further subdivided. For the purpose of this report, the classification shown in Fig 1.2. is adopted. As in any natural system, the boundaries are arbitrary and were selected to establish zones within which the hazards to offshore operations can be conveniently discussed.

TABLE 1.1

SEASONAL LANDFAST ICE REGIME*

(BARRY, 1977)

(i) new ice formation - late September/early October

(ii) first continuous fast-ice sheet - mid/late October
Unstable outside bays and the barrier islands

(iii) Extension and modification of fast-ice - November to February
No direct observations cover this period. The general sequence involves:

- seaward progression of the ice edge
- ridging of successive ice edges
- incursions of older ice
- grounded ice masses, formed _in situ_ or driven shoreward

(iv) stable landfast-ice inside about the 15m isobath - November-December

(v) stable ice inside about the 30m isobath - March-April/May

(vi) estuarine flooding of ice - late May

(vii) melt pond formation on ice - early June

(viii) melting and weakening of ice - June (Attached ice decays May/June)

(ix) breakup - late June to August

(x) open water in favorable years - August/September
Some deep-draft older ice and ridge fragments remain in the nearshore zone.

* There is a spatial variability along the coast making these dates ± 2-4 weeks.

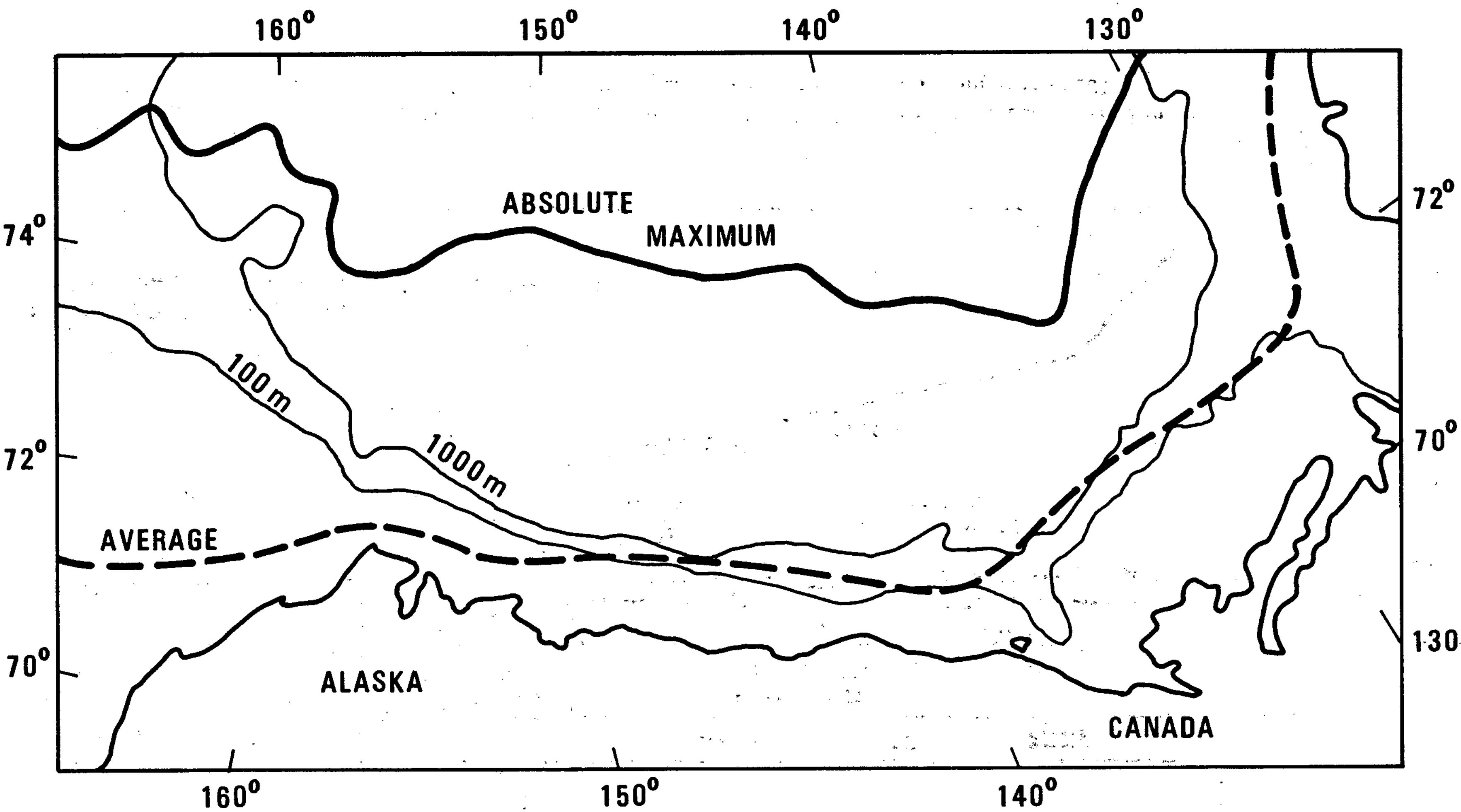

Figure 1.1 Average and absolute maximum retreat of the edge of pack ice along the Beaufort Sea coast (modified from American Geographical Society map of the Arctic Region, 1975).

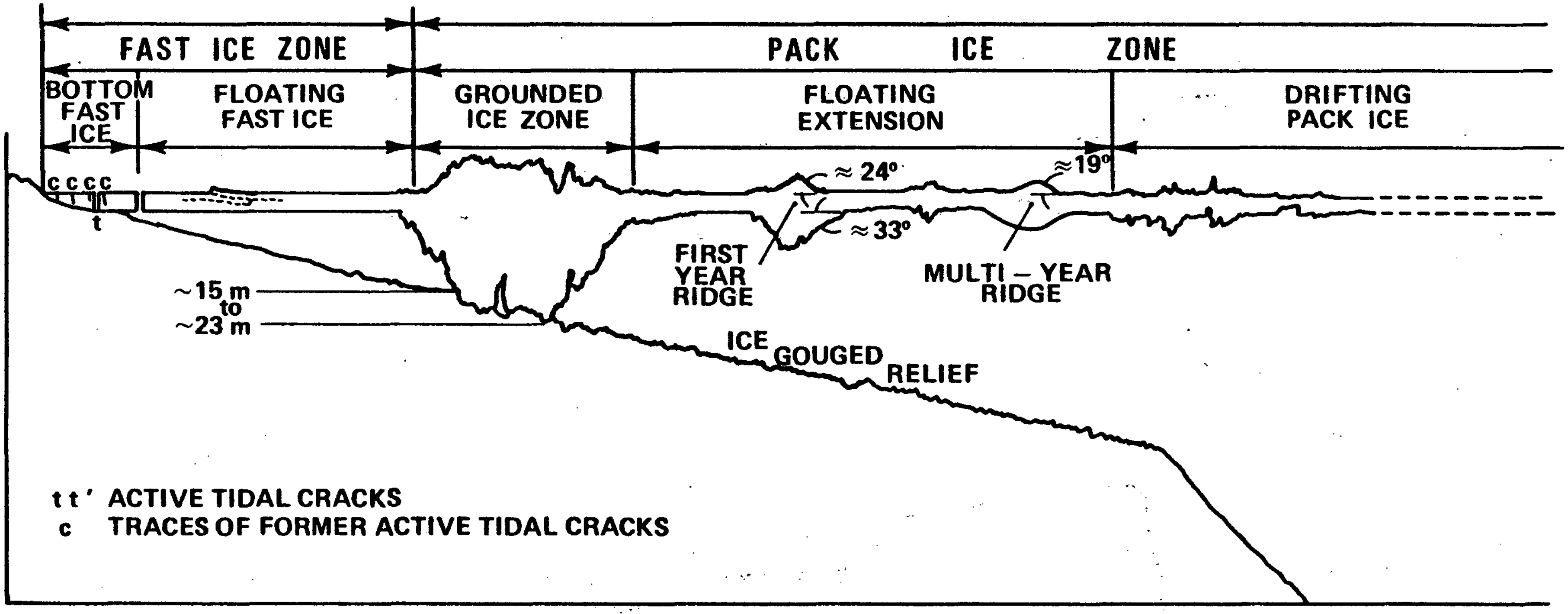

Figure 1.2 Late winter ice zonation of the Alaska Beaufort Sea coast indicating terminology used in this report (modified from Kovacs, unpublished).

Landfast Ice Zone

The landfast ice zone (as defined in Fig 1.2) can be subdivided into two units, the bottom fast ice zone and the floating fast ice zone.

The bottom fast ice zone is that part of the landfast ice which is continuously (in space) in contact with the sea floor and the shoreline. At any time during the ice year, it extends from the shoreline to some depth determined by the thickness of ice. The extent of the bottom fast ice zone thus increases throughout the winter, reaching about to the 2 m isobath by May, so that its width varies from a few meters to several kilometers depending upon location. The seaward boundary of the zone is marked by one or more active tidal cracks which form as the result of the ice flexing with the ocean tides. Several such cracks form during the year as the margin of the zone grows seaward, with movement only at the outermost cracks.

Throughout most of the year movements within the bottom fast ice zone are probably negligible. Large motions are possible only during freeze-up, when the ice is thin, or during breakup. In either case, only first year ice will be involved, with thicknesses limited by the water depth. Exceptions to this generality can occur as the result of summer storm surges carrying heavy ice into shallow water, or by extreme pressure from the pack ice during winter causing the grounded ice to be thrust toward shore. The first of these occurs during summer storms (Barnes and Reimnitz, 1977). The second occurs in areas where the bottom fast ice zone is no more than a few meters wide, such as along the offshore side of the barrier islands. Such events have been reported from the Barrow area which faces the Chukchi Sea where, as an example, ice piles up to 10 m in height formed along the beach in January, 1978. However, along the Beaufort Sea coast, most ice piling along the beaches appears to occur in late fall, and involves ice less than 30 cm in thickness (Barnes and Reimnitz, 1977). The possibility of more severe events cannot be entirely excluded, however, because overriding of one of the barrier islands about 15 km east of Barrow occurred during the winter of 1978. In that case, ice of at least 60 cm thickness was piled to a height in excess of 10 m.

The floating fast ice zone, as defined here, extends from the edge of the bottom fast ice zone seaward to the inshore boundary of the zone of ridges which separates the landfast ice from the pack ice (Fig. 1.2). Thus it can be considered to occupy the area generally between the 2 m and 15 m isobaths. However, there are wide differences in the depth over which the boundaries occur at different points along the coast during any one year, or between successive years.

A significant part of the area occupied by the floating fast ice zone lies behind the barrier islands. Within this area, the ice is essentially all first-year ice, with only occasional fragments of multi-year ice. In areas unprotected by the barrier islands, the floating fast ice zone consists primarily of first-year ice, although multi-year floes and ice island fragments can be common in some areas. These can be formidable ice masses (Kovacs, 1976) which drift into the zone prior to freeze up. When grounded they may tend to stabilize the first-year ice which freezes around them through the winter, but during breakup they generally drift free again.

Movement of the floating fast ice sheet in the vicinity of Narwhal Island was monitored during March, April and May of 1976 and 1977 (Weeks and Kovacs, 1977) by a combination of laser and radar ranging systems. The target arrays used in the 1976 study are shown in Figs. 1.3 and 1.4. The results of this work (upon which the following discussion is based) constitute the only quantitative data in the public domain on movement of the floating fast ice along the Beaufort Sea coast of Alaska.

Movement of the ice behind the barrier islands is limited, except during freeze up when winds and currents can move the thin, young ice through distances of up to a few hundred meters. However, between the time when the ice reaches a thickness of about 0.5 m and breakup, the net movement of the ice is probably in the range of a few meters. The largest movement measured within this area during the OCSEAP studies was 60 m, just southwest of Narwhal Island (Weeks and Kovacs, 1977) near a pressure ridge which extended between two of the islands. Examination of the movement records suggests that the motion of the ice behind the barrier islands is related to either thermal expansion and contraction of the ice, or to larger meteorological events.

Outside of the barrier islands, large movements can also be anticipated during freeze up and breakup, but during the remainder of the ice year movements were generally restricted to a maximum of a few tens of meters in the area monitored by Weeks and Kovacs (1977). However, it should be noted that within the area off Narwhal Island encompassed by this study, the zone of floating fast ice outside the barrier islands is less than 15 km wide. This is relatively narrow compared to other reaches of the coast, and in particular, to areas such as off Harrison Bay where the barrier islands are absent and the floating fast ice sheet reaches a width of up to 80 km. The greater width of the zone in such areas might permit larger movements of the ice sheet to occur, but there are no data available to substantiate this.

No data exist in the public domain regarding the pattern or extent of movement of the landfast ice sheet along the Beaufort Sea coast during breakup. However, studies on the Chukchi Sea coast at Barrow (Shapiro, Harrison and Bates, 1977) show that the ice sheet can become quite mobile at that time of year as the result of two processes. First, the ice melts along the shoreline, breaking the bond between the ice and the beach. Second, mass loss through melting of both surfaces of the ice sheet and any enclosed grounded features which anchor it, cause the sheet to float higher, therefore reducing the strength of the bond to the sea floor. The ice sheet is then free to move under appropriate driving forces. The general warming trend also increases the ice temperature and thus increases its ductility (the ability to flow rather than fracture in response to applied forces). This in turn permits the ice sheet, which, if cold, would tend to fracture and pile after only minimal movement up a sloping surface (such as a beach or the flank of a gravel island), to be driven up such a slope for relatively large distances during breakup. Such events are common at Barrow (Shapiro,

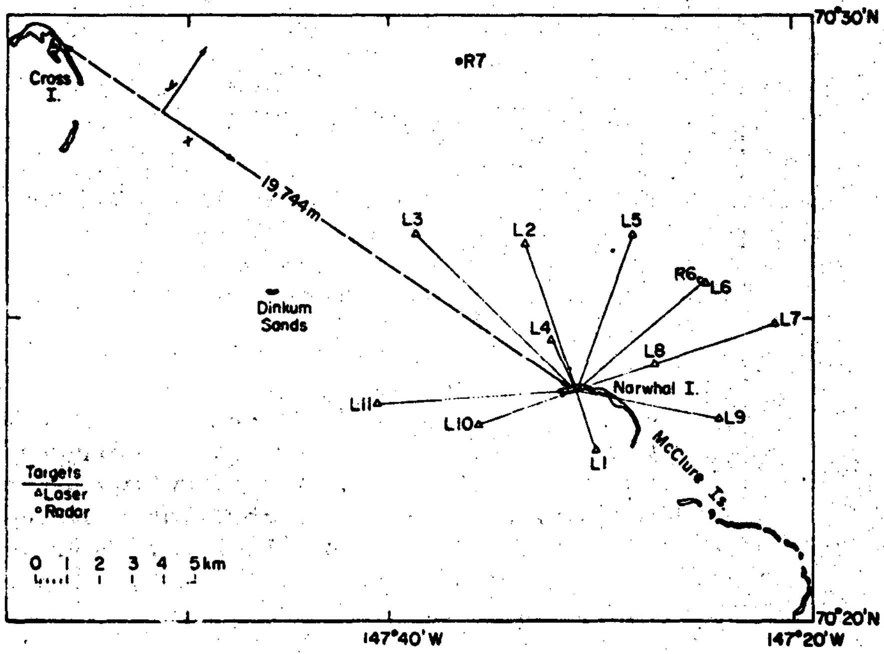

Figure 1.3. Target array for laser ranging system used in 1976 (Weeks et al., 1977).

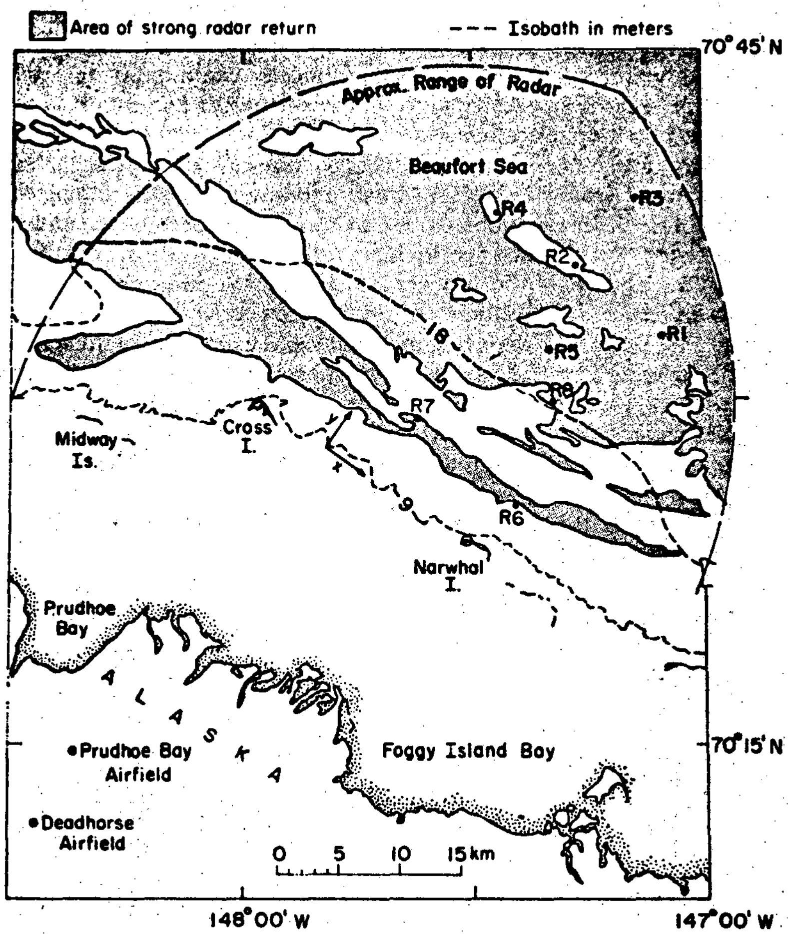

Figure 1.4. Target array for radar ranging system used in 1976 (Weeks et al., 1977). Dark area indicates strong radar return due to the presence of rough ice.

Harrison and Bates, 1977), but the only report of a similar occurrence along the Beaufort Sea coast is provided by local residents (H. Leavitt and K. Toovak, private communication). It involved the advance of the ice sheet about 30 m up the beach near Cape Halkett in late June.

The crystal structure of the floating fast ice both inside and outside the barrier islands has been examined during field studies conducted from Narwhal Island (Weeks and Kovacs, 1977). Details are described in Gow and Weeks (1977), Weeks and Gow (1978) and Kovacs and Morey (1978). Briefly, previous studies of the formation of sea ice had shown that the crystals which compose the ice sheet were invariably elongated normal to the plane of the ice sheet and parallel to the direction of growth. This places the crystallographic c-axis in a horizontal plane (Weeks and Assur, 1967). Schwarzacher (1959), Peyton (1966) and Cherepanov (1971) noted that this axis is not randomly oriented in the horizontal, but instead, tends to be aligned in preferred directions. The results of the recent studies cited above now show that there is a consistent orientation in the horizontal plane of the c-axes of the crystals which form the landfast ice sheet. That is, the c-axes tend to align along the same direction, and this is valid for distances on the order of tens of kilometers. Figs. 1.5, 1.6 and 1.7 show the preferred c-axis directions on ice samples collected offshore from Prudhoe Bay. Note that at sites near the mainland the c-axis alignment is generally parallel to the coast. At sites near islands the alignment tends to curve following the outline of the islands, while in the passes between islands, the alignments are parallel to the axes of the passes. At sites outside the barrier islands, the alignments are roughly normal to the coast.

The data available indicate that the alignment reflects the mean current direction at each site. However, irrespective of the cause, the effects of this orientation are significant. As examples:

1. Orientation of the crystals causes the strength of the ice to be different depending upon the direction in which forces are applied. Perfect alignment tends to increase the compressive strength of the ice in some direction so that the maximum force which the ice can exert against a structure will also be increased.

2. Thermal expansion and contraction of the ice would be directionally dependent.

3. There is some indication that aligned ice is capable of entrapping more spilled crude oil than non-aligned ice (Martin, 1977). However, it is not clear why this should be so.

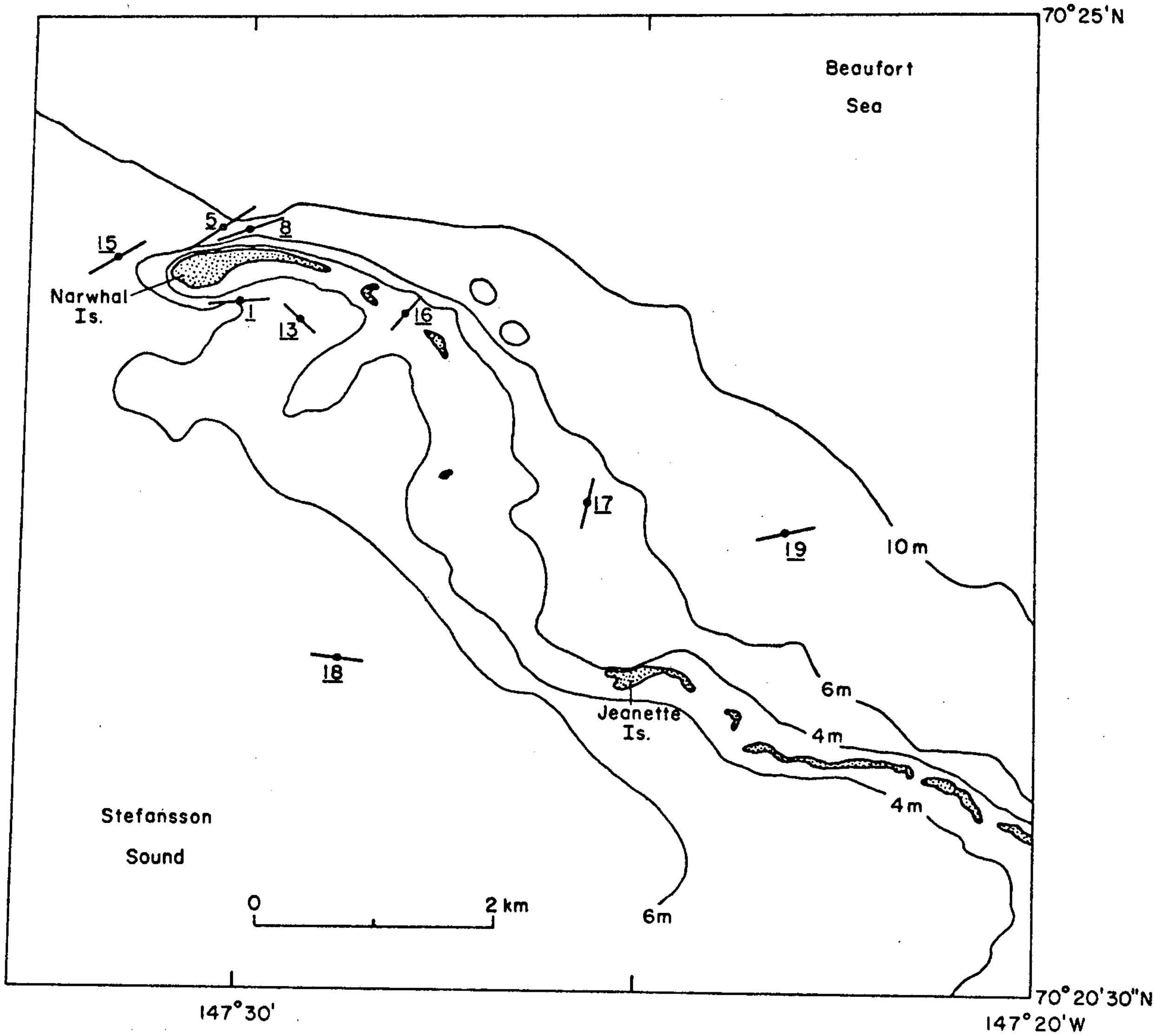

Figure 1.5. C-axis orientations measured in the vicinity of the McClure Islands (Gow and Weeks, 1977).

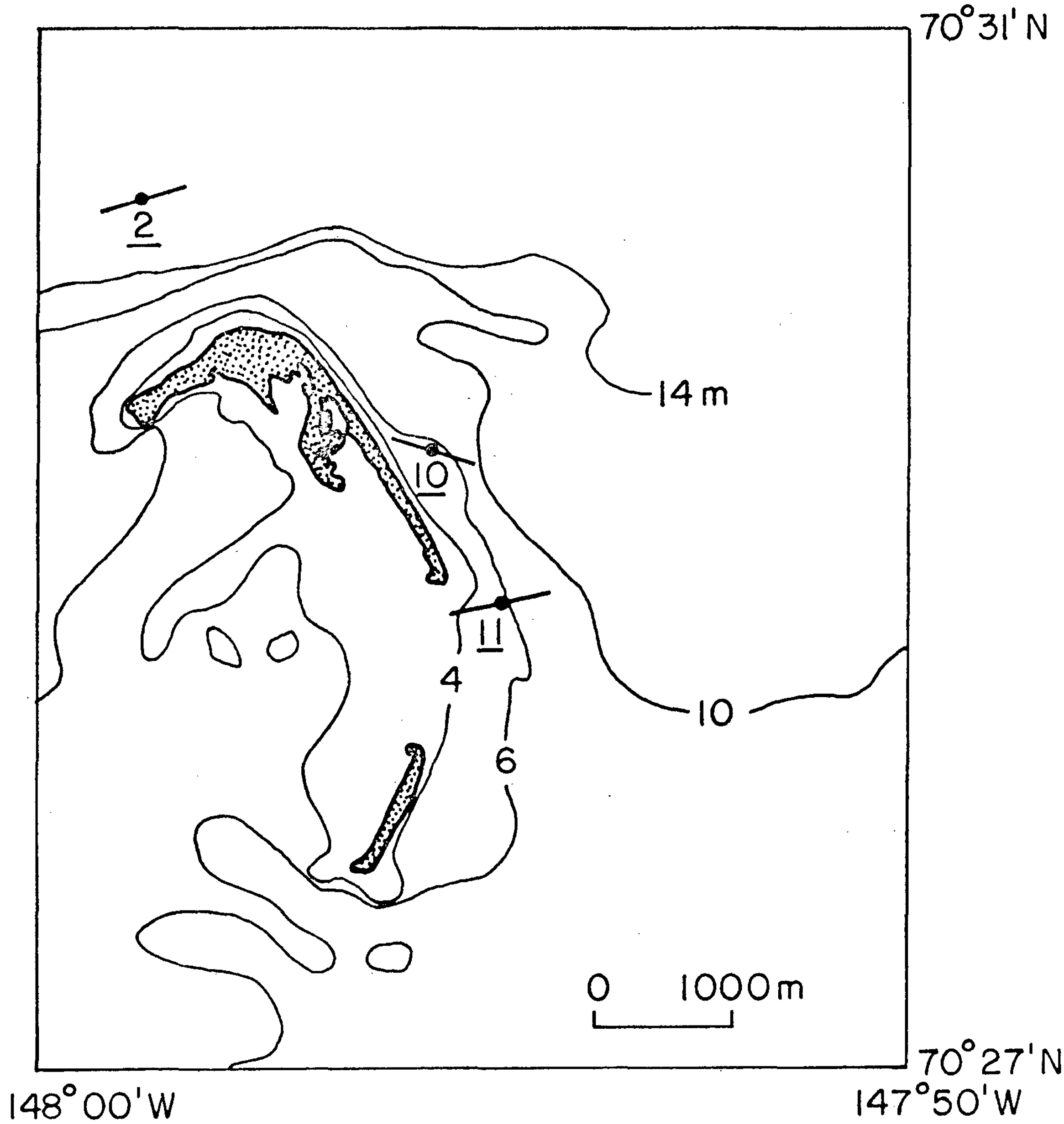

Figure 1.6. C-axis orientations measured in the vicinity of Cross Island (Gow and Weeks, 1977).

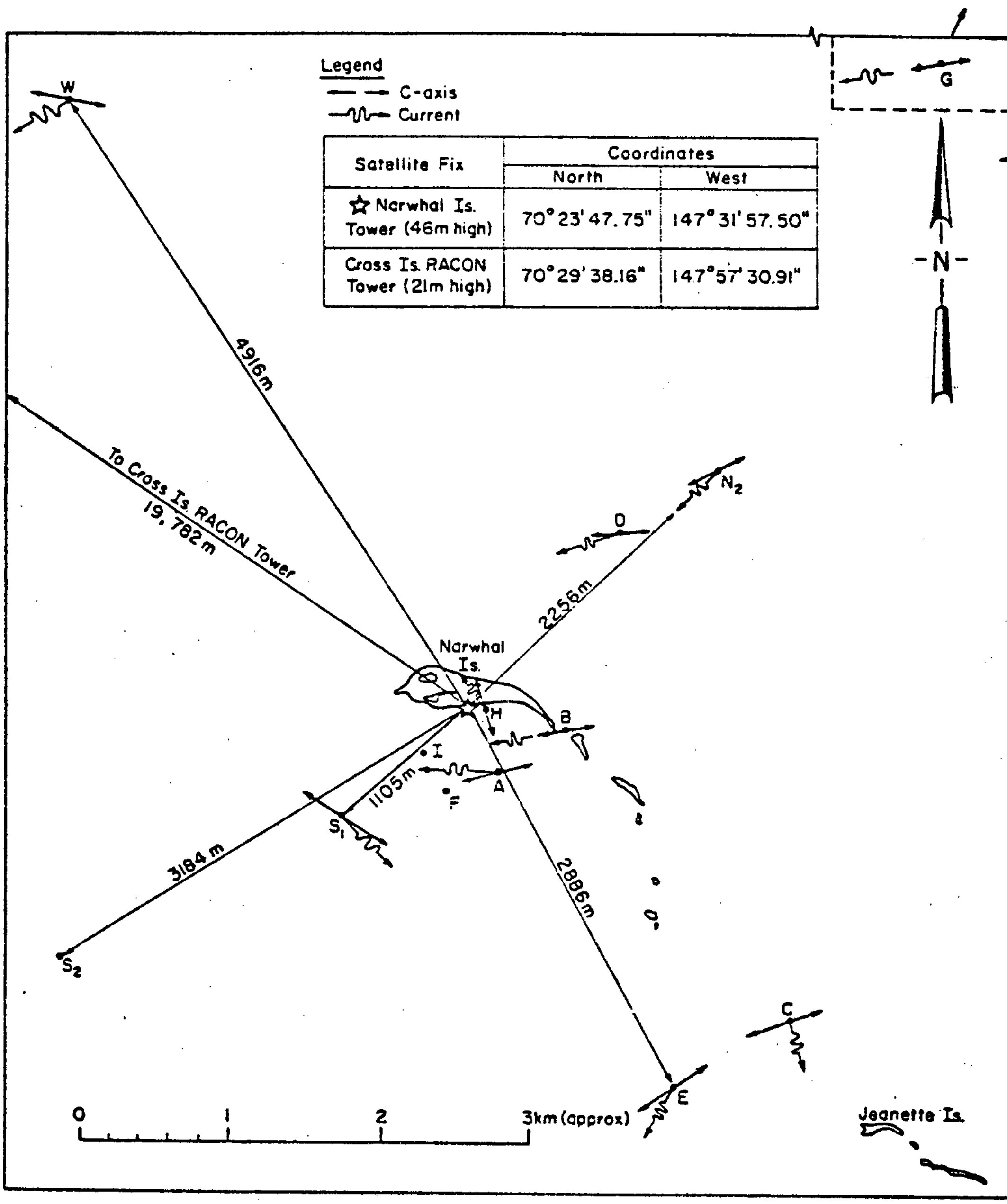

Figure 1.7. C-axis orientations compared to current measurements near Narwhal Island (Kovacs and Morey, 1977).

Pack Ice Zone

As defined in Fig. 1.2, all of the ice seaward of the edge of the floating fast ice zone is assigned to the pack ice zone. Thus, the grounded ice zone and the floating extension of the fast ice are classified here as pack ice. As noted above, this classification was adopted to emphasize the importance of the seaward edge of the landfast ice zone to the consideration of hazards to offshore development presented by sea ice. That is, offshore from that boundary, the environment presents the possibility of large movements of heavy ice through most of the year, while inshore the possibility of movements and occurrence of heavy ice are reduced.

The grounded ice zone marks the zone of early winter interaction between the edge of the landfast ice and the pack ice. It consists primarily of a complex of shear and pressure ridges (many of which are grounded) interspersed with floes of first-year and multi-year ice, and ice island fragments. The intensity of ridging, however, establishes the character of the zone (Figs. 1.8 and 1.9). Individual ridges can be of variable length but the zone is usually identifiable as a unit along the entire length of the Beaufort Sea coast of Alaska. The fact that grounding is apparently common throughout the zone contributes to the winter stability of the floating fast ice inshore by serving to anchor the ice sheet, and possibly to transmit forces exerted by the drifting pack into the sea floor. The extent of grounding is indicated by the frequent gouging of the sea floor in this area (Barnes and Reimnitz, 1977). A more detailed description of the characteristics of the zone during winter is given by Kovacs (1976).

The width of the zone indicated in Fig. 1.2 is taken as approximately coinciding with the distance between the 15 and 23 m depth contours at any locality. However, variations from these values are common both along the boundary in any one year and from year to year at any point. Based upon the extent of bottom gouging, the zone may extend to the 40 m depth contour in some years (Reimnitz et al., 1977). Approximate offshore limits of the zone along the Beaufort Sea coast are indicated by the mid-June extent of ice which is contiguous with the shore as shown in Fig. 1.10.

Many of the large, grounded ridge systems which form within the zone survive the melt season well into the summer. During this time, melt water percolates down into the cores of the ridges, where it refreezes forming large, virtually void-free ice masses of low salinity and high strength. As long as they remain in place they can form a barrier which tends to keep the pack ice offshore (Barnes and Reimnitz, 1977). If they survive the summer, they protect the shallow areas from incursions of heavy ice during freezeup thus permitting the floating fast ice zone to freeze to a uniformly smooth sheet. However, if they become free-floating as the result of mass loss through melting, they are ultimately entrained in the pack ice.

An overview of ice characteristics within the remainder of the the pack ice zone of the Beaufort and Chukchi Seas, and their variations with the seasons, is given in Table 1.2 (Weeks and Kovacs, 1977).

Explanation of Major Zones delineated in Fig. 1.8

I. This zone represents the most stable ice along the Beaufort coast. After December it is extremely safe for surface travel, and ice piling is at a minimum.

The greatest hazard observed to occur in this zone was the mid-winter formation of tidal and tension cracks. These cracks occur generally during very cold temperatures in December and open to a width of 2-3 m. There appears to be some repetition of these cracks from year-to-year; one major tension crack appears annually between Thetis Island and Oliktok Point.

Ridging occurs within this zone only early within the ice season, with the participating floes generally on the order of 30-40 cm in thickness. Major ocean floor plowing should not be expected from these events. After December and January the active edge of ice is well seaward of this zone. Between the end of January and the end of May no ice failure events with deformations more than a few tens of meters have been observed to occur within this zone.

II. Like Zone I, this zone consists of stable fast ice during late winter and early spring. However, the relative hazards related to this zone are somewhat greater than those related to Zone I. During the five year observation period reported here, failure to the point of large scale displacement (10 km) was not observed within this zone.

Generally the zone is safe for surface travel during winter and spring. Structures are subjected to varying amounts of ridging, and varying amounts of displacement can take place. However, this is still within the zone of "stable fast ice" generally held in place by grounded ice features along its seaward edges. Oil spilled under this zone should encounter a relatively smooth undersurface and might spread significantly. This process would be aided by lunar and barometric pumping of water in the confines between the ocean floor and bottom of the ice.

III. This major zone is defined by the statistical envelope of observed flaw leads. During mid-winter, flaw leads quickly freeze over after formation, but during late spring they tend to freeze much more slowly and consequently remain active much longer. During the mid-winter periods when the Beaufort flaw lead has frozen in this vicinity, a vast area seaward of this zone is often covered by fast ice. The term "flaw lead" loses its significance during this period. However, when a flaw lead does appear, it has the greatest probability of occurring within Zone III.

Hazards in Zone III are significantly greater than in Zone II because of the high probability of formation of flaw leads and because this zone lies almost entirely seaward of the 20 m isobath, increasing the possibility of incursions by ice islands and other deep-draft ice features. Under-ice oil spills located within this zone face a high probability of exposure to the water surface through the creation of flaw leads.

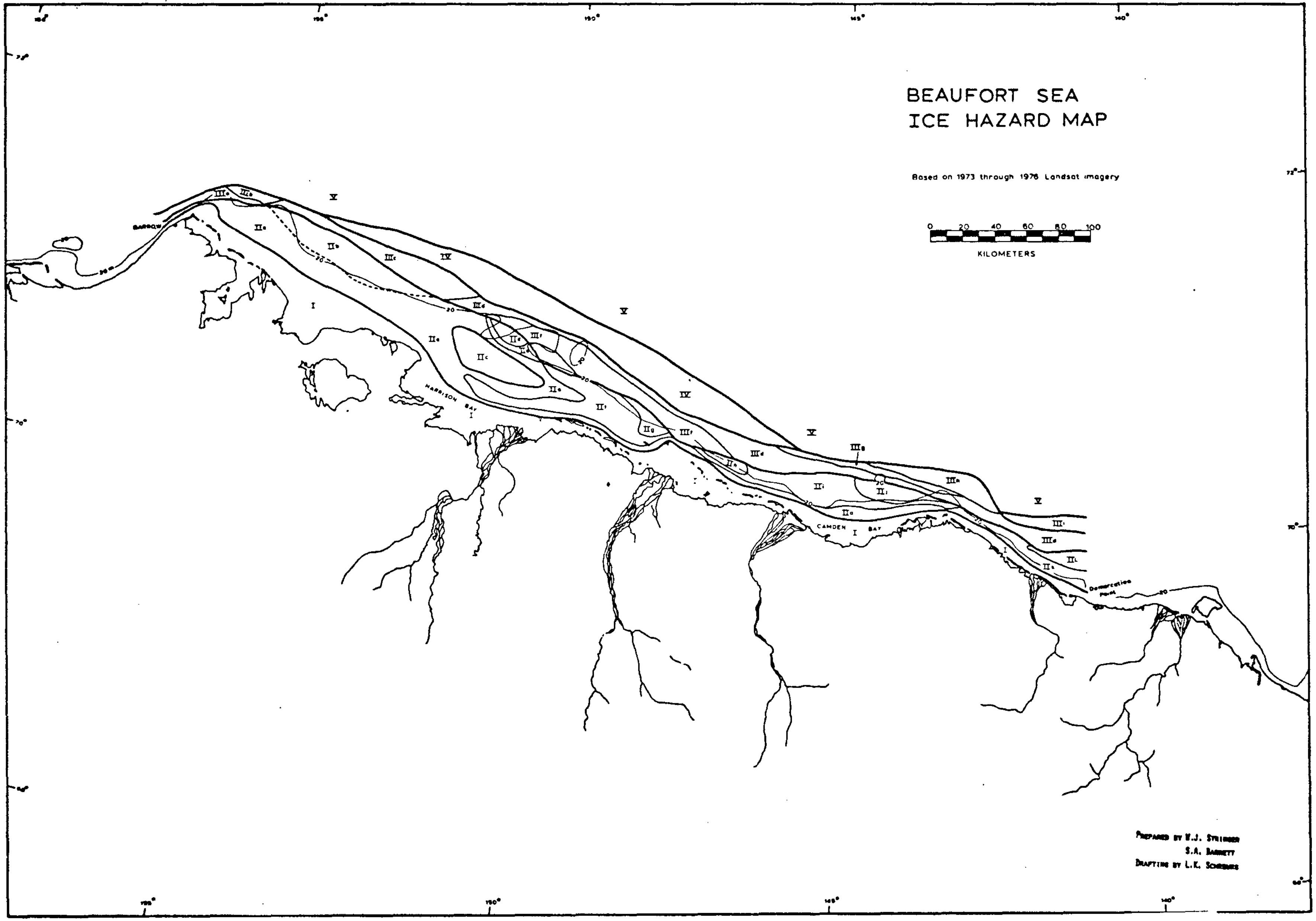

Figure 1.8 Morphology and hazards of nearshore ice along the Beaufort Sea coast as determined from LANDSAT imagery 1973-1977. For each of the zones delineated here, a morphological description of ice behavior and associated hazards has been prepared. These zones were identified by combining statistical data on flaw lead locations and probability density of major ridging (Stringer, 1977).

It should be noted that whereas Zone II could be thought of as having a good probability of remaining static thorughout winter and spring, with large ridging probabilities indicating stability through grounding and consequent anchoring of ice, a high ridge probability in Zone III indicates instability through flaw lead formation and building of ridges which do not ground.

IV. This zone contains ice with a moderate probability of major ridge formation as a result of ice interaction with the shore, yet there is a high probability that flaw leads will be found shoreward of this zone. Because of the shore-linked aspect of its morphology and hazards, it has been differentiated from Zone V, which contains essentially pack ice.

Surface operations in this zone should not be performed without provisions for non-surface evacuation. Structures placed in this zone will be subject to major ridge formation, while ice island and floeberg incursions are entirely possible. Oil spilled under this zone would tend to be pooled significantly by major ridges but be subject to introduction to the ocean surface during lead-forming events.

V. This zone is essentially the pack ice zone. Here, influences of shore on ice morphology and hazards have been reduced to regional influences. In the region north of the Beaufort Sea there are periods of stable ice extending up to six weeks duration. During that time, field operations could be carried out here subject to the provision for non-surface evacuation if necessary. However, the relative danger is actually diminished from that in Zones III and IV because of the smaller chance for major shear deformation in this zone. It is very unlikely structures will ever be placed in this zone. An under-ice oil spill would essentially be a spill into pack ice.

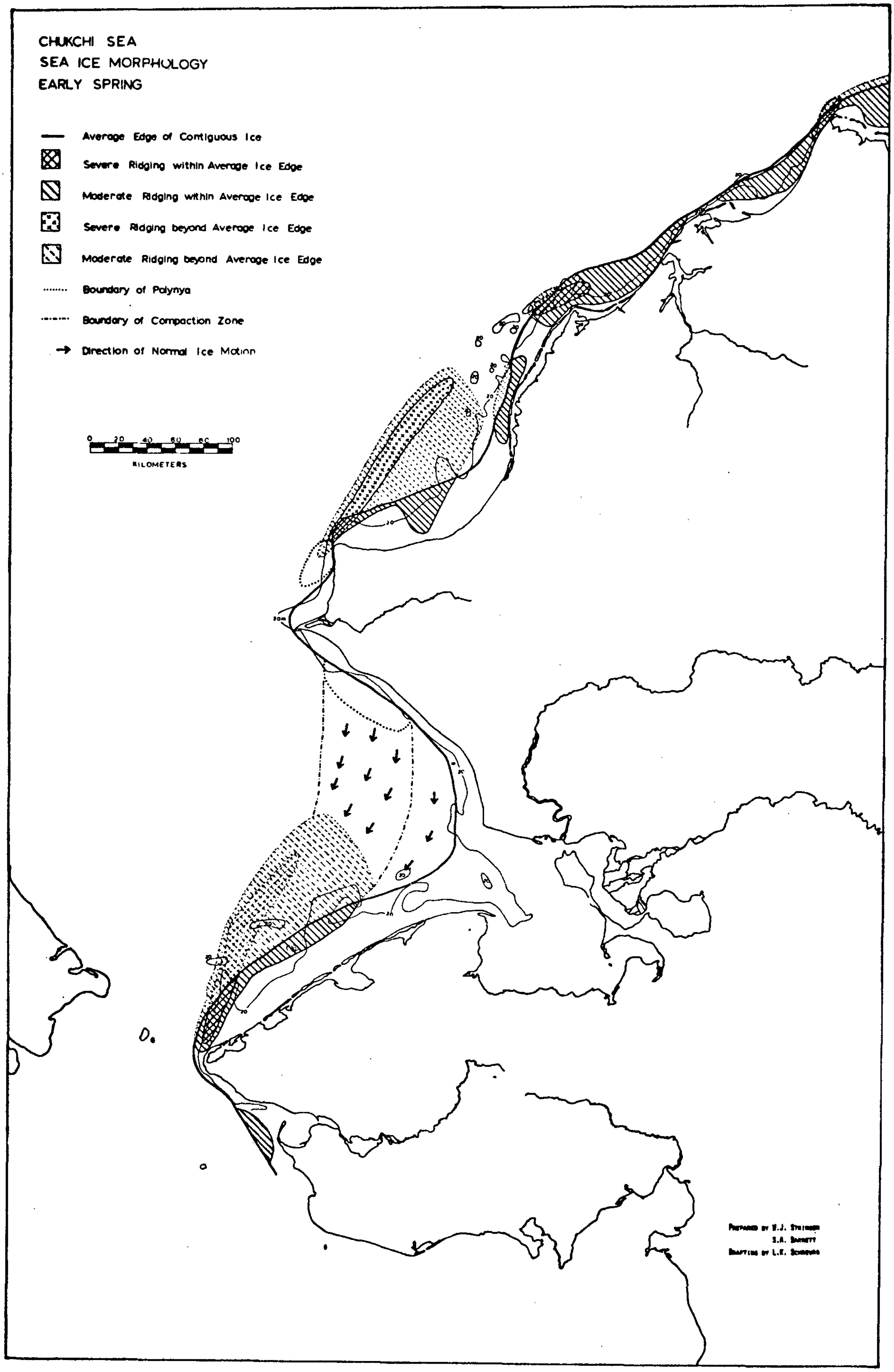

Figure 1.9. Chukchi Sea ice morphology (Stringer, 1978).

Explanation of Fig. 1.9

Chukchi Sea Early Spring Nearshore Morphology

This map has been constructed to show Chukchi Sea nearshore morphology in early spring. During winter and spring, Chukchi Sea ice is much more dynamic than the Beaufort Sea ice. While the Beaufort Sea exhibits a vast area of static ice with an occasional much larger area attached, there is an extremely active flaw lead along the Chukchi coast with new ice being formed, detached, piled, and transported almost constantly.

Two fundamental ice features have been utilized to construct this figure: the edge of contiguous ice, which essentially coincides with the flaw lead, and large massive ridge systems. In some respects these two ice features are independent of one another; the edge of contiguous ice is, in general, controlled by season--being farther offshore during winter and advancing toward shore with advancing season-while the location of large ridge systems appears to be controlled mainly by bathymetric configuration.

The Chukchi Sea Ice Morphology Map has a much different appearance than does the Beaufort Sea Map (Fig. 1.8). One major reason for this is the opportunity for ice in the Chukchi to move out through Bering Strait. All during the late winter and early spring period, ice moving events take place along the Chukchi coast, often creating shear ridges along shoals jutting seaward from the string of capes and headlands prominent along the coast. Increasingly as one travels to the south, the edge of contiguous ice between headlands is more poorly defined and the ice contained is more prone to seaward motion, leaving areas of open water behind.

In general, there is often a lead system extending the length of the coast from Barrow to Cape Lisburne. Just south of Cape Lisburne and north of Point Hope is an area with a constantly reopened polynya.

South of Point Hope the effect of ice motion out through Bering Strait is even more prominent. Another recurring polynya occurs just southeast of Point Hope, formed by southward ice motion. This polynya persists until late spring when changing weather patterns push drift ice against this shore. Kotzebue Sound is generally covered by stable ice during much of the ice year, but the presence of a zone of weak, and often moving, ice just seaward hints that this sheet of ice is probably potentially unstable.

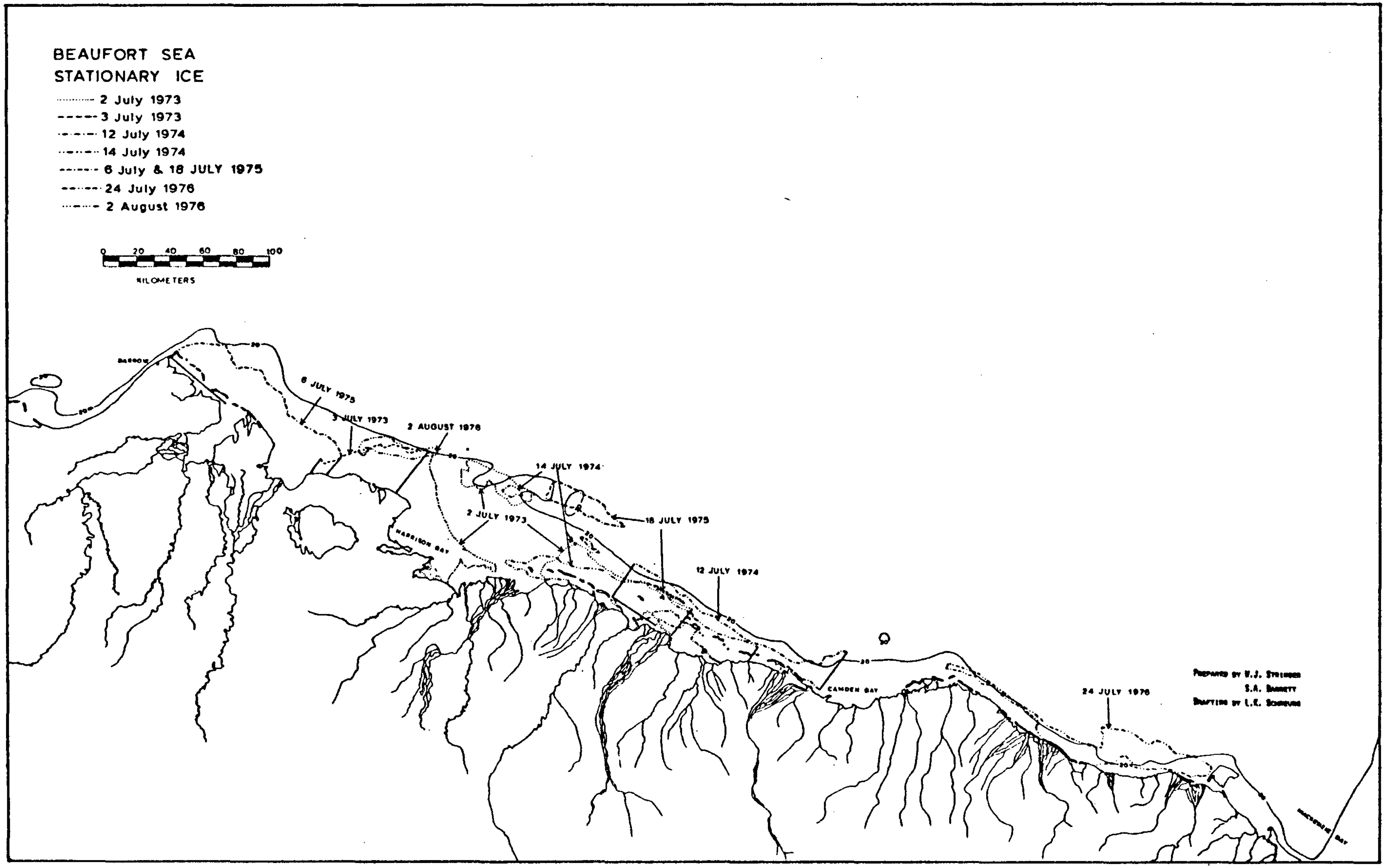

Figure 1.10. Limit of fast ice continuous with the shore in mid-June, 1973–1975 (Barry, 1977).

Explanation of Fig. 1.10

Along the Beaufort Sea coast, large ridges form during winter in a zone parallel to the shore. These ridges have keel depths sufficient to cause grounding approximately to the 20 m bathymetric contour. This zone of grounded ridges varies from a few to many tens of kilometers in width and effectively shields the smoother ice inshore from the effects of pack ice motion. The zone of immobile ice is usually referred to as the "fast ice zone." When summer break up occurs, these grounded ridges are often the last ice forms to dislodge.

Four years' data were analyzed for stationary ice - 1973, 1974, 1975 and 1976 by using LANDSAT satellite imagery. The data were combined in Fig. 1.10, and extended from Point Barrow to Herschel Island. The smallest stationary ice object plotted was approximately a kilometer in diameter. Analysis of this map shows that:

1. Stationary ice is generally located inshore of the 20 m bathymetric contour. Inshore areas that are usually clear of stationary ice include the majority of Harrison Bay and the immediate river mouth vicinities.

2. Areas where stationary ice recurs were difficult to determine because of insufficient data. One area where it recurs and seems to last most of the summer is along the 20 m contour north of the Colville River in Harrison Bay. Each year a large hummock field forms, causing a seaward bulge in the edge of the fast ice and persisting until late summer. Another area where stationary ice was seen to recur was between Oliktok Point and the Sagavanirktok River, extending from shore to the 20 m contour.

3. In 1976, stationary ice was last seen to exist on 2 August in one small area west of Harrison Bay. The next image of the area was not obtained until 20 August (one LANDSAT cycle later). By then, the stationary ice had disappeared completely. Therefore, it can be concluded that stationary ice is generally gone by mid-August. One exception to this was seen in 1974. A large piece of a ridge system north of Oliktok point was observed to remain throughout the summer of 1974 and was still there in the spring of 1975. However, it did not remain as stationary ice in 1975.

TABLE 1.2. Ice characteristics according to area and season. Source: Birdseye flights

Characteristics		GEOGRAPHIC AREA* S. Chukchi Sea				N. Chukchi Sea				Beaufort Sea			
		SEASON** S	F	W	Sp	S	F	W	Sp	S	F	W	Sp
Overall ice concentration %	average	40	74	98	74	80	94	99	96	76	97	99	94
	range	10-100	10-100	90-100	0-100	10-100	10-100	96-100	70-100	10-100	68-100	70-100	0-100
Areal % of different ice type	1st year ice	54	25	60	70	32	34	42	23	37	30	26	36
	old ice	35	14	26	8	42	32	48	58	41	38	58	53
Areal % of deformed ice	ridged ice	6	5	25	18	17	14	27	28	20	20	24	25
	hummocked ice	--	--	--	--	6	5	--	2	2	4	2	--
	total deformed ice	6	5	25	18	23	19	27	30	22	24	26	25
Number of openings per 100 km	openings <30m	--	14	--	13	41	34	77	9	38	15	68	17
	openings >30m	--	12	--	15	42	20	15	6	40	46	21	11

* S. Chukchi Sea: ocean area enclosed by Bering Strait to 80¼ N and 157.5¼ W to 180¼ W; N. Chukchi Sea by 70¼ to 75¼ N and 157.5¼ W to 180¼ W; and Beaufort Sea by 70¼ to 75¼ N and 135¼ W to 157.5¼ W.

** S, F, W, Sp indicate summer (August-October), fall (November-December), winter (January-May), spring (June-July) respectively.

Average maximum and minimum seasonal limits of the extent of the pack ice are shown in Fig. 1.1. The yearly variability of ice conditions is high, however, as shown on the maps (Figs. 1.11, 1.12, 1.13) which illustrate "good", "fair" and "poor" ice years. Along the Beaufort Sea coast the average seasonal variation occurs over a zone approximately 260 km in width. Long-term changes of ice conditions are also apparent. Hunt and Naske (1978) have compiled long-term records of early expedition ships, whalers, etc. Their maps (Figs. 1.14, 1.15 and 1.16) show indications of significant long-term changes in the extent of the ice, with more open water in August and September since about 1940 than between 1860-1919. However, temperature records taken at Barrow since 1921 indicate a slowly declining trend (Rogers, 1978, in press) and this has been associated with an increasing frequency of heavy-ice seasons since about 1953 (Barnett, 1976). These sea ice and climate data demonstrate that long-term economic developments along the Beaufort Sea coast must take account of the variability of ice conditions on a time scale of at least 50 years. Inferences about variability in climate and ice conditions cannot be based solely on the recent, more detailed records.

The pack ice includes a mixture of first-year ice (both ridged and smooth), multi-year ice floes of varying dimensions (see below), and ice islands of all sizes. Over most of the area occupied by this zone, the ice is in a state of almost constant motion. However, during part of the winter and early spring, large areas of the pack ice off the Beaufort Sea coast have been observed on satellite imagery to become temporarily attached to, and continuous with, the offshore boundary of the grounded ridge zone as indicated by the floating extension in Fig. 1.2.

Some of the position markers shown in Fig. 1.4 lie near the inner boundary of this "temporary" fast ice, and data on the movement in this area have now been accumulated over a two-year period. Figs. 1.17 and 1.18 show the components of motion measured parallel and perpendicular to the coast, along with the comparable components of the wind for both years (Tucker et al., 1978). In general, there was not a strong correlation between the wind and the displacement of the position markers. However, the greatest displacements measured during both years did occur after periods of high, sustained offshore winds. During these periods leads 100-500 m wide developed at the outer edge of the grounded ridge zone, but these closed rapidly when the wind either abated or shifted in direction, the ice then returning nearly to its original position. The largest net displacement measured was greater than 5 km, and occurred in 1976. During 1977, motion was more frequent, but only in the range of 0.5 to 1.5 km.

The fact that no consistent westward drift of the ice along the offshore boundary of the grounded ridge zone was observed indicates a data gap. Movements of that type are known to occur at other times of year, and detailed information on typical velocities in that area is needed for estimating probabilities of impact of large ice masses with offshore structures. In addition, the problem of determining the mechanism of stress transmission from pack ice to landfast ice requires an understanding of ice movements along this boundary.

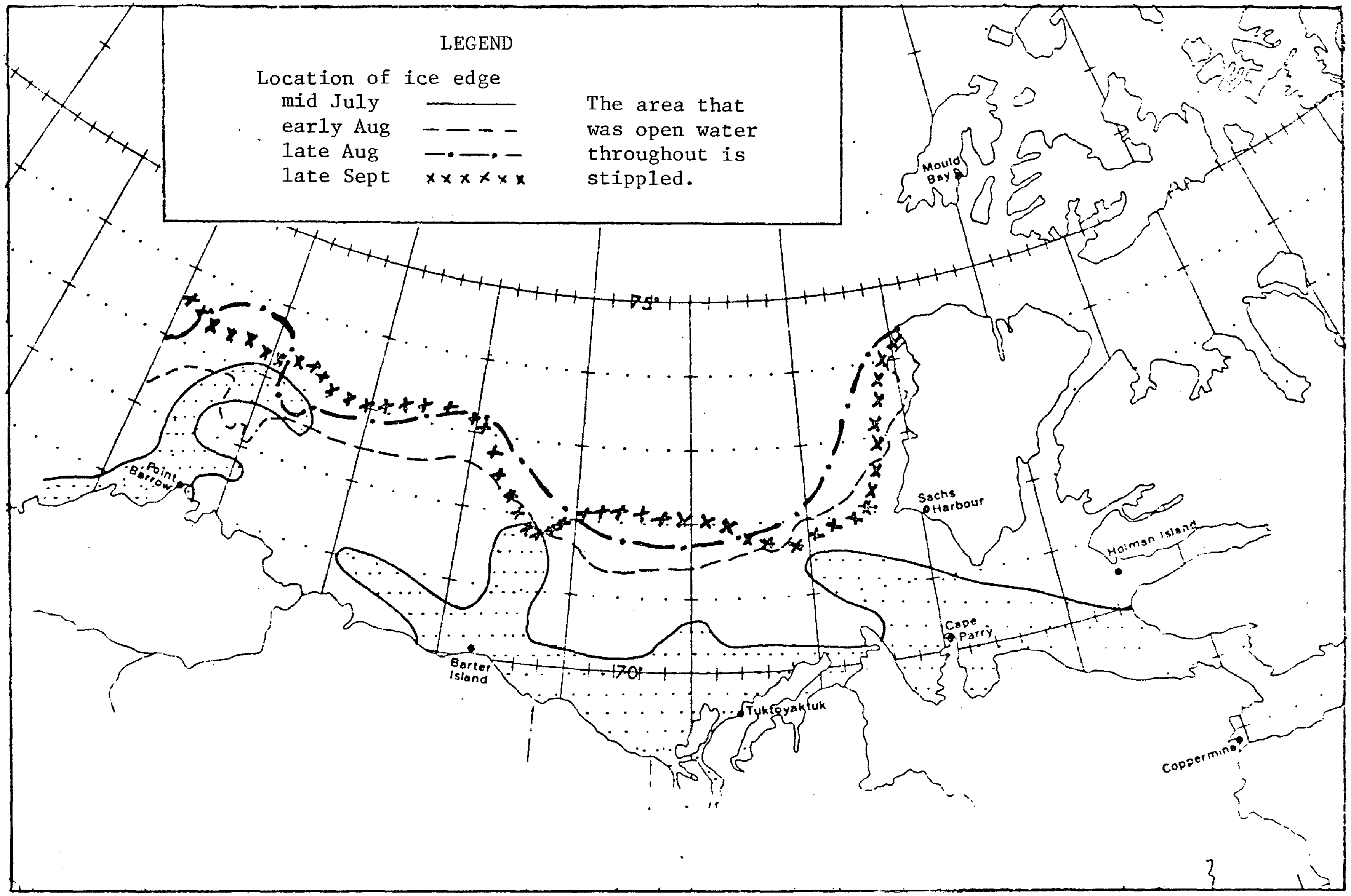

Figure 1.11. 1968, a "good" ice year. Although the Cape Bathurst polynya was poorly developed in May and June, the ice retreated rapidly in July and easy access around Point Barrow was possible by July 20 (Markham, 1975).

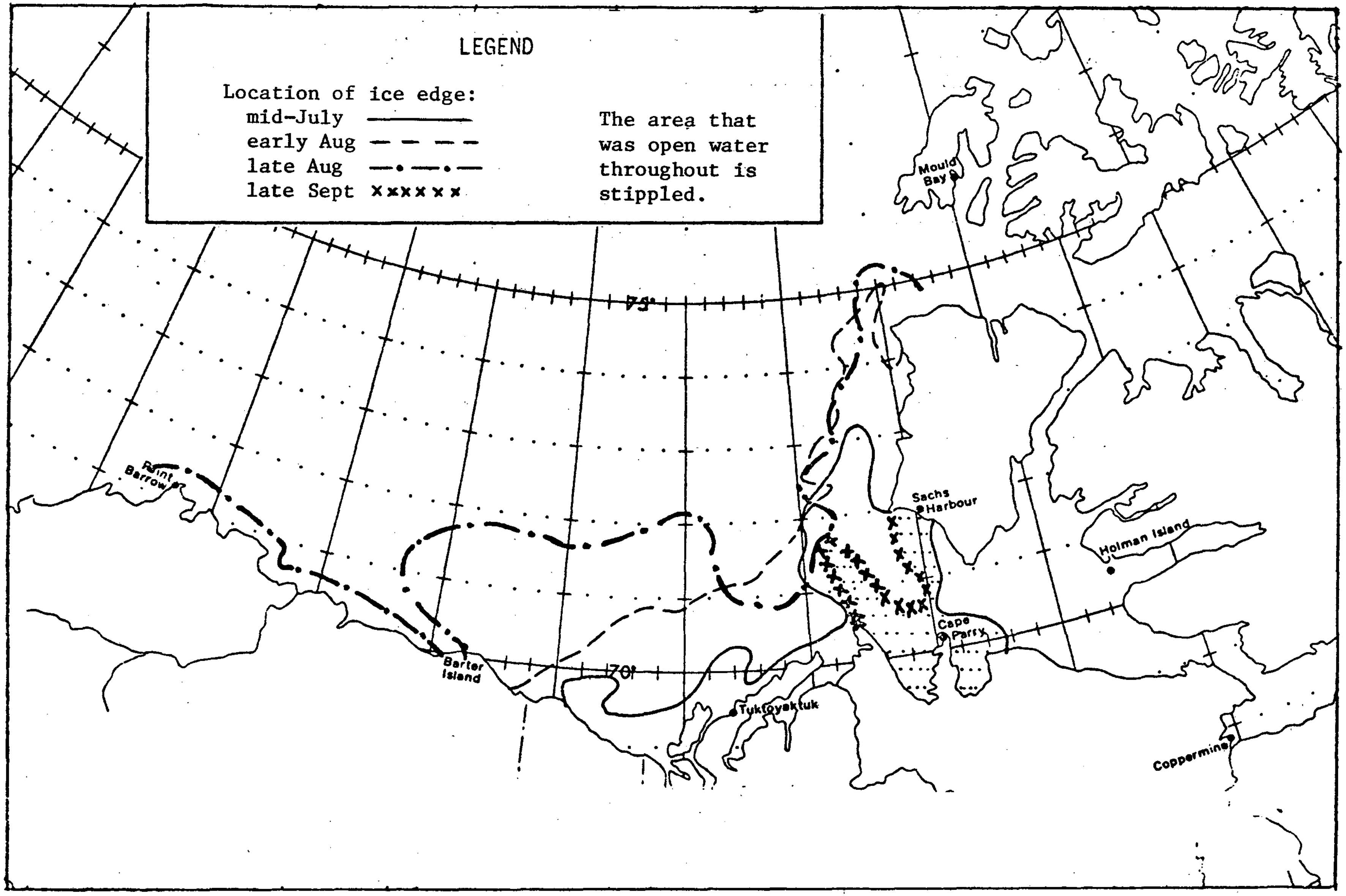

Figure 1.12. 1970, a "fair" ice year. Even though the polar pack was far from shore in the spring months, onshore winds were frequent until mid-July and the polynya in the southern Beaufort Sea was slow in developing. Onshore winds and an early freeze up advanced the end of the season (Markham, 1975).

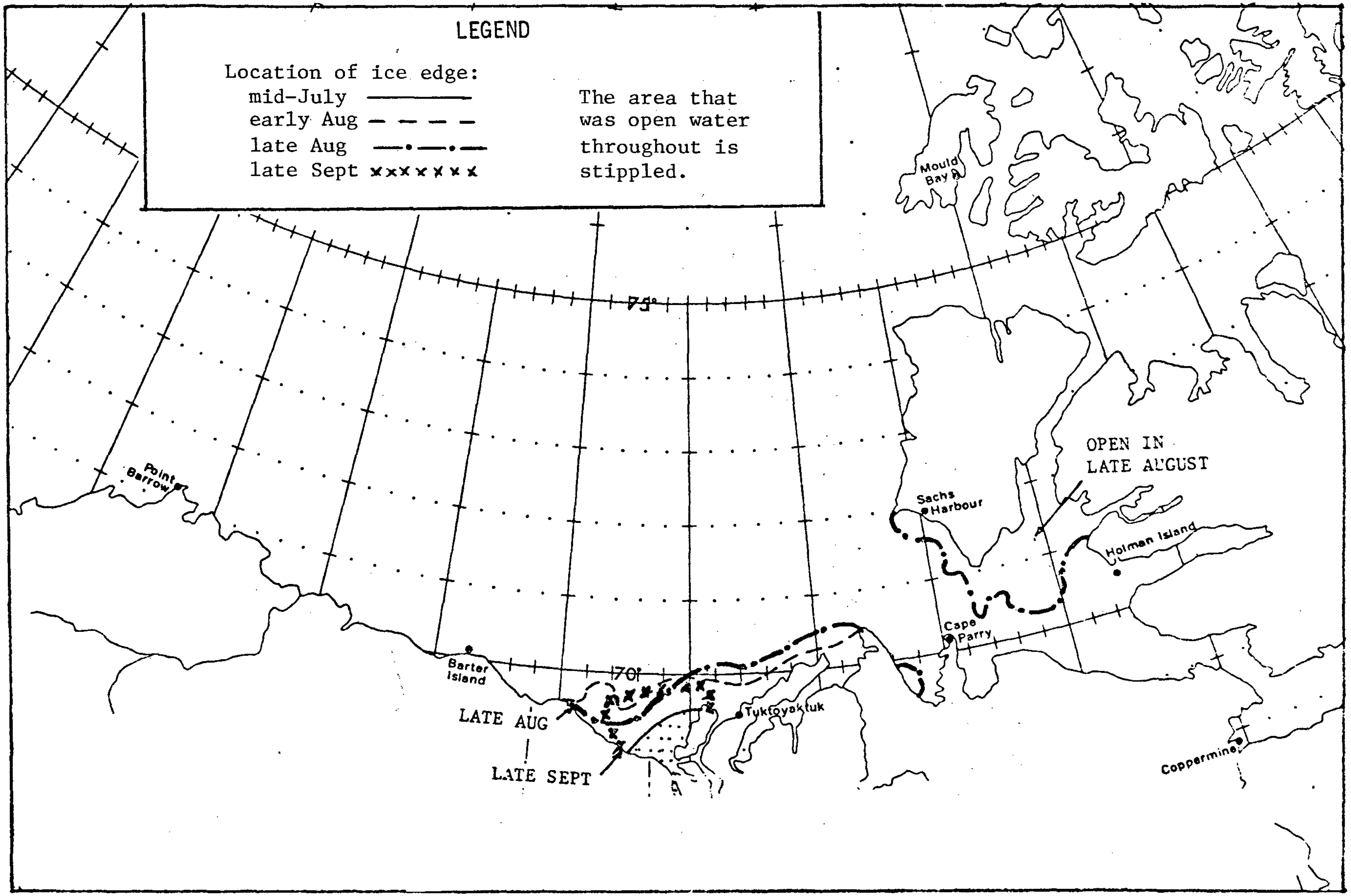

Figure 1.13. 1974, a "poor" ice year. Onshore winds and resulting low temperatures persisted through most of the summer resulting in one of the worst ice years on record. (Near Barrow, open water areas may have been more extensive than shown here. Ed.) (Markham, 1975).

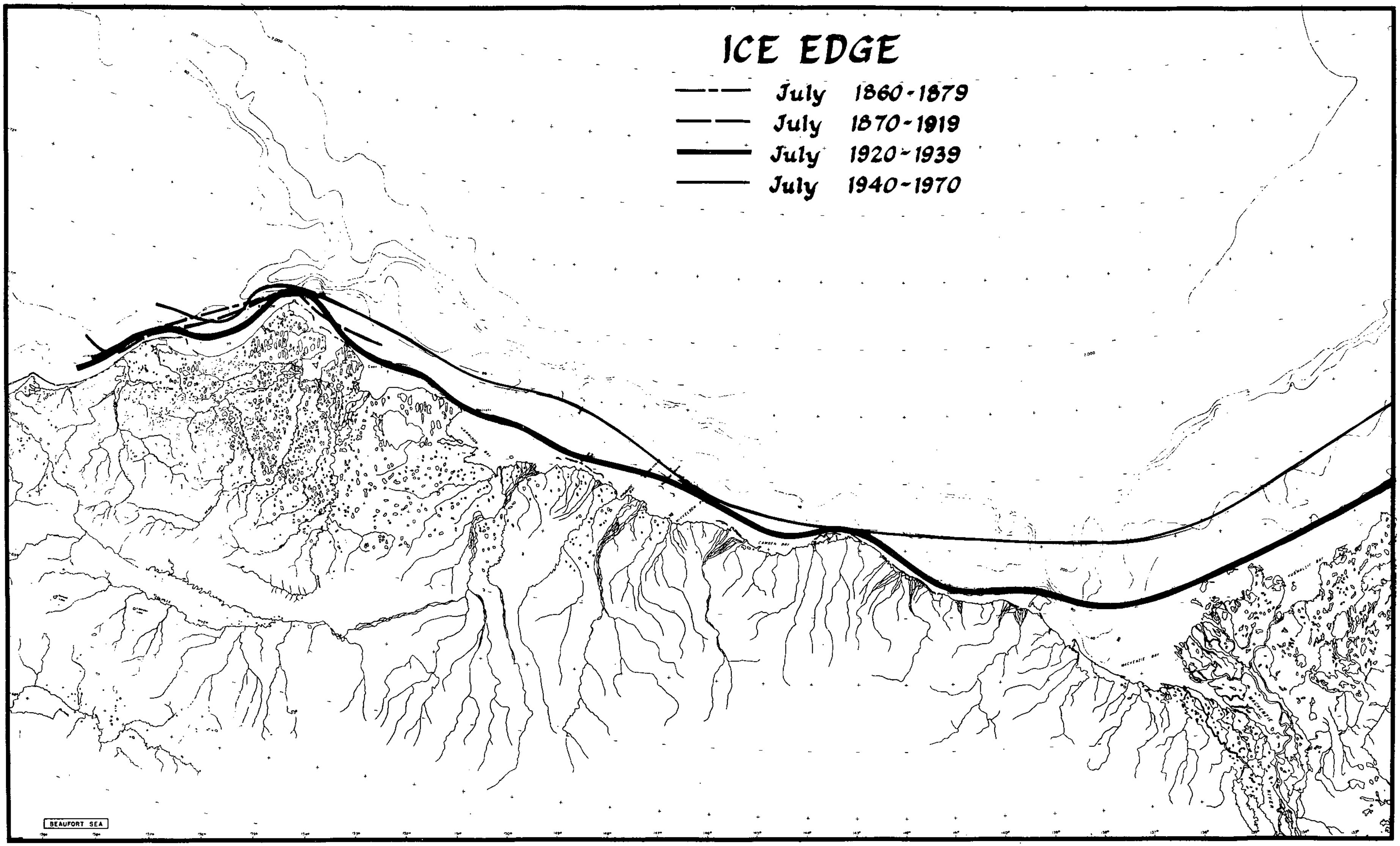

Figure 1.14. Average July pack ice edge for the years shown (Hunt and Naske, 1978).

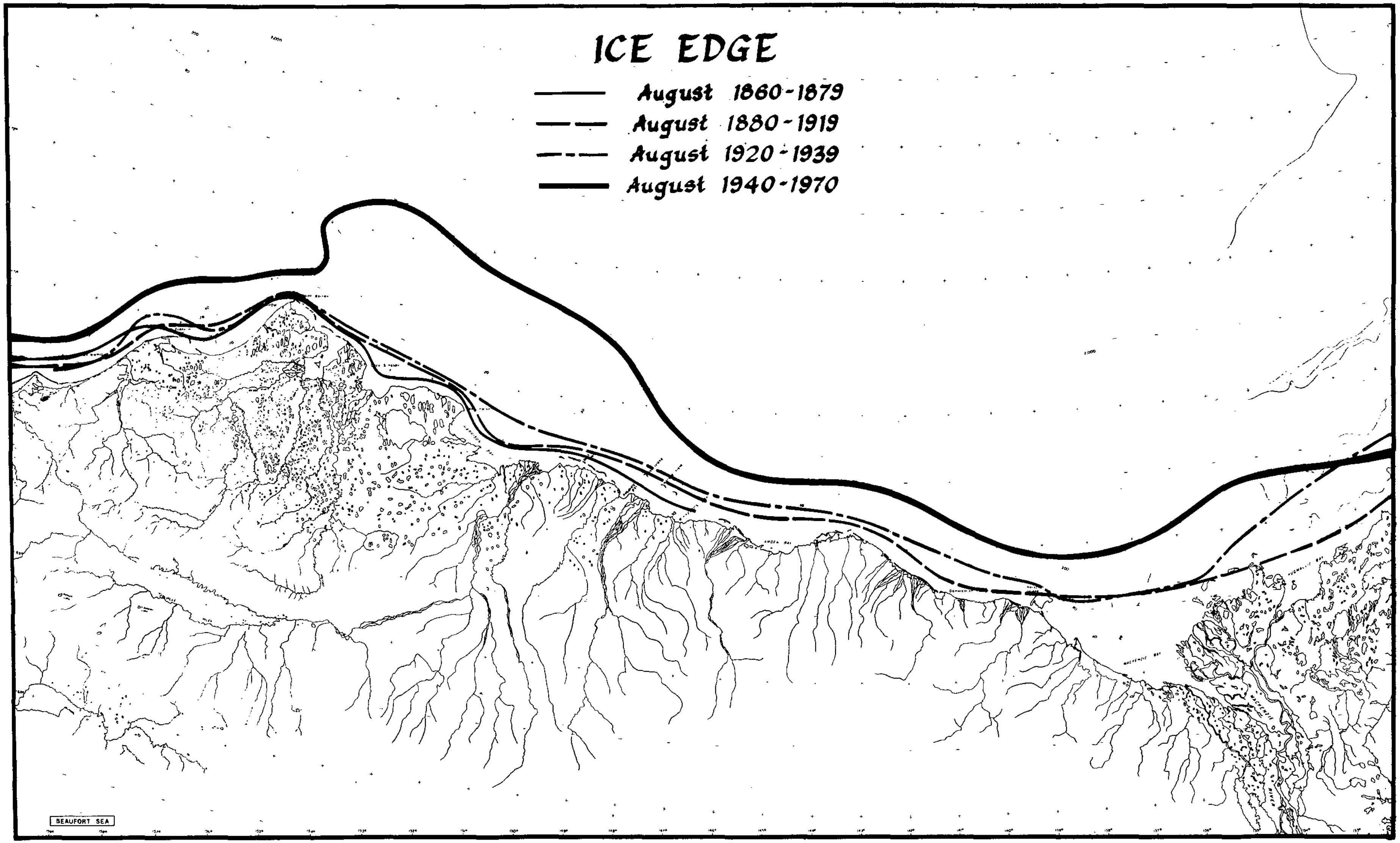

Figure 1.15 Average August pack ice edge for the years shown (Hunt and Naske, 1978).

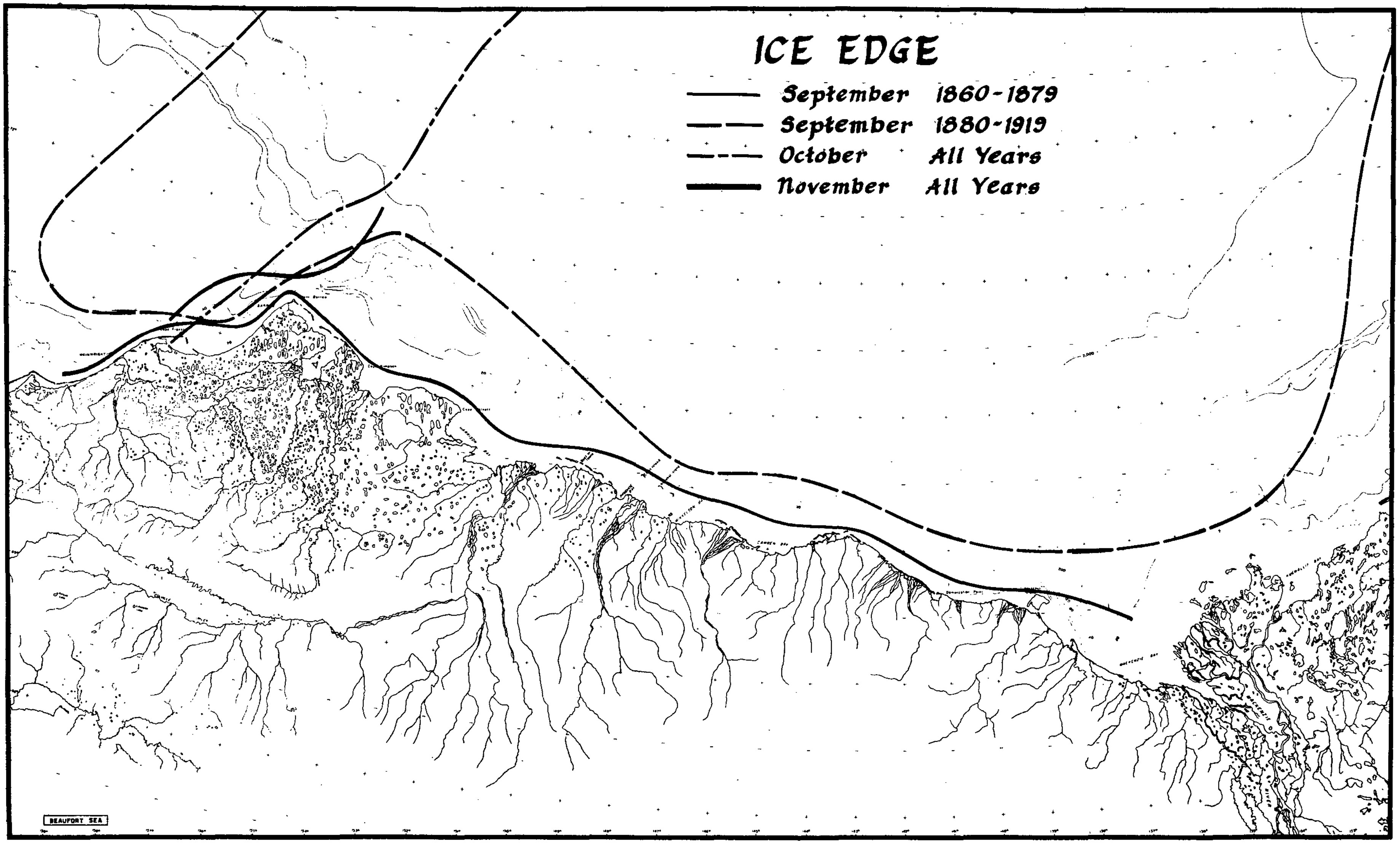

Figure 1.16. Average pack ice edge for the months and years indicated (Hunt and Naske, 1978).

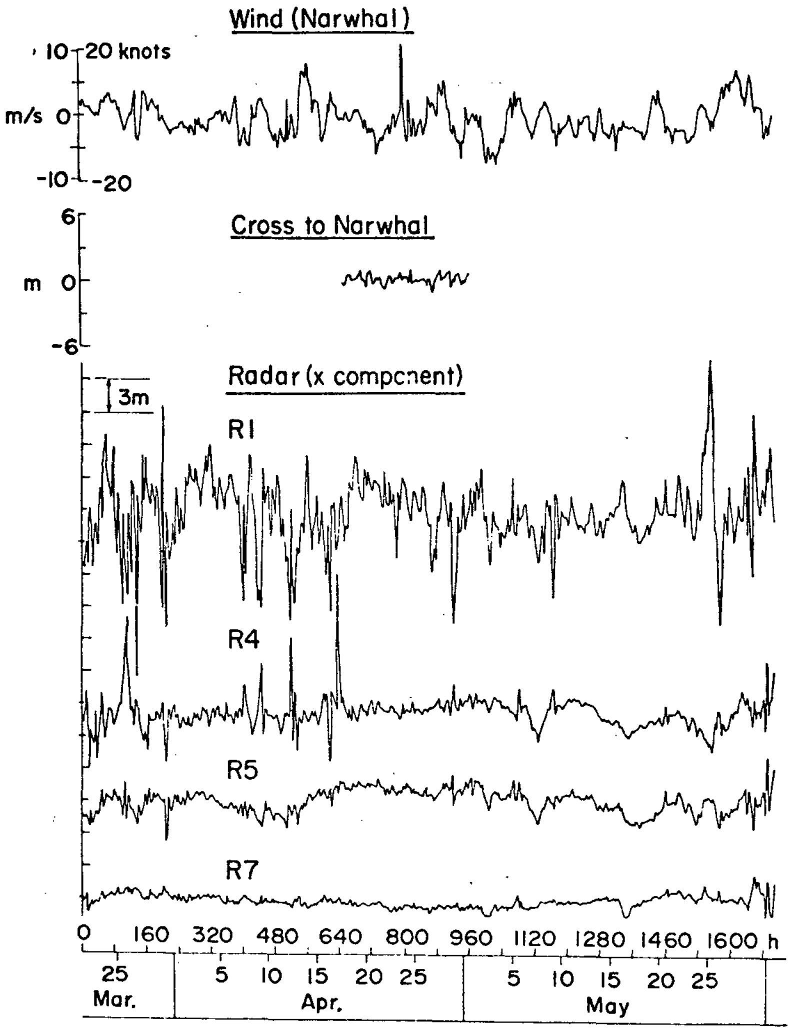

Figure 1.17. Time series showing the variation in the position (x-component measured perpendicular to the coast) of transponders placed on fast ice north of Narwhal Island (Weeks et al., 1977). See Figure 4 for locations.

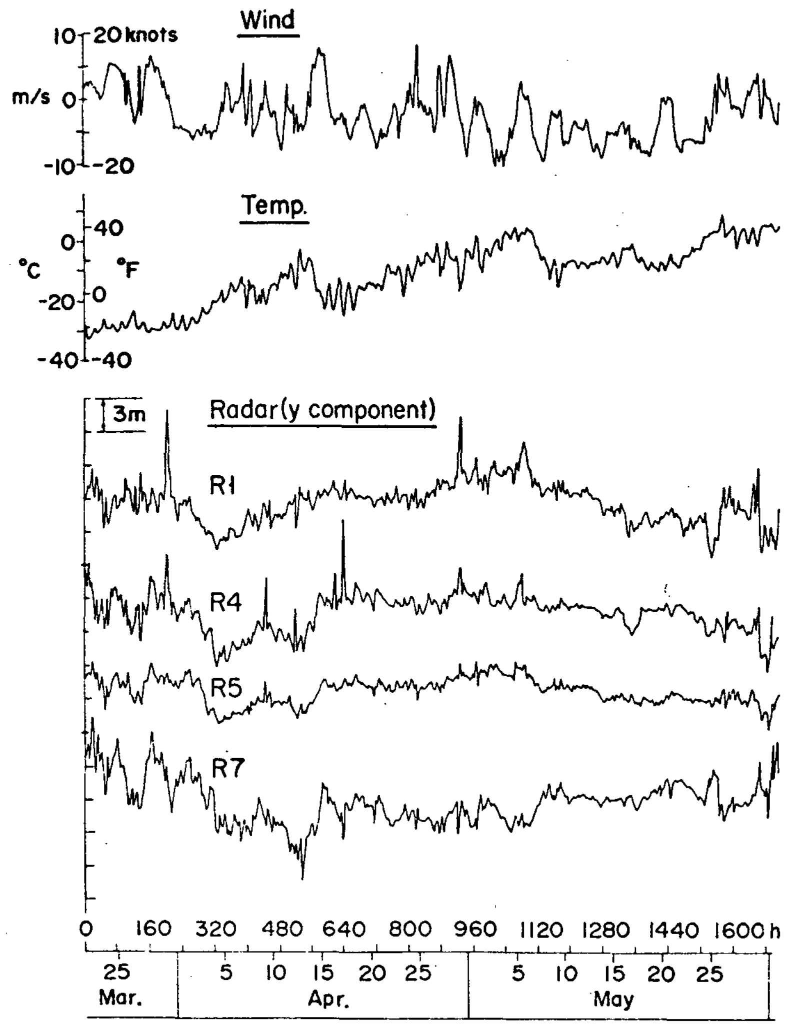

Figure 1.18. Time series for y-component of data shown in Figure 1.17.

The pack ice motion within the Beaufort Gyre has been the subject of the nearly completed AIDJEX project, which used the development of a mathematical model to describe the motion. Under OCSEAP sponsorship a number of data buoys were deployed during 1975, 1976, and 1977 in both the central and nearshore areas of the Beaufort Sea (Untersteiner and Coon, 1977; Thorndike and Cheung, 1977). The drift tracks which these followed are shown in Fig. 1.19 as monthly averages.

These tracks clearly indicate the clockwise westward drift of the Beaufort Gyre, paralleling the mean geostrophic wind field. The speed of the ice in the Gyre averaged nearly 20 km/month in winter, and up to 80-100 km/month in summer, in the direction indicated. However, shorter term motions in other directions with velocities up to 25 km/day, occurred in response to individual storms. From Fig. 1.19, it is apparent that some of these diversions were large enough to influence the monthly drift tracks.

The motion of the ice cover of the western Beaufort Sea is strongly influenced by the motion of the ice of the Chukchi Sea. Shapiro and Burns (1975) have identified occasional major breakouts of ice through the Bering Strait into the northern Bering Sea. Such breakouts, along with other events producing westward motion of the ice in the Chukchi Sea, tend to lower the concentration of ice in that area. This permits large westward motion of the ice to occur in the Beaufort Sea under appropriate driving forces. Note, however, that a major reversal in the direction of movement occurs during June, July and August (see Fig. 1.19), when the flow of ice is largely from the Chukchi Sea into the Beaufort Sea.

The AIDJEX numerical model noted above has been used to simulate a major ice deformation episode which occurred during January and February 1976 for which the motion of the data buoys was known and satellite imagery was available. The model accurately reproduced the observed motion of the data buoys, and also predicted the position of a major lead system which developed during the storm (Pritchard, 1977, in press). This demonstrates the potential of the model as a tool for determining the motion of the pack ice from climatologic and oceanographic information, with the potential for short-term prediction of events which could present hazards to offshore operations.

Characterization of the pack ice in terms of the distribution of multiyear ice, ice islands and pressure ridges is important for assessment of the hazard to offshore development. Features such as these represent large masses of ice which can move against a structure generating large forces. Therefore, there is a need to know the frequency with which one or more of these features can be expected to drift across any point within an area of potential operations. The first step in evaluating the probability of such an event occurring is to develop an accurate description of the distribution of these features in the pack ice and progress in that direction has been initiated (Weeks and Kovacs,1977).

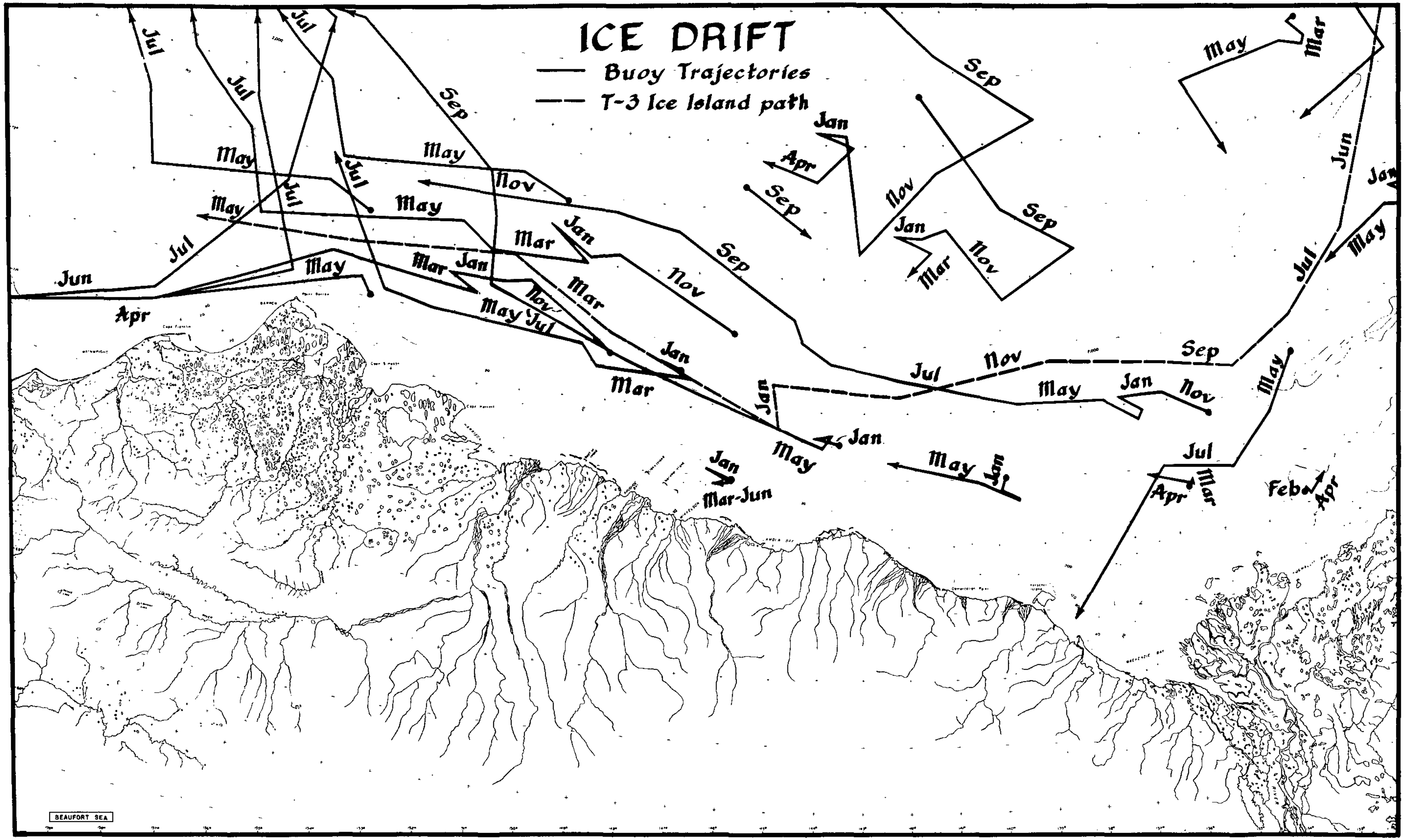

Figure 1.19. Drift tracks by month for data buoys deployed during 1975-1977. Note trajectory of Ice Island T-3.

The data upon which this work is based were acquired during a series of flights along lines extending 200 km to sea from Barter Island, Cross Island, Lonely, Barrow, Wainwright and Point Lay. The flights took place during February, April and December of 1976, and continuous observations were made using a laser profilometer, which gives a detailed topographic profile along a flight line, and a Side-Looking Airborne Radar (SLAR) system. Details are given in Weeks et al. (1978) and Tucker and Weeks (1978, in press). Note that because the flight lines originated at the shoreline, the survey includes the area of floating fast ice and the grounded ice zone, as well as the pack ice zone.

Figure 1.20 shows the frequency histograms of the heights of pressure ridge sails as measured on 100 km of laser sample track during February 1976. These indicate an exponential decrease in frequency with increasing sail height as has been found in previous studies (Hibler, 1975; Wadhams, 1976). Figs. 1.21, 1.22, 1.23 and 1.24 are plots of three variables which describe the degree of deformation of the ice vs. the distance from shore. The variables are: 1) number of ridges per 20 km of flight line; 2) the mean height of ridges higher than a lower cut-off of 1 m; and 3) the ridging intensity (I_r) which is an index of the total volume of ice incorporated into ridges. These show that the most intensely deformed ice occurs off Barter Island with the degree of deformation decreasing towards the west. Further, there is an increase in the degree of deformation in all areas between the data taken in December and that in February, but little if any difference between February and April. Finally, comparison of Figs. 1.21 and 1.23-1.24 shows that the number of ridges and the ridging intensity reach a maximum between 30 and 50 km from the coast, in the area corresponding to the grounded ice zone.

The data presented above could be used to calculate the probability that a fixed structure at some distance from the shore will be impacted by ridges of a particular height. Details of the calculations are given in Wadhams (1976), Weeks et al. (1978) and Tucker and Weeks (1978). These studies all indicate the need for accurate values of the ice drift velocity of the nearshore part of the pack ice cover and, as described above, this information is still lacking. Note that part of the proposed lease area lies within the nearshore pack ice zone.

The SLAR data acquired during the above flights has been used to estimate the extent of the ice cover which is occupied by deformed (i.e., ridged or broken) ice, and to determine the distribution of multi-year ice floes in the cover. Fig. 1.25 shows the percentage of the surface of 5 x 5 km areas of sea ice which give a strong return, indicating the presence of ridges or broken ice, plotted as a function of distance from the coast north of Lonely from data acquired in April 1976. This indicates that the most highly deformed areas were close to shore, decreasing with distance seaward. Fig. 1.26 shows histograms of the diameters and length/width ratios of multi-year ice floes identified on flights from Barrow and Lonely. The length/width ratios (the largest of which was 5.2) show that the floes are largely circular with the largest having a diameter of 3.6 km. The rounding apparently results from abrasion during drift. An interpretation of the fact that the floe size distributions are approximately negatively exponential is given in Weeks et al. (1978).

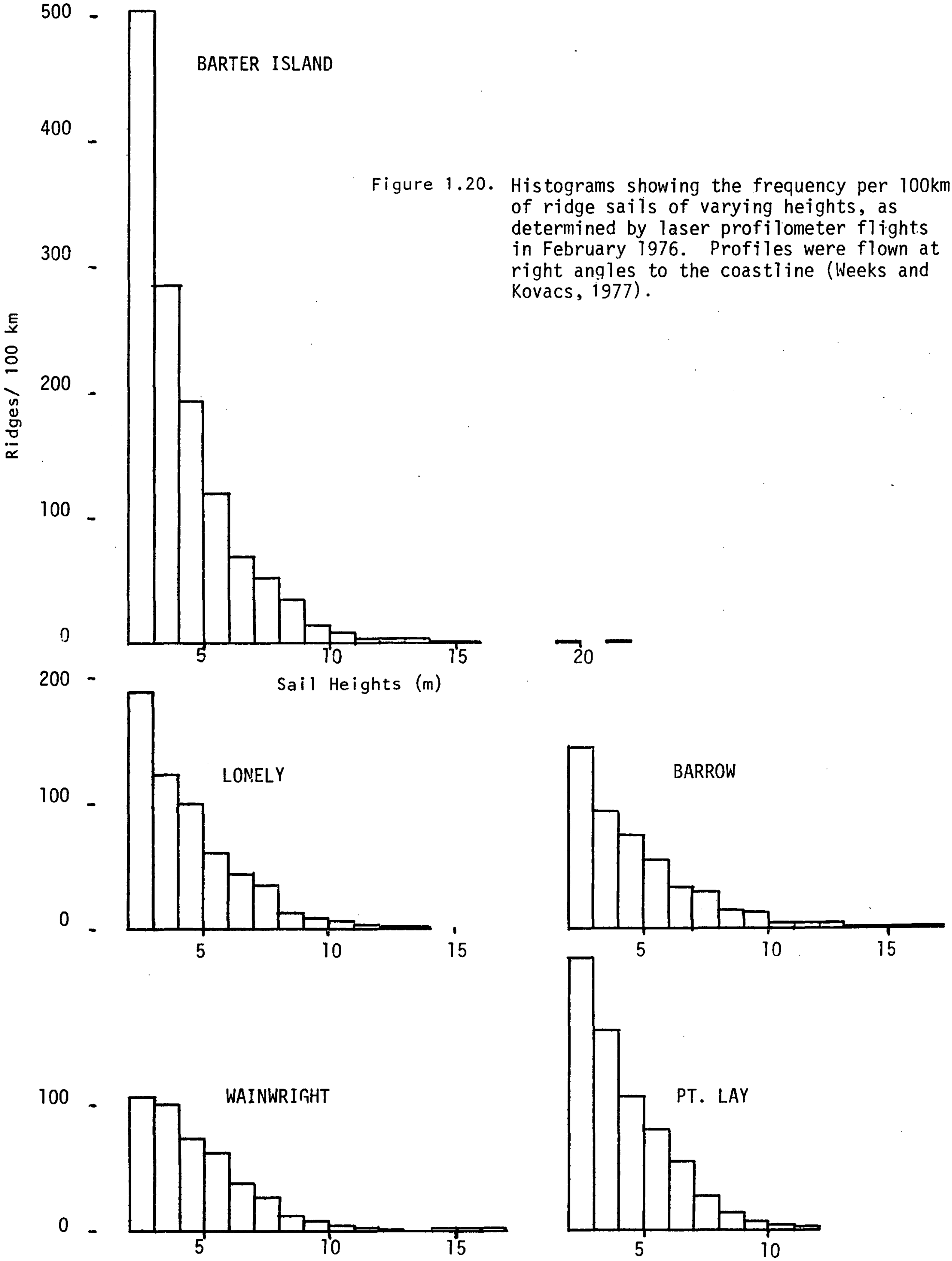

Figure 1.20. Histograms showing the frequency per 100km of ridge sails of varying heights, as determined by laser profilometer flights in February 1976. Profiles were flown at right angles to the coastline (Weeks and Kovacs, 1977).

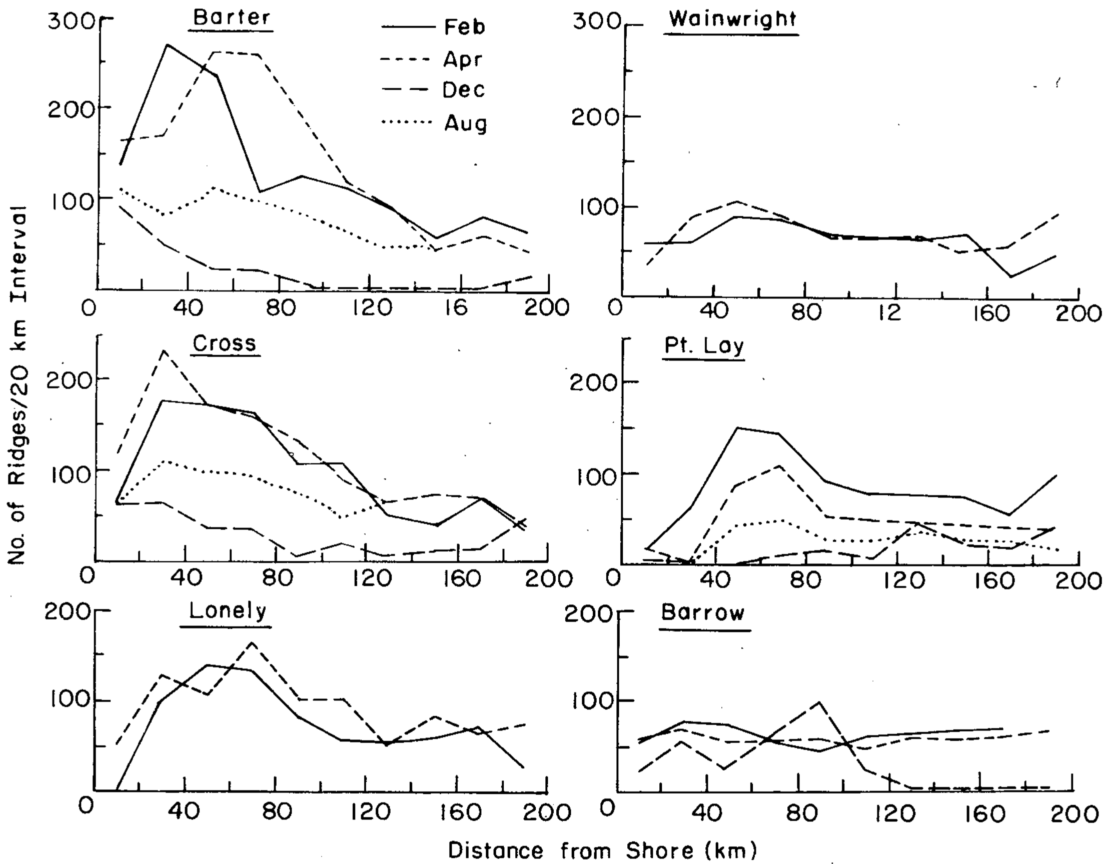

Figure 1.21. Number of ridges per 20 km interval for flight lines normal to the coast originating at locations indicated during 1976 (Weeks et al., 1978).

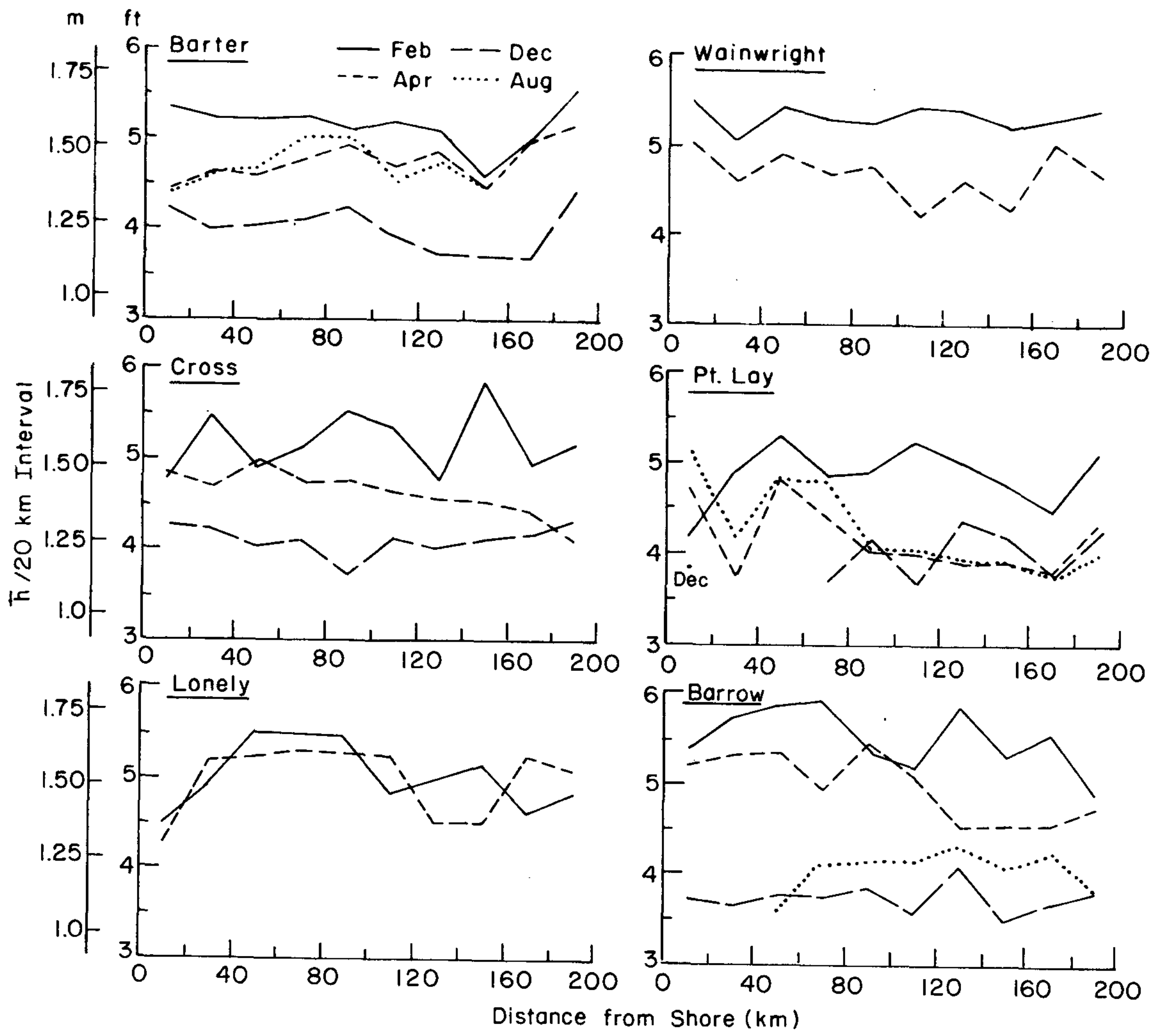

Figure 1.22. Mean height of ridges greater than 1 m for flight lines shown in Figure 1.21.

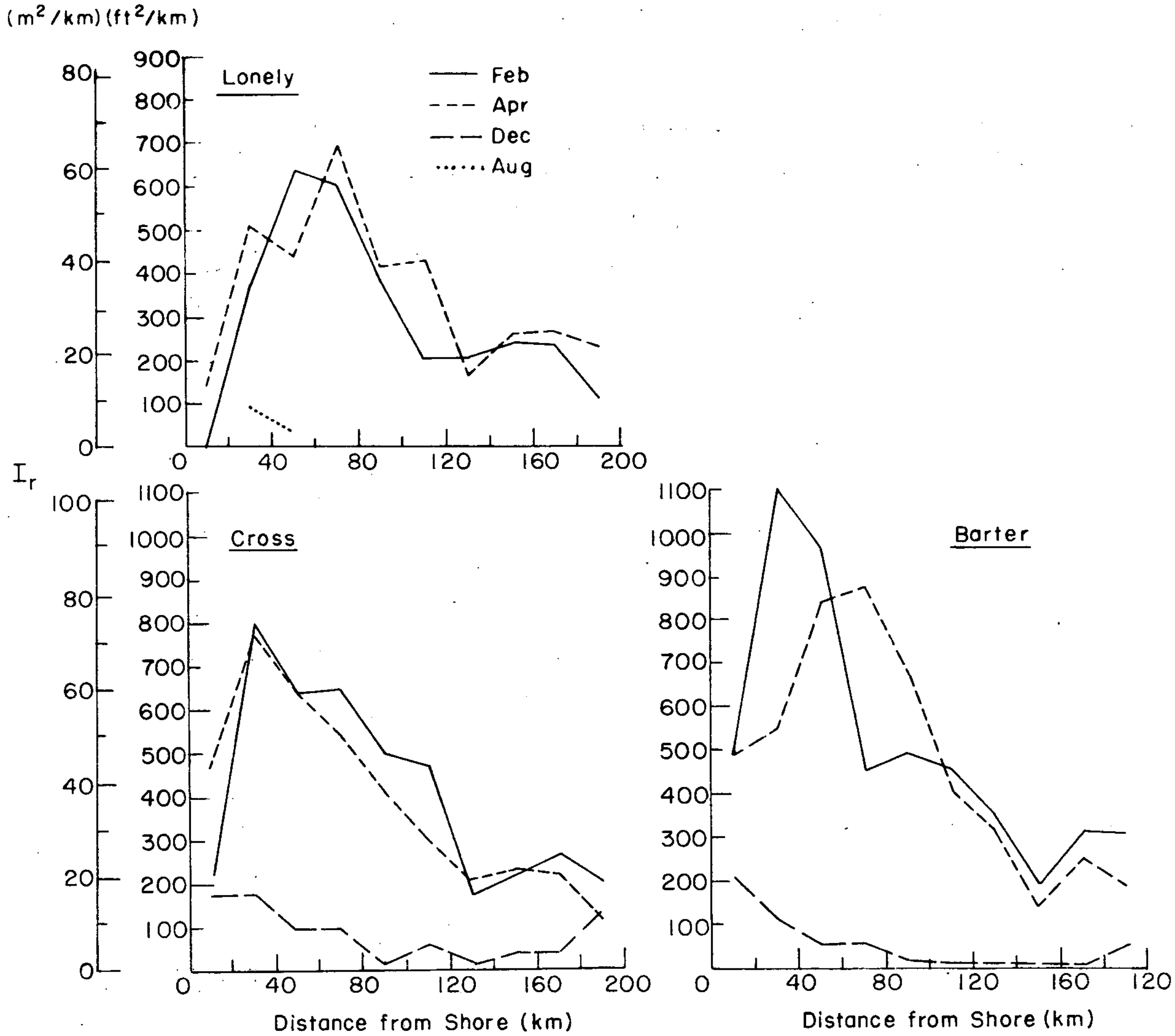

Figure 1.23. Ridging intensity along flight lines shown in Figure 1.21.

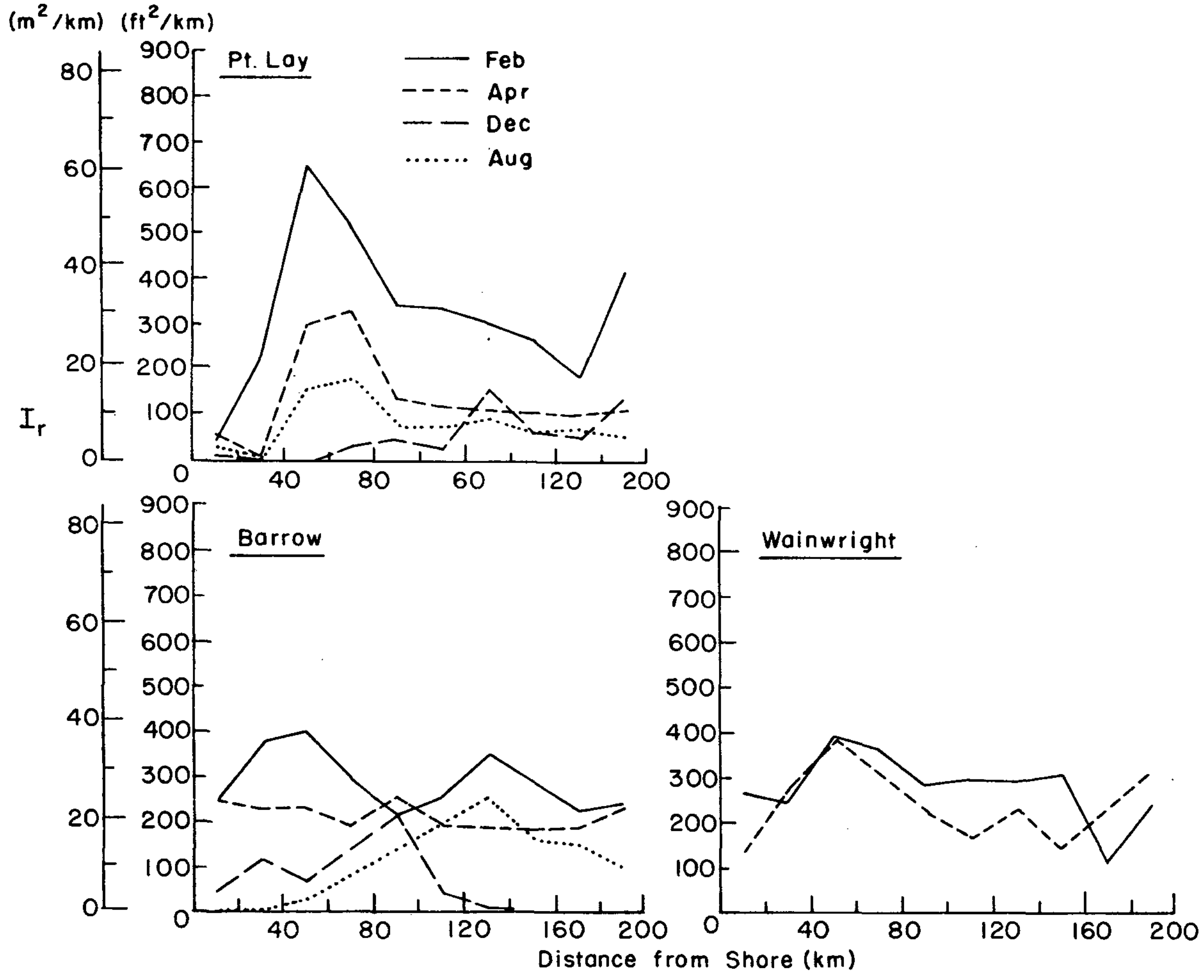

Figure 1.24. Ridging intensity along flight lines shown in Figure 1.21.

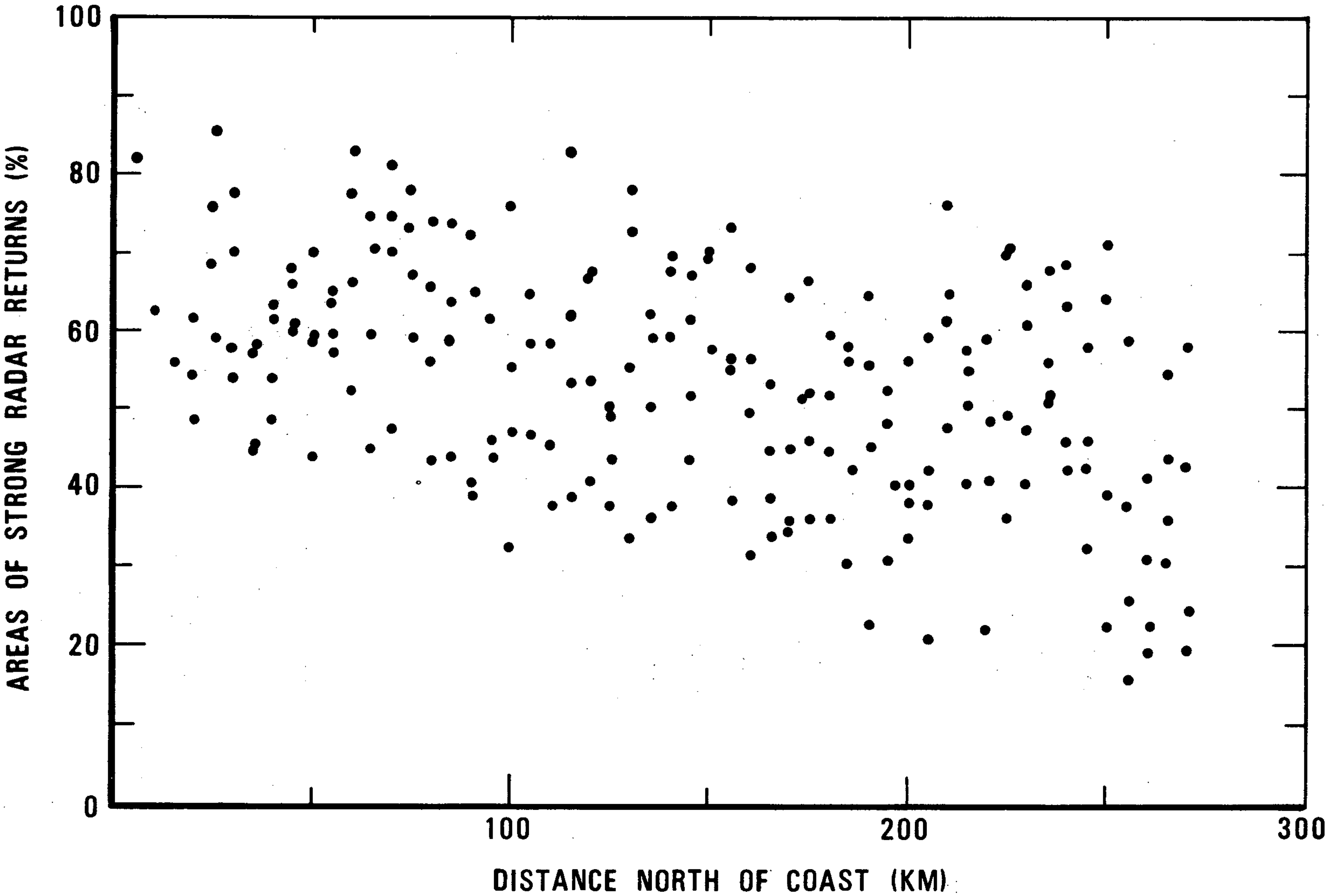

Figure 1.25. Percentage of 5 x 5 km^2 areas containing deformed ice plotted as a function of distance north of the coast at Lonely (Weeks et, al., 1978).

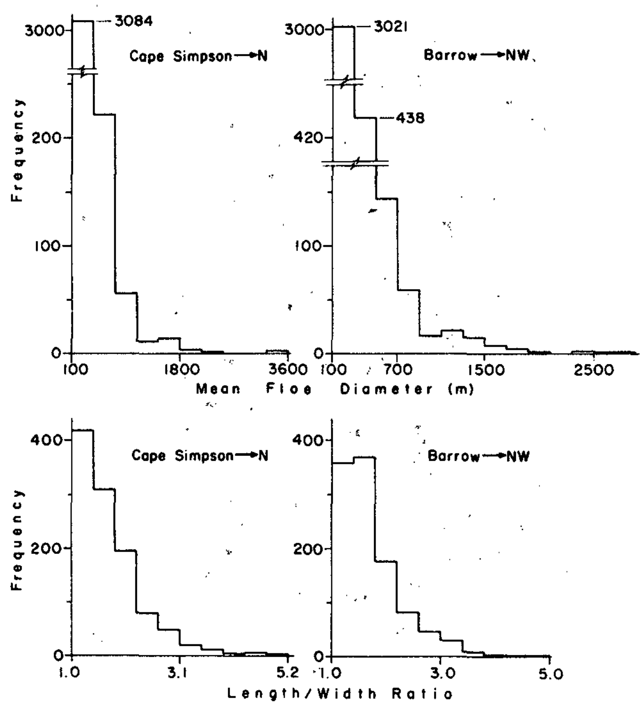

Figure 1.26. Histograms of diameters and length/width ratios of multi-year ice floes identified on flights of 200 km originating at Lonely and Barrow (Weeks et al., 1978).

Special Problems

Stress in the Sea Ice Cover

As noted in the introduction, the motion of the ice cover occurs in response to stresses of meteorologic and oceanographic origin, which are capable of being transmitted over large distances. These stresses will be termed "geophysical stresses" for the purpose of this discussion. The actual force which a structure must withstand depends upon the geometry of the structure and the strength of the ice in the mode of failure with which it is expected to break upon impacting that structure. Geophysical stresses enter calculations of force on a structure by determining the direction, velocity and duration of motion of the ice in the vicinity of a structure. Direction may be unimportant in many situations, but velocity and duration can be critical. The velocity influences the rate at which the force against the structure increases, and the strength of the ice is strongly dependent on this rate. The duration of motion defines the volume of ice moved against the structure, which can pile into rubble fields or ridges causing the geometry of the interaction between the ice and the structure to change from that which was anticipated in the design. For structures located seaward of the grounded ridge zone, the geophysical stresses directly determine the motion of the ice. However, shoreward of this zone, these stresses are probably modified by interaction with the grounded ridges. In addition, within the landfast ice sheet, stresses arising from thermal expansion and contraction of the ice sheet may also be important.

A program of stress measurements, funded by the NOAA Sea Grant Program, was conducted in 1976, in the area in which the ice motion was being monitored by radar ranging as described above. The results of these measurements have been correlated with the ice motion data (Nelson et al., 1978, in press) and indicate that peak stresses associated with thermal expansion of the ice are about 0.14 MPa (20 psi). Stresses correlated with pack ice motion were about 0.07 MPa (10 psi) and an average stress at the boundary between the pack ice and the landfast ice of 0.21 MPa (30 psi) was inferred. This set of measurements, however, is unique and needs to be repeated.

As noted above, during breakup at Barrow the ice sheet is often thrust onto the beach, resulting in the formation of pressure ridges in very shallow water. Field study of these features (Shapiro, Harrison and Bates, 1977) has provided the basis for calculation of the stresses required to cause these movements. Two independent calculations can be made from the data. The first considers the force required to drive the ice sheet up the inclined plane of the beach, while the second involves a modified form of the pressure ridging model of Parmerter and Coon (1973) which accounts for the fact that the ridges formed along the shoreline are grounded. The results of these calculations can be compared with the measurements by Nelson et al. (1978, in press) given above, and appear to be similar. The maximum stress calculated for thrusting up the beach was 0.17 MPa (25 psi), applied to a front of about 0.5 km along the beach. The average value calculated for the stress which drove the ice up the beach was probably lower, and in the range of 35-65 kPa (5-10 psi). Stresses calculated from the ridging model were lower still, with values in the range of 10-20 kPa (1.5-3 psi).

The measurements and calculations described above appear to indicate that a value of about 0.21 MPa (30 psi) is a reasonable upper limit for the magnitude of the geophysical stress transmitted from the pack ice to the edge of the landfast ice during the time periods covered by the data. However, calculations of stresses in the pack ice (Untersteiner and Coon, 1977) show that values as much as an order of magnitude greater than this can be generated under some conditions. The question of whether such stresses can be transmitted into the ice of the fast ice zone is still open and requires further work.

The presence of grounded features in the ice, either natural or man-made, causes the stresses transmitted through the ice to become concentrated at the point of grounding. It is of interest to attempt to measure the stresses in the ice around such natural features as a means of determining stress levels which can be reached when drifting ice collides with obstacles. For this purpose, two sets of field measurements were made (Sackinger and Nelson, 1978). The first of these was made in April, 1976 at "Katies's Floeberg," a large grounded ice mass which forms yearly near $70^{\circ}00'$ N., $162^{\circ}00'$ W., about 100 km from Barrow. An array of stress sensors was embedded in the pack ice adjacent to the grounded feature for the purpose of monitoring the stress level developed when the pack was driven against the stationary object. The results indicated predominantly compressive stresses with high frequency pulses reaching at least 1.7 MPa (250 psi). The data also indicate that the floe in which the sensors were located was not destroyed during the movement.

The second set of measurements was made in fast ice on the seaward side of a grounded pressure ridge off Barrow between February and June, 1977. During this period predominantly tensile stresses were measured. In one case, these reached a magnitude of 0.69 MPa (100 psi) during a period of high, offshore winds which caused narrow leads to open in the landfast ice sheet. At that time the stresses had the form of rectangular pulses of several minutes duration. Similar stresses were recorded during breakup and, in this instance appear to have been caused by the irregular nature of the interaction between floes at the margin of the landfast ice zone. This emphasizes the point made above regarding the lack of understanding of the deformational characteristics of the ice along this boundary.

Finally, it is of interest to note that several events have been observed in the fast ice, in which rising stress levels in the ice have been accompanied by a vibration of the ice sheet with a period of about 10 minutes (Shapiro, Harrison and Bates, 1977; Nelson et al., 1978, in press). The physical basis for this association is currently under study and, if understood, may provide a useful method of anticipating stress increases and possible movement of the landfast ice sheet.

Prediction of Summer Ice Conditions

As noted above, the study of the correlation between meteorological data and ice conditions along the Beaufort Sea coast of Alaska has led to a procedure for predicting the severity of ice conditions in that area as it might affect summer operations (Rogers, 1977, 1978; Barry, 1977). The method is based upon the air temperature at Barrow which tends to be persistent over the summer, with months of above normal or below normal temperatures seldom occurring in the same year. The details and description of the statistical basis for this conclusion are detailed in the reference above. The results of the study are shown in Table 1.3 in which 5 stages of breakup and retreat of the ice along the coast have been identified, and the number of accumulated thawing degree days (TDD's) required to reach each stage are indicated. The prediction capability follows from the result that the total number of TDD's which are likely to occur in any one month of the melt season (except May, the first month) is statistically related to the number of TDD's accumulated prior to the month.

TABLE 1.3. STAGES OF ICE BREAKUP AND FREQUENCY OF OCCURRENCE OF ASSOCIATED TDD ACCUMULATIONS DURING SUMMERS 1921-1976 AT BARROW.

Stage of ice breakup and retreat	Associated TDD accumulation	Freq. of occurrence during Barrow summers	
		1951-52	1953-76
(1) Initial thawing of fast ice	<100	0	0
(2) Fast ice breaking up, open water appears	100 to 250	1	1
(3) Fast ice gone, pack starts melting	250 to 400	3	10
(4) Pack retreats up to 100 km	400 to 500	12	5
(5) Pack retreats over 100 km	>550	16	8
	Mean summer TDD accumulation	559	494
	Standard Deviation	173	187

The two columns on the right of Table 1.3 for each of the 5 stages, indicate the number of summers for which that stage represented the final retreat of the ice for the years indicated. The break between 1952 and 1953 is based upon a change in the number of TDD's accumulated annually which is, on the average, lower than the long-term mean accumulation by about 65 TDD's. This corresponds to a temperature change of $-0.4^{\circ}C$ over an assumed 90-day summer. The above results suggest that an indication of the severity of ice conditions for any summer can be obtained by late spring, in time to influence the planning of summer operations.

Oil in Sea Ice

Martin (1977) has studied problems related to the interaction of oil with sea ice. These studies have taken place in the laboratory, at several controlled spills of small quantities of oil in the Canadian Arctic, as part of the Canadian Beaufort Sea Project, and at the Buzzards Bay, Massachusetts, 86,000 gallon oil spill of January 1977.

This work has emphasized the vertical movement of oil in sea ice over the season of ice growth, and the overall characteristics of the ice which determine how and where the oil is entrained. For first-year sea ice, the results of both the Canadian and Martin's studies are as follows:

1. Oil is trapped in natural undulations under the ice where, because of its thermal properties, it acts as an insulator and decreases the rate of addition of new ice below the oil layer.

2. Oil released under the ice tends to migrate into the skeleton layer at the base of the ice sheet which can entrain over 5% by volume of oil. A similar quantity of oil was observed to be entrained between platelets in strongly oriented columnar ice.

3. Oil tends to migrate upward through the ice sheet following brine channels. During the winter months, when the brine channels are small, movement is restricted, but during spring the channels enlarge and the oil can pass completely through them and spread over the surface.

4. The porous surface layers of the ice sheet entrain oil which rises through the ice sheet. Additional oil is trapped in a zone of bubbles which is commonly present above the freeboard level of the ice.

5. The presence of oil near and on the ice surface increases the local absorption of solar radiation, which results in the formation of melt ponds earlier in the year than would otherwise occur. There is evidence from the Beaufort Sea Project that these oily melt ponds attract migratory birds.

Both the laboratory experiments and the Buzzards Bay spill show that in moving pack ice, some of the oil spilled under the ice will eventually rise to the ice surface. In laboratory experiments with pancake ice, approximately 50% of the oil released under an oscillating field of pancake floes was washed onto the surface. For the Buzzards Bay spill, which took place in an actively moving ice field composed of floes with diameters of 10-20 m, most of the spilled oil flowed to the ice surface through cracks around pressure ridges and rubble fields, and up into ponds with depths of 0.1-0.2 m formed by rafting of the ice floes. The Buzzards Bay spill is described in detail in an OCSEAP report (Deslauriers, Martin, Morson and Baxter, April 1978) which contains a wealth of information on the interaction of oil with a field of small ice floes. However, basic information is still lacking on how a well blow-out, for example, would interact with the massive ice in the proposed lease areas.

The bottom topography of the ice sheet is critically important to the dispersal of oil under the ice. Kovacs (1977) has determined the bottom roughness of both first-year and multi-year ice along traverses of a few hundred meters, and additional, more extensive studies by Barnes and Reimnitz are in progress. Preliminary results from Kovacs indicate possible oil entrapment volumes of 0.03 m^3/m^2 for first-year ice, and 0.3 m^3/m^2 for multi-year ice within the limited area surveyed.

Mechanical Properties of Sea Ice

Schwarz and Weeks (1978) have recently reviewed the status of knowledge regarding the engineering properties of sea ice. Table 1.4, taken from that report, lists the problem areas and the information requirements for the solution of engineering problems within each area. Details of the review are beyond the scope of this report, but it can be stated that important data gaps exist with respect to many of the variables of interest. In particular, values of the strength of sea ice in different failure modes as functions of the rates of loading, salinity, temperature and orientation of crystals have been investigated primarily for loads applied in one direction only and the results to date are not as definitive as is desirable. The effect of confining pressure, that is, simultaneous loading in two or three mutually perpendicular directions, is clearly important for engineering problems, but little published work exists on this subject. Finally, most of the work done to date on the strength of sea ice has involved laboratory samples with dimensions of a few centimeters (the exception to this is the use of large beams in *in situ* bending.) As described above, the structure and properties of the ice sheet change drastically from top to bottom with a strong gradient in temperature superimposed as well. As yet, however, there is no acceptable method for using the results of small-scale laboratory tests to define the strength of the ice sheet as it exists in nature. Given an acceptable procedure through which the necessary calculations could be made, it would still be necessary to conduct a series of tests on the full thickness of an ice sheet to verify the results. Few such tests have been done, and the results are not conclusive.

TABLE 1.4. DATA REQUIREMENTS FOR SELECTED PROBLEMS IN SEA ICE ENGINEERING

		Sea Ice Characteristics Required			
General Problem Areas	Specific Problems	Mechanical	Friction and Adhesions	Thermal	Electro-magnetic
1. Ships transiting sea ice	a) Ice resistance during breaking	X	X	X	
	b) Impact loads on hull plates	X	X		
	c) Forces exerted by converging ice	X	X		
	d) Ice reconnaissance			X	X
	e) Ice forecasting	X	X	X	
2. Design of offshore structures for Arctic sites	a) Ice forces on structures	X	X	X	
	b) Estimation of ice pile-ups	X	X	X	
	c) Abrasion of structural elements	X	X	X	
	d) Ice erosion of gravel islands	X	X		
	e) Remote sensing of ice thickness			X	X
	f) Reconstruction of ice dynamics from past metero-logical data	X	X	X	
3. Large loads on ice	a) Calculation of short term failure	X	X		
	b) Calculation of long term creep	X	X	X	
	c) Remote sensing of the ice thickness			X	X
4. Ice gouging of the sea floor	a) Forces exerted by grounded ice features	X		X	
	b) Ice reconnaissance			X	X
	c) Reconstruction of ice dynamics from past meteoro-logical data	X	X	X	

A program is in progress with the objective of correlating the results of one-directional, small-scale laboratory tests and similar tests on larger samples in situ (Shapiro, 1977). The program includes three aspects: 1) development of procedures for the necessary in situ tests; 2) analysis of published data on small-scale tests, and 3) comparison of the results of the small-scale and in situ tests. To date most of the required development has been accomplished, and a stress-strain law to describe the small-scale tests has been derived. Extension of the results to multi-axial loading has yet to be considered.

Information Gaps

The data gaps which exist and are outlined below are due to three interrelated factors. First, they reflect the relatively short time available for these studies, in that it is impossible to study phenomena which do not occur during the time of the investigation. As an example, there are no observations of the effects of a severe winter storm on the fast ice along the Beaufort Sea coast, because no such storm has occurred during the two field seasons of OCSEAP sea ice studies. Although doubtful, it may be, in fact, that the worst possible case of such an event did occur during this time, but this will not be known until the data base is extended in time. Second, the projects performed were necessarily limited by the available funding. Third, some data gaps either could not be recognized with the information available at the time the program was organized or, if recognized, the information required to properly address them was not available. An example of the latter case would be the problem of developing a predictive model for ice movement in the fast ice zone. Without the availability of a model for pack ice deformation and for transmission of stress to the fast ice, it is questionable whether a model for fast ice motion could be developed. The AIDJEX model is now available, and a start has been made towards examination of the pack ice motion in the nearshore areas, where it interacts with the fast ice. Thus, it might now be feasible to begin to design a program to develop a predictive model for motion of the landfast ice.

The following information gaps have been identified. Highest priority is given to (1), (2) and (3) because of their relevance to potential problems in the proposed Beaufort lease area.

1. Oil dispersal under the ice. As noted above, the bottom topography of the ice is critical to the dispersal of oil, as is the ocean current regime. Additional surveys of bottom topography will probably be required to accurately define the entrapment volumes for various ice conditions. Continuously grounded ridges may serve as barriers to dispersal, but the continuity of grounding even within the "grounded ridge zone" is unknown. The problems of oil dispersal in moving ice also require further study.

2. Frequency of occurrence and mechanism of override of beaches and barrier islands, particularly during breakup. Overriding of beaches resulting from large ice movements is a common occurrence along the Chukchi Sea coast, particularly during the breakup period. Such events are apparently less common along the Beaufort Sea shoreline, but may present a problem to offshore structures. Further work is required on the pattern of ice motion during breakup along the Beaufort Sea coast, and on the override mechanism.

3. Mechanisms of pressure and shear ridging, with emphasis on the grounded ice zone. Studies are required on the geometry and degree of cohesion of ridges, in particular those which remain grounded through part of the melt season and become reinforced by meltwater seeping down from the surface and refreezing in voids within the ridge. Additional model calculations focusing on the local forces are also needed, as is an analysis of wind and synoptic weather data in relation to ridging events. Finally, the influence of bottom topography on the localization of ridges, and on ice zonation in general, requires further work.

4. Characterization of pack ice features. It is important that a data base be established and continuously improved upon regarding the distribution and occurrence of multi-year ice and ice islands in the pack ice zone. The information gathered should include size, frequency in space and time, strength parameters where possible, and geometry of embedded ridges (for multi-year ice). In addition, a program of developing modeling techniques for predicting the frequency of formation of ice islands and their potential drift tracks would be valuable.

5. Movements in the nearshore pack ice zone. As indicated in the discussion above, the motion of the pack ice in the area outside the grounded ridge zone was found to be not in accord with what was anticipated, reflecting the fact that the interaction between the pack ice far from shore, the nearshore pack ice, and the fast ice is not well understood. A better understanding of this interaction is required for modeling fast ice motion, and velocity data are needed for predicting the frequency with which multi-year ice and ice islands can be anticipated to transit the nearshore area.

6. Mechanical properties of sea ice. Additional studies are required on the mechanical properties of sea ice in general, but in particular, on the strength of ice in various modes of failure. It is very likely that large scale tests will be required at some stage in the study.

Of the information gaps listed, (1), (2), and (3) apply specifically to the landfast ice zone and grounded ridge zone included in the proposed lease area. Of the remainder, (4) and (5) as well as (1) and (3) are applicable to the area outside the landfast ice zone. Information on mechanical properties (6) is required for all zones.

In addition to the information gaps, the following recommendations for additional studies are offered:

1. Development of a long-term data base. The period of detailed observations of processes which represent potential hazards to offshore development has been short, so that the total range of unusual or extreme events which could affect such development has probably not been observed. A continuing program of observations of ice conditions and events using LANDSAT, SEASAT and airborne remote sensing systems should therefore be maintained in order to fill this need. In addition, the data base concerning such events might be extended backward in time, through interviews with local residents, particularly with regard to the nearshore area.

2. Model of motion in the landfast ice zone. The development of a predictive model for ice motion in the landfast ice zone would serve to reduce the hazard of environmental damage during operations within this zone by providing early warning of impending movement of the ice. Such a model would provide time for defensive measures to be taken.

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2. PHYSICAL OCEANOGRAPHY AND METEOROLOGY

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Introduction

In order to show how oil or other contaminants move from a source to a biological target, the transport, dilution and change of the contaminant along its trajectory must be understood. This involves studies of ocean currents, circulation, waves and the hydrographic regime.

Progressing seaward we can identify four different oceanographic regimes:

1. A nearshore regime, in which there are both sheltered lagoons and more exposed embayments--in summer they are essentially wind-driven estuaries.

2. An inner shelf regime, which for discussion purposes may be taken to be bounded by the 10 and 50 m isobaths. While this area must be regarded as very poorly understood, it is probably primarily wind-driven, at least in summer.

3. An outer shelf regime, extending seaward to the shelf break. This is an energetic area even in winter. It is occupied in part by water from the Bering Sea.

4. The Beaufort gyre, which is part of the large-scale Arctic Ocean circulation.

We shall discuss these regimes further after some general considerations of winds, astronomic and storm tides, and fresh water discharge (see also Table 2.1).

Winds

Winds are of crucial importance to the nearshore and shelf circulations. Wind statistics for the North Slope are based on National Weather Service (NWS) observations. Compilations can be found in Figure 2.1 (Searby and Hunter, 1971) and Figure 2.2 (Hufford et al., 1976). The wind at Barter Island blows predominantly from two directions: from ENE-E (55-100°T) 35% of the time, and from WSW-W (235-280°T) 23% of the time. The mean wind speed in both sectors is 13 knots (6.7 m/sec). The most frequent wind direction at Barrow is from ENE during all seasons. The difference in wind direction at the two locations is probably due to the proximity of the Brooks Range to the coast in the eastern part of the region. Specifically, Schwerdtfeger (1974) has suggested that the difference is due to mountain barrier baroclinicity resulting from the piling up of cold air against the Brooks Range. The accompanying west wind parallel to the mountain range would then result in local westerlies occurring at Umiat and Barter Island more frequently than at Barrow. Such a topographic effect would be most marked in winter, but on occasion it could also be important in summer.

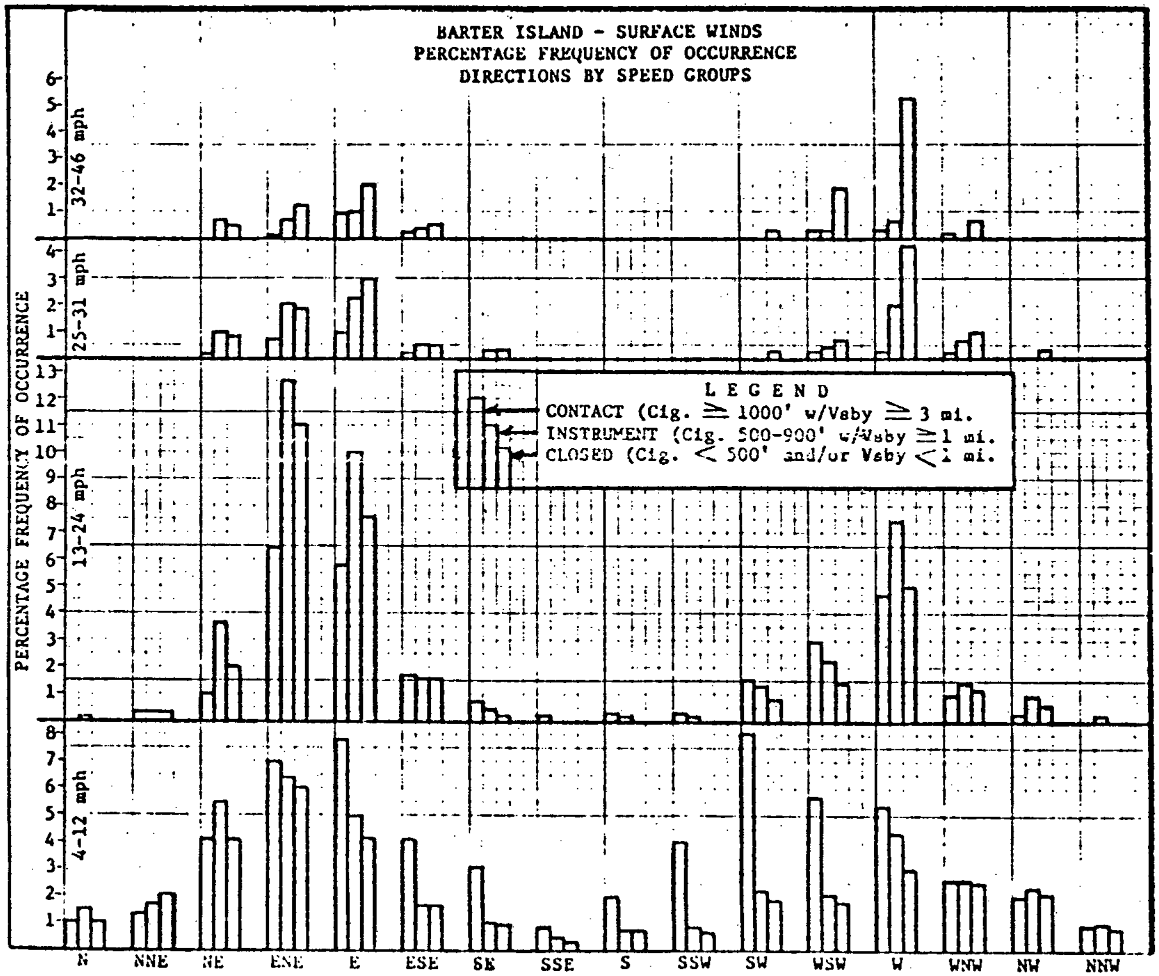


Fig. 2.1 Surface winds at Barter Island (Searby and Hunter, 1971)

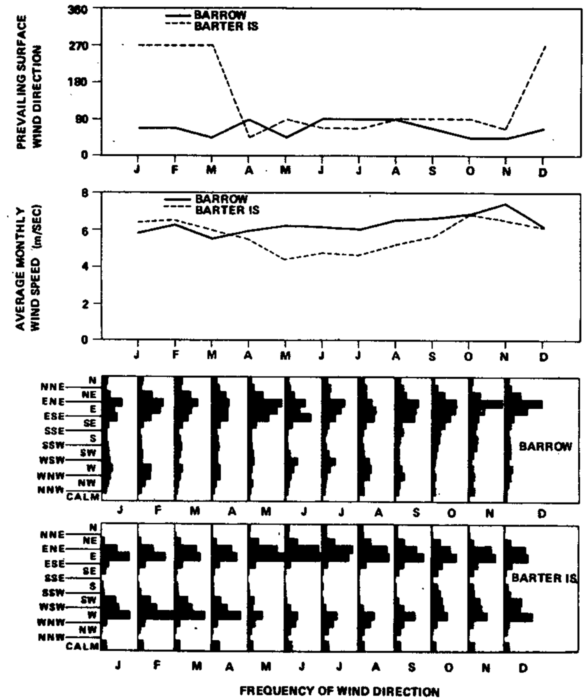


Fig. 2.2 CHARACTERISTICS OF THE WIND AT BARROW AND BARTER ISLAND, ALASKA.

Except for the few NWS stations, wind information for the coastal and offshore regions is sparse. The traditional method of obtaining surface winds from geostrophic winds computed from the surface pressure field is hampered by a lack of data, both inland from the coast and offshore. Carsey (1977) has shown that data from only two coastal stations some 600 km apart, viz. Barrow and Barter Island, can lead to significant forecasting errors. For example, Fig. 2.3, taken from Carsey, shows the increased detail in the pressure field when data from OCS buoys and additional measuring sites on land were added to the NWS data set. Geostrophic wind directions in the two analyses differ as much as 60°.

The use of inland stations (e.g., Umiat or Prudhoe Bay Airport) to deduce coastal winds is further complicated by a sea breeze circulation (cf. Moritz, 1977), which is generated by the land-sea temperature gradient. During summer the air over the land may warm to $15-20^{\circ}C$, while that over the water is only -1° to $5^{\circ}C$. Studies by Carsey (1977) in the summers of 1976 and 1977 suggest that the sea breeze occurs about one-third of the time. The sea breeze is most pronounced in the shallow nearshore region, precisely where one would expcet a priori the strongest wind-driven effect on the circulation.

It would thus seem worthwhile to examine the mesoscale pressure effects further through establishment of temporary stations to measure surface winds and pressure both inland and offshore. In particular, determining the extent of influence of both the sea breeze and the barrier wind circulations appears to be important in constructing realistic surface wind prediction models.

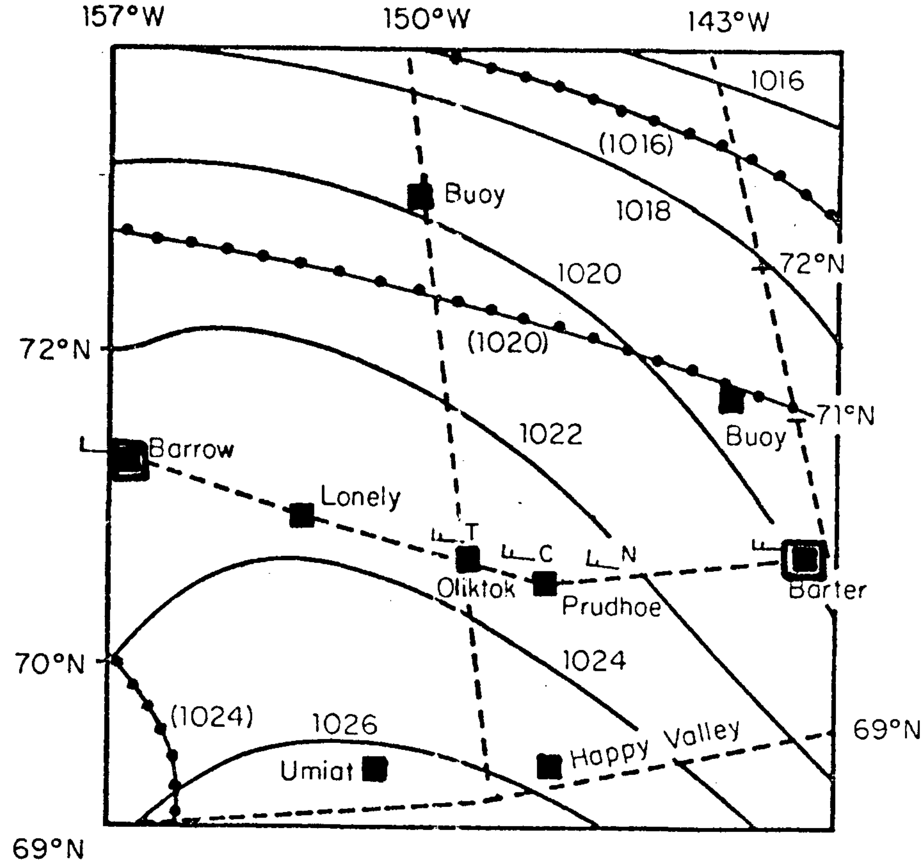
Tides

Almost no work on the tides of the Alaskan arctic coast has been published since the work of the Ray Expedition (Ray, 1885) and the Mikkelson-Leffingwell Expeditions as reported by Harris (1911). Hunkins (1965) measured the tides on the shelf northwest of Point Barrow from a grounded ice island and also reported on the wave spectrum (Hunkins, 1962).

The astronomic tides in the Beaufort Sea are very much smaller than the meteorologic tides. They are generally mixed semidiurnal with mean ranges from 10-30 cm. Matthews (1971) has given the amplitude of the principal lunar tide (M_2) at Point Barrow as 4.7 cm. This value agrees well with that derived by Harris (1911) from Ray's data. The tide appears to approach the shelf from the north, showing little phase change from Barrow to Demarcation Point. Callaway and Koblinsky (1976) also made direct measurements of tides at Stockton and Thetis Islands and found a tide normal to the coast. This motion is not inconsistent with the observed and computed tides in the Canadian sector (Huggett et al., 1975, 1977) which suggest an M_2 tide normal to the coast in the U.S. sector and several amphidromies in Mackenzie Bay. The tidal amplitude variation along the Alaskan coast and shelf has not been measured. This is a noticeable data gap.

Storm Surges

Storm surges significantly increase or decrease sea level from its mean level, and in the Beaufort Sea surges are in fact the most important sea level variation. They are usually associated with storm systems moving under the influence of the Siberian and Alaskan high pressure systems. The storms are most frequently generated near the Aleutian chain



PRESSURE CONTOURS-MB

---- Approximate Coast Line Orientation
AUG 22-000 GMT (1976)
•—•—• National Weather Service - MB
(T C N) Wind Measurements from Cottle and Narwhal Islands and Tolaktovut Pt.

Fig. 2.3 Example of errors in National Weather Service surface pressure map, shown when data from OCSEAP buoys and additional shore stations supplement data from the two NWS coastal stations (Carsey, 1977).

and pass through Bering Strait, although occasional storms move eastward from the Siberian shelf (Searby and Hunter, 1971). The storm tracks generally lie north of the Alaskan Beaufort Sea coast, and the storms progress toward the east. The greatest increases in sea level occur in September and October, when long stretches of open water increase the fetch, resulting in large waves at the shoreline. However, winter surges in December and January (even as late as February) are not infrequent, though the elevations are generally less than in summer. Negative surges also occur and appear to be more frequent in the winter months.

Very little has been published on surges in the Beaufort Sea, and only one sea level gauge has operated for more than a year, at Barrow in 1969-72 (Matthews, 1971). Consequently information is based either on short-term sea level records or more frequently on secondary observations. Observations of strandlines along the whole Beaufort Sea coast tend to confirm extreme surge values of 2-3 m (Hume, 1964; Wiseman et al., 1973; Henry, 1975; Henry and Heaps, 1976; Brower et al., 1977), with the highest values on westwardfacing shores. Schaeffer (1966) reported a surge height at Barrow of 3.0 m on 3-5 October 1963. The responsible storm had sustained gusts of 42 knots and short gusts to 65 knots; it is assumed to be the 100-year event. Beach and cliff erosion was large and Hume (1964) reported a retreat of the shoreline of 13 m southwest of Barrow. The surge height decreased towards both the east and the southwest, with 1.5 m reported at Barter Island and 2.7 m at Point Lay. From the very small number of simultaneous sea level records it appears that the impact of surges may be major in one region, but relatively minor some distance removed along the coast. For example, surges reported by Henry (1975) at Tuktoyaktuk in 1972-73 were hardly noticeable at Oliktok Point (Matthews, 1978).

Negative surges, i.e., levels falling appreciably below mean sea level, can have important effects, especially in winter when little water remains beneath nearshore ice. They can occur at all seasons, but Henry's (1975) observations in Mackenzie Bay suggest that they are most common in December and January. The heights are smaller ($\sim$1 m or less) than for positive surges. Matthews has unpublished data for Barrow showing a negative surge of 60 cm in December 1969, which was the largest observed during three winters. He also observed one of 89 cm at Oliktok Point in November 1972.

There appears to be a clear need for long-term sea level observations along the Alaskan arctic shelf to give a seasonal picture of storm surge propagation and frequency of occurrence and to complement the information available from the Canadian shelf. Surges play a major role in coastline erosion, as documented by several writers (Hume and Schalk, 1967; Wiseman et al., 1973), and catastrophic surges could have significant impact on activities associated with oil development.

Fresh Water Discharge

Carlson et al. (1977) and Childers et al. (1977) have published data on stream flow and its variability for North Slope rivers. Only three rivers have been gauged: The Kuparuk, Putuligayuk and Sagavanirktok.

Generally the river flow is highly seasonal, with a large percentage of the annual flow occurring within a 10-day period ofter breakup. These features are quite apparent from the hydrographs from the Kuparuk and Sagavanirktok rivers shown in Fig. 2.4 (note the logarithmic scale). The three gauged North Slope rivers can be compared with other Alaskan streams by using the flow statistics shown in Figs. 2.5-2.7 (all from Carlson et al., 1977).

The largest of the North Slope rivers, the Colville, has not been gauged. Walker (1973) has estimated its total discharge during the period 27 May - 15 June 1971 to be 5.7×10^9 m^3. He believed this three-week discharge to represent nearly 60% of the total annual value.

The Nearshore Regime

The nearshore regime is composed both of semienclosed lagoons and open embayments; examples are Simpson Lagoon and Harrison Bay, respectively, both of which have been studied to some extent. Simpson Lagoon (Fig. 2.8) is bounded by Harrison Bay on the west and Prudhoe Bay on the east. The lagoon is 50 km in length, narrowing from 9 km in the west to 1 km in the east. Depths within the lagoon typically range between 1 and 2 m, although entrance depths can reach 6 m or more; the entrances are deepest on the western side. The possibility exists that some of the narrow entrances may be closed or severely restricted relatively short time scales.

The circulation appears to be strongly wind-driven, with flushing rates and currents closely related to local winds. Considerable lateral variation in salinity and temperature can occur in the lagoon. These variations probably have a first-order effect on the biology of the region, but only a secondorder effect on the circulation. The lagoon is influenced by fresh water inflows, particularly those of the Kuparuk, Colville, and Sagavanirktok Rivers. The most dramatic river influence occurs during the short period of peak river discharge, much of which may occur before ice has left the lagoon.

Local winds are predominantly from the ENE (some 70% of the time), but tend to be NW during storms. As discussed earlier, surges associated with these storms can be as much as 3 m. During winter negative surges of up to 1 m would result in the displacement of a large percentage of the unfrozen lagoon water. The astronomic tide within the lagoon has a range typical of the Beaufort Sea, about 30 cm. Numerical modeling indicates the associated tidal currents to be about 5 cm/sec.

A summary of meteorological and oceanographic conditions in the lagoon has been prepared by Dygas (1975). He has found significant wave periods of about 2 sec at Oliktok Point, near the somewhat exposed western end of Simpson Lagoon. These were probably wind waves generated within the lagoon, and they had heights of 20 cm or less. On the seaward side of the barrier islands, rather similar waves have been observed by Wiseman et al. (1973), who measured significant waves at Pingok Island with a period of 2-3 sec and heights of 10-30 cm. However, considerably longer and larger waves are possible and the same investigators have measured storm waves at Pingok Island with a period of 9-10 sec and significant heights exceeding 1.5 m. In fact, the wave sensor was destroyed by surf when the waves reached 2 m.

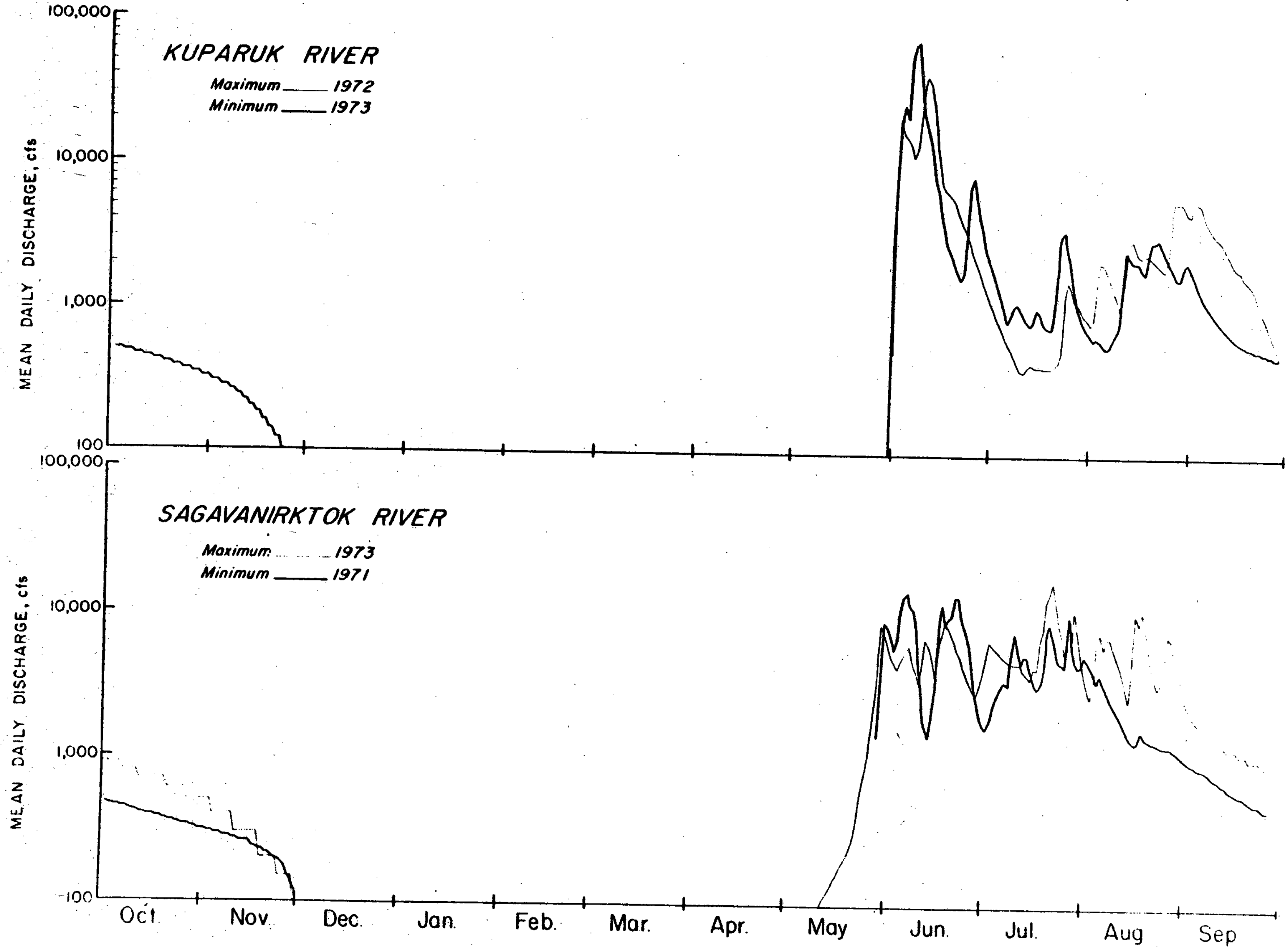


Fig. 2.4 **HYDROGRAPHS - Kuparuk River / Sagavanirktok**
(Carlson et al.; 1977)

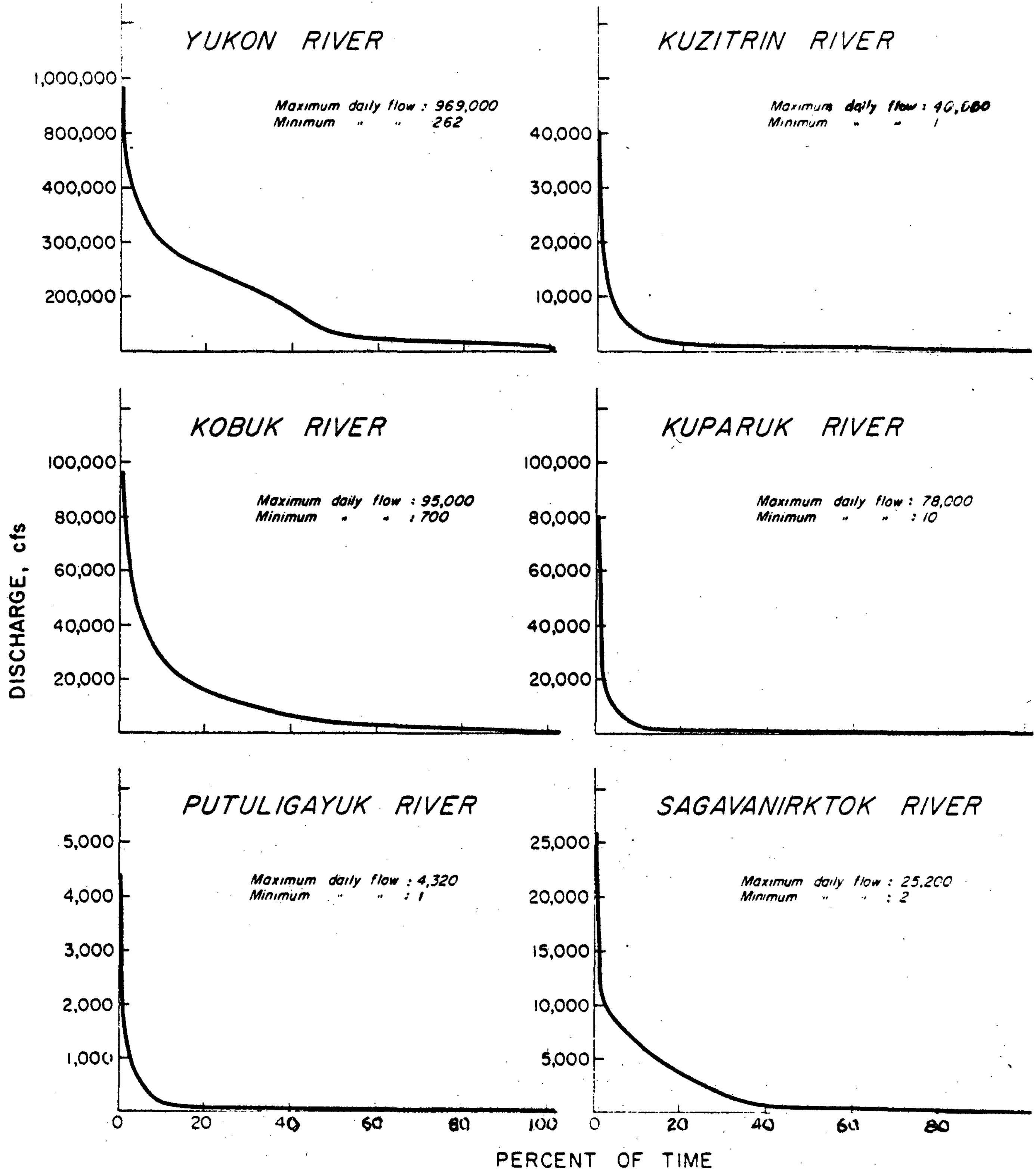


Fig. 2.5 FLOW DURATION CURVES
Yukon, Kuzitrin, Kobuk, Kuparuk, Putuligayuk and Sagavanirktok Rivers (Carlson et al., 1977)

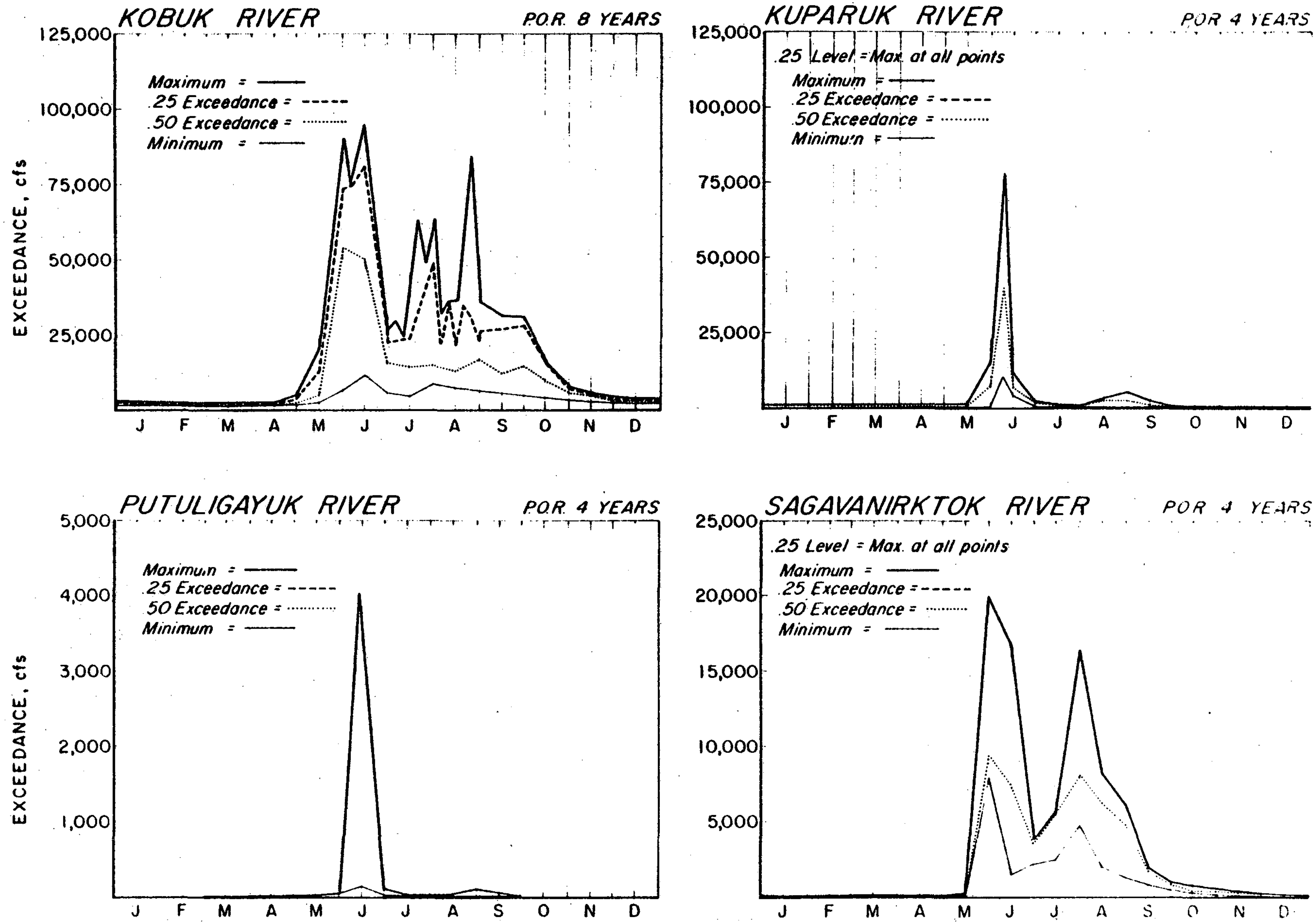


Fig. 2.6 **EXCEEDANCE PROBABILITIES BASED ON PERIOD OF RECORD (POR)**
Kobuk, Kuparuk, Putuligayuk & Sagavanirktok Rivers (Carlson et al., 1977)

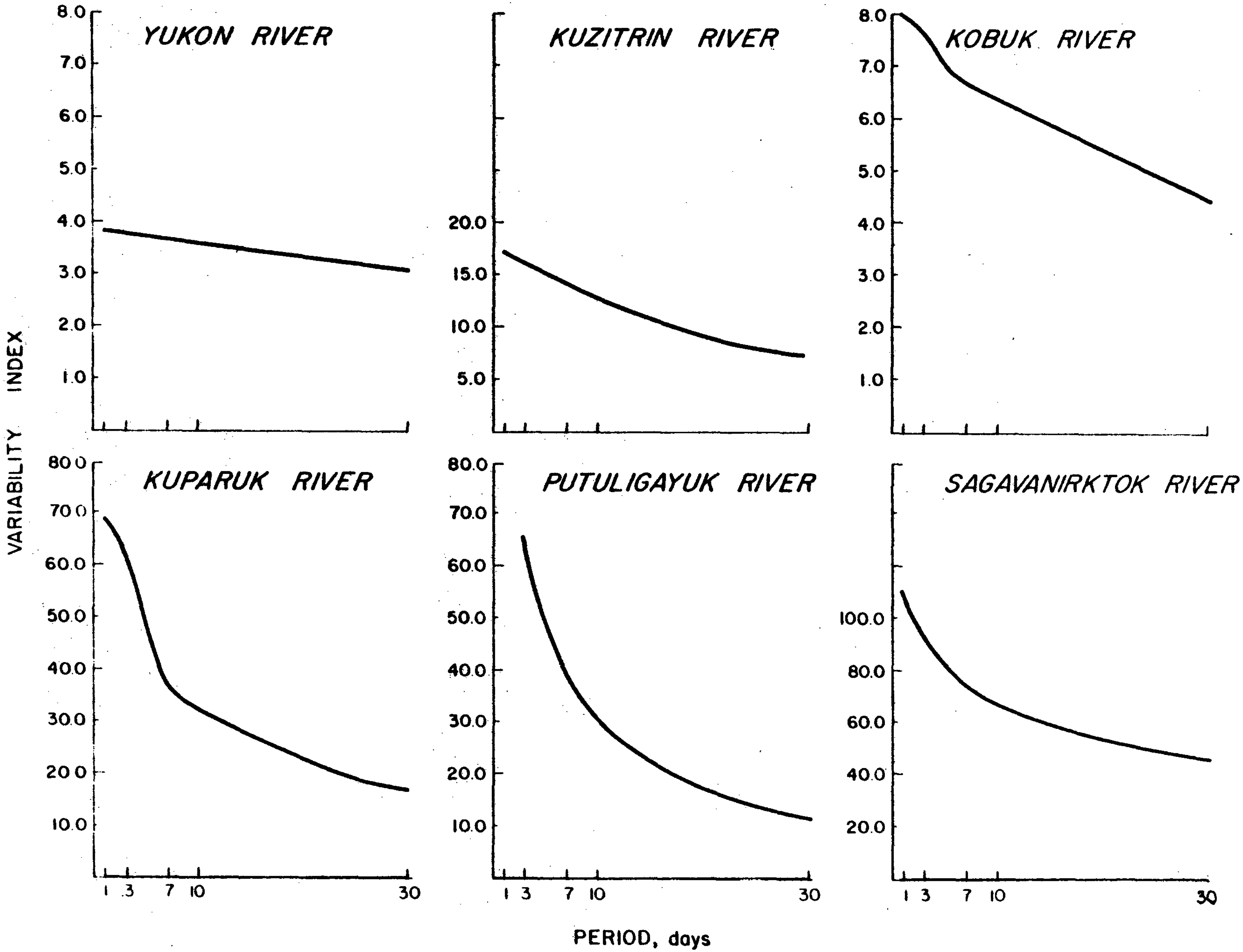


Fig. 2.7 **SHORT-TERM VARIABILITY INDEX**
Yukon, Kuzitrin, Kobuk, Kuparuk, Putuligayuk & Sagavanirktok Rivers
(Carlson et al., 1977)

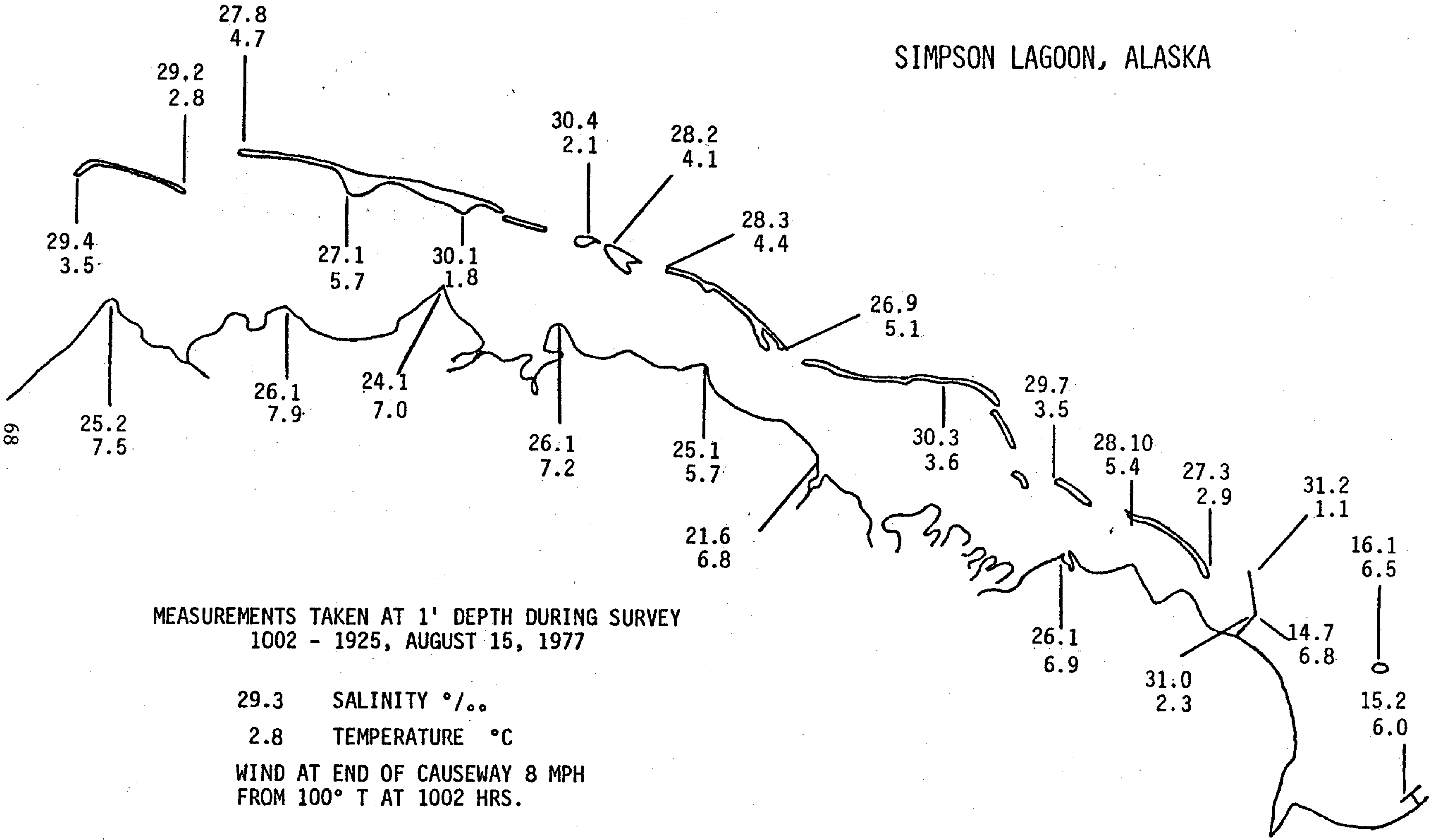


Fig. 2.9 Measurements taken at depth of 1 ft during survey of August 15, 1977. (Mungall, 1978)

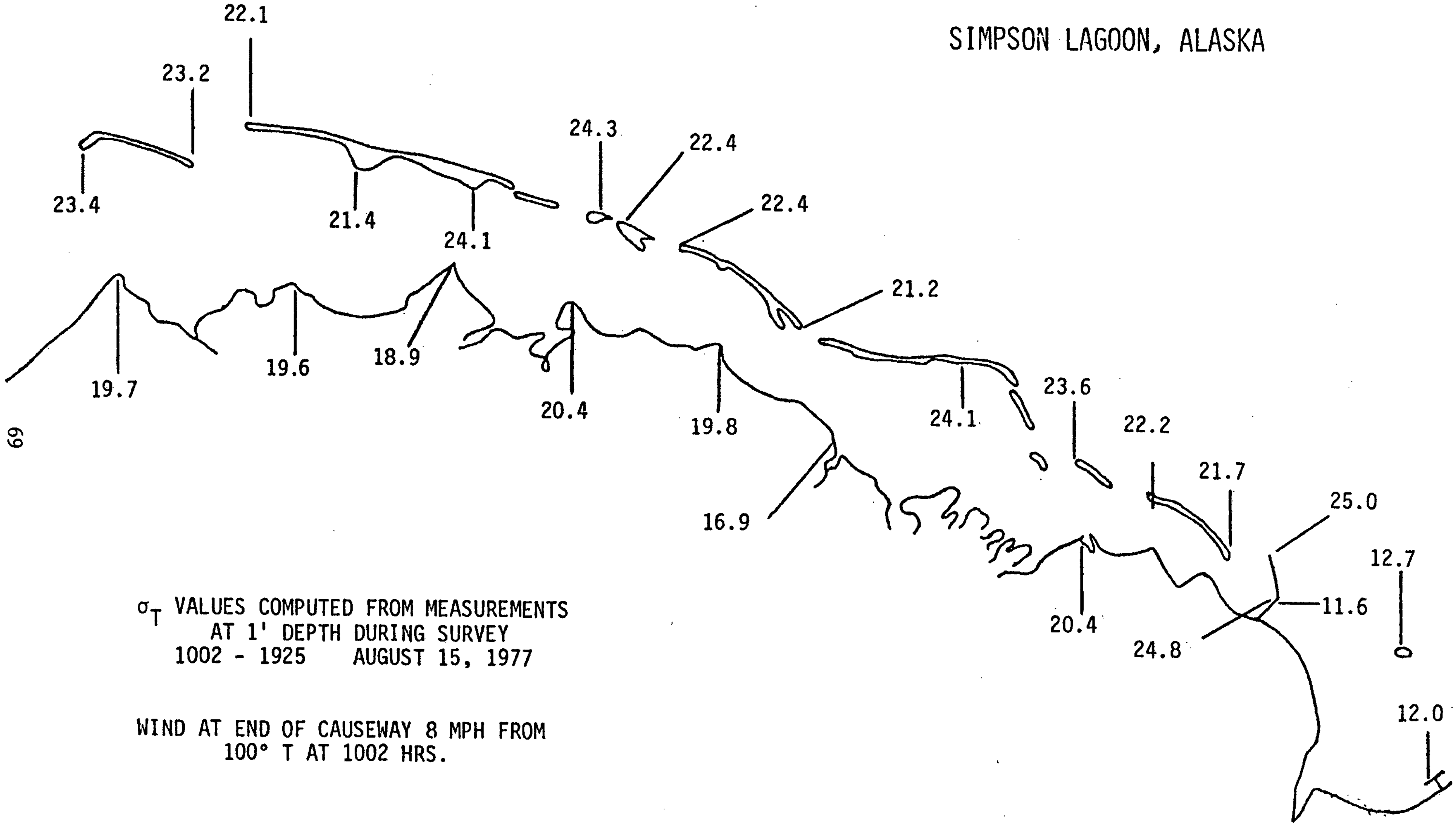


Fig. 2.10 σ_T values computed from measurements taken at depth of 1 ft during survey of August 15, 1977. (Mungall, 1978)

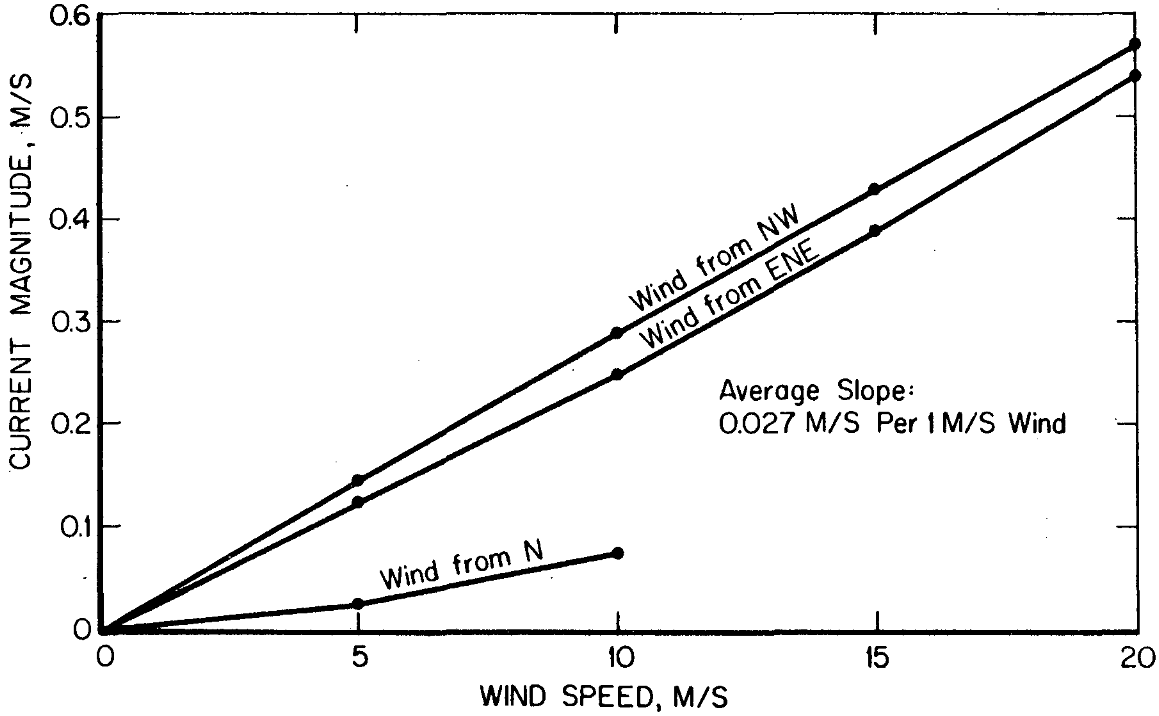


Fig. 2.11 Simpson Lagoon 2-D model results (unverified), showing mid-channel current magnitude off Milne Point (Mungall, 1978).

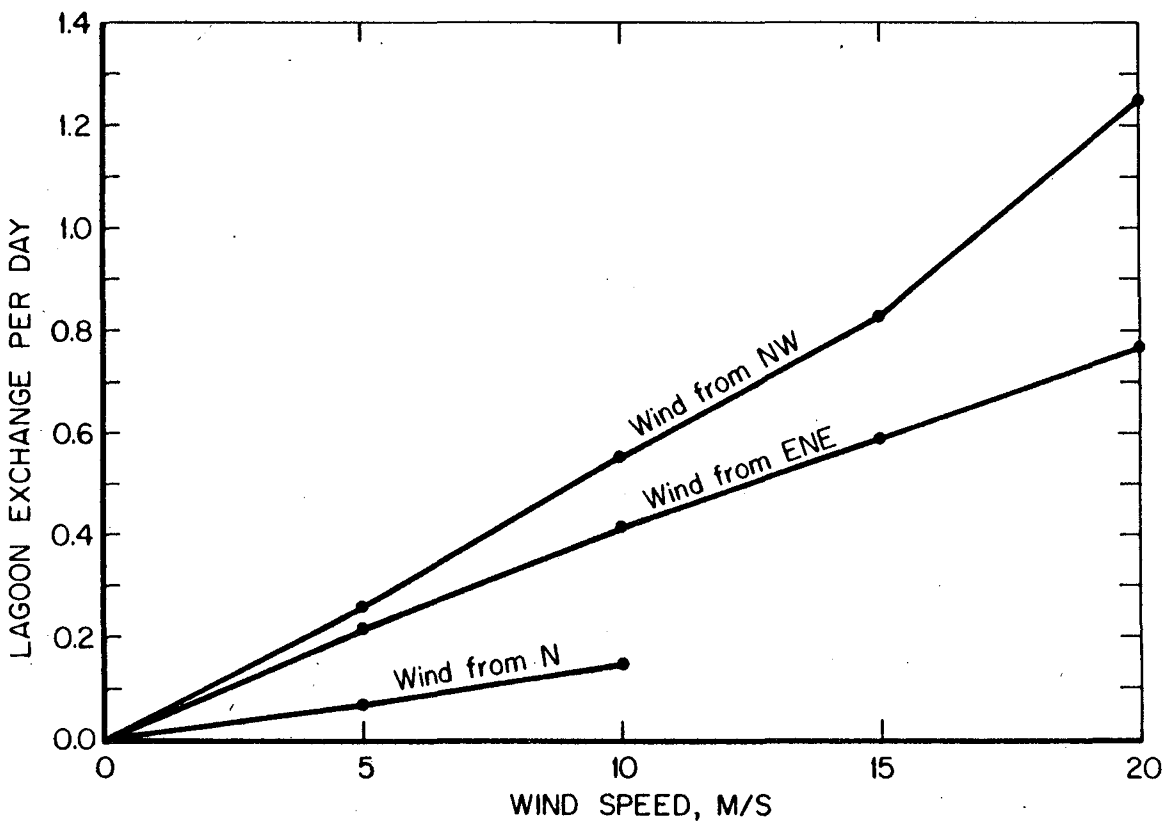


Fig. 2.12 Simpson Lagoon 2-D model results (unverified) (Mungall, 1978).

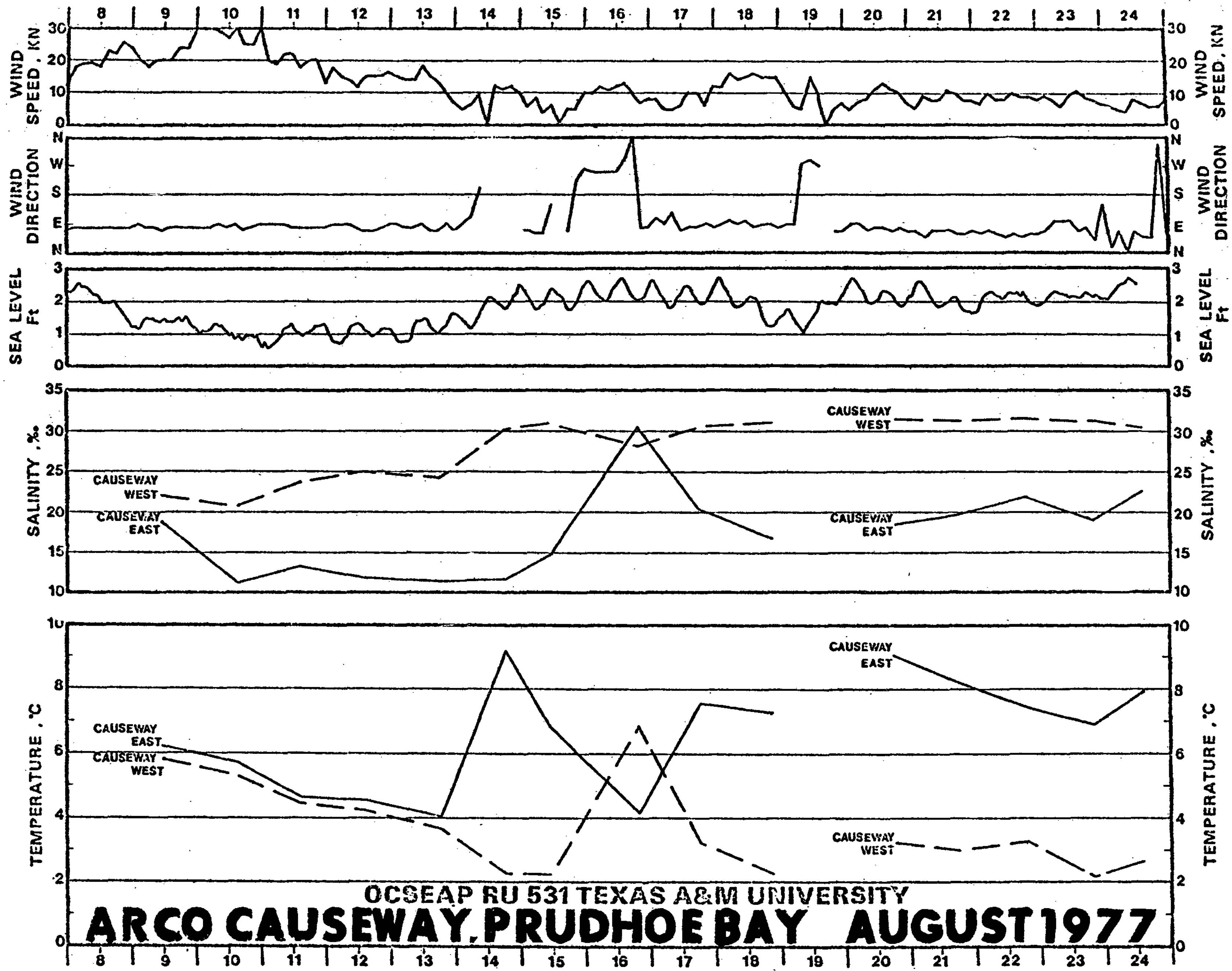


Fig. 2.13 Summary of salinity and temperature measurements taken on the east and west side of the middle of the causeway, 9 through 24 August 1977. Wind and sea level data provided by NOAA (Mungall, 1978).

of the lagoon as a whole. A similar extent of influence upon the currents is indicated by the modeling efforts of Callaway and Koblinsky (1976). Figs 2.14 and 2.15, respectively, show the simulated near-surface circulation in the absence and presence of the causeway. Boundary conditions are the same for both cases, namely, wind from 260°T at 13 m/sec, M_2 tidal amplitude of 8 cm, and river flow normalized to 5 cm/sec. Simulations are shown for hours 6, 9, 12, 15, and 18. At hour 6, the disturbances are confined to 1-2 km NE of Stump Island, and immediately windward and downstream of the causeway. At hour 9, differences are apparent 11.5 km east of the causeway in the shear zone between the cyclonic gyre and northward flowing coastal current on the east side of Prudhoe Bay. By hour 12, the circulation in an area of about 16 km^2 is clearly affected by the causeway. The simulations for hours 15 and 18 do not show significant further changes. In this model it is the interaction between the wind-driven circulation and the causeway that is of importance. Simulations using only tidal input (tidal wave normal to the coast) showed little interaction.

Little is known about Simpson Lagoon in winter. By late winter the fast ice in the lagoon is about 2 m thick. The salt exclusion associated with freezing gives rise to very high salinities in the remaining unfrozen water; values of 80-100 o/oo are common in May, with even higher salinities possible in isolated pockets. In early summer the ice melts, the process being substantially influenced by river discharge which floods the ice and deposits large amounts of detritus.

We consider next Harrison Bay, an example of an open embayment within the nearshore regime; it is in fact the largest of such embayments on the northern Alaskan coast, extending some 90 km from Cape Halkett to Oliktok Point. Depths are generally less than 10 m. The Colville empties into the eastern side of the bay. However, one-half to two-thirds of the total annual discharge occurs within a 2-3 week period in early summer, so that estuarine effects are not felt strongly through most of the year. For example, no effluent plume could be detected in an airborne temperature survey conducted in early August 1973 by Hufford and Bowman (1974).

Instead, the circulation off Harrison Bay appears to be primarily wind-driven (Hufford et al., 1974). Figure 2.16 shows the surface movement during 14 August 1977 (Hufford, unpublished data). Water motion varied widely within the range 5-50 cm/sec, and there was a general westerly trend. Both features appear to be typical of summer. Winds both at the time of measurement and for several days preceding were in fact also typical of summer, viz., NE at about 5 m/sec. Surface current measurements in western Harrison Bay in August 1976 (Hufford et al., 1977), under conditions of SE winds, also suggested that the flow was wind-driven. At times of westerly winds, the water motion appears to be toward the east. For example, Hufford and Bowman (1974) showed a tongue of cold and clear water penetrating eastward into the warmer, turbid waters of Harrison Bay. This coincided with westerly winds caused by a low pressure system moving eastward along the coast. In considering locally wind-driven systems of this type, it is important to bear in mind the considerable geographic variability in the wind field, as was discussed in an earlier section.

The winter circulation in Harrison Bay is essentially unknown. A single current meter mooring near Oliktok Point showed that the currents

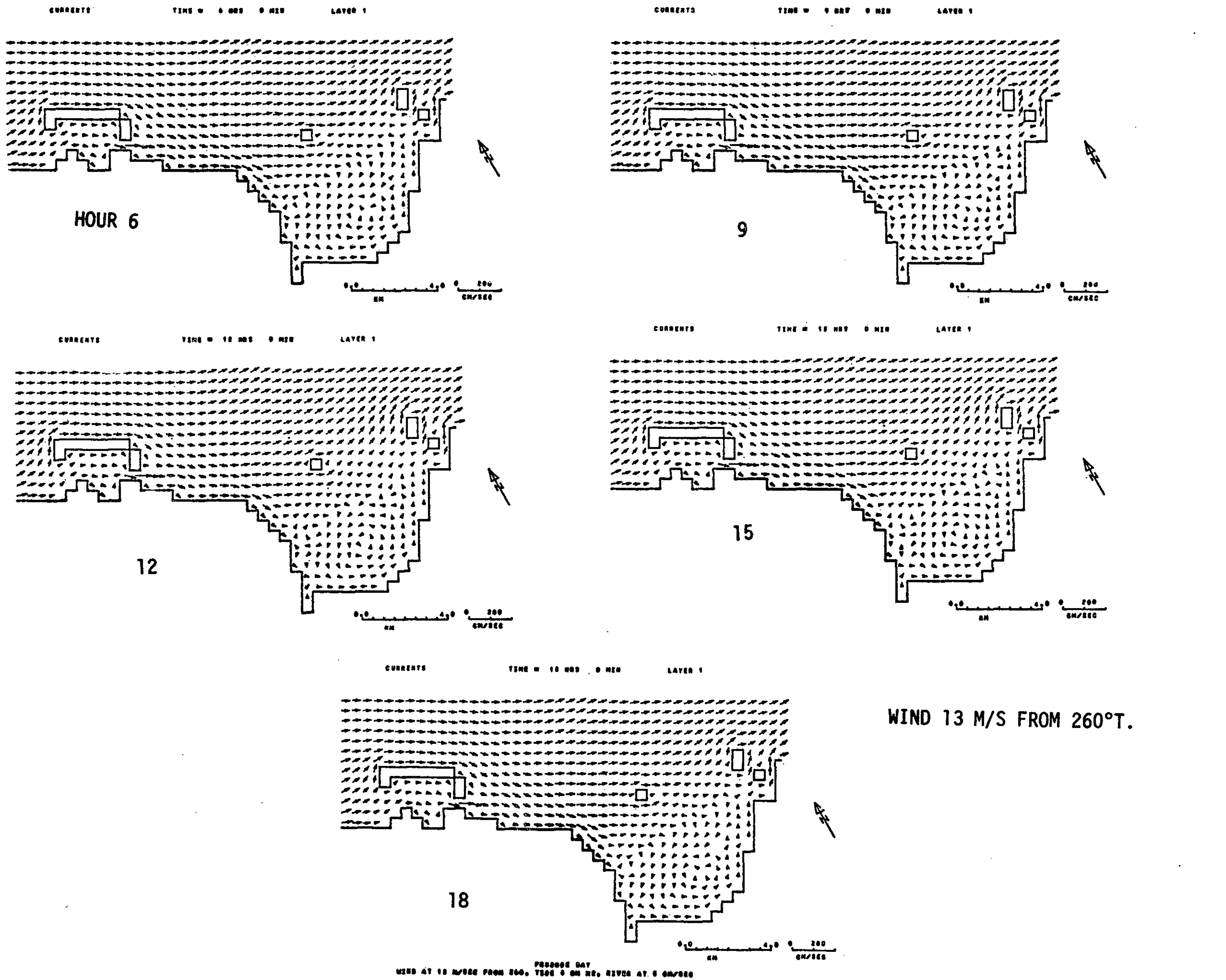


Fig. 2.14 Simulated near-surface circulation in the absence of the ARCO causeway (Callaway and Koblinsky, 1976).

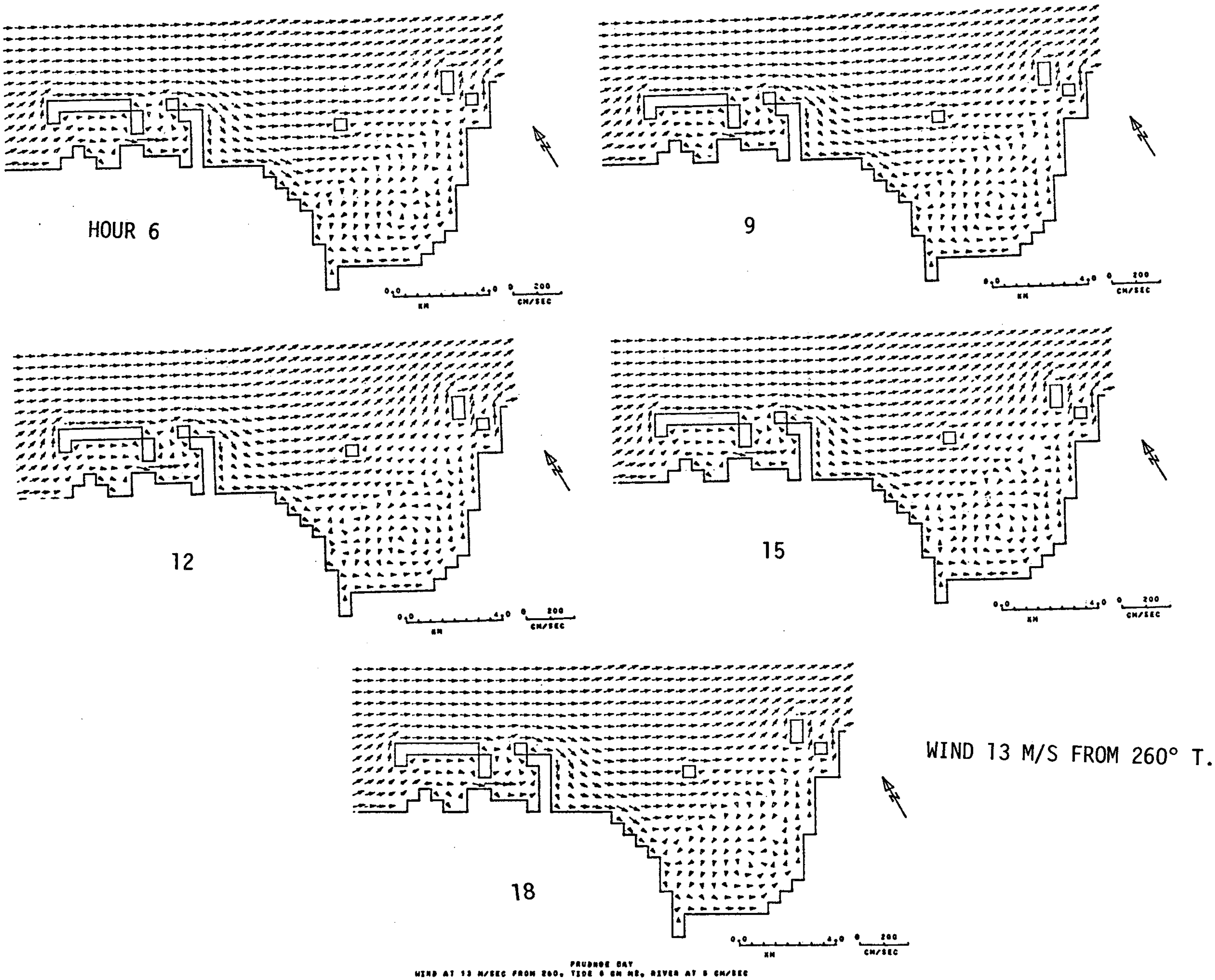


Fig. 2.15 Simulated near-surface circulation with the ARCO causeway in place (Callaway and Koblinsky, 1976).

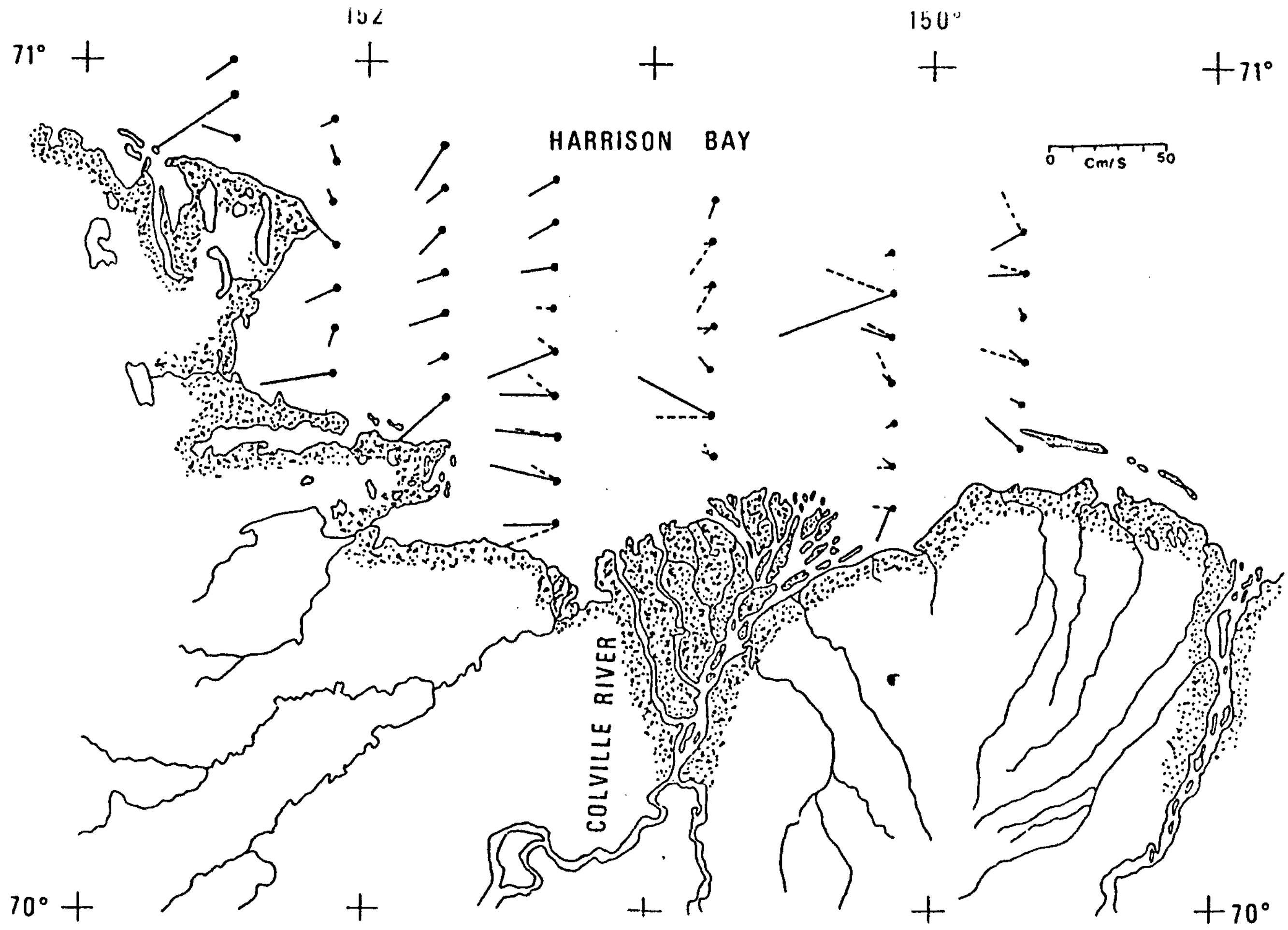


Fig. 2.16 Surface movement of water on 14 August 1977 (dashed line) and 15 August (solid line), Hufford, 1977.

were generally less than 5 cm/sec with a net drift to the west (Barnes et al., 1977c). There is also some indirect evidence for episodes with higher speeds, possibly representing winter surges.

In fact present indications are that the conditions described for Harrison Bay and Simpson Lagoon are representative of much of the nearshore regime in the Beaufort Sea. For example, the large gradients and variability of temperature and salinity during summer are common all along the coast, while their dynamic importance to the circulation appears to be secondary. (One noteworthy exception is the role of stratification in suppressing vertical exchange.) The general westward motion along the coast during summer, apparently as a response to the prevailing winds, also appears to be a feature that Simpson Lagoon and Harrison Bay have in common with most of the Beaufort coastal waters. For example, Barnes and Reimnitz (1974) have deduced such motion based on satellite imagery of turbid water plumes; Wiseman et al. (1974) have shown the dependence on the winds of the near-surface current off Pingok Island, and off Prudhoe Bay Barnes et al. (1977b) have directly measured near-bottom currents that were well correlated with the local winds. Figure 2.17 taken from Barnes et al. (1977b), schematically shows the flow for the different wind conditions at the site off Prudhoe Bay.

During winter, motion nearshore generally appears to be slow (a few cm/sec), although Barnes and Reimnitz (1973) have reported tidal currents of 25 cm/sec in shallow water where the tidal prism apparently was fed through passages severely restricted by ice. Such rapid flow is probably exceptional in winter.

It is clear that to date the physical oceanographic effort in the nearshore regime has been modest and that many pieces of the puzzle are missing. Major examples are: a statistical knowledge of nearshore wind-induced wave and current structure, such as is required for assessing sediment and detritus depositon and erosion; more information on flow during winter and its variability and causes; and an understanding of the exchange of water (and the substances it transports) between the nearshore region and the inner shelf. However, it is also clear that at least in summer the nearshore region is strongly wind-driven. Given the inherent difficulty in making local wind forecasts, it therefore follows that future research efforts must be aimed at understanding mechanisms and processes, rather than at attempting detailed predictions of water motion and quality.

The Inner Shelf

The inner shelf can somewhat arbitrarily be considered to lie between the 10 and 50 m isobaths. It is a region which, from the standpoint of physical oceanography, has been studied very little, in large part because of its relative inaccessibility, whether from the landward or seaward side.

Since it is a comparatively shallow region, somewhat removed both from lateral boundaries and from sources and sinks of water, one might expect *a priori* that its dynamics are those appropriate to a flat, unconstrained,

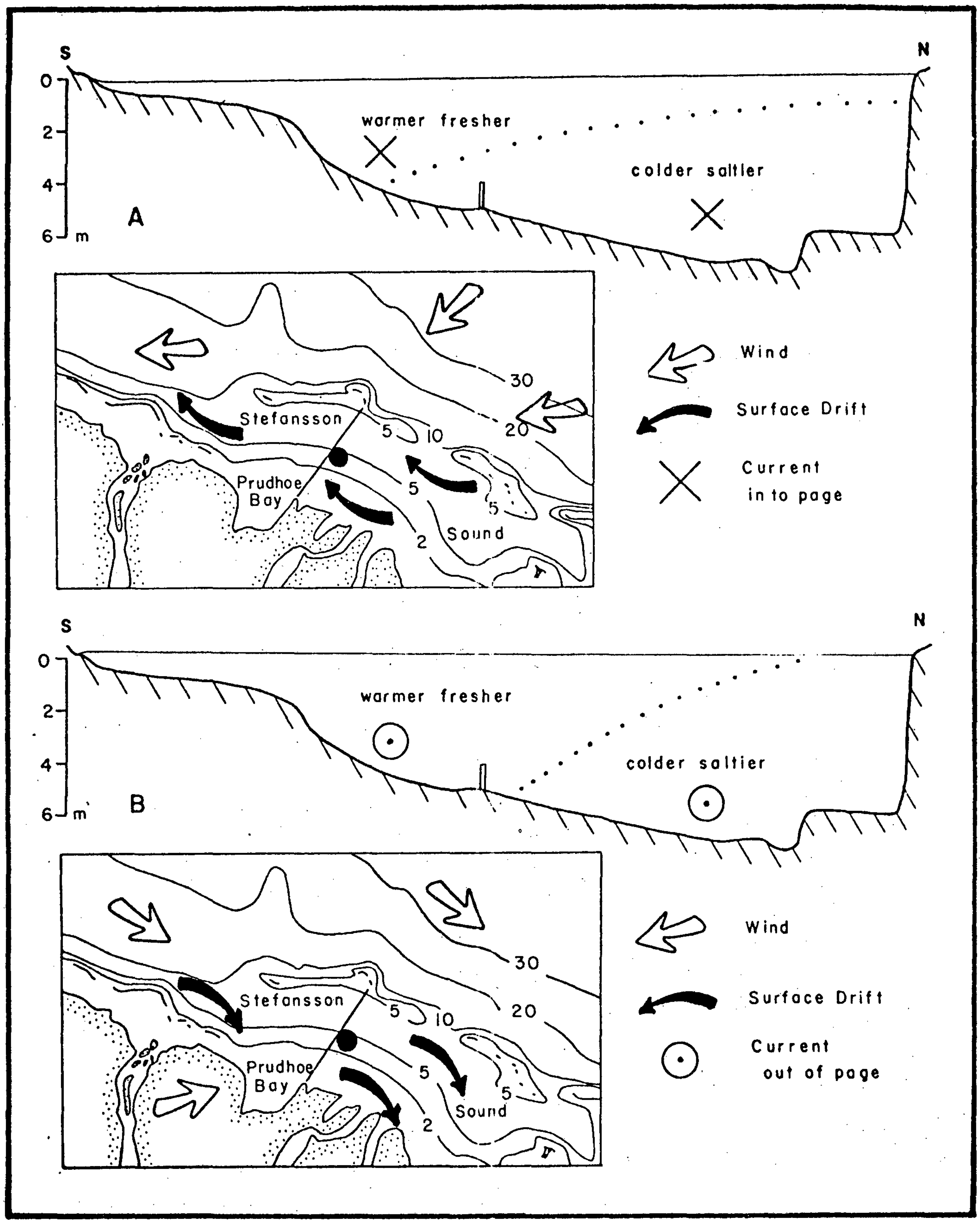


Fig. 2.17 Schematic presentation, showing water flow for different wind conditions at a site off Prudhoe Bay. (Barnes et al., 1977)

wind-driven shelf sea. In fact the few summer measurements of water motion, as well as several lines of indirect evidence, do point toward a general westward motion corresponding to the prevailing easterlies. There also appears to be a rapid response to changing winds, such that under westerly winds, motion is eastward (cf. Hufford et al., 1974; Drake, 1977; Hufford et al., 1977 and Fig. 2.16).

Current meter time series have been obtained on the inner shelf in winter by Aagaard and Haugen (1977). Two instruments, separated by about 14 km, were deployed 10 m below the ice in water 30-40 m deep offshore from Narwhal Island during March-April 1976. Both sites were effectively within the fast ice. Currents never exceeded 10 cm/sec and were generally less than 5 cm/sec. The mean flow during three weeks was respectively 0.1 and 0.3 cm/sec toward WSW at the outer and inner meters, but there was no apparent correlation between fluctuations in water motion at the two sites. Both diurnal and semi-diurnal tidal currents had amplitudes near 1 cm/sec.

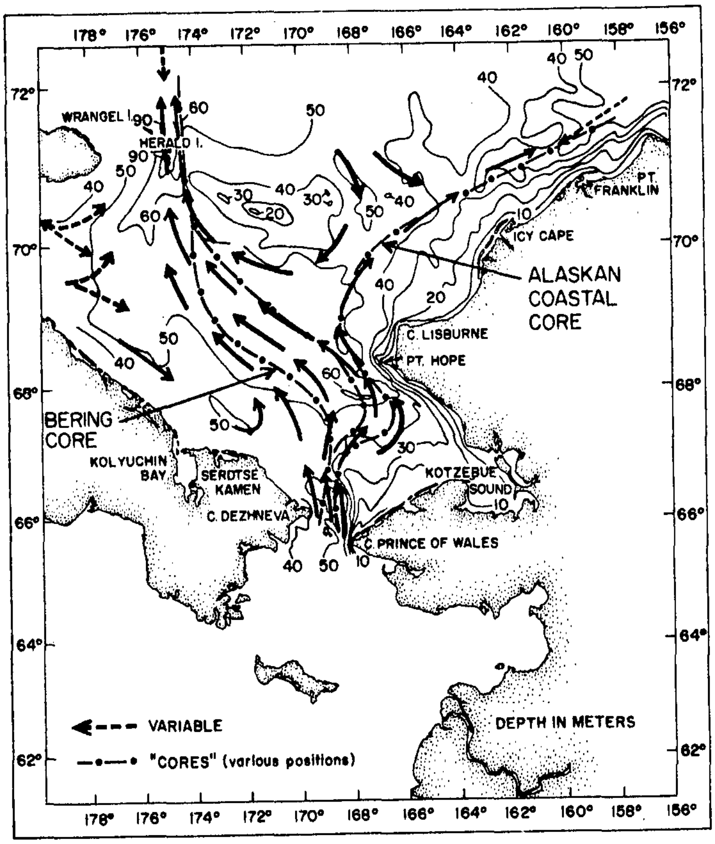
During summer, both temperature and salinity show very large ranges and temporal variations, both short-term and year-to-year (cf. Hufford et al., 1974; Barnes et al., 1977a). When freeze-up occurs in the fall, gradients are greatly reduced, and by mid-winter the water on the inner shelf is at the freezing point for its salinity, the latter typically being in the range 30-32 o/oo (Aagaard, 1977). These conditions persist until early or mid-summer.

The inner shelf is the least-known of the regions we are considering in this report. In particular, it would seem crucial to learn the relative importance to the summer circulation of both direct local wind forcing and baroclinicity and the extent and nature of cross-shelf circulation, e.g., whether there is a net offshore movement in the upper layer, driven by either the wind or the density distribution.

The Outer Shelf

This regime may be considered to extend from about the 50 m isobath to the shelf break. It has been studied by a number of investigators over a period of some years (e.g., Hufford, 1973; Hufford et al., 1974; Mountain; 1974). The strongest hydrographic signal on the outer shelf is the summer subsurface temperature maximum associated with the eastward flow of water originating in the Bering Sea. Along with its influence on the hydrography, this flow has a marked effect on the plankton, carrying Pacific forms into the Arctic. The influx was first described by Johnson (1956), and it has since received considerable attention, from Hufford et al. (1974), Mountain (1974), and Paquette and Bourke (1974). Mountain particularly has provided an intensive analysis, of both the hydrography and the dynamics.

Figure 2.18 taken from Coachman et al. (1975) schematically shows the flow of Bering Sea water through the Chukchi. The water that eneters the Beaufort has come through eastern Bering Strait and followed the Alaskan coast to Barrow, with a definite tendency to flow along isobaths. In fact the warm intrusion on the outer Beaufort shelf is composed of



Schematic of lower layer flow in the Chukchi Sea. (Dotted arrows indicate variable currents. Various positions of "cores" of Bering Sea water mass are indicated.)

Transport (Sv; + north) of Water Masses, July-August 1972
[Oshorô Maru; Station Nos. in ( ) from Figs. 7, 79, 81, 83]

Section	Date	Bering Sea	Alaskan Coastal	Section Total
Bering Strait	7/24–25	1.1 (89–97)	0.6 (85–88)	+1.7
Lisburne	7/27–28	0.2 (109–111)	0.7 (98–102)	+1.3
SE of Wrangel	7/29	0.8 (116–119)	.	
Herald Island-C. Franklin	7/31–8/1	0.3 (125–128)	1.3 (133–139)	+2.3

Fig. 2.18 Schematic of lower layer flow in the Chukchi Sea (from Coachman et al., 1975).

two water masses, termed by Mountain (1974) Alaskan coastal water and Bering Sea water. The former can have summer temperatures west of Barrow as high as 5-10^{o}C, but the salinities are low, being less than 31.5 o/oo. The Bering Sea water is more saline and is contained in the density range, sigma-t equals 25.5 to slightly over 26.0, as has been demonstrated in the lengthy analyses of Mountain (1974) and Coachman et al. (1975). Mountain has estimated that the northward transport west of Barrow represents about one-half the total transport through Bering strait, or about 8 x 10^5 m^3/sec. The portion of this flow that actually moves eastward on the Beaufort shelf is uncertain, although geostrophic calculations suggest that a major portion of the water does so, at least initially. Based on four-month long current meter records in Barrow Canyon, Mountain et al. (1976) described large, low-frequency variations in the flow which they modeled as a linear response to variations in the atmospheric pressure gradients.

Figures 2.19-2.21 are taken from Mountain (1974). They show the concentration of the eastward flow on the outer shelf and slopes, and they also demonstrate the difference in influence of the two water masses. The Alaskan coastal water mixes with the surrounding Arctic surface water as it moves eastward, and is not clearly identifiable east of about 148^{o}W. On the other hand, the Bering Sea water, with its temperature maximum deeper (in the sigma-t range 25.5-26.0), can be traced at least as far as Barter Island at 143^{o}W. The patchiness of the temperature distribution in Fig 2.20 is of particular interest. Mountain (1974) has attributed such features to variations in the influx of warm water to the shelf, due to a combination of adverse local wind stress and atmospheric pressure effects on the flow through Barrow Canyon. In this view, the eastward flow over the outer shelf is driven externally by the momentum flux of the Barrow Canyon flow, with its attendant pulsations as described earlier. Both scale analysis and observations suggest the interpretation to be reasonable. However, it is not clear why the current should follow the isobaths in its eastward movement, as it appears to, for the geometry would tend to destabilize an eastward flow as it conserves potential vorticity.

The temperature maximum on the shelf is primarily a summer phenomenon. Figure 2.22 shows the T-S correlation in the depth range 30-52 m at two stations on the middle shelf north of Lonely. Station W 25-19 was taken in early November and W 27-1 at the same location the following March. The temperature maximum of about -0.9^{o}C at 43 m at station 19 occurred at σ_t = 25.8, which unquestionably represents Bering Sea water having rounded Point Barrow earlier in the year at a higher temperature. The underlying water, including the deeper temperature maximum with a salinity in excess of 34 o/oo, represents water having moved onto the shelf from intermediate depths in the Arctic Ocean. The temperature signal of the Bering Sea water was thus being eroded by heat diffusion into the water both above and below. Sometime later in winter the temperature signal is effectively erased on the shelf, as shown by the T-S correlation in the upper 50 m at station W 27-1. Down to about 40 m, where the density is 26.5 in σ_t, the temperature is at the freezing point. These conditions, i.e., the direct influence of freezing (as evidenced by temperatures at the freezing point) extending into or past

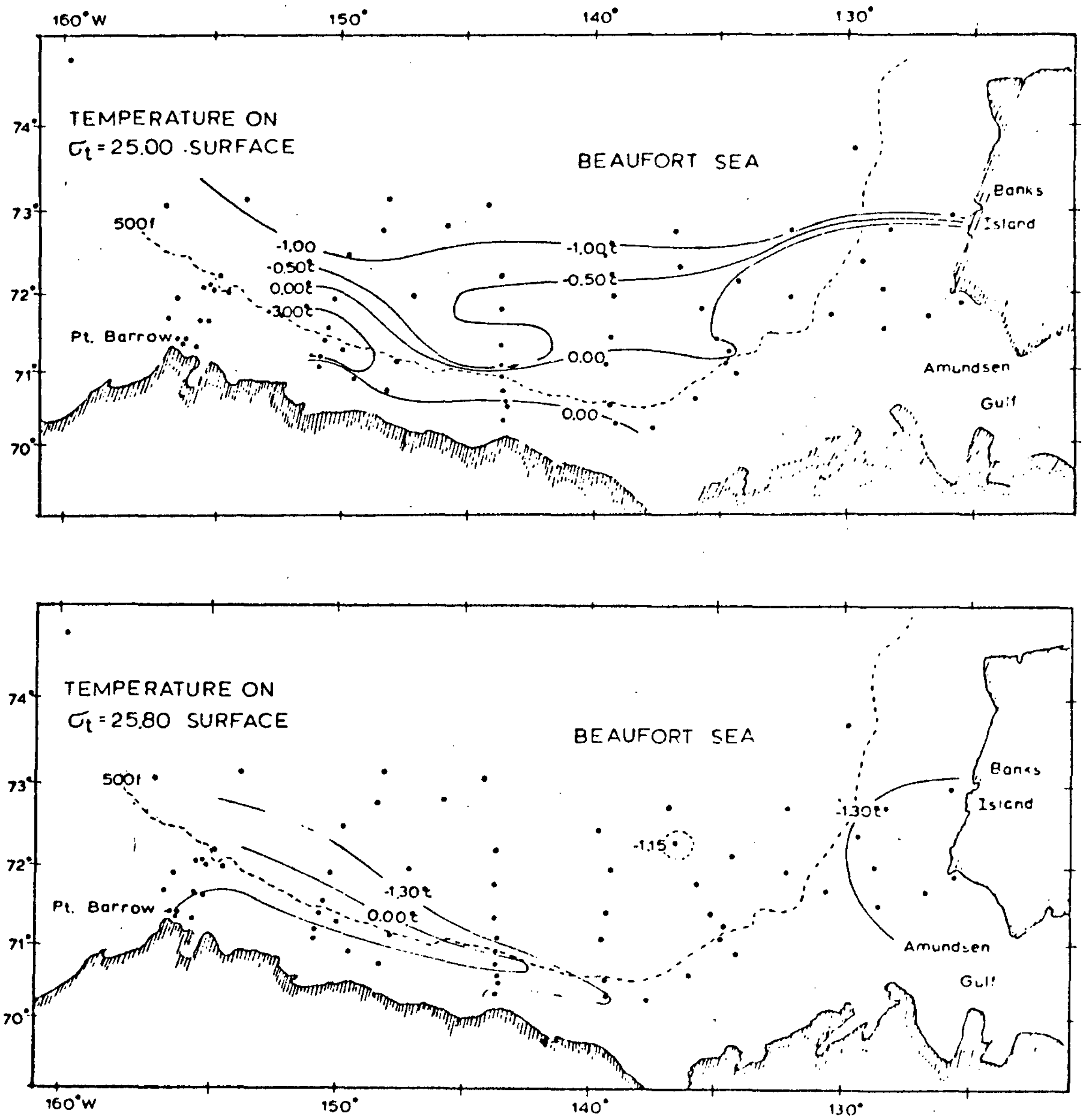


Fig. 2.19 **Temperature (°C) on density surface 25.0 σ_t (top) and 25.8 σ_τ (bottom) for August-September, 1951 (Mountain, 1974).**

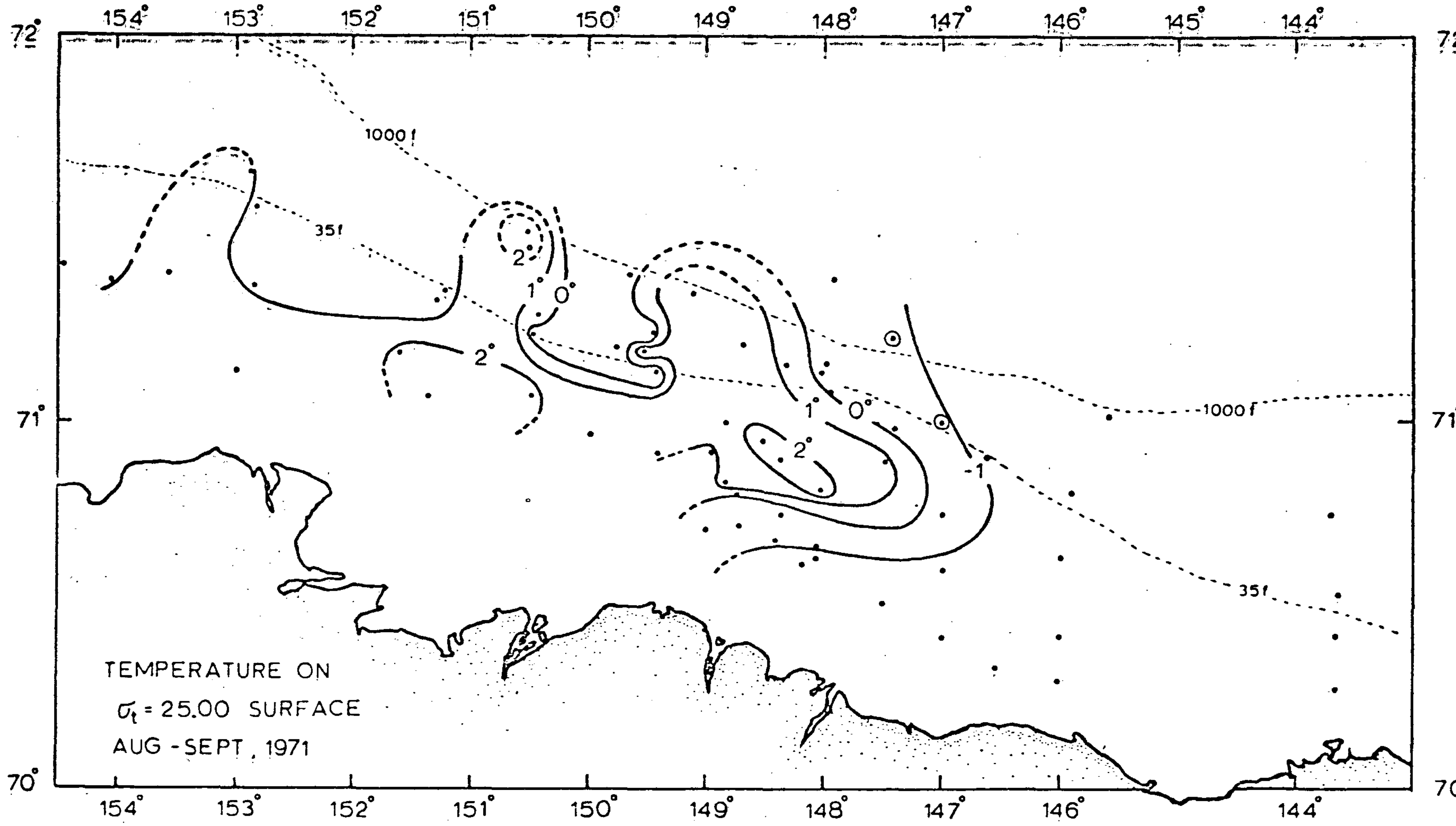


Fig. 2.20 Temperature (°C) on density surface σ_t = 25.0 for August-September 1971 (Mountain, 1974).

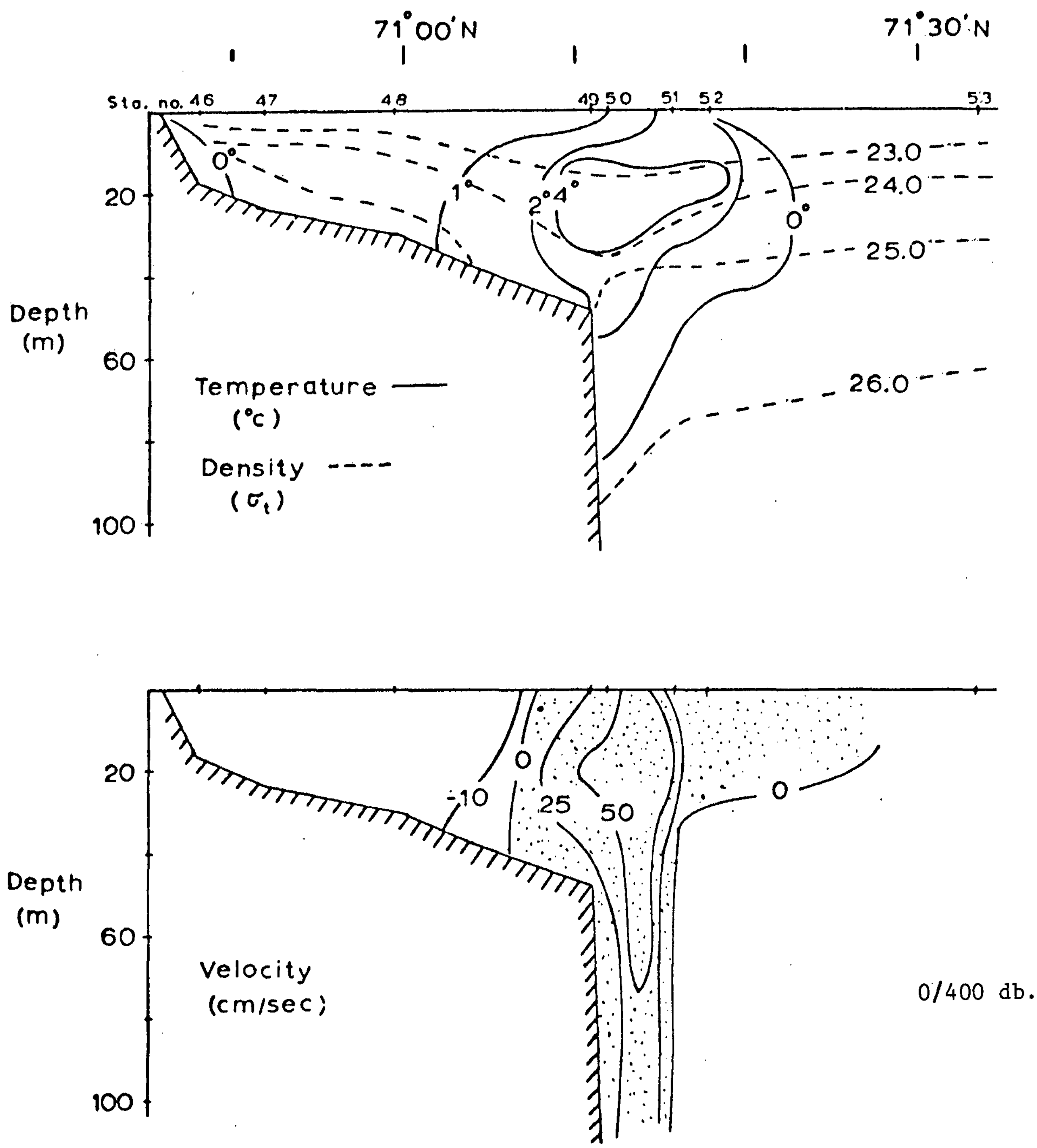


Fig. 2.21 Temperature (–) and density (– – –) distributions (top) and corresponding calculated geostrophic currents (bottom) for transect at 150°W in Figure 20. Velocities >0 are eastward. (Mountain, 1974)

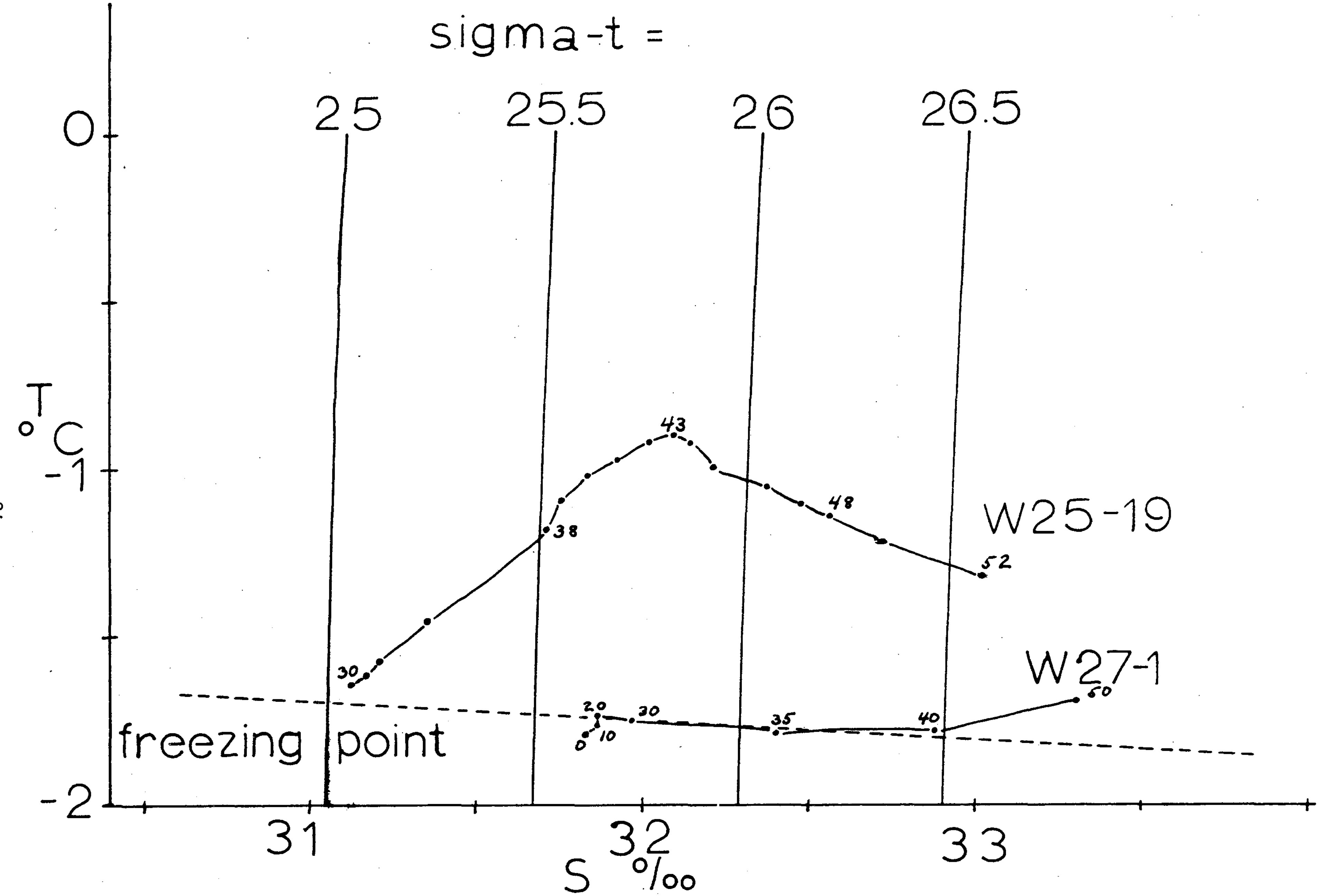


Fig. 2.22 T-S correlation at two stations on the middle shelf north of Lonely. W25-19 is from November 1976 and W27-1 from the same location in March 1977 (Aagaard, 1977).

the density range of the core of Bering Sea water, are typical on the shelf in winter. Only at occasional stations is a Bering Sea influence still clearly visible. Principally, these stations occur over the slope, an example being station W 27-8 (Fig 2.23), where a small temperature spike can be seen just below 50 m. Both above and immediately below the spike, the water is near the freezing point. One can, in fact, find near-freezing temperatures extending throughout the density range of the Bering Sea water as early as November, and therefore, it is not likely that one could trace Bering Sea water on the Beaufort shelf much past the time of freeze-up in the fall.

A second hydrographic signal has also been identified on the outer shelf, that is, one of water being found at shallower levels over the shelf with characteristics appropriate to a relatively deep location offshore. Such water is relatively cold, low in oxygen, and high in nutrients. An example is shown in Fig 2.24, taken from Hufford (1974), who ascribed the distribution to wind-driven upwelling. Mountain (1974) has analyzed data from several years and has also examined the applicability of a number of wind-driven upwelling models, concluding that summer upwelling has been observed only on the eastern portion of the Beaufort shelf, where it represents a response to strong easterly winds.

A similar distribution, one in which the isopleths over the slope rise on approaching the shelf, appears to be a common occurrence during other seasons. The most remarkably developed case observed to date was during the fall of 1976 (Aagaard, 1977). In each of the four sections taken, Atlantic water (or water closely akin to it), normally found well below 200 m farther offshore in the Beaufort Sea, could be seen on the shelf. For example, in the Oliktok East section (Fig. 2.25) water warmer than $0^{\circ}C$ and more saline than 34.5 o/oo was observed at 91 m; and at the Lonely West section (Fig. 2.26) the effect of relatively warm and saline water was apparent even at the innermost station, where the bottom 10 m were warmer than $-1^{\circ}C$ and more saline than 34 o/oo. It is important to note, however, that the inclined isopleths observed in the fall of 1976 are not readily explainable as the result of wind-driven coastal upwelling, as has been proposed by summer investigators. This is because neither during, nor within at least 10 days prior to, the section occupation were the necessary strong easterly winds present.

The general seasonal cycle of hydrographical conditions over the outer shelf appears to be as follows (Aagaard, 1977). Shortly after freeze-up in the fall, the entire shelf is still markedly stratified in salinity (and therefore in density), with a strong gradient below 20-30 m. This is a remnant of summer conditions. Above the pycnocline, the salinity varies considerably, both in time and space, but at any given station the upper layer is nearly homogeneous in both temperature and salinity. The temperature in this layer is very close to the freezing point, reflecting the conditioning of the layer by the freezing process with its attendant thermohaline convection.

In the winter, the overall stratification on the shelf is markedly less than in the fall, and the upper mixed layer extends deeper, typically below 30 m. At the same time, the upper-layer salinity is also higher, generally being above 31 o/oo everywhere on the shelf. A curious feature is that the upper-layer salinity decreases across the shelf, normally by at least 0.5 o/oo. Finally, the winter temperatures are

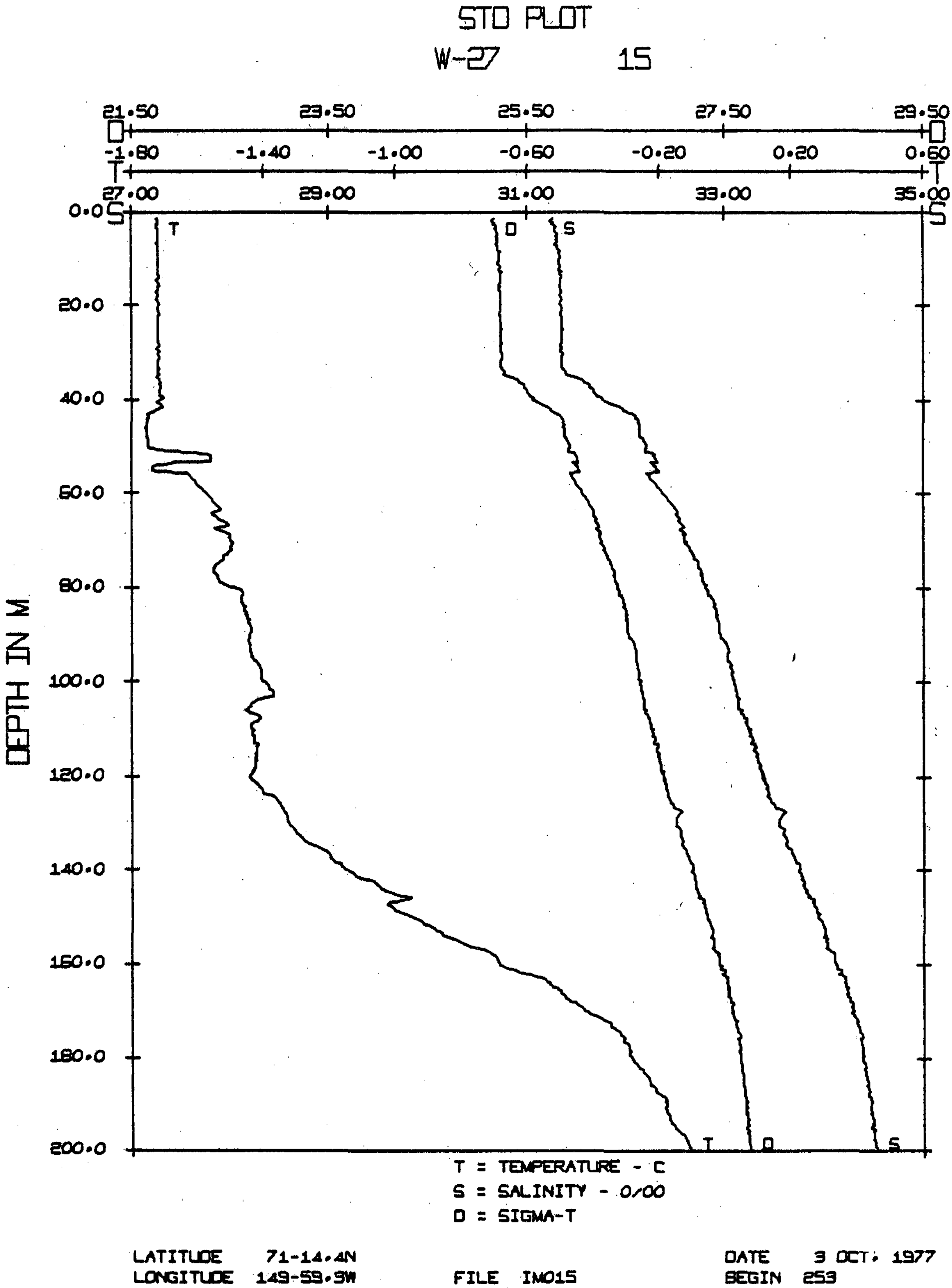
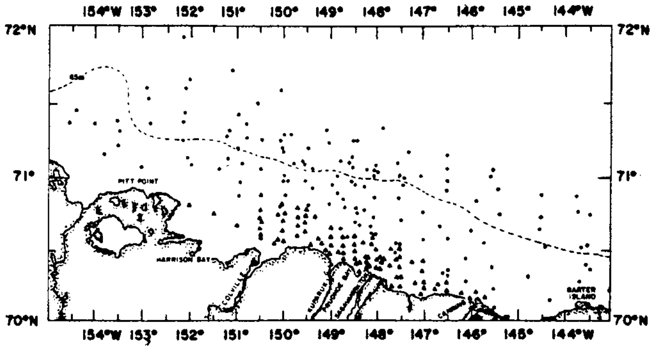
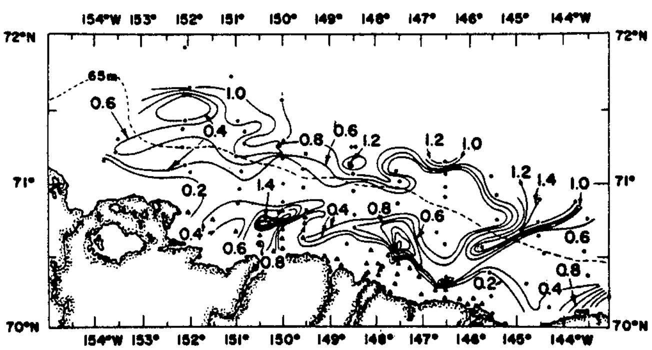


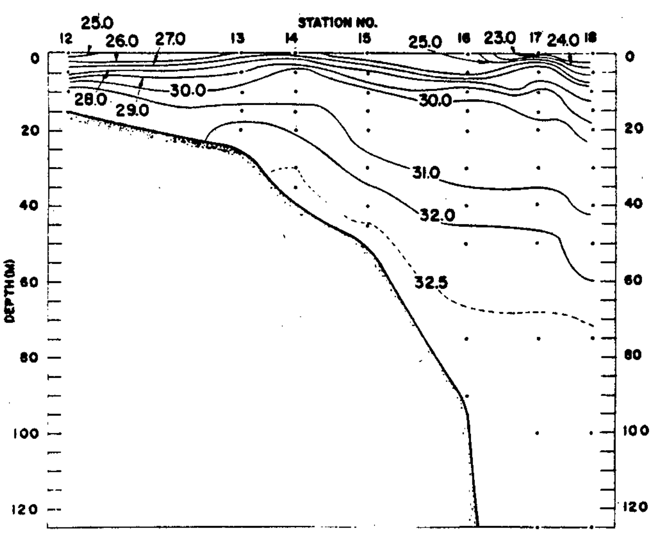
Fig. 2.23 Vertical distribution of temperature, salinity, and density (sigma-t) at a station over the continental slope, March 1977 (Aagaard, 1977).



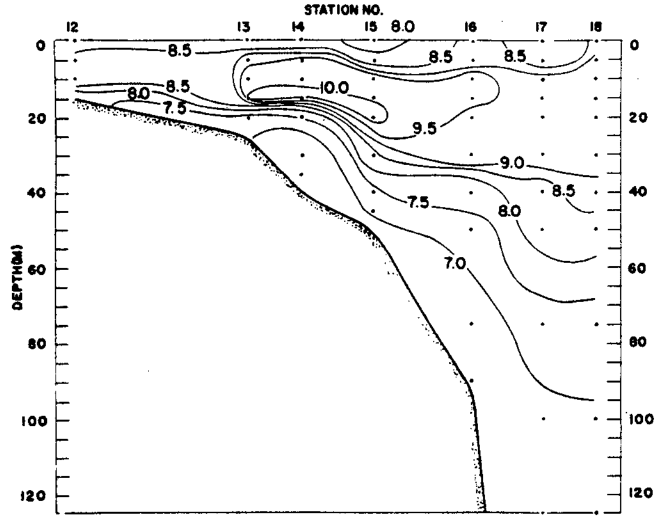
Location of hydrographic stations and section taken in the southern Beaufort Sea, August-September 1972. Circles are *Glacier* samplings, and triangles are *Natchik* samplings.



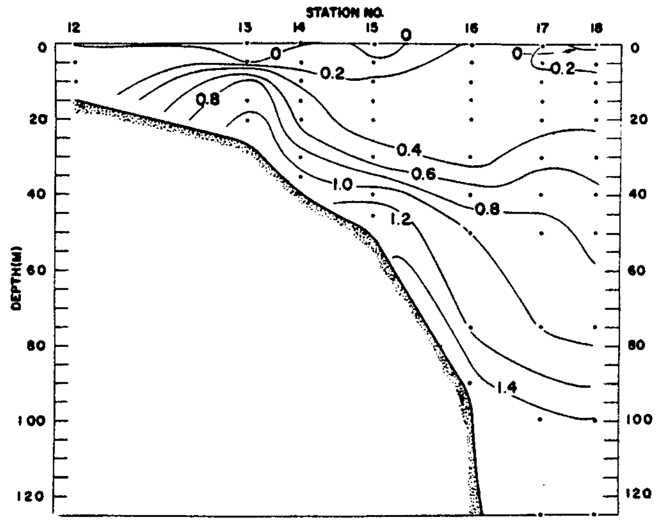
Horizontal distribution of inorganic phosphate in the shelf bottom waters and at 75 m off the shelf, August-September 1972.



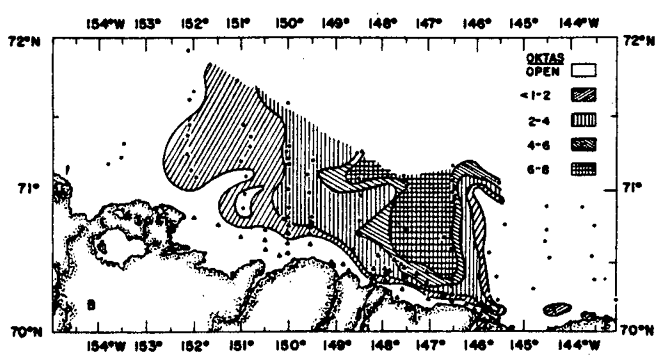
Vertical profile of salinity (‰) along 145°W during August 8-10, 1972.



Vertical profile of dissolved oxygen (ml/l) along 145°W during August 8-10, 1972.



Vertical profile of inorganic phosphate (μg atom/l) along 145°W during August 8-10, 1972.



Ice concentrations encountered during August-September 1972 (based on *Glacier* and *Natchik* observations). Concentration is in oktas (scale of eight).

Fig. 2.24 Distribution of various parameters over the Beaufort shelf, summer 1972 (Hufford, 1974).

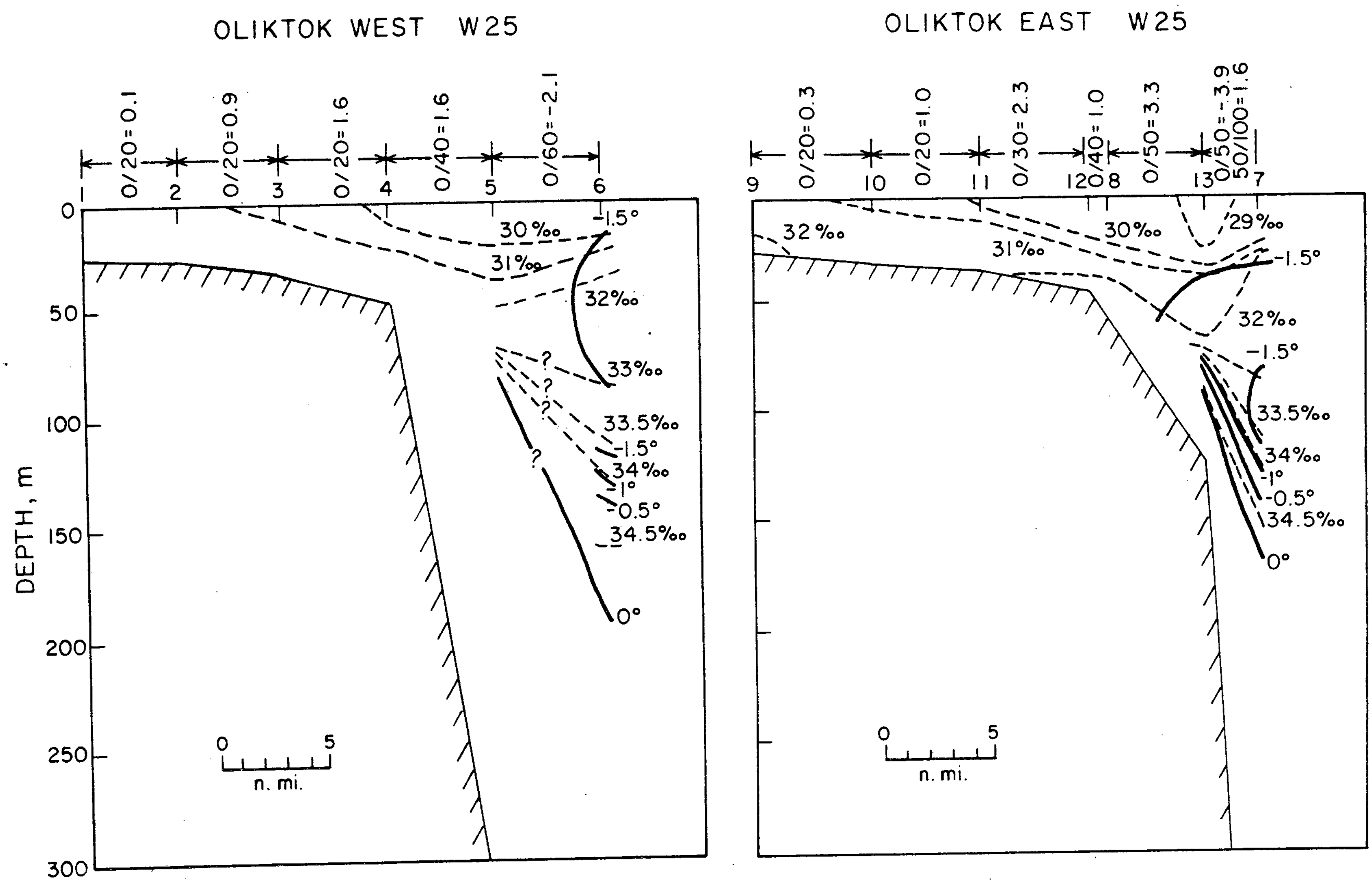


Fig. 2.25. Two profiles across the shelf north of Oliktok, October-November 1976 (Aagaard, 1977).

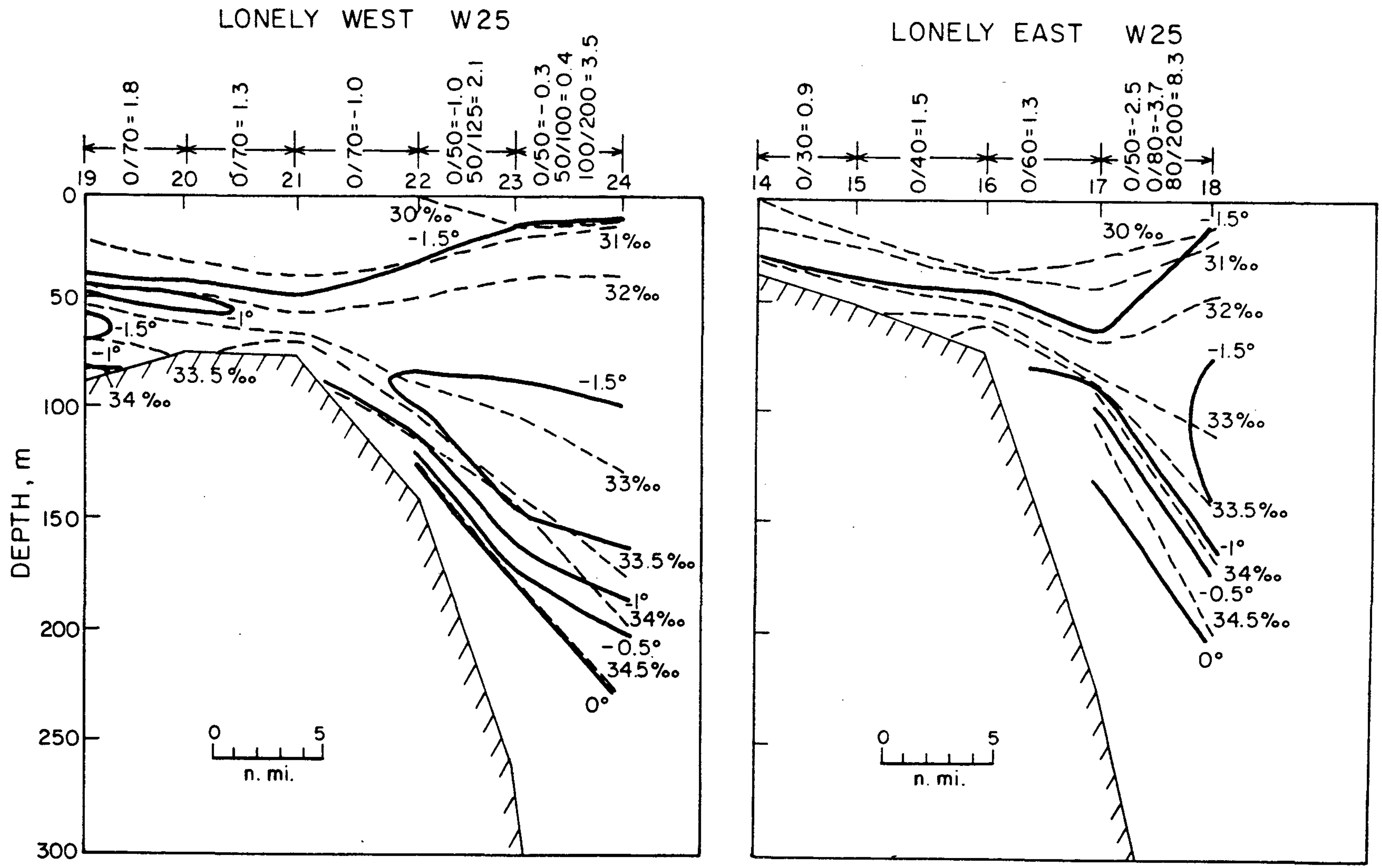


Fig. 2.26 Two profiles across the shelf north of Lonely, November 1976 (Aagaard, 1977).

characteristically about $0.1^{\circ}C$ colder than in fall, and there is indication of a slight supercooling, a few hundredths of a degree, relative to the freezing point at surface pressure.

In spring, conditions appear very similar to those in winter. The salinity and density structures are about the same, but there are some slight differences in the temperature of the upper layer. It is not quite as cold, beginning instead to show a small spring warming. Specifically, there is not much evidence of supercooling (relative to surface pressure); rather the temperature near the surface varies from the freezing point to $0.1-0.2^{\circ}C$ above freezing. This warming is restricted to a thin layer (e.g., the upper 5 m) and is frequently accompanied by a salinity that is slightly lower than that of the underlying water.

Several of these features are worth further comment. First, the depth to which a layer is mixed, in the sense that above this depth the density is nearly uniform, is considerably shallower than the depth to which the water is at the freezing point. Two examples are shown in Fig. 2.27, portraying both a fall and a winter station. At both stations, a noticeable pycnocline (of about 0.05 in σ_t per meter) begins at about 20 m, while the water is at the freezing point for more than twice this depth. Thus, water that has been clearly conditioned by the freezing process, subsequently can be found within or below a pycnocline. Most probably the water has simply moved obliquely down to the depth locally appropriate to its density. An observed water column is thus not simply representative of a local and vertically extensive mixing process driven by freezing, but rather it represents a layering of waters that may have been influenced by freezing at a variety of locations and times. After being cooled, and probably also changing salinity, the various parcels of water then arrange themselves in a stably stratified layer through differential motion. In other words, T-S distributions, such as the two shown in Fig. 2.27, suggest that the time history of a column of water involves considerable vertical shearing.

Second, there are considerable year-to-year variations in the hydrography. A good example is afforded by comparison of the salinity distributions from the winter of 1976 with those from the winter of 1977. In both years, the nearly-homogeneous upper layer was about the same depth (32 m on the average), but the mean density of this layer was greater in 1977 by 1.0 in σ_t, corresponding to a salinity difference of 1.2 o/oo. Likewise a comparison of the preceding fall conditions in 1975 and 1976, shows considerably lower salinity in the earlier year. Therefore, not only can there be appreciable salinity differences from year-to-year, but such differences can persist through an entire seasonal progression.

Third, the seaward decrease of surface salinity across the shelf in winter (typically by 0.4-0.9 o/oo) is of some interest. While the mechanism behind this distribution must still be considered uncertain, it appears likely that it is caused by an onshore flux of salt in the lower part of the water column over the shelf. There are several reasons for this tentative conclusion. First, the isohalines in general tend to slope upwards toward the coast at all depths above at least 100 m. Therefore the seaward decrease of salinity at some level is not merely a near-surface phenomenon. Second, since the sloping of the isohalines is generally seen to extend down to and including the 33 o/oo isopleth

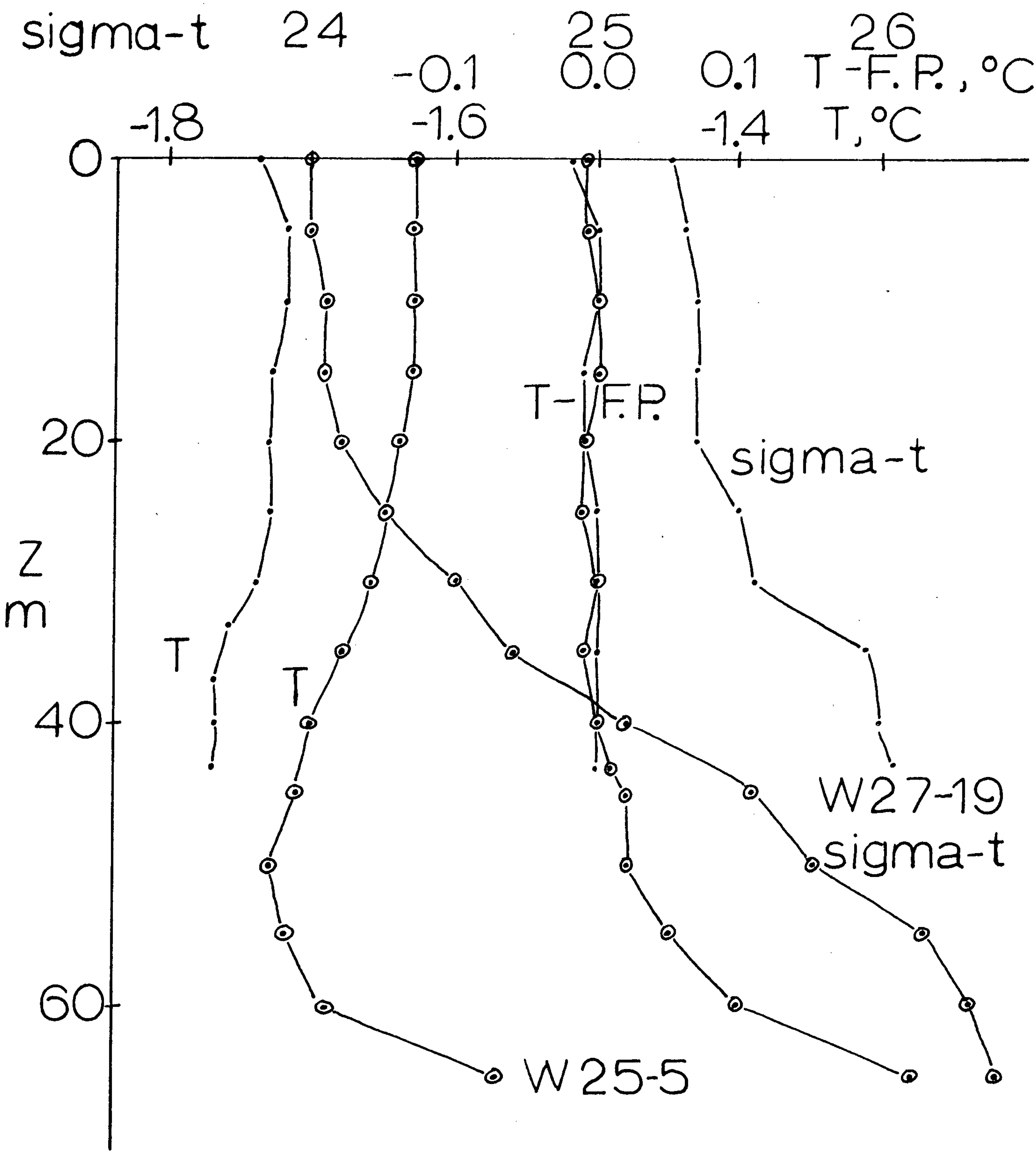


Fig. 2.27 Vertical distribution of temperature, density (sigma-t) and deviation from freezing point at two stations on the outer shelf north of Oliktok. W25-5 is from October 1976 and W27-19 from March 1977 (Aagaard, 1977).

(corresponding to a density in excess of 26.5 in σ_t), the slope cannot reasonably be attributed to the offshore flow of dense water originating on the shelf; there simply are no significant amounts of water this dense that are native to the shelf. For example, the relatively dense Bering Sea water, so apparent on the shelf in summer and fall, does not extend much beyond $\sigma_t = 26$. Third, there is observational evidence for a deep onshore flux of salt, particularly in the fall 1976 sections, when saline Atlantic water was found on the shelf in the presence of a very strong geostrophic shear (Aagaard, 1977).

All this is not to say that there is a simple, steady transverse circulation across the shelf. Rather, among other complications, it is probably that a strong time dependence is involved. It may well be that the salt flux is in some sense a series of pulsations. Nonetheless, it seems likely that in the mean there is a net flow of saline water onto the shelf in the lower part of the water column.

There have been several direct measurements of currents on the outer shelf. Hufford (unpublished data) measured the flow at 25 m in water 54 m deep some 60 km east of Barrow for two weeks in August 1972. He found a strong eastward flow, averaging 60 cm/sec the first week. The current then decreased to less than 10 cm/sec, and on occasion reversed its direction, before resuming its eastward flow at more than 40 cm/sec a week later. The decrease during the second week occurred during a period of strong easterly winds.

Aagaard and Haugen (1977) have reported a current series from 100 m in water 225 m deep, north of Oliktok. The measurements extended from late May to the beginning of September 1976, during which time the velocity varied between 56 cm/sec easterly and 26 cm/sec westerly. The entire 95-day record was dominated by large low-frequency oscillations which had a typical peak-to-peak amplitude exceeding 50 cm/sec and a time scale of approximately 10 days. In effect, the oscillations represented long bursts of high easterly velocity separated by shorter periods of lesser flow towards the west. Between the easterly bursts there were frequently smaller oscillations with amplitude and time scales of about 10 cm/sec and 2 days, respectively. August showed particularly large and long eastward bursts. The flow did not alternate strictly between east and west, for there were also appreciable north-south motions. Rather there was a tendency for the water to have a southerly component of motion when moving eastward, and northerly when moving westward. The relative magnitude of these components was such as to direct the oscillations along the line 100-280° T. This is identical to the local isobath trend, so that the oscillations nearly represent alternating motion along the shelf edge. The mean motion also appears to be steered by the bathymetry. During 27 May - 14 July the mean set was 7.0 cm/sec toward 100°T and during 16 July - 1 September the mean set was 18.5 cm/sec toward 98°T.

These same records show rather clear tidal signals, considerably larger than those recorded on the inner shelf by Aagaard and Haugen (1977). The tidal amplitude was in the neighborhood of 5 cm/sec, and there appeared to be a diurnal inequality near the time of maximum lunar declination. Examination of the spectral estimates in the tidal band showed typical amplitudes of 2-4 cm/sec for the M_2, S_2, K_1 and O_1 constituents. Neither the wind nor the surface pressure records from shore stations during the period of current measurement have shown any convincing correlation with the flow measured in 1976.

Aagaard (unpublished data) has also obtained current measurements from the outer shelf north of Lonely from late March to late October 1977. Again, flow was primarily along the isobath, and showed frequent directional reversals and large speed fluctuations; maximum speeds were about 60 cm/sec. The energy was concentrated at low frequencies, corresponding to time scales of 3-10 days, but the statistics of the flow appear to be highly non-stationary, even for base periods exceeding three weeks. A short period of overlapping current records indicates that the low-frequency fluctuations were vertically coherent. The mean flow at 150 m over six and one-half months was 3.4 cm/sec at 135°T, which is probably very nearly the isobath trend. However, even over periods of a month or so, the mean flow can be in the opposite direction.

The picture emerging from these measurements is of a regime that is highly energetic over a broad band of sub-tidal frequencies, although the mean flow calculated for a sufficiently long period (possibly up to several months) is unquestionably eastward. The flow appears to be steered by the local bathymetry and although the energetic time scales of the flow are those of synoptic meteorological events, no clear relationship between atmospheric and oceanic events has been shown to date, even as phenomena.

The most important areas for further investigation on the outer shelf relate to the dynamics of the along-shore (or nearly so) low-frequency flow scales revealed by the current measurements and to the cross-shelf exchanges indicated by the hydrography.

The Beaufort Gyre

Offshore from the shelf there is a general westerly flow which, at least for the surface layer, has been recognized for many years as being part of the general anticyclonic circulation in the Canadian Basin of the Arctic Ocean. The gyre is centered near 76°N, 145°W, coinciding very nearly with the mean atmospheric pressure anticyclone. Temporal variations in the surface drift have been indicated to occur at time scales up to multi-year. A general discussion of these matters can be found in Newton (1973) and in Coachman and Aagaard (1974).

The most recent dynamic topography chart for the gyre is that of Newton (1973), shown in Fig 2.28. The indicated mean surface flow is generally slow, about 2 cm/sec in the central portion of the gyre, but it is intensified north of Alaska, reaching 5-10 cm/sec at the longitude of Barrow. The Beaufort gyre appears to be driven by the curl of the wind stress (Newton, 1973), with the intensification in the southwestern Beaufort Sea being due to topographic effects (Galt, 1973). Newton (1973) has also re-examined the subsurface flow of Atlantic water in the gyre, finding evidence that northwest of Barrow there may be a deep counterflow along the Chukchi Rise, possibly continuing toward the continental slope.

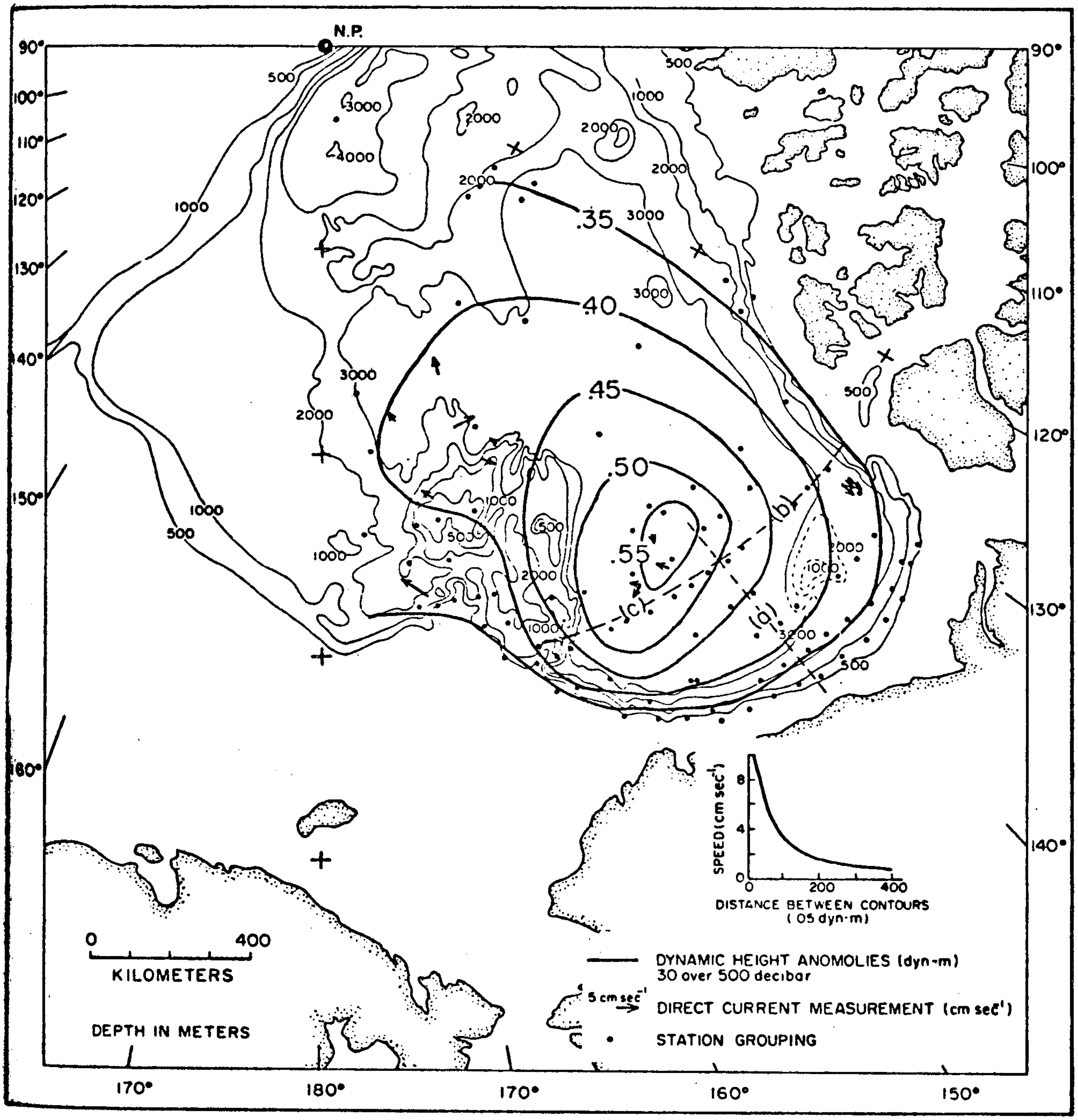


Fig. 2.28 Dynamic topography of the Canada Basin. Dashed line segments (a), (b), and (c) show the locations of the transport sections. The length of the direct current legend vector indicates a velocity of 5 cm sec^{-1} (Newton, 1973).

The importance of the gyre to the shelf circulation is that it can serve both as a source and a sink for shelf waters. It is in this perspective that one might anticipate future work under OCSEAP auspices on the southern part of the Beaufort gyre.

Dispersal Mechanisms for Oil

The wind-driven circulation in the coastal areas, cross-shelf exchanges and large-scale circulation on the shelf have been discussed. During the winter, ice plays a major part in the dispersal and transport of spilled oil. For a more detailed discussion of the behavior of spilled oil see Section 10 where the sequence of events following summer and winter spills is discussed. During the open water season in summer other mechanisms that disperse oil are summarized in Table 2.1 and their relative importance in the dispersal of oil indicated.

Table 2.1. Dispersal Mechanisms for Oil in Summer for the Beaufort Sea Shelf

Mechanisms	Importance
Tides	Very small (range of tide less than 30 cm).
Waves	Generally small (limited fetch due to ice cover; however, during storms in the ice-free season, wave heights of 6-9 m have been observed).
River Flow	Small (limited to breakup period in June when it can be large locally and extend up to 10 km or more from the river mouth).
Surges	Large (surges of 1-3 m, both negative and positive, increasing towards the east).

Ocean Hazards to Structures

A quite separate aspect of OCSEAP oceanographic research deals with ocean hazards to structures, Although in the Beaufort Sea these are dominated by sea ice problems, open water problems nevertheless pose constraints to the design of structures. For a summary of these oceanographic hazards, prepared by the Alaska Oil and Gas Association, see Appendix I in Section 12 on Environmental Hazards.

Summary of Information Gaps

1. To date the physical oceanographic effort in the nearshore region has been modest, and many pieces of the puzzle are missing. Major examples are: a statistical knowledge of nearshore wind-induced wave and current structures, such as is required for assessing sediment and detritus deposition and erosion; more information on flow during winter and its variability and causes; and an understanding of the exchange of water (and the substances it transports) between the nearshore region and the inner shelf. However, it is also clear that at least in summer the nearshore region is strongly wind-driven. Given the inherent difficulty of making local wind forecasts, it therefore follows that the future research efforts must be aimed at understanding mechanisms and processes, rather than at attempting detailed predictions of water motion and quality.

Specific studies in the nearshore area should include:

a. Mesoscale wind fields, by establishing temporary stations to measure wind and pressure, since the variation of surface wind with distance offshore is poorly known.

b. Seasonal picture of storm surge propagation and frequency of occurrence through long-term sea level observations.

c. Wave measurements.

d. Gauging of the Colville River.

2. The inner shelf is the least known portion of the Beaufort shelf. (For these purposes we can define the inner shelf as lying between the 10 and 50 m isobaths.) In particular, it would seem crucial to learn:

   a. the relative importance to the summer circulation of both direct local wind forcing and baroclinicity;

   b. the extent and nature of cross-shelf circulation, e.g., whether there is a net offshore movement in the upper layer, driven either by the wind or the density distribution.

3. The most important subjects for further investigation on the outer shelf relate to:

   a. the dynamics of the nearly along-shore low-frequency flow, which is the major velocity signal;

   b. the cross-shelf exchange, both with the nearshore regime and with the southern part of the Beaufort gyre.

4. The importance of the Beaufort gyre to the shelf circulation is that it can serve both as a source and a sink for shelf water. While we make no specific recommendations, it is from this perspective that one might anticipate future work under OCSEAP auspices on the southern part of the Beaufort gyre.

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3. GEOLOGICAL SCIENCES

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A broad range of earth-science studies in the Beaufort and Chukchi Sea areas has been supported by OCSEAP. However, it should be recognized that the foundation on which the geologic science synthesis is built is not based on OCSEAP-generated information and efforts alone but also on a wealth of information existing before OCSEAP studies began and some contemporary research efforts on the part of other agencies, represented by the contributors to this section. Some of the studies, such as the examination of the ice-gouging on the sea bottom, and the estimates of coastal stability, were conceived as studies of obvious geologic hazards to exploratory drilling activity, production islands or platforms, pipelines, and support facilities.

Other studies, such as the analysis of the distribution of bottom sediment type and character, and the study of rates and mechanisms of dispersal of sediments were originally conceived in support of the biological investigations and as baseline characterizations. However, the Barrow Synthesis meeting made obvious to us the interdependence of the biological, physical, chemical and geological investigations and demonstrated very satisfyingly to our group that geologic studies can contribute in many ways to minimizing environmental damage and to optimizing the use of scarce resources during the inevitable future exploitation of the petroleum reserves of the continental shelves of arctic Alaska.

Due to the priorities of existing OCS lease schedules, this summary will focus chiefly upon studies of the continental shelf of the Beaufort Sea and will give only peripheral consideration to the Chukchi Sea. However, it should be kept in mine that many of the techniques developed in the Beaufort studies as well as many process-related studies will be readily applicable to the Chukchi area. Under each earth science heading we have outlined the present state of knowledge along with the relevant literature apart from our reports to OCSEAP. Secondly, we have at tempted to define research areas where additional geological studies are necessary to understand the impact of envisioned OCS activities in the arctic. Stated authorship is shared among those who actually attended the Barrow Synthesis meetings, but the report also contains data contributed by G. Boucher, A. Delaney, S. Eittreim, S. Estes, L. Gedney, A.H. Grantz, M.O. Hayes, A.H. Lachenbruch, R.I. Lewellen, J. L. Morack, C. Pearson, C.H. Rudy, and L. J. Toimil.

Seismicity

Most parts of the arctic coastal plain and the continental shelf of the Beaufort Sea are aseismic, except for a seismically active zone around Barter Island. It is located about 100 km from the boundary line between the United States and Canada and on a trend with the earthquake belt that runs through the center of Alaska (Figure 3.1). The primary sources of seismic information for the above seismic zone, prior to 1968, are teleseismic data. These showed that the zone is isolated from central Alaska by a seismic gap about 100 km wide.

From the beginning of 1968, the improved seismic coverage in the western part of Canada and central Alaska shows a much higher level of seismic activity in both space and time for northeast Alaska. To detail the nature of the seismicity for this area, a local seismographic network comprising ten telemetered stations was emplaced in 1975 (Biswas et al., 1977). The analysis of the data gathered to date reveals the following (Figure 3.2):

(1) The seismic zone around Barter Island is an integral part of the central Alaskan seismic zone. The earthquakes located in the area are shallow (focal depth ranges from 0-20 km). The seismic gap mentioned above resulted from the lack of local seismic coverage in the past.

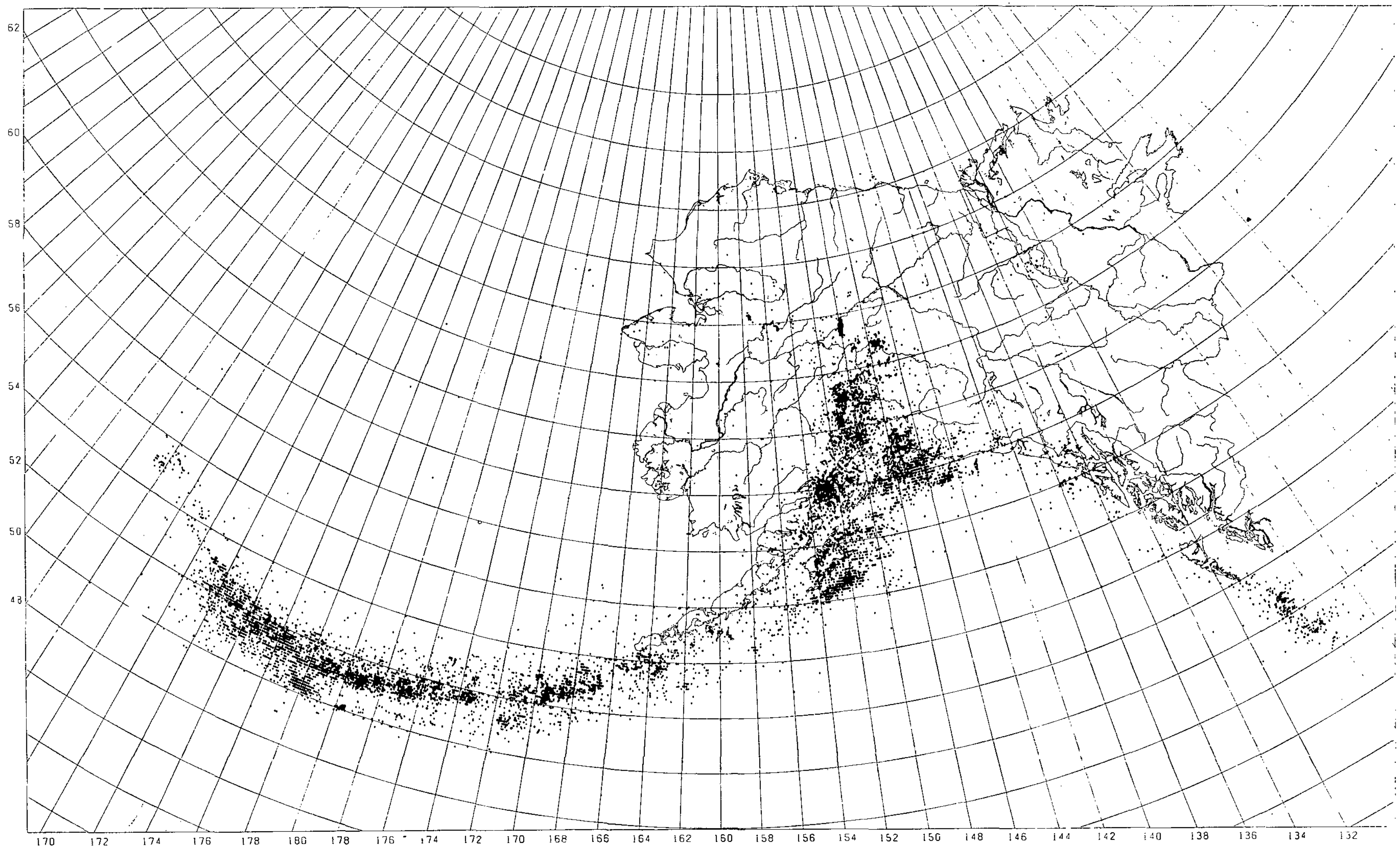
(2) Within the last 10 years, the largest earthquake (M_L = 5.3) occurred in an area located about 30 km offshore from Barter Island. The main shock was followed by a series of aftershocks, the locations of which show a ENE-WSW seismic trend along the axial traces of the offshore folded structures.

(3) The available data represent too short a time interval for the determination of recurrence rates for earthquakes of magnitude greater than 5.0 in the study area. However, the data are indicative of the design need for man-made structures to withstand ground vibrations from a shallow earthquake of magnitude at least 6.0.

(4) The remainder of the earthquakes located in northeast Alaska are of magnitude smaller than 5.0 and tend to be distributed on the eastern side of the interface between the Colville geosyncline and the Romanzov Mountains. A notable concentration of epicenters occur on and around the Porcupine fault and the Kobuk trench on the south side of the Brooks Range. Linear structures, like the pipelines, should have appropriate design provisions for periodic displacements of small extent at the crossings of these two seismically active geological structures. It seems reasonable to assume that episodic motions of small magnitude may eventually add up to a significant ground displacement over a lengthy period of time.

Sea Level History

Knowledge of sea-level history is needed for estimation of longterm sedimentation rates, for coastal stability studies, for geothermal modeling to predict the distribution of offshore permafrost, and for determining the areas most likely to contain submerged archaeological sites. Figure 3.3 is a plot of the estimated positions of sea level relative to modern sea level during the past 30,000 years on the



NOAA/EDS/National Geophysical and Solar-Terrestrial Data Center

Fig. 3.1 **EARTHQUAKES IN AND NEAR ALASKA (THRU 1974)**

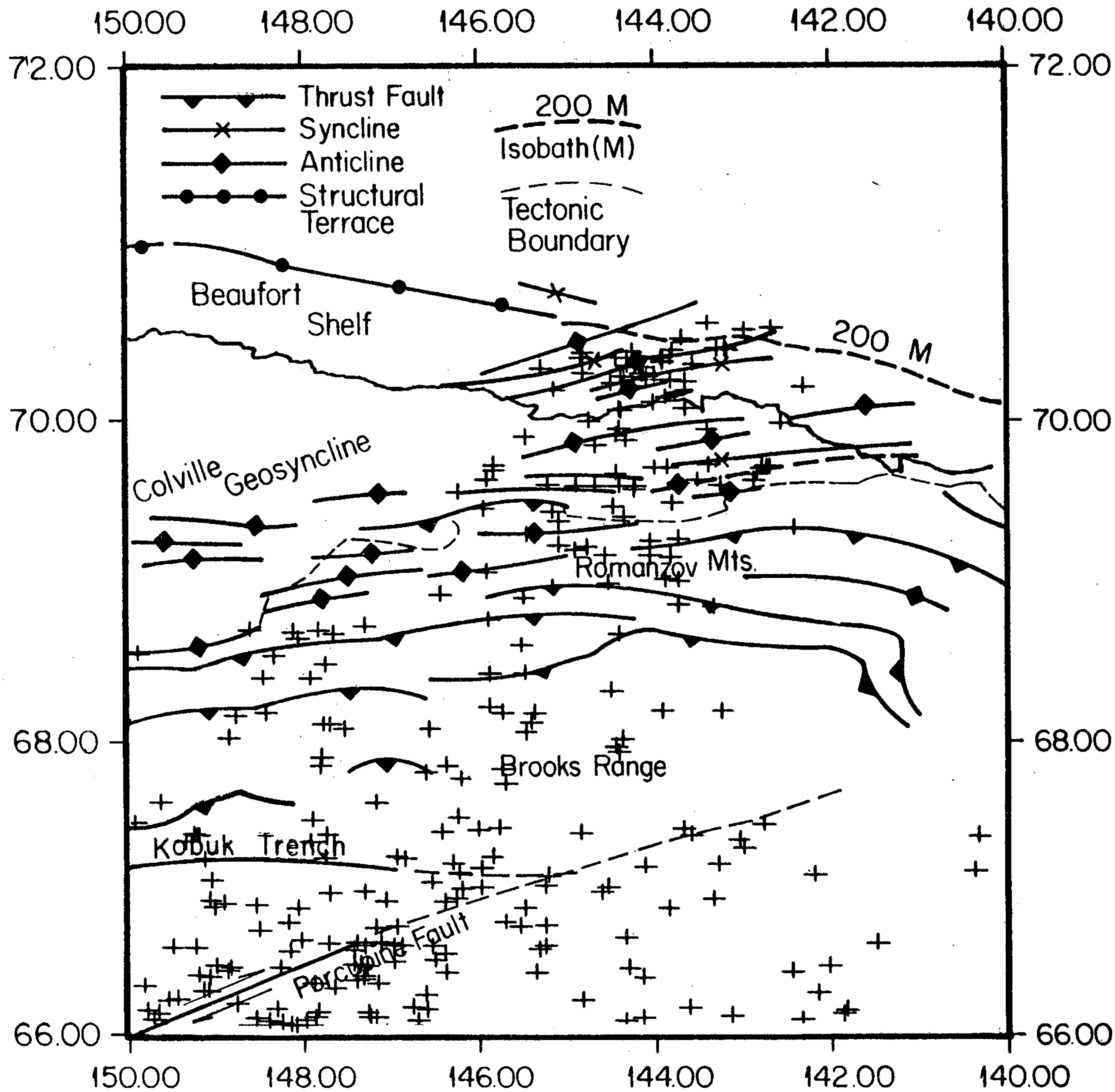


Figure 3.2 Epicenters (+) of earthquakes located during 1976 and 1977 by the local seismographic network having rms of travel-time residuals $\leq$ 1.5 sec plotted on an overlay of the structural traces in northeast Alaska. The epicenters shown north of 70°N. latitude are from Canadian catalog. (Biswas, 1977).

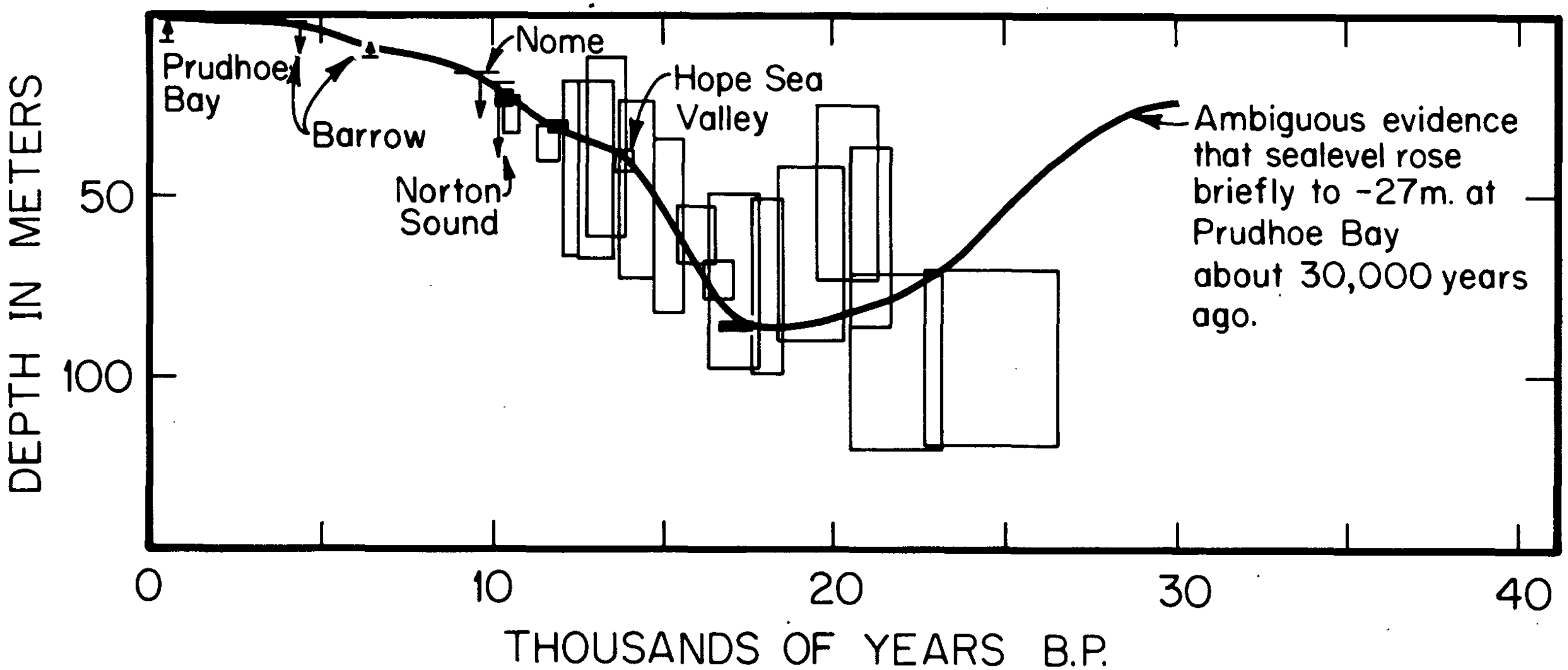


Figure 3.3 Reconstruction of sea-level history on the continental shelves of western and northern Alaska. Width of boxes indicates uncertainty of age and height indicates uncertainty of position of sea level. Small boxes solid to emphasize good data points. Down-pointing arrows mark maximum possible position of sea level, based on subaerial peat below beach sediments. Up-pointing arrows mark minimum possible position of sea level based on driftwood in marine mud above beach sediments. (Data by D.M. Hopkins from several sources.)

continental shelf areas off western and northern Alaska. Most of the data are from the Bering Sea. The Beaufort Sea curve may need significant revision as more local data become available.

Distribution and Character of Bottom Sediments

The bottom sediments are reasonably well mapped between Point Barrow and Canada, except on the inner shelf west of Cape Halkett and east of the Canning River (Figure 3.4) (Barnes and Reimnitz, 1976; Naidu and Mowatt, 1974). The sediment character of the Chukchi Sea floor is fairly well known, primarily from the work of Creager and McManus (1967). Extreme diversity even over short distances is perhaps the most distinctive characteristic of arctic shelf sediments.

The sediments consist chiefly of poorly sorted silty clays and sandy muds containing varying amount of intermixed gravel. The sediments become generally coarser eastward; clayey sediments predominate on the continental shelf west of Cape Halkett and areas of sandy bottom are essentially confined to shelf areas to the east and along the coast (Figure 3.4). Lateral variations in mineral assemblages in the sand and clay fraction indicate that the fine sediments are of local derivation, introduced from the major North Slope rivers and by erosion of the coastal bluffs (Naidu and Mowatt, 1974). The finer grain size of bottom sediments west of Cape Halkett reflects the fact that all of the streams west of the Colville River have low gradients and head toward the arctic coastal plain. Rivers east of the Canning flow northward in steep courses from mountains a few tens of kilometers south of the Beaufort Sea coast and bring in coarser material.

Holocene sediment — that is, marine sediment laid down during the last 10,000 years — covers only part of the continental shelf. The thicker accumulations consist of silty fine sand and clayey silt less than 10 m thick (Figure 3.5). Furthermore, sedimentation rates vary widely. Data from seismic reflection profiling and from the offshore permafrost program suggest rates of less than 10 cm/century for much of the shelf, both inshore and offshore from the barrier islands. However, drillhole data show that sediments in the sheltered basin of Prudhoe Bay have been accumulating at the much more rapid rate of 60 cm/century. High sedimentation rates might be expected off the mouths of the major rivers, but the apparent limited thickness of Holocene sediments and the stability of both the subareal shoreline and the delta front platform off the Colville River seem to indicate accumulation rates of less than 5 cm/century there. By comparison, sedimentation rates are about 10 cm/century on the continental slope north of the Mackenzie River (Pelletier and Shearer, 1972), and rates of less than 5 mm/1,000 years are reported for the deep arctic basin away from sites of turbidite deposition.

Some areas of the shelf lack any substantial thickness of Holocene sediment. In these areas, the Pleistocene Flaxman Formation overconsolidated marine sandy silt containing dropstones of Canadian origin (Leffingwell, 1919) crops out on the sea floor, underlies a few centimeters of soupy, sandy silt, or lies beneath a veneer of gravel.

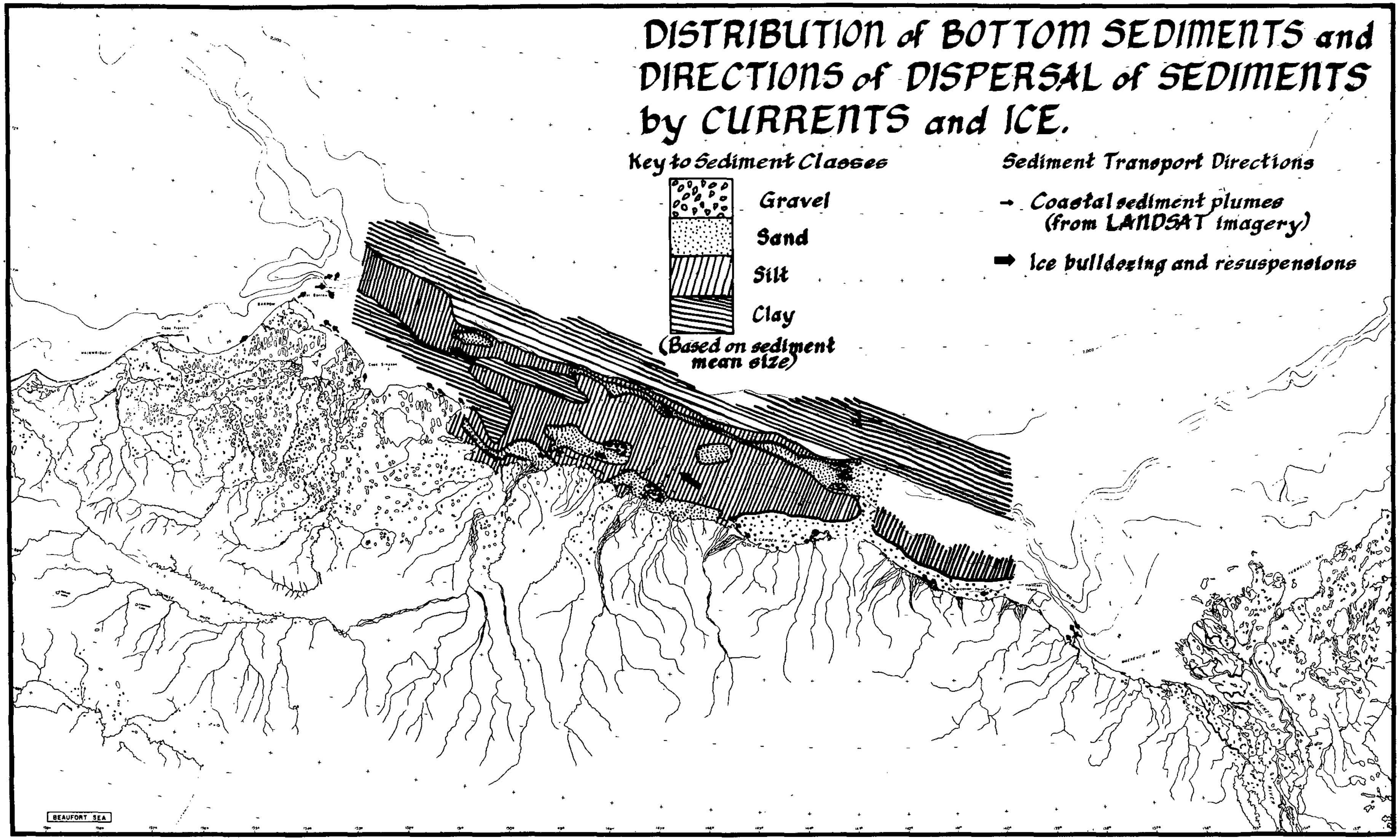


Figure 3.4 Distribution of Bottom Sediments (Barnes and Reimnitz)

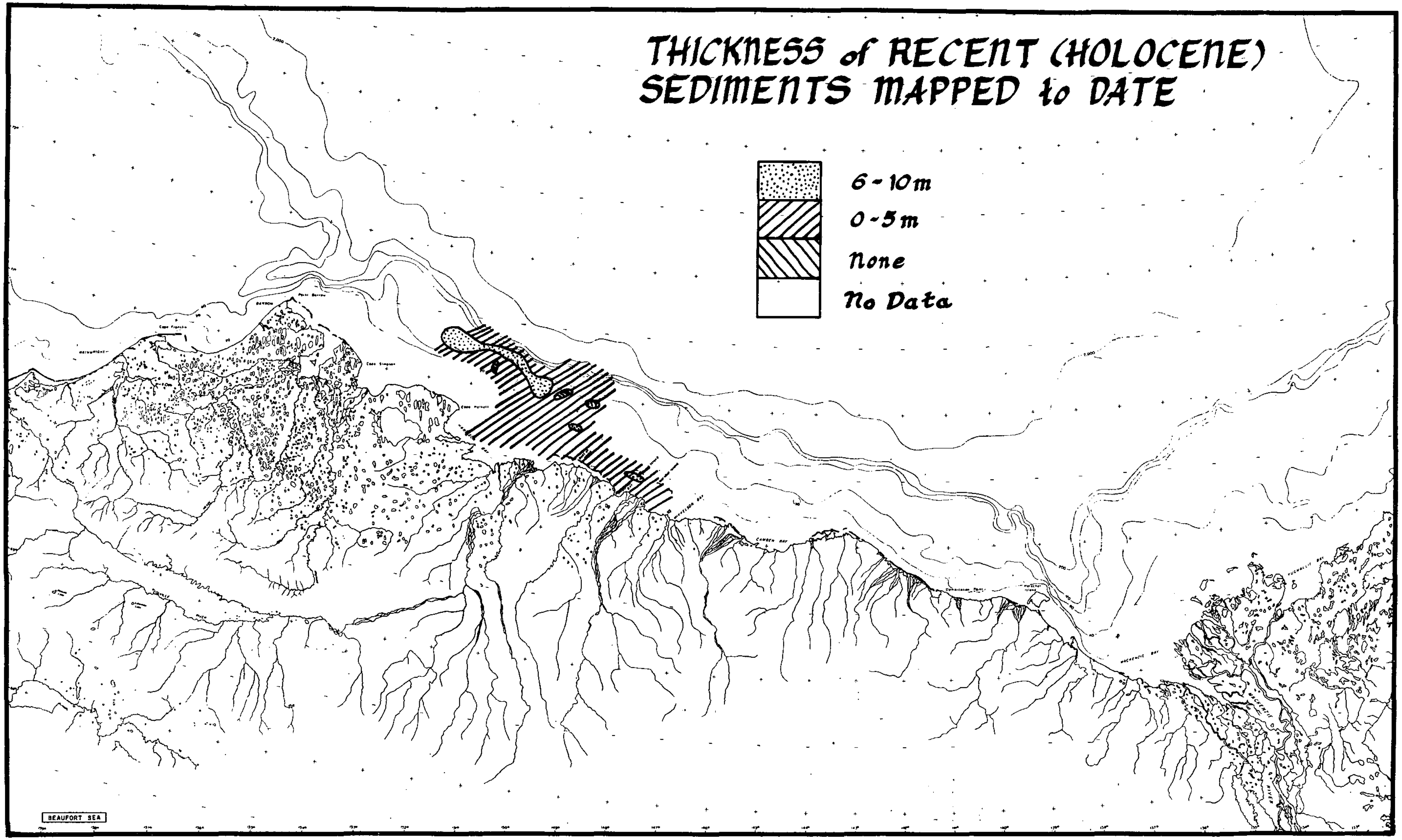


Figure 3.5 Thickness of Sediments (Barnes and Reimnitz)

Patches of gravel and isolated boulders are scattered on the sea bottom. The gravel patches are generally less than 1 m thick and commonly thinner than 15 cm (Figure 3.5). They increase in abundance and extend eastward toward the Canadian border and northward toward the outer shelf margin. East of Prudhoe Bay, the gravel consists predominantly of lithologic types that are not native northern Alaska rocks (Rodeick, 1975), but that are found in the Flaxman Formation. However, chert gravel derived from the Brooks Range is found in shallow water off some mainland beaches, and most barrier islands west of Prudhoe Bay are composed of similar gravel. No gravel is being supplied by modern ice-rafting from distant sources (Barnes and Reimnitz, 1974), and only small amounts are icerafted short distances from local sources. Much of the gravel was supplied by erosion of the coastal bluffs during the transgression, similar to the way in which it is introduced today. The surficial gravel locally and perhaps generally, overlies outcrops of Flaxman Formation on the sea floor. Evidently most of the gravel accumulations are lag deposits that have resulted from the erosion of considerable thicknesses of the Flaxman Formation.

The thickness of gravel deposits merits special consideration, because of the potential requirement for gravel fill for artificial islands and causeways. Aside from the river deposits and the barrier islands, which have been traditional sources of gravel borrow, the only significant gravel sources on the shelf are thought to be widespread Pleistocene gravels lying below finergrained surface deposits on the shelf. Gravels have been encountered in the permafrost drill holes north and south of Reindeer Island. Access to these gravels may be hindered by the presence of the overlying Holocene marine section and by overconsolidated clays such as those encountered during drilling in the vicinity of Reindeer Island or by the stiff gravelly muds found in vibracores north of Cross and Reindeer Islands.

Studies of soil properties, in detail in the Prudhoe Bay area under the permafrost drilling program (Chamberlain and other, 1978), and reconnaissance information gathered over wide regions using shear vanes, cone penetrometers, and rates of vibracore penetration, show that there are very large variations. The very stiff, overconsolidated silty clay of the Flaxman Formation is dewatered to the plastic limit or lower. The unit apparently underlies large areas of the shelf, locally cropping out at the surface. The Holocene marine sediments, covering the shelf in general with a 5 to 10 m thick layer, have a higher water content and lower strength, but characteristically are much firmer than lower latitude shelf sediments, judging from the lack of coring success with anything but vibratory or rotary tools.

The mechanism causing the overconsolidation of the very dense clays has not been determined with certainty. However, Chamberlain et al. (1978) suggest that the overconsolidation has probably resulted from freezing and thawing. The strength properties and excavation characteristics of the overconsolidated clays are much different from those of more typical, normally consolidated marine silts and clays. For instance, similar overconsolidated clays occur in the North Sea and provide stable foundations for drilling platforms. However, the cyclic action of waves against the drilling platforms causes a significant reduction in the strength of the overconsolidated clays. Access to significant quatities of offshore gravel may require excavation of a surficial layer of the overconsolidated material. For these and other reasons, the distribution and thickness of these sediments is important to the planning for offshore structures.

Dynamics of Sedimentation: Effects of Waves, Currents, and Sea Ice

Both water and sea ice function to move sediments and modify the bottom. Wave action affects the sediments during the summer openwater season and then only in shallow, nearshore waters. Currents in the water column are most intense during the summer open season, when windshear can augment the effects of tides, atmospheric pressure differences, and the rotation of the earth. The presence of extensive areas of grounded ice restricts winter circulation in lagoons and bays. However, subice currents are apparently sufficient to scour the Prudhoe Bay channel each winter. Winter currents on the open shelf remain adequate to transport fine material resuspended by the ploughing of the bottom by grounded ice. The relative intensities of wave, current, and ice-induced sedimentation processes during summer and winter are shown diagramatically on Figure 3.6. Subice winter currents, particularly where scour may be intensified by restrictions such as in tidal inlets, and in the vicinity of the grounded ice ridges of the stamukhi zone, have not been adequately studied.

The Mackenzie River contributes substantial amounts of sediment during the open season, but most of that sediment drifts in a broad plume eastward away from Alaska. An evaluation of the relative contribution of rivers versus coastal bluffs, analysis of the distribution of suspended sediment plumes, and comparison between the thickness of Holocene sediments and heights of coastal bluffs susgests that coastal erosion is a very significant sediment and nutrient source and possibly the dominant one on the Alaskan sector of the Beaufort shelf.

At the time of initial flooding, the rivers inundate the ice to depths of 1 3 m in areas extending many kilometers offshore (Figure 3.7). Sediment is deposited on the fast ice during this flooding. The water eventually funnels through strudel, swirling drainage patterns that converge on cracks and holes in the ice. Strudel drainage can create cylindrical scour depressions as much as 4 m deep and tens of meters across (Reimnitz and others, 1974). Previously deposited sediments resuspended by the turbulent drainage currents are redeposited in debris mounds flanking the scour depression. Strudel scour and flooding of the shorefast ice may influence development activities off river mouths. The river water draining from the ice forms a turbid freshwater wedge that extends seaward under the ice to distances at least equal to the initial overflow (Walker, 1974). Within a few days after the flooding begins, the ice near the delta front melts and much of the earlier icedeposited sediment is released into the water column. Thus most of the flood sediment is ultimately deposited in this delta front shore lead either directly, or, at later stages of the flood by release from melting ice.

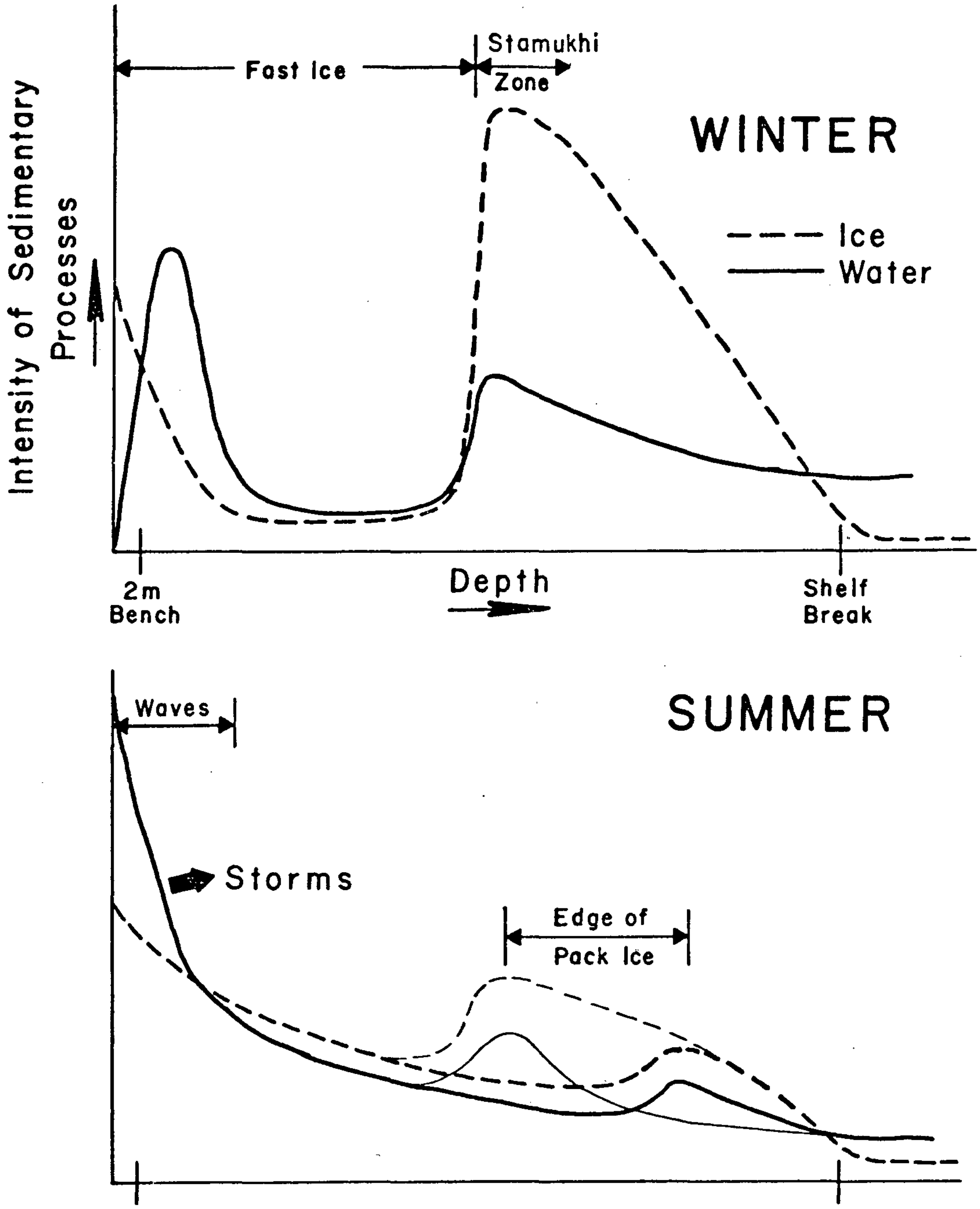


Figure 3.6 Relative intensities of waves, currents, and ice-induced sedimentary processes during summer and winter in the Beaufort Sea. Compiled by Barnes and Reimnitz.

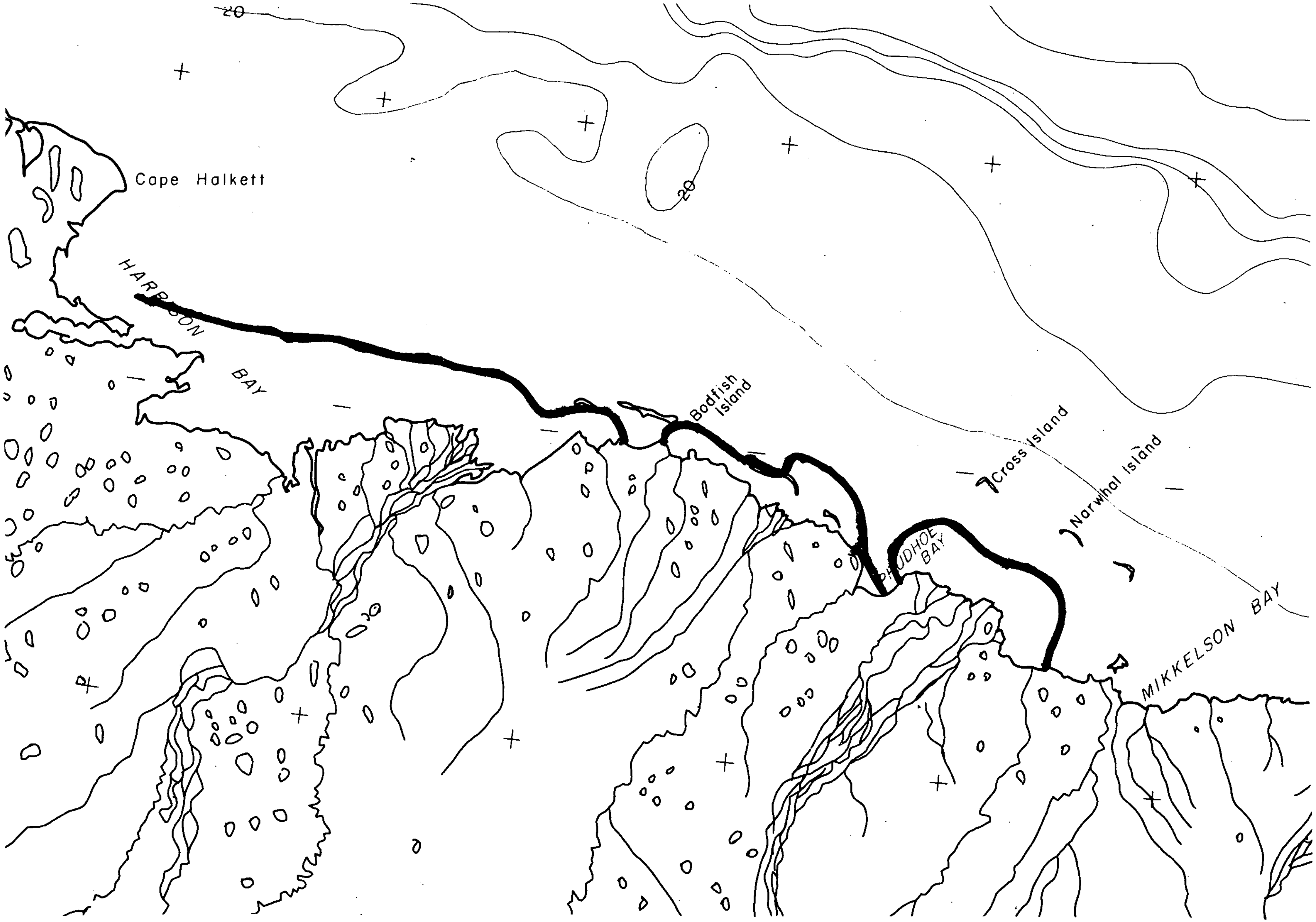


Fig. 3.7 Outer limit of "strudel" scouring, observed between Harrison Bay and Prudhoe Bay (Barnes and Reimnitz, 1977).

Ice rafting also plays a small role in introducing sand and gravelsized material to the Beaufort Sea. Layered mixtures of ice, sand, and gravel are formed on arctic beaches at freeze up. During break up, some of this material can be lifted and rafted a short distance on and offshore. Sand is also blown from beaches onto nearshore ice during winter and may then be dispersed further by rafting during break up. A minor quantity of coarse debris is transported by ice island fragments derived from the Ellesmere Island ice shelves that occasionally become grounded in the Beaufort Sea. Sediments may also be icerafted as a result of being incorporated, probably along shear planes, into grounded ice ridges. During subsequent ice movement or in succeeding summers the ice ridges float, and sediments may be rafted a considerable distance.

Sea ice reworks sediments and modifies bottom topography by impacting, plowing and gouging the bottom (Figure 3.8A). Ice gouge densities, depths of incision, and dominant trends are reasonably well known for the region between Cape Halkett and Flaxman Island inside 15 m (Figures 3.8 and 3.9) but poorly known in deeper water and in the easternmost and westernmost parts of the Alaskan sector of the Beaufort shelf (Reimnitz and Barnes, 1974).

Ice gouge distribution on the inner shelf is closely related to the ice zonation and bottom morphology. The area of intense interaction between the stationary coastal ice and the moving polar pack is marked by a zone of grounded ice ridges, the stamukhi zone (Reimnitz and others, 1977). This zone is also known as the grounded ridge zone. The inner edge of this zone is generally located in the area between the 10 and 20 m isobath, and is commonly associated with shoals. Offshore development activities will be markedly more risky and technically difficult seaward of the inner edge of the stamukhi zone. Ice gouging is especially intense in the stamukhi zone and on the seaward slopes of bathymetric highs.

Ice gouge incisions are commonly more than one meter deep within and seaward of the stamukhi zone and generally less than one meter deep shoreward from the stamukhi zone (Figure 3.10), although maximum values are much greater. Extreme observed incision depths are 4.5 m in 38 m of water in the Chukchi Sea, 5.5 m in the same water depth in the Alaskan sector of the Beaufort Sea, and in excess of 6.5 m in water depths between 40 and 50 m in the Canadian sector (Lewis, 1977). Individual furrows may be oriented in any direction, but by far the majority are oriented parallel to the coastline (Figure 3.9), reflecting the westward drift of the polar pack. Inside the stamukhi zone there is a subordinate trend southwestward obliquely toward the coast, reflecting onshore ice movement, although the dominant trend is still parallel to the coast. Detailed studies northwest of Oliktok Point indicate that ice gouging in shallow water occurs yearly at all water depths studied (Figure 3.10). Gouging occurs frequently enough to rework essentially the entire sea floor to a depth of 0.2 m in less than 100 years (Figure 3.8B). The recurrence rate for ice gouging within the stamukhi zone, although presently unknown, is no doubt much greater. Large variations in shear strength occur across individual gouges, with much greater strength in the gouge troughs than on the flanks, ridges, or undisturbed bottom.

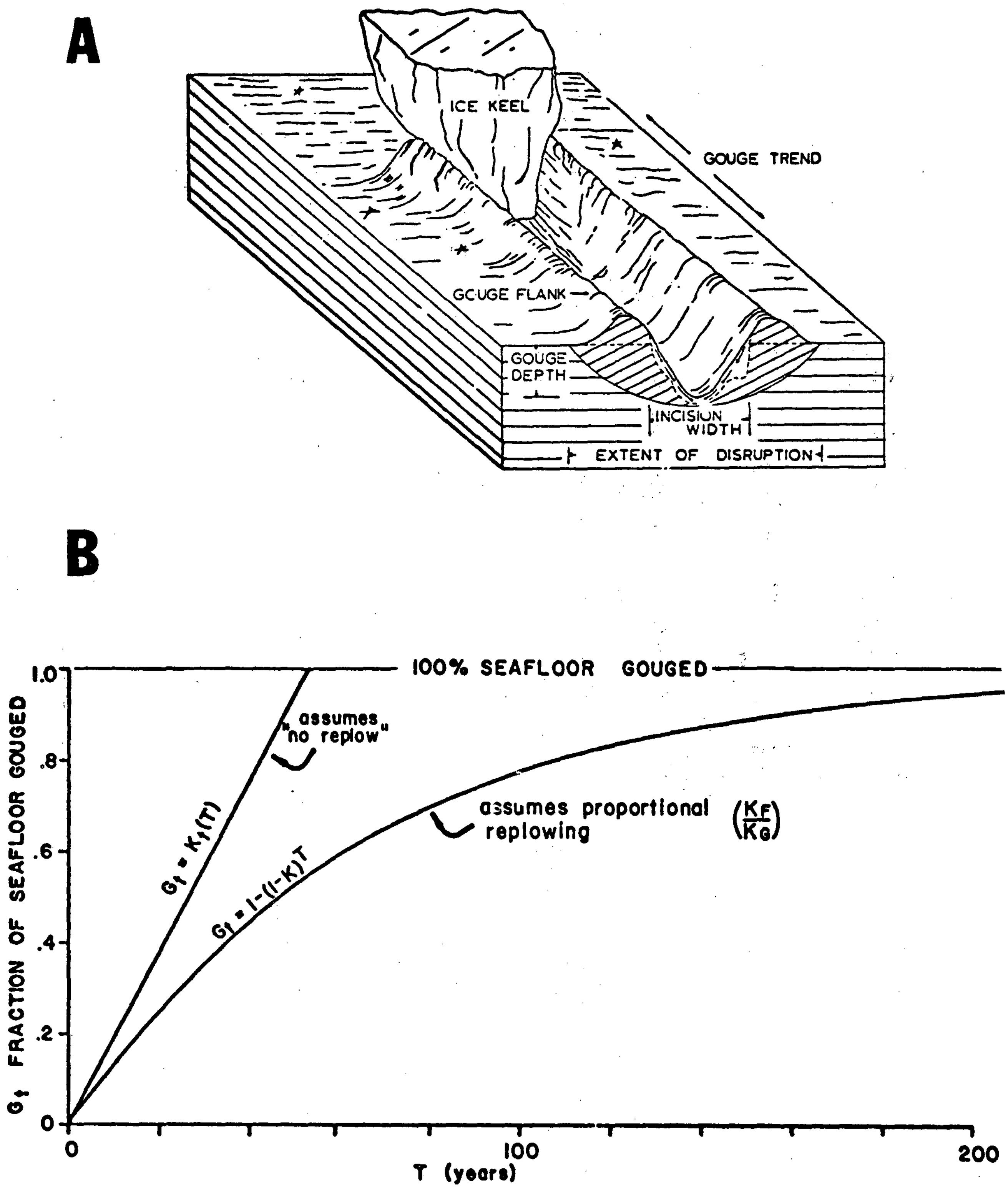


Figure 3.8 A) Drawing of an idealized ice gouge feature with terminology showing the disruptive effect on the sea floor. B) Graph illustrating fraction of the sea floor disrupted by ice (G_t) as a function of time, assuming no replowing $K_t(T)$ and proportional replowing $1-(1-K)^T$.

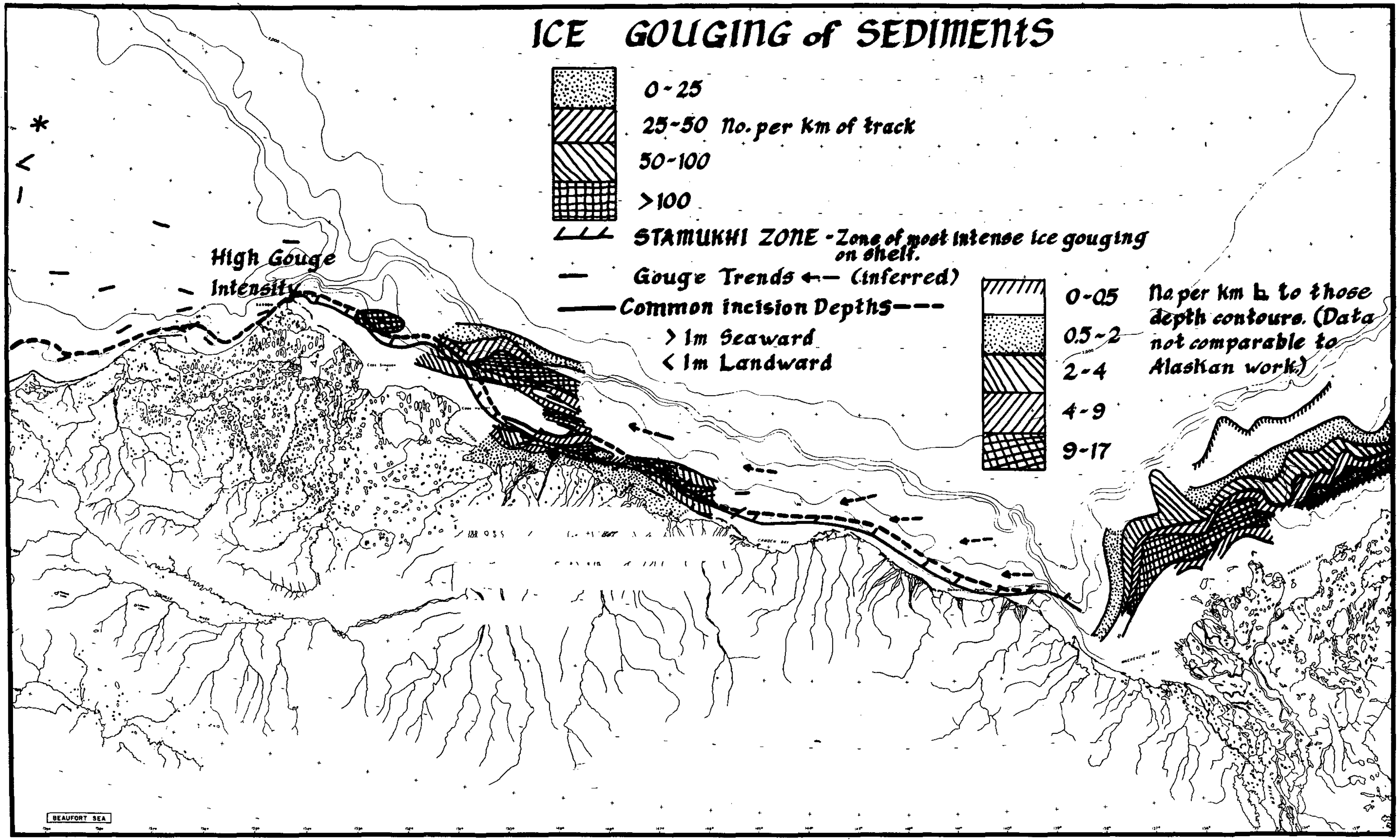


Figure 3.9 Ice Gouging of Sediments (Barnes and Reimnitz)

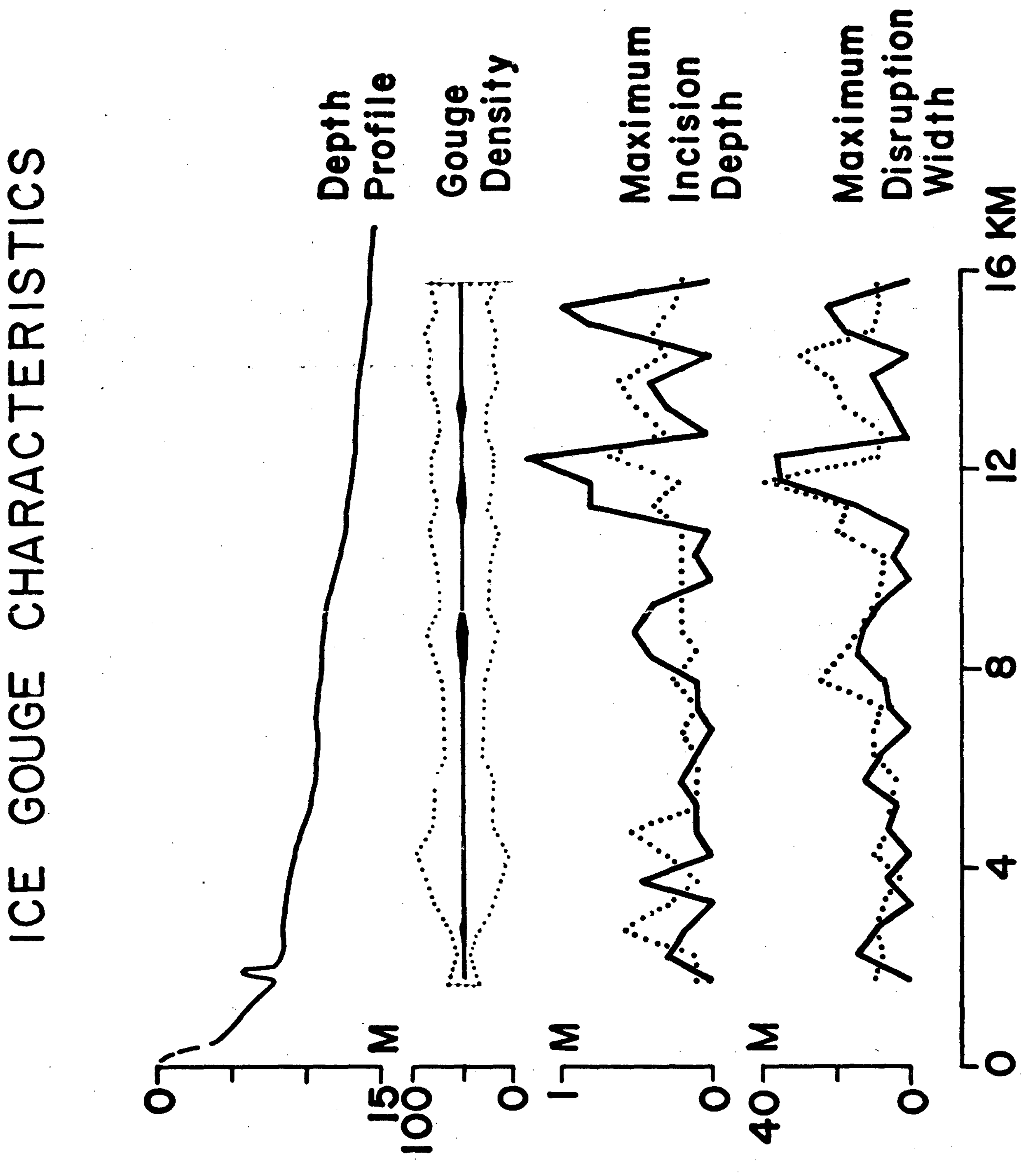


Figure 3.10. Ice gouge characteristics along a trackline northwest of Thetis Island in Harrison Bay. Data has been summarized for 500 meter segments. The dotted lines represent a summary of all gouges observed on 1975 data while the solid lines represent the characteristics of new gouges that were made between 1975 and 1976. (Barnes and Reimnitz)

It may be that repeated physical impacts by ice are responsible for the overconsolidated sediments previously mentioned. Repetitive summer surveys show ice gouging can occur both in summer as well as winter, although it is believed to be most intense in winter. Canadian researchers believe that gouges at water depths greater than 50 m are relict (Lewis et al., 1977; Pelletier and Shearer, 1972). Researchers in the U.S. have cautioned against that hypothesis. Diver observations of the process of erosion and deposition around individual gouges, the presence of strong current pulses on the outer shelf, the association of gouges with hydraulic bedforms, and the consideration of sediment strength suggest that gouging may presently be occurring in water depths from 50 m to the shelf break in both the Chukchi and Beaufort Seas.

Communities of benthic organisms are severely disrupted by ice gouging, with lower abundances being recorded in the stamukhi zone. On the other hand, ice gouging must function to bring buried nutrients to the surface. In water depths shallower than 15 m, the bottom is reworked by ice to depths on the order of ten times the sedimentation rate, which should almost completely obliterate bedding and bioturbation structures. The ubiquitous presence of welldefined crossbedded sand layers in 1.5 m cores from this region is presently unexplained. Data from farther seaward on the shelf are limited to the upper 50 cm and generally show complete disruption of sedimentary structures.

As discussed in more detail earlier, storm surges are triggered by atmospheric low pressures and severe westerly winds. Severe surges reach levels up to 3 m above sea level, and occur at about 25 to 100 year intervals. Loss of land by bluff erosion, changes in coastal and barrier island configuration, and sediment movement may all be greater during these rare events (which last several days) than normally during a decade. At these times transport is eastward, contrary to the long-term net movement.

Subsea Permafrost

In contrast with the recent belief that subsea permafrost did not extend more than a few hundred meters offshore, OCSEAP studies now indicate that ice-bearing subsea permafrost may be widely distributed on the Alaskan Beaufort Sea continental shelf. However, knowledge of distribution and characteristics is rudimentary.

Permafrost is simply soil, sediment or rock with a mean annual temperature less than 0°C. A more important characteristics of permafrost from the standpoint of OCS development is the amount and character of ice. Ice-bearing permafrost may or may not be mechanically ice-bonded and, particularly if salt is present, may contain both a liquid and a solid phase of water. For the most part, subsea permafrost in the Beaufort Sea is relict from a time when the climate was colder and most of the shelf area was exposed. Modern bottom water temperatures are generally below 0°C on the Beaufort Sea Shelf and sub-zero temperatures are believed to extend deep into the sea bed throughout most and perhaps all of the shelf.

The three areas of the Beaufort Sea in which permafrost studies have been conducted thus far differ markedly in their geological and oceanographic environment. The character of the subsea permafrost itself might be expected to be similarly variable.

The Canadian study area off the Mackenzie River delta is exposed to extensive periods of relatively warm, fresh river water (Hunter et al., 1976). In the past, part of the Canadian shelf has been glaciated and thus protected from the extremely cold air temperatures affecting other parts of the shelf during the glacial interval. Using both government and industry seismic data, the Canadians have prepared a preliminary map of the top of the ice-bonded permafrost over a large segment of the Canadian shelf (Figure 3.11) (Hunter and others, 1976).

On the Alaskan Shelf, which has remained free of glacial ice, studies have centered around the area near Prudhoe Bay, and Elson Lagoon near Barrow (Osterkamp and Harrison, 1976; Lewellen, 1973; Sellman et al., 1977; Lachenbruch and Marshall, 1977). A combination of drilling, coring, probing, and seismic data along with model studies and regional data compilations suggests that the permafrost distribution on the shelf is complicated by differences in shelf stratigraphy and thermohaline history. At the present time these data are not sufficient to develop an understanding of the distribution and character of subsea permafrost.

Two study lines in the Prudhoe Bay area provide some data on what is known of the distribution and character of this permafrost (Figures 3.11 and 3.12). The top of the ice-bearing permafrost appears extremely variable, based on seismic and borehole data. Nearshore, it may be only a few meters below the sea bed. Offshore, in Stefansson Sound, this depth increases to 90-150 m. However, just north of the barrier islands, both seismic and borehole data suggest that the top of the ice-bearing permafrost is present at depths as shallow as 20-30 m below the sea floor (Figure 3.12A). To the east, off the delta of the Sagavanirktok River, similar shallow depths are suggested by the seismic data (Figure 3.12B). It seems highly probably that the ice-bearing and ice-bonded permafrost may be completely absent in some areas up to several kilometers in diameter and that the upper surface may have an irregular relief of tens of meters. The differences in the depth to the top of the ice-bearing layer are primarily related to differences in sediment grain size, physical state prior to freezing, pore-water salinities and/or thermal history.

The subsea permafrost distribution can be inferred in a <u>very general way</u> on the basis of the bathymetry (Figure 3.11) as follows:

(1) Shallow, inshore areas where ice rests directly on the sea bed are underlain at depths of a few meters by ice-bonded permafrost. Ice-rich permafrost and seasonal fressing in an active layer must be anticipated wherever the water is less than 2 m deep.

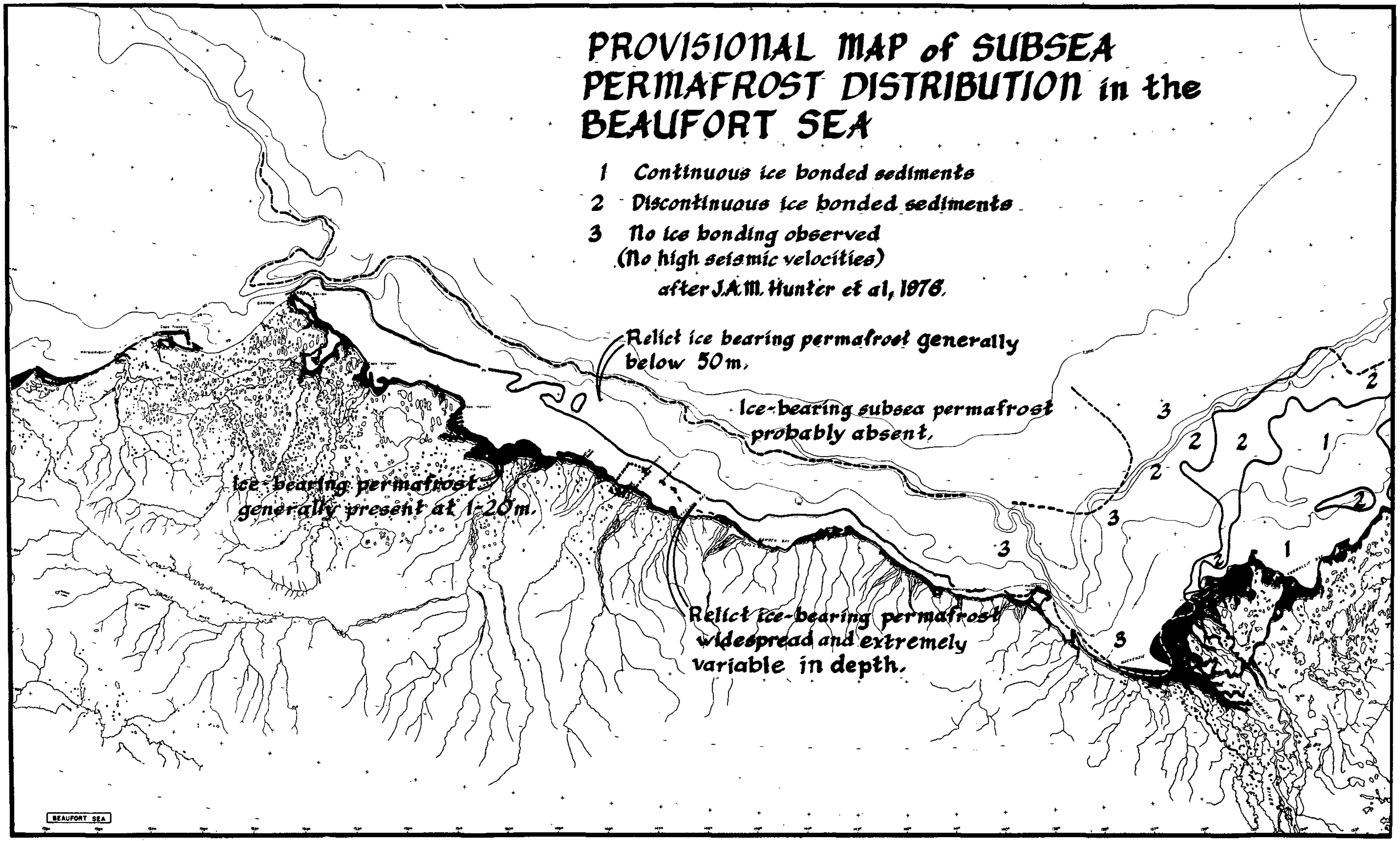


Figure 3.11 Provisional Map of Subsea Permafrost Distribution in the Beaufort Sea (Hunter et al., 1976)

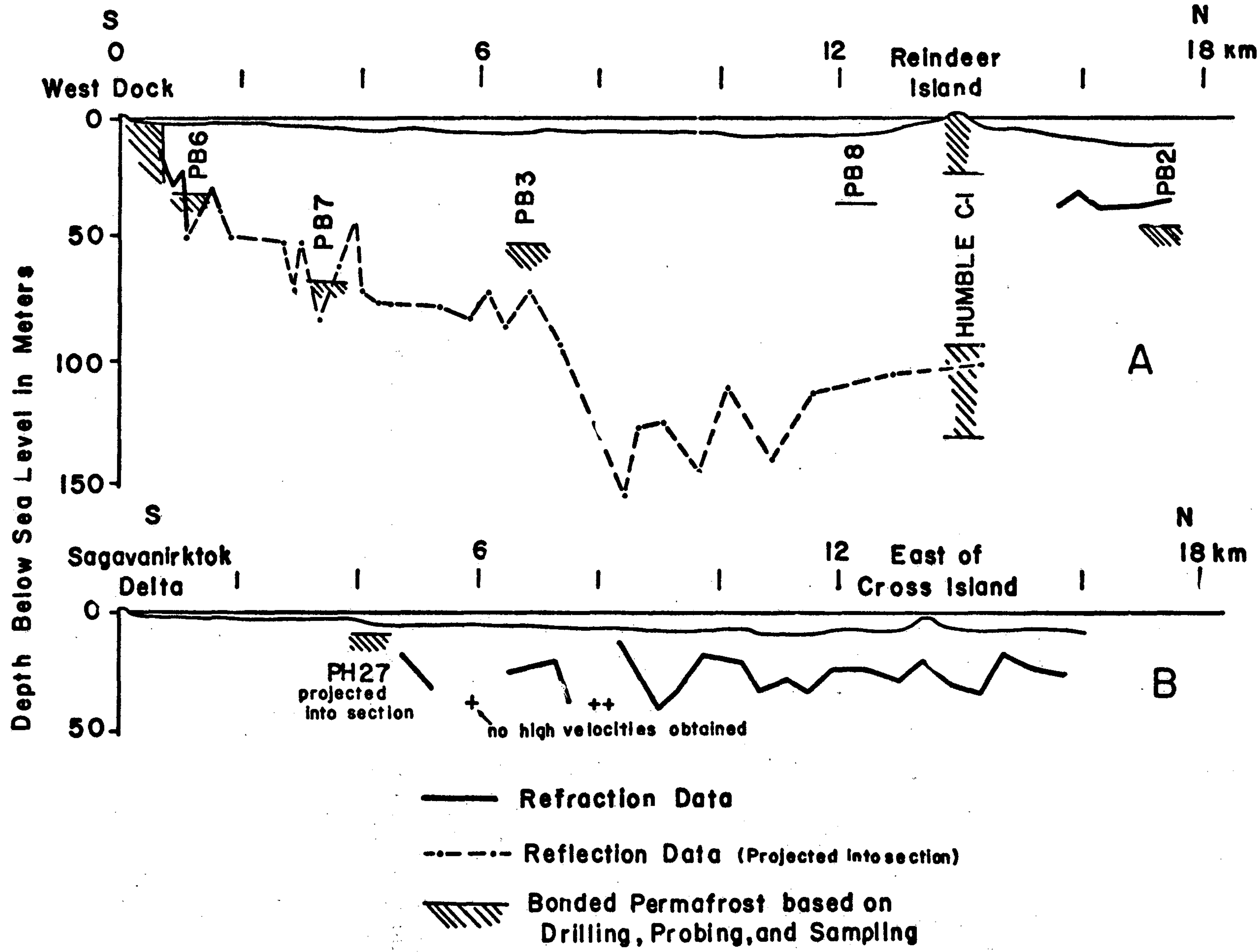


Figure 3.12 A. Subsea permafrost data gathered on a line northeast from the west dock through Reindeer Island. Refraction and reflection data does not exactly correspond with drill hole information and might be responsible for some of the discrepancies. B. Refraction data gathered on a line northeast from the Sagavanirktok Delta and passing just to the east of Cross Island. Probe data from PH27 projected eastward into section.

(2) Ice-bearing permafrost was once present beneath all parts of the continental shelf exposed during the last, low sea-level stand (Figure 3.3), and consequently relict ice-bearing permafrost may persist beneath any part of the shelf inshore from the 90 m isobath. Observed depths to relict ice-bonded permafrost range from a few meters near the present coast to 250 m far off the Canadian coast.

(3) Ice-bearing permafrost is probably absent from parts of the Beaufort Sea shelf seaward from the 90 m isobath, although subsea temperatures are probably below 0°C.

Even this very general distribution of subsea permafrost must be heavily qualified by variations in sea level curves, coastal erosion rates, temperature and pore water salinity, hydraulic conductivity, and textural and engineering properties of sea shelf sediments.

The relationship between permafrost and temperature is complex. Where sea ice freezes to the sea bed, generally inside the 2 m isobath, ice formation and partial ice bonding may take place annually to depths of several meters in response to the cold mean annual sea bed temperatures of -2° to -5°C. Even in water depths greater than 2 m, seasonal freezing can occur in areas where fresher sediment pore water is subjected to very cold saline bottom water, which commonly develops in response to sea ice growth in winter.

The temperatures at the top of the ice-bonded layer offshore in the Prudhoe Bay area range from -1.8° to -4.5°C, depending on the phase equilibrium between ice, salty pore water and soil particles. Where ice-bearing subsea permafrost exists, theory indicates that temperatures should be within about 1°-2°C of its melting point after roughly 2000 years of submergence, assuming that there was little salt available during permafrost formation, at lower stands at sea level. Temperatures at the base of the permafrost have not been measured offshore (except possibly by industry); however, at Prudhoe Bay they range from about 0° to -1°C in holes drilled on land. Nor has the thickness of offshore permafrost been measured, although theory suggests that permafrost may extend to depths on the order of 500 m at the drill hole sites in Figure 3.12A, assuming shelf conditions were similar to those onshore at present, prior to sea level rise. Only additional drill hole information offshore will answer present questions about the thickness and character of the base of the permafrost.

Pore water salinities at Prudhoe Bay differ significantly from one place to another but are poorly known. In silty sands and gravels typical of Prudhoe Bay, hydraulic conductivities have been measured in the range of 2-12 m per year. The associated salinities generally vary within 5 o/oo of normal sea water and are nearly constant with depth. In the clays found in Elson Lagoon, a hydraulic conductivity value of about three orders of magnitude less was measured. In one borehole nearly fresh pore water in clays was encountered a short distance below the sea bed. There is a wide variation in pore water salinities where sea ice freezes to the sea bed or where circulation below the sea ice is restricted, with values ranging from less than normal sea water to 70 o/oo or more. The pore water salinity at the top of the ice-bonded permafrost implies a reduced degree of ice bonding.

Seismic studies show that only the wider parts of the barrier islands of the Beaufort Sea are underlain at shallow depth by firmly ice-bonded permafrost (shallow permafrost is no doubt also present in the areas of Pleistocene sediments that form the core of some of the older islands such as Pingok and Cottle Islands). Island areas underlain at shallow depth by recent firmly ice-bonded permafrost (in contrast to the relict permafrost found at greater depth beneath sea floor and barrier islands alike) are readily recognized by the presence of frost cracks. These areas are also old enough so that a few salt-tolerant plants have become established. Thermal calculations indicate, however, that recent ice-bearing permafrost should be expected beneath even the younger parts of the actively migrating barrier islands. Reduced ice bonding and diffuse phase boundaries caused by the presence of salty pore water and fine-grained sediments or the occurrence of very open coarse-grained sediments seem to be responsible for the low seismic velocities and lack of frost cracking in these young areas, although the process is poorly understood.

The ice content of the relict, ice-bonded permafrost beneath the sea floor is unknown, although at depth onshore it may be typically 40% by volume (Gold and Lachenbruch, 1973). However, several observations in the Prudhoe Bay area suggest the possibility that as much as 3-10 m of subsidence may have taken place as a consequence of deep thawing beneath large thermokarst lakes or beneath newly submerged areas after transgression of the shoreline. If the observations are correctly interpreted, they suggest that excsss ground ice in gravel extends to depths of 50 m or more offshore in the Prudhoe Bay area.

The Alaskan subsea permafrost studies confirm Canadian work that has shown: a) that permafrost is widespread on the Beaufort Sea continental shelf, b) that ice-bonded permafrost is present at surprisingly shallow depths, c) that the ice content may be much higher than had been anticipated, and d) that its surface relief is likely to be highly irregular. The factors involved in this irregular distribution of ice-bonded permafrost are still very poorly understood, and we are still far from being able to evaluate the seriousness of shallow ice-bearing permafrost as a geologic hazard in those areas where it is known to exist. It should be noted that subsea permafrost is usually warm and salty and therefore much more easily disturbed than terrestrial permafrost.

Coastal Morphology, Coastal Erosion and Barrier Islands

The climatic regime of the coast and islands of arctic Alaska is characterized by ice-covered and open water seasons. During the open water season on the Beaufort coast, wave energy is limited. The arctic ice pack generally lies only a few tens of kilometers offshore. Tidal energy is also limited due to small (10-20 cm) astronomical tides, although wind- and barometric pressure-related storm surges may be associated with sea level setups of 3 m or more and sea level set-downs of 1 m or more (Reimnitz and Barnes, 1974).

In autumn, Beaufort Sea beaches become sheathed in ice and ice-cemented sands and gravels, and later in snow. For beaches protected from coastal ice motion the remainder of the winter and spring are quiet. On coasts and beaches exposed to ice motion, at promontories such as Barrow and along the seaward face of the offshore islands (Cross and Narwhal Islands), ice furrows and push features may be created during the fall when the fast ice is still in motion, and at spring break up (Hume and Shalk, 1967). During the melt season, a coastal lead tens of meters across is common along the coastline. Off the rivers, the pre-break up flooding may expand this lead to several kilometers.

The composition of the eastern coastal plain is dominated by frozen sands and gravels which form a series of coalescing alluvial and glacial outwash fans. Some places in the immediate coastal area are occupied by the Flaxman Formation, a marine sandy mud of Pleistocene age containing boulders and cobbles foreign to Alaska (Leffingwell, 1919).

Throughout the region, the Pleistocene marine, alluvial, and glaciofluvial sediments are mantled by 2 or 3 m of late Pleistocene and Holocene thaw-like sediments consisting mostly of peat and mud (Williams et al., 1977). The Pleistocene and Holocene sediments are perennially frozen at depths greater than a few tens of centimeters, and the near-surface sediments contain variable but generally large quantities of ground ice.

A series of en echelon islands resembling barrier chains serve to provide a relatively straight outer coast in some regions, but other deeply embayed coastal segments, notably Harrison Bay and Smith Bay lack protective island chains. Where offshore islands are present, they offer minimal wave shelter to the mainland coast, because they commonly enclose wide shallow lagoons, wide enough to allow considerable fetch. Furthermore, the sheltered waters become free of floating ice relatively early in the summer, and so the lagoon shores are exposed to wave action for longer periods. The islands do afford considerable protection from ice push on mainland coasts.

The mainland shores are characterized by narrow, low-lying beaches backed by coastal bluffs generally less than 10 m and commonly only 2 to 3 m high. The beaches are rarely wider than 20 m and commonly are only a few tens of centimeters thick. Most, if not all, of the coarse sediment comprising the beaches is derived from erosion of coastal bluffs. Rivers deliver no coarse material to the mainland or island beaches.

Sand and gravel reach the beach in small quanitities from coastal bluffs carved in alluvial and glacial-outwash fans away from the immediate vicinities of the river mouths and in areas where coastal bluffs are carved in the Flaxman Formation or into the pebbly sand of the hillocks and ridges marking the sites of Pleistocene islands. Large segments of the Beaufort Sea coast, especially in the stretch extending from northwestern Harrison Bay to Barrow village, are backed by coastal bluffs in which gravel-sized particles are lacking, and sand-sized particles are scarce.

A minor amount of sand and gravel is provided to some beaches by ice push. Ice-plowed gravel ridges on Cross and Narwhal Islands and along the low-lying coast near Cape Simpson DEW line station, among other places, contain cobbles and boulders coarser than any that can be found onshore nearby, indicating that grounded ice is plowing gravel to the beach from a submerged nearshore source.

The direction of sediment drift is generally westward (Figure 3.13), although many local reversals exist. Some of the island chains form integrated west-drifting transport cells, but most islands seem to consist of isolated slugs of gravel and sand migrating southwestward without interchange with other islands or with the mainland coast.

Because wave energy is low and the open season short, total amounts of sediment transport along the beaches are small. The rate of longshore drift of sediment has not been estimated for points on the mainland coast, but Wiseman et al. (1973) estimate longshore transport on the outer coast of Pingok Island at 10,000 m^3/yr during the summer and autumn of 1972. The observed rate of lengthening of western Pingok and Leavitt Islands between 1955 and 1972 (Wiseman et al., 1973) suggests that this rate has been sustained over a long period. A lower rate of mass transport is indicated for the Maguire Islands. However, the observed rate of island migration there (Wiseman et al., 1973) indicates that mass transport is slightly more than 5,000 m^3/yr. Mass Transport is unknown but probably lower along most parts of the mainland coast.

Despite the short open season and the prevalence of a low wave-energy regime, the coast of the Beaufort Sea is retreating at a spectacular pace due to thermal erosion. For example, rates of coastal erosion observed are in order of magnitude faster than those reported for the Chukchi Sea coast (McCarthy, 1953; Hopkins, 1977).

The arctic coastal plain and islands composed of ice-rich Pleistocene sediments are affected by thermokarst collapse. Localized thawing in onshore areas results in subsidence due to the melting out of excess ground ice, and the resulting subsidence basins become occupied by rapidly growing thaw lakes. Abrupt changes in the outline of the coast can result when the retreating shoreline breaks through into lake basins.

Thermal erosion is most rapid and effective along coastal segments where the bluffs are composed of ice-rich frozen mud, silt, or fine sand containing few or no stones. Thawing and erosion of bluffs composed of pebbly sand or sandy gravel release enough coarse sediment to thicken the beach and reduce undercutting. The fibrous, interlacing structure of arctic peat and turf makes these materials also somewhat resistant to wave attack. Surficial turf commonly drapes like a robe over the face of an actively retreating bluff undercut to depths as great as 6 or 8 m in fine sediment. Most of the bluff erosion takes place during late summer and autumn.

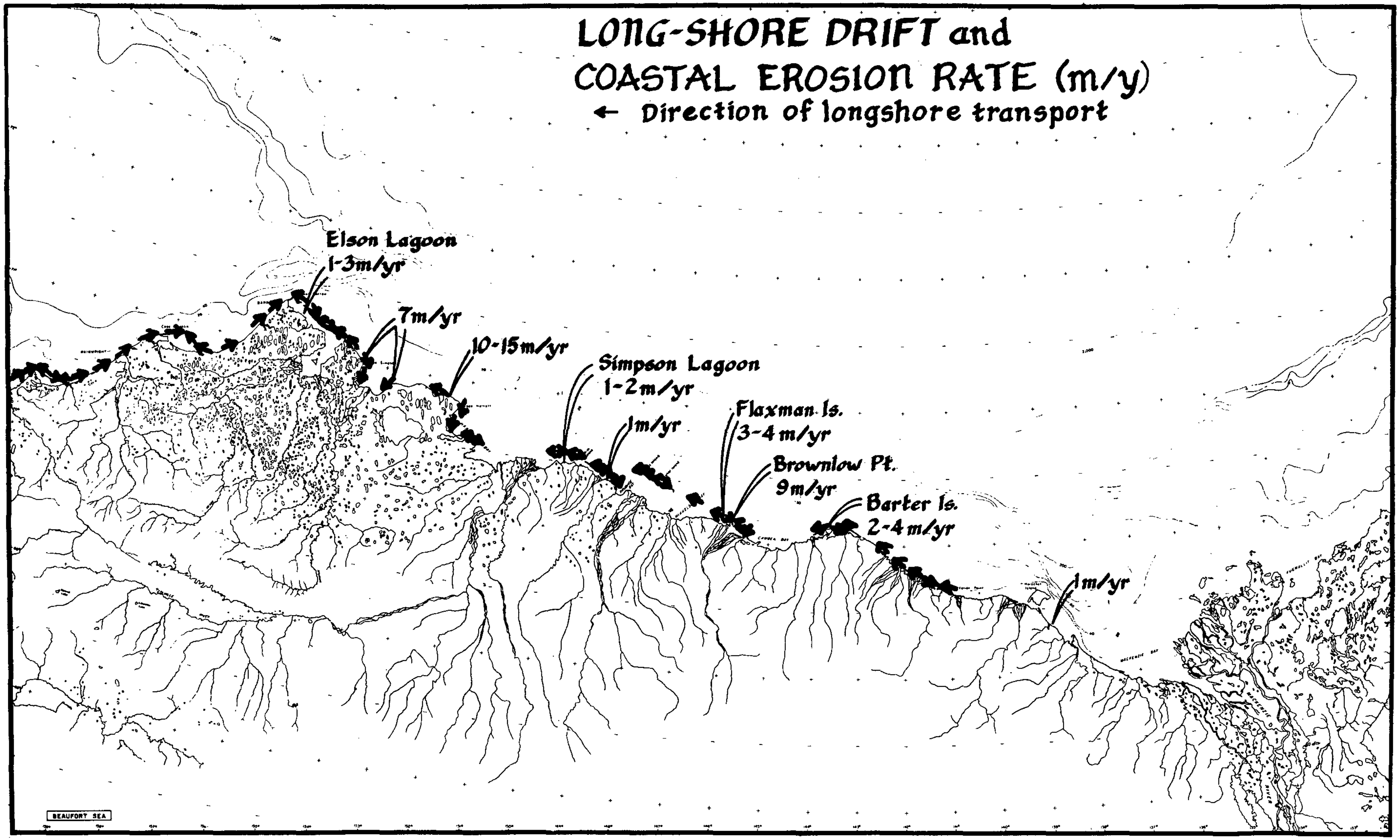


Figure 3.13 Long-Shore Drift and Coastal Erosion Rate
(Hopkins et al., 1977)

Rates of coastal retreat differ depending not only upon variations in the composition of the coastal bluffs, but also upon exposure and upon morphology of the adjoining sea bottom. The highest rates of coastal retreat are recorded on promontories and points. Nevertheless, many bays and estuaries have persistently cuspate outlines, evidently indicating that thermal erosion and thermokarst collapse tend to cause parallel retreat of the shoreline, regardless of coastal orientation.

Coastal bluffs protected by deltaic deposits retreat much less rapidly than do coastal segments adjoined by deeper water. Conspicuous examples are Heald Point and Point Brower on either side of the mouth of the Sagavanirktok River. Rates of coastal retreat also vary dramatically from one year to another, depending upon the time of break up of sea ice, variations in size of open water areas, and timing and intensity of late summer and autumn storms.

In many areas coastal retreat is so rapid as to pose a serious hazard to man-made structures near the coast. Rates of coastal retreat have consequently been measured in many places and on many occasions (Leffingwell, 1919; MacCarthy, 1973; MacKay, 1963; Hume and Schalk, 1967; Lewellen, 1970; Dygas et al., 1972; Wiseman et al., 1973; Lewis and Forbes, 1975).

Coastal retreat proceeds at the relatively modest average rate of about 1 m per year along the Canadian Beaufort Sea coast between the Mackenzie River Delta and Demarcation Point (Figure 3.13). Coastal retreat along the mainland coast between Demarcation Point and the Colville River averages about 1.6 m/yr, although local short-term rates may be much higher. Rates of shoreline retreat on the Pleistocene remnants range from 1.5 m/yr on Pingok Island to about 3.5 m/yr on Flaxman Island. The sand and gravel islands are retreating at slightly higher rates, between 3 and 7 m/yr (Dygas et al., 1972). Average rates of mainland coastal retreat are highest from Harrison Bay westward to Barrow. An average retreat rate as high as 4.7 m/yr is suggested for this segment of the coast, and Leffingwell reported short-term erosion rates as great as 30 m/yr at Drew Point and Cape Simpson (Leffingwell, 1919).

Areas of progradation may be entirely restricted to the immediate vicinity of the mouths of the larger rivers, although a study of the Colville Delta does not show measurable growth either at the shoreline nor at the seaward edge of the 2m bench.

The offshore islands are obviously prime candidates for siting petroleum exploration and production facilities, or, alternatively, prime candidates for gravel quarrying. On the other hand, they profoundly affect water circulation and sediment movement on the inner shelf, anchor sea ice and widen the zone of shorefast ice, offer shelter to large shorebird populations during the late summer molt, and, in a few exceptional areas, provide important nesting habitat. Thus, it has become important to obtain a clearer idea of their origin, sources of sediment, and probable future.

Three chains of curvilinear islands resembling barrier chains are present off the Beaufort Sea coast. The eastern chain extends from Brownlow Point through Flaxman Island to Reindeer Island; the central chain from Pt. McIntyre through Stump Island to Thetis Island; and the western chain from Cape Simpson DEW line station through the Plover Islands to Point Barrow. All three chains diverge northwestward from the mainland coast. The eastern and central chains are open westward so that both Reindeer and Thetis Islands lie about 14 km offshore. The Plover Island chain is closed on the west by Point Barrow spit which extends the Chukchi Sea coast 7.5 km northeastward from the mainland at the Naval Arctic Research Lab.

The islands are mostly recent constructional accuulations of sand and gravel, but Flaxman Island and several islands in the center part of the central chain (Cottle, Bodfish, Bertoncini, and Pingok) have cores of Pleistocene sediments. These erosional remnants stand 3-10 m above sea level and support a continuous cover of non-halophytic tundra vegetation. All are disappearing rapidly by wave erosion and thermokarst collapse. The constructional parts of the islands may be as long as 9 km and are nowhere higher than 3 m. They generally range from 90-110 m in width but may be as wide as 450 m in the rare areas of accretionary beach ridges and spits. Within the groups, individual islands are sinuous and are separated by ephemeral passes generally a few hundred meters wide and only 1 or 2 m deep. Migration of islands, filling of old passes, and development of new ones (Wiseman et al., 1973) result in rapid changes in morphology. The occasional autumn storm surges may be responsible for much, if not most of the observed alterations.

Ice-push affects different islands to different degrees. Most affected are Cross and Narwhal Islands in the eastern chain. These islands lie far offshore, near the boundary between shorefast ice and the arctic ice pack. Narwhal and Cross Islands feature as many as three belts of ice-push ridges as much as 1.5 m high extending as much as 30 m inland from the ocean beach. These features may persist through an open water season depending on wave climate.

The constructional islands are migrating westward and landward at a rapid pace. Migration rates westward ranging from 13-30 m/yr and landward ranging from 3-7 m/yr have been established for various islands in the eastern and central chains (Lewellen, 1970; Wiseman et al., 1973). The more arcuate and isolated islands, such as Narwhal, Cross, Spy, and Thetis Islands appear to be migrating southwestward en masse at rates of 4-7 m/yr. The pace of landward or southwestward migration is such that most parts of the constructional islands would require only 30 or 40 years to cross a given point on the sea floor. Firmly ice-bonded permafrost is present beneath the older, sparsely vegetated recurved spits and spurs. These areas can be recognized by the presence of frost cracks extending across ancient wave-constructed ridges and swales. However, most areas in the constructional parts of the islands lack firmly bonded permafrost. Although interstitial ice was found in the sediment in a borehole on Reindeer Island, the interstices in the sediment beneath the younger parts of the island must be filled with a two-phase mixture of brine and ice. Evidently 40 to 50 years are required for freezing to progress to a point where brine is either excluded or frozen and the sediment becomes bonded firmly enough to crack when subjected to the extremely cold winter temperatures.

Pebble lithology differs from one island group to another, reflecting differences in the sources of material making up the islands. The sand and gravel in all island groups within the eastern chain is entirely derived from the Flaxman Formation with its non-Brooks Range lithologies. Gravel in the central island chain consists mostly of Brooks Range pebble types with a 10-25% admixture of Flaxman lithologies. There is little difference in coarseness of gravel from one island group to another, but the coarsest gravel on strongly arcuate Spy and Thetis Islands is found at the northeastern, leading edge of these islands. Gravel lithology in the western chain differs from one island group to another as a consequence of a series of stepwise changes at Eluikrak and Eluitkak Passes. East of Eluikrak Pass, Flaxman lithologies comprise more than 30% of the gravel; between Eluikrak and Eluitkak Passes the gravel contains a 30% admixture of Brooks Range lithologies; and west of Eluitkak Pass, Brooks Range lithologies make up more than 60% of the gravel.

It is clear that the major passes within the Beaufort Sea island chains are barriers to sediment transport and serve to isolate the different island groups from one another. Confirmation comes from the observation that the deepest part of Leffingwell Channel is floored with compact, current-scoured mud (not sand and gravel), and from the fact that relative proportions of Brooks Range and Flaxman pebble types change in stepwise fashion across two passes in the western island chain. Some of these observations come from passes that seem to be nowhere deeper than 2.5 m, indicating that sediment cannot bypass a trough deeper than 2.5 m in this low-energy sea.

Several lines of evidence demonstrate that the island chains are not unified sediment transport systems, but rather that many of the island groups have or once had their own sediment sources. Gravel on Jeanette, Narwhal, and Cross Islands is much coarser than the gravel comprising islands that lie eastward and updrift, and suggests strongly that a source of sediment lies or once lay somewhere seaward on the continental shelf. The eastern islands within the Plover chain are, or once were, fed from the bluffs east of Cape Simpson DEW line station, while the peninsula leading from Eluitkak Pass to Point Barrow may be fed by sediment moving northward up the Chukchi Sea coast and eastward around Point Barrow; but the islands between Eluikrak and Eluitkak Pass differ enough to indicate that they originated from a sediment source that has now disappeared. Leavitt Island, in the center part of the central chain, is obviously fed by the erosion of Pingok Island and other Pleistocene remnants that lie eastward and updrift; but Long, Egg, and Stump Islands lie still further updrift and must have originated from a different source. Similarly the source for the outermost islands in the eastern chain, Cross and Narwhal, is no longer evident. However, the constructional area of Flaxman Island is fed by coastal drift of sediment eroded from the Pleistocene remnants that form the island core. The Maguire Islands, and possibly the Stockton Islands, may originally have been westward continuations of this barrier chain, which became isolated as a result of storm breaching and tidal deepening of intervening channels. If this speculation is correct, then Flaxman Island would have once been a much larger and more adequate source of sediment.

Long term comparisons seem to indicate that the islands are migrating with only slow loss of area and mass. Wave overwash during storm surges helps to move sand and gravel from the nearshore zone onto the body of the island, and ice-push rakes the coarsest partcles from deep water and returns them to the island surface. However, the islands will eventually disappear. The Dinkum Sands may be examples of members of the chain that eventually lost mass and became completely submerged.

Because of islands in the Beaufort Sea island chains are mostly lag deposits derived from sand and gravel sources that have now disappeared, they must be regarded as irreplaceable. If they were removed, they would not be restructured by natural processes, and the local oceanographic and biological regime would be irreversibly perturbed.

Research Needs

The above discussion clearly shows that our limited data base is not sufficient to develop enough understanding to answer all questions regarding earth sciences as they relate to proposed or anticipated development activities on the arctic shelf of Alaska. Although we have made giant advances in the past three years, additional knowledge is needed. Future research should consider the needs and problems listed below to assure a geologic understanding of the implications both to and from OCS development.

Research needs of high importance:

(1) The offshore permafrost program has provided a great deal of information in the Prudhoe Bay area on the distribution of ice-bonded permafrost, on the configuration of its upper surface, on the distribution of gravel, and on the distribution, thickness, and geotechnical characteristics of the Flaxman Formation and the less consolidated Holocene mud. With one exception, noted below, information gathered in the immediate Prudhoe Bay area now seems adequate, although site-specific studies will obviously be needed. Attention should now be turned to other parts of the lease area and to segments of the shelf beyond the proposed 1979 lease tracts. We recommend that lines of core, jet, auger, and probe holes now be extended from the mainland coast seaward to the stamukhi zone at approximately 50-km intervals along the Beaufort Sea coast; that ice-bonded permafrost in the areas between the lines be mapped, using existing commercial multi-channel lines; and that any remaining information gaps be filled by seismic refraction profiles.

There is a critical need to know more about the ice content of subsea ice-bonded permafrost, because indirect evidence suggests that excess ice may be present in quantitites capable of causing several meters of subsidence when the permafrost thaws. Unfortunately, the coring techniques used thus far have been incapable of penetrating more than a few tens of centimeters into ice-bonded permafrost, and consequently we have no direct observations of the distribution and amount of ice in the sediment. New techniques may have to be developed for coring and for preserving and examining cores at the precise temperatures at which they emerge from the ground. When new techniques are available, one or more holes should be bored to extend several tens of meters into ice-bonded permafrost in the Prudhoe Bay area as well as elsewhere on the Beaufort Sea shelf.

The following questions about subsea permafrost are particularly difficult or even impossible to answer within our present data base:

a. What is the configuration of the upper surface of ice-bearing and ice-bonded subsea permafrost?
b. What is/has been the effect of different environments (e.g. rivers, lagoons) on subsea permafrost?
c. What is the chemical (especially saline) and geologic environment of subsea permafrost?
d. Are frozen gas hydrates associated with ice-bearing subsea permafrost?
e. How have the recently built causeways and artificial islands influences the permfrost regime?

(2) The installation of causeways and artificial islands has a direct influence on the transport of sediment along the coast. At present we have virtually no knowledge of the rates, pathways, quantities and seasonal variation of sediment migration along the mainland coast. Coastal sediment budget studies will be needed to fully address these problems.

(3) Offshore gravel structures, along with other developmental activities (gravity structures, pipelines, etc.) will be dependent on the composition and engineering character of the near-surface sediments for integrity and as a possible source of material. The distribution of overconsolidated silts and clays and the availability for borrow of the widespread gravels which may exist below the clays should be studied.

Research needs of lesser importance:

(4) Ice gouge characteristics are critical for the design of pipelines and other subsea structures. Data are lacking on the age or rate of gouging in water depths greater than 15 m, as are data regarding the forces imparted to the bottom by grounding ice at different incision depths. New approaches and techniques may need to be developed in order to carry out this research.

(5) Near-surface gas-charged sediments have been reported in the northern Bering Sea and in the Beaufort Sea. Furthermore, the presence of discontinuous seismic reflectors in the Alaskan Beaufort suggests the presence of gas. Studies should be carried out to analyze seismic records and to sample sediments in different seismic environments to assess this problem.

As was mentioned earlier, much of the knowledge gained by the study of the Beaufort Sea shelf is applicable to other areas of the Beaufort shelf, and even to the Chukchi Sea. This is particularly true where topical "basic" research has addressed the questions of how processes operate. However, there are regional differences in distribution and regional differences in the parameters that control processes (such as sea level history and lithology data for permafrost determinations) which will have to be assessed as these regions come under closer scrutiny. More than likely the first areas which should receive additional emphasis for geologic studies are east of Prudhoe Bay in the Camden Bay area, and west of Prudhoe Bay from Harrison Bay towards Barrow.

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The references listed below do not include all of the literature on which the preceding section is based, but are a listing of the major references outside of the OCSEA Program reporting system. By far the bulk of the data, results, and interpretations which represent the "state of knowledge" on which we have based this report is contained in the quarterly and annual reports to the OCSEAP program. The pertinent OCSEAP research units are: 059, Nummedal; 105, Sellmann; 205, Barnes and Reimnitz; 253, Osterkamp and Harrison; 271, Rogers; 407, Lewellen; 432, Grantz; 467, Naidu and Cannon; 473, Hopkins and Lachenbruch; 483, Biswas; 516, Vigdorchik. A considerable volume of information also exists in the series of reports generated from the Canadian Beaufort Sea study distributed by the Beaufort Sea Project in Victoria, B.C.

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4. MARINE MAMMALS

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Introduction

No group of Alaskan mammals has received as much public attention as marine mammals. From time immemorial the Inuit have traversed the sea ice and coastal waters to hunt oogruk (bearded seal), aivik (walrus), agvik (bowhead whale), kilalugak (belukha whale), and natchek (ringed seal) for food and useful byproducts. At the turn of the century commercial whalers came to Alaska in search of bowhead whale and walrus for whale oil to light the New England homes, and ivory for scrimshaw. Various innate characteristics of marine mammals have led to their aesthetic appreciation in recent years. Concomitant with this appreciation of marine mammals there has been concern expressed for the health of marine mammal populations and the ecosystems in which they live. This concern for marine mammals by citizens of the United States is so great that it has been legislated in the Marine Mammal Protection Act of 1972 (Public Law 92-522), which states in part:

Sec. 2. The Congress finds that -

1. certain species and population stocks of marine mammals are, or may be, in danger of extinction or depletion as a result of man's activities;

2. such species and population stocks should not be permitted to diminish beyond the point at which they cease to be a significant functioning element in the ecosystem of which they are a part, and, consistent with this major objective, they should not be permitted to diminish below their optimum sustainable population. Further measures should immediately be taken to replenish any species or population stock which has already diminished below that population. In particular, efforts should be made to protect the rookeries, mating grounds, and areas of similar significance for each species of marine mammal from the adverse effect of man's actions;

3. there is inadequate knowledge of the ecology and population dynamics of such marine mammals and of the factors which bear upon their ability to reproduce themselves successfully;

4. negotiations should be undertaken immediately to encourage the development of international arrangements for research on, and conservation of, all marine mammals;

5. marine mammals and marine mammal products either-

   a. move in interstate commerce, or

   b. affect the balance of marine ecosystems in a manner which is important to other animals and animal products which move in interstate commerce, and that the protection and conservation of marine mammals is therefore necessary to insure the continuing availability of those products which move in interstate commerce; and

6. marine mammals have proven themselves to be resources of great international significance, aesthetic and recreational as well as economic, and it is the sense of the Congress that they should be protected and encouraged to develop to the greatest extent feasible commensurate with sound policies of resource management and that the primary objective of their management should be to maintain the health and stability of the marine ecosystem. Whenever consistent with this primary objective, it should be the goal to obtain an optimum sustainable population keeping in mind the optimum carrying capacity of the habitat.

Marine mammal research programs are trying to develop a basic understanding of the natural history, abundance, distribution, and interrelationships among ecological elements of the Beaufort Sea system. An understanding of these parameters is essential in predicting the effects of petroleum development on these animals and, of even more importance, on the ecosystem of which these animals are integral components. It is only on the ecosystem level that conservation and management can truly be accomplished (Wagner, 1969). As the naturalist Alexander von Humboldt pointed out in an essay in 1807 (Humboldt, 1850): "In the great chain of causes and effects no thing and no activity should be regarded in isolation."

The disciplinary discussions which dealt with mammals in the Beaufort and Chukchi Seas and on which this report is based have produced two types of information products. The first product consists of two maps with associated tables. One map (Fig. 4.1) deals with the winter-spring period (approximately November through May), corresponding to the period of extensive sea ice cover. The second map (Fig. 4.2) deals with the summer-fall period (approximately June through October) when sea ice coverage is normally much reduced. On each map, several general categories of sea ice habitat are indicated. The boundaries represent average conditions as determined from analysis of several years of remote sensing information. Some features (e.g., the flaw zone during the winter-spring period) vary little from year to year, while others (e.g., the southern limit of pack ice during the summer-fall period) vary greatly. The accompanying tables indicate the relative abundance of the various species of mammals present in each of the habitat classifications. On the winter-spring map, several sensitive animal-habitat classifications have been indicated. On the summer-fall map, several sensitive areas have been tentatively delineated.

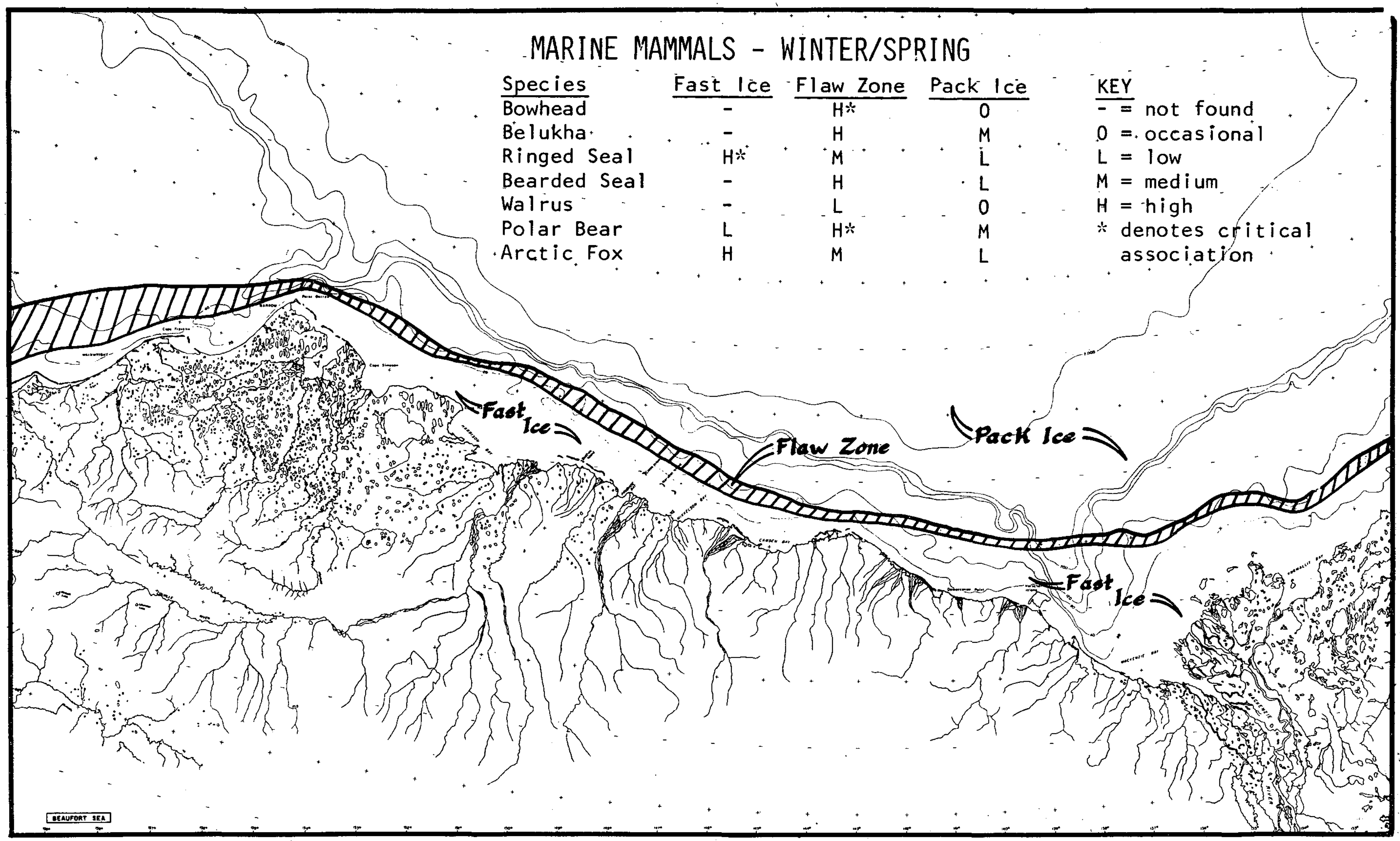
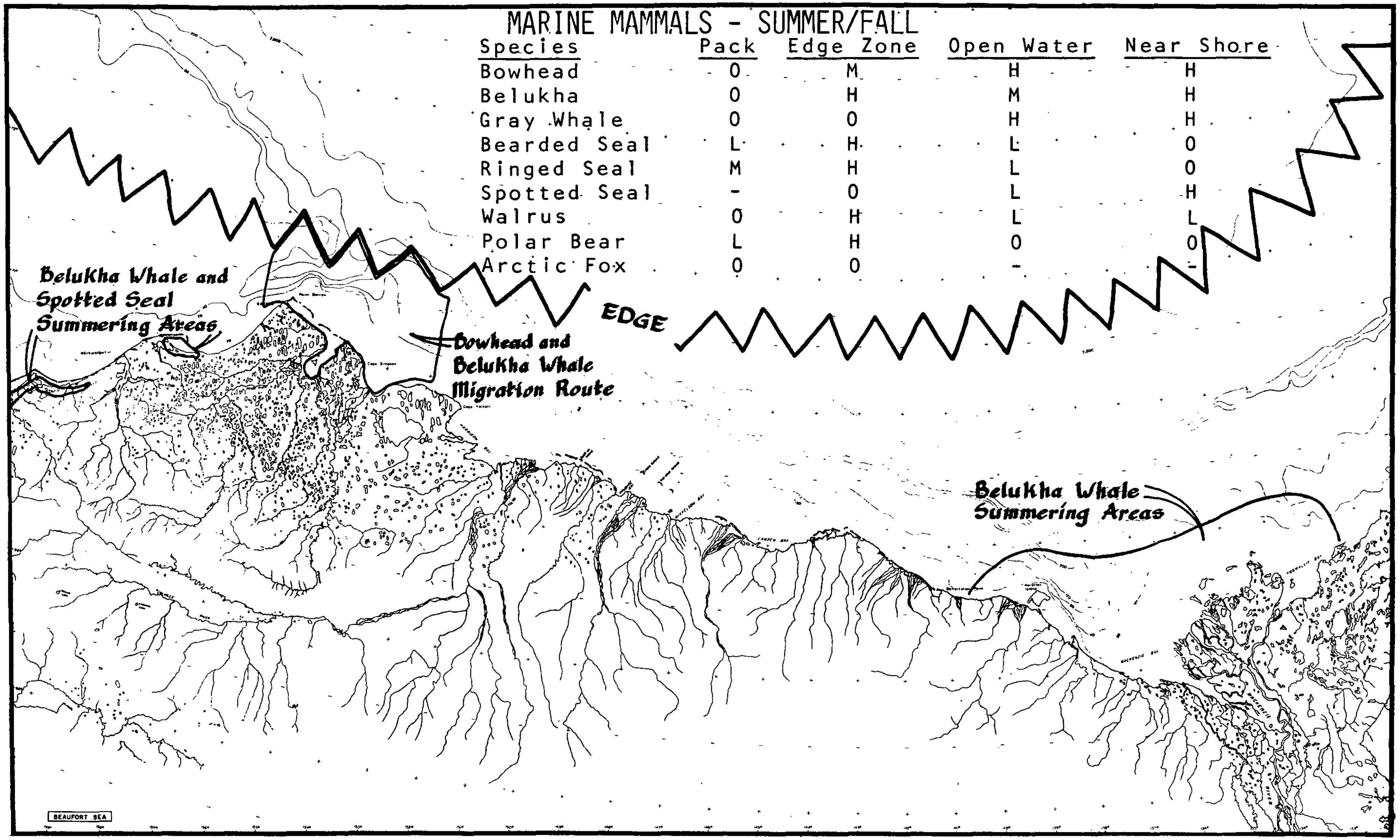

MARINE MAMMALS - WINTER/SPRING
Species | Fast Ice | Flaw Zone | Pack Ice
Bowhead | - | H* | O
Belukha | - | H | M
Ringed Seal | H* | M | L
Bearded Seal | - | H | L
Walrus | - | L | O
Polar Bear | L | H* | M
Arctic Fox | H | M | L
KEY
- = not found
O = occasional
L = low
M = medium
H = high
* denotes critical association
Fast Ice
Flaw Zone
Pack Ice
Fast Ice
BEAUFORT SEA

FIG. 4.1



Species	Pack	Edge Zone	Open Water	Near Shore
Bowhead	0	M	H	H
Belukha	0	H	M	H
Gray Whale	0	0	H	H
Bearded Seal	L	H	L	0
Ringed Seal	M	H	L	0
Spotted Seal	-	0	L	H
Walrus	0	H	L	L
Polar Bear	L	H	0	0
Arctic Fox	0	0	-	-

FIG. 4.2

The second product is a summary text of the group discussions, the primary purpose of which is:

1. to supplement the information provided on the maps and to give numerical values for abundance of the various species when appropriate and possible,

2. to provide a brief summary of the pertinent aspects of the biology of the mammal species involved,

3. to outline some potential effects of OCS development,

4. to identify gaps in our present state of knowledge which, if filled, would significantly increase the ability to predict effects of OCS development.

This summary text is intended to supplement, but not replace, the data contained in Annual and Final Reports prepared for the Alaskan Outer Continental Shelf Environmental Assessment Program.

Sixteen species of marine mammals have been recorded in the Beaufort Sea and at least six additional species could conceivably enter it. These mammal species, which are of concern when considering development of the Beaufort Sea continental shelf, will be discussed in three broad categories: year-round residents, summer seasonal visitors, and special cases.

Year-Round Residents

Ringed Seals (*Phoca hispida*)

Ringed seals are the most common and widespread of seals found in the Beaufort Sea. Ringed seals are usually found close to shore in the landfast ice and flaw zone and as a result have been important in the economy of the coastal Eskimos as a source of food and usable by-products. This is the species taken in largest numbers by Eskimo seal hunters. Ringed seals in the Beaufort Sea have been surveyed in early June in 1970, 1975, 1976, and 1977 and the densities are higher on landfast ice (0.4-6.2 observed seals) than in the pack ice (about 0.1-0.2 observed seals) (Burns and Harbo, 1972; Burns and Eley, 1976, 1977). Densities of ringed seals throughout the Beaufort Sea have declined approximately 50% between 1970 and 1977 and this decline is apparently due to heavy ice during 1975 and 1976 (Stirling et al., 1975; Burns and Eley, 1977). Ringed seal densities in the northern Chukchi Sea have decreased approximately 35% from 1970 to 1977. In more southerly areas such as Norton Sound, the Bering Sea, and southern Chukchi Sea there appears to have been an increase in ringed seal densities. Apparently what has occurred is a net western and southwestern displacement of ringed seals from the Beaufort and northern Chukchi Seas into areas of more favorable ice conditions. If ice is the proximate causative factor for the decline, then we should see a gradual increase in ringed seal densities after the better ice years of 1977 and 1978.

Ringed seal pups are born in late March and April in lairs excavated in snowdrifts and pressure ridges (Smith and Stirling, 1975; Eley, 1978). Stable landfast ice is the preferred breeding habitat. There are indications that adults are territorial during the breeding season (Stirling, 1973). Pregnancy rates vary between 70% and 90%. Factors causing this variation are unknown, but they appear to be related to food availability. During the pupping and breeding periods adults on landfast ice are generally less mobile than animals in other habitats; they depend on relatively few holes and cracks for breathing (Smith and Stirling, 1975). Pups are confined to the birth lair during the nursing period which lasts for four to six weeks. During this reproductive period nonbreeding animals are frequently found along cracks in the flaw zone.

During May, June, and early July ringed seals undergo a period of molting (shedding and regrowth of the hairs). At this time they often bask on the ice for long periods on sunny and warm days (McLaren, 1958, 1961; Eley, 1978). Apparently the warmth and rest are required for rapid regrowth of the hairs. Throughout the pupping, breeding, and molting periods, feeding appears to be at a reduced level and the animals metabolize a considerable amount of blubber.

In the summer and fall, feeding is intensive. The transition to summer ice conditions results in a seasonal concentration of animals along the edge of the pack ice and in ice remnants along the coast. The specific migration routes used are not well delineated but are presumably diffuse, with greatest numbers in the nearshore area. Ringed seals redistribute to the south as ice cover increases in the fall.

Important predators of ringed seals are polar bears (Ursus maritimus), Arctic foxes (Alopex lagopus), and man. Polar bears have a varied diet, including various species of ice-inhabiting pinnipeds, birds, small cetaceans, and carrion. However, ringed seals are the most important food item throughout the polar bear range, particularly in spring and early summer (Stirling and McEwan, 1975; Eley, 1977). The life history and annual cycle strategy of the polar bear appears to have evolved in response to an abundant food source, ringed seals (Erdbrink, 1953, Stirling, 1975). Polar bears prey on all age and sex classes of ringed seals, although the composition of the prey depends upon what is available rather than showing a selectivity towards a certain age or sex group. Seals are killed at breathing holes, in lairs, in open water, and when they are basking on the ice. Arctic foxes prey chiefly on newborn ringed seals in their birth lairs, and fox predation appears to be the major source of natural mortality during the seals' first year of life (Smith, 1976). Predation by Arctic foxes may reach as high as 45% of up to one-year-old ringed seals. Specific predation rates vary in relation to the cyclic abundance of foxes.

Ringed seals are hunted by Alaskan coastal residents chiefly in the spring, for human and dog food, and for skins for clothing, equipment and crafts. The harvest in all of Alaska has declined steadily in recent years from 10,000-20,000 per year in the 1950s and 1960s to 4,000-5,000 per year during recent years. This decline is due to many factors, including availability of other food sources, increased employment opportunities, changes in general dietary patterns, decline in the use of dog teams, and a restricted market for seal skins due to the Marine Mammal Protection Act. However, the ringed seal harvest could increase in response to increasing restrictions on the take of walrus (Odobenus rosmarus), whales, and caribou (Rangifer tarandus).

As is the case in other areas, ringed seals in the Beaufort Sea feed on small- to medium-sized crustaceans and fishes. Arctic cod (Boreogadus saida) are eaten throughout the year. They appear to be a dominant component of the diet in fall and winter months and may be the primary food in offshore areas during the summer. In late winter and spring, gammarid amphipods and mysids made up the bulk of the stomach contents of seals from the western Beaufort Sea. Seals collected nearshore at Barrow during late spring and summer ate euphausiids (Thysanoessa spp.), isopods (Saduria entomon), and gammarid amphipods. Summer foods may vary between localities. Near Barrow, euphausiids were the predominant item, especially in animals collected during August 1976. In a sample of seals collected north of Prudhoe Bay in August 1977, hyperiid amphipods (Parathemisto libellula) made up almost the entire stomach contents. Seals collected east of Prudhoe Bay during summer had eaten small amounts of gammarid amphipods, mysids, and shrimp.

Although the temporal and spatial coverage of ringed seal stomach samples from the Beaufort Sea is still very sparse, a tentative model for ringed seal feeding in the area is as follows. Gammarid amphipods, mysids, and shrimp are widely distributed in the Beaufort Sea and are suitable foods for ringed seals. These types of organisms, with the addition of isopods in shallow waters, form the bulk of the diet at areas and times when more abundant (or perhaps more preferred) prey is not available. In such circumstances the volume of food consumed is quite small. With the coming of biological spring and summer, medium-sized zooplankton reach high densities in certain coastal areas. In the vicinity of Barrow, euphausiids were the most common such species in 1975 and 1976, while north of Prudhoe Bay in 1977 hyperiid amphipods were dominant. Under these circumstances ringed seals forage very heavily as indicated by the large volumes of stomach contents. Such feeding associations are likely to be critical for attainment of an adequate yearly food intake. Temporal and spatial distribution of zooplankton blooms and causative factors involved are poorly known for the Beaufort Sea. Arctic cod is the most important single prey species of ringed seals in the Beaufort Sea. Off Prudhoe Bay and Barrow in November 1977, ringed seals had eaten large volumes of arctic cod. North of Prudhoe Bay, arctic cod were apparently not uniformly abundant. Seven seals taken at the same time and place had a mean volume of stomach contents of 369 ml (94% of which was arctic cod) while six seals taken singly or in pairs within 40 km of this group had a mean stomach contents volume of 45 ml (44% arctic cod and 52% Parathemisto). Such food resource patchiness could be a major factor influencing the distribution of ringed seals and as such could be of considerable significance to OCS development effects. Data on foods of ringed seals in the northeastern Chukchi and Beaufort Seas are presented in Lowry and Burns (1976) and Lowry, Frost and Burns (1977a,b).

Ringed seals collected from the USCGC GLACIER during August 1977, although in generally good physical condition, did exhibit a number of pathological conditions. Five individuals had microabscesses in the liver that appeared to be migration paths of parasites (L. Shults and F. Fay, pers. comm.). At this time there is no known parasite of ringed seals that makes such a path. Two ringed seals had wounds on the ventral surface that were either completely healed or nearly so, and the probable cause of the wounds is unknown (L. Shults and F. Fay, pers. comm.). One seal had extensive necrosis of the liver and the cause of the necrosis is unknown. Another seal had calcified nematodes in the lungs, but because of the calcified state no identification was possible.

Bearded Seals (*Erignathus barbatus*)

Bearded seals are also a circumpolar ice-associated species. Although they can maintain breathing holes in ice, they appear to do so only rarely and are thus largely excluded from the winter fast ice zone. The winter density of bearded seals in the Beaufort Sea is low (about 0.1 animals/square mile) with animals found in the flaw zone and nearshore pack ice (Burns and Eley, 1976, 1977).

Bearded seal pups are born on top of the ice from late March through May, chiefly in the Bering and Chukchi Seas, although some pupping occurs in the Beaufort. Pups are capable of swimming shortly after birth and are weaned in 12-18 days (Burns, 1967). Subsequent to pupping, animals breed and molt.

As is the case with ringed seals, a seasonal concentration of animals occurs during summer. As they are primarily benthic feeders, few bearded seals remain with the summer pack ice when the southern edge is over deep water. They redistribute south with winter ice formation. The majority of animals winter in the Bering Sea and in the highly fractured ice north of the Bering Strait (Burns, 1967; Burns and Eley, 1976, 1977).

The number of stomach samples examined from bearded seals in the Beaufort and northeastern Chukchi Seas is too small to allow a detailed evaluation of feeding of this species in these areas. A list of items most commonly eaten in order of approximate overall importance is as follows:

Shrimps	- *Sabinea septemcarinata*, *Sclerocrangon boreas*, *Eualus gaimardii*, *Argis lar*
Spider crabs	- *Hyas coarctatus*, *Chionoecetes opilio*
Amphipods	- *Stegocephela inflatus*, *Acanthostepheia behringiensis*, *Rhachotropis aculeata*
Clams	- *Mya truncata*

Isopods	- Saduria entomon, S. sabini
Octopus	- Octopus spp.
Fishes	- Boreogadus saida and sculpins (several genera)
Hermit crabs	- Pagurus spp.
Snails	- Natica clausa, Polinices pallida, Buccinum spp.

The food items found in individual stomachs often vary greatly from others collected in apparently similar areas. This is probably indicative of the patchy nature of epifaunal communities and the diversity of items suitable as forage for bearded seals. Data on food items of bearded seals in the northeastern Chukchi and Beaufort Seas can be found in Lowry, Frost and Burns (1977a,b).

Generally speaking, the five bearded seals examined during the August 1977 cruise of the USCGC GLACIER were in good physical condition. One seal had severe ulcerations within the small intestine due to a very heavy infection with the acanthocephalan Corynosoma validum (L. Shults and F. Fay, pers. comm.). Another seal had extensive biliary fibrosis with associated necrosis due to an infection with the trematode, Orthosplanchnus fraterculus.

Polar Bears (Ursus maritimus)

Polar bears are also distributed throughout arctic waters. In summer they are found on the pack ice, with greatest densities along the edge. In Alaskan waters they extend their range south through the Bering Strait during the winter advance of seasonal ice. They are primarily found in areas of high abundance and availability of ringed and bearded seals and walrus which are their primary prey items (Stirling, 1974; Eley, 1977). They also feed extensively on carrion, with large numbers of bears sometimes found on carcasses of whales and walruses (Eley, 1977).

Pregnant females seek denning sites in October and November and give birth in December and January in dens constructed in areas of sufficient snow accumulation (Lentfer, 1968). Denning occurs in landfast ice, on moving pack ice, and on land (Lentfer, 1975). The proportions of bears denning in these three habitat types are unknown but undoubtedly change annually with variations in environmental conditions (primarily snow and sea ice). Cubs, numbering one to three (usually two), and their mothers are confined to the dens until late March or April when they move out onto the sea ice and begin to hunt (Lentfer, 1976). Males and non-pregnant females remain active year-round, making temporary lairs during periods of inclement weather.

There are indications of two centers of polar bear abundance in Alaskan waters. One group, numbering about 2500 animals, ranges from north and east of Point Barrow to at least Barter Island and south to about Cape Lisburne. The second ranges from the Wrangell Island area to and south of the Bering Strait and numbers about 6500-7000 individuals (Lentfer, 1972, 1974). Although this distribution was stable for many years, we are presently in a period of very active movements and redistribution of bears which appears to be related to the significant changes in ringed seal distribution and density. There appears to have been a net westward and southward movement of bears from the eastern part of the Beaufort Sea into the Chukchi and Bering Seas. Bears tagged in the eastern Canadian Beaufort Sea have been recovered in Barter Island, Barrow, and Point Hope. In addition, large numbers of bears have been recorded south of the Bering Strait, much farther southwest than normal, at such locations as Shishmaref, Little Diomede, St. Lawrence Island, Nome, Norton Sound. and Hazen Bay.

Summer Seasonal Visitors

Bowhead Whales (*Balaena mysticetus*)

In spring, bowhead whales migrate north from poorly delineated wintering grounds in the Bering Sea. They travel northeast through leads in the flaw zone, passing close to shore off Point Barrow in late April and May* as they enter the Beaufort Sea. East of Point Barrow, during the spring only, bowheads probably migrate in offshore leads which extend to the west coast of Banks Island and Amundsen Gulf.

A large segment of the whales which move past Barrow spend the summer (June-August) feeding in the Canadian sector of the Beaufort Sea and Amundsen Gulf. Analysis of stomach contents reveals that bowheads do not usually feed during spring migration. Feeding activity on wintering grounds is unknown; however, appropriate foods are available in the Bering Sea. We speculate that during heavy ice years, which may restrict easterly movement, or during periods of high food (zooplankton) availability in the Beaufort Sea, many bowheads may spend the summer in the U.S. sector of the Beaufort Sea.

An unknown but probably large proportion of bowheads move nearshore along the Alaskan coast of the Beaufort Sea during the first part of the fall migration (August-October). East of Point Barrow, whales probably move offshore in a route toward Herald Island, where they then head south, perhaps near the Soviet coastline (October-November). During heavy ice years bowheads may move closer to shore in the Chukchi Sea. Bowhead whales have been seen in the region of Barrow as late as November.

Limited surveys conducted during spring at Point Barrow account for a population of at least 1000 animals. This is at least an order of magnitude lower than the population level prior to commercial exploitation (beginning about 1850) (Scammon, 1874; Rice, 1974).

Samples of stomach contents of three bowhead whales, taken by Eskimo hunters at Barrow, have been examined. An animal taken in May 1977 had eaten primarily copepods (mostly *Metridia longa* and *Calanus glacialis*) (L. Lowry, unpubl.). Samples from two whales taken in September 1976 contained 90% euphausiids (*Thysanoessa* sp.), 7% gammarid amphipods, and 3% hyperiid amphipods (*Parathemisto libellula*) (Lowry et al., 1978).

*Ed's. Note: A recent estimate of numbers of bowhead whales ranging from 1,783 to 2,865, with a "best estimate" of 2,264, was supplied in June 1978 by H. Braham to the IWC. Reference: Braham, H., B. Krogman, S. Leatherwood, W. Marquette, D. Rugh, M. Tillman, & J. Johnson. 1978. Preliminary Report of the 1978 Spring Bowhead Whale Research Program Results, June 6, 1978, JWC Proc. 51 pp. or OCSEAP Quarterly Report, April-June 1978.

Belukha Whales (*Delphinapterus leucas*)

Belukha whales are also summer seasonal visitors to the Beaufort Sea. The migration route they follow is generally similar to that of bowheads. However, belukhas are less restricted to the flaw zone and frequent the pack ice.

During the summer some segments of the population make extensive use of nearshore areas, presumably for calving (Sergeant and Hoek, 1974; Sergeant and Brodie, 1975; Braham and Krogman, 1977). The rest of the population is distributed throughout the region, being most abundant near the edge of pack ice (McVay, 1973). The number of belukhas spending the summer in the Beaufort Sea is several thousand. A large proportion of this population is in the Mackenzie River delta in July and August (Sergeant and Hoek, 1974; Fraker, 1977).

The food of belukha whales in the Alaskan part of the Beaufort Sea is entirely unknown. In other areas they feed on fishes, cephalopods, and shrimps (Fay, 1971). Percy (1975) lists ciscoes, capelin, boreal smelt, and saffron cod as food items of MacKenzie River belukha.

Spotted Seals (*Phoca vitulina largha*)

Spotted seals appear along the Beaufort Sea coast in July. Their numbers in this area are very low and decrease to the east. They make use of the nearshore areas, commonly hauling out on coastal beaches and barrier islands. They frequently enter estuaries and sometimes ascend rivers, presumably to feed on anadromous fishes. Food items of spotted seals in the Beaufort Sea are completely unknown.

Spotted seals leave the area in fall as ice reforms. They spend the winter and spring in the Bering Sea ice front where pupping, breeding, and molting occur.

Special Cases

Walruses (*Odobenus rosmarus*)

By far the majority of the Pacific walrus population winters in the Bering Sea. In spring they follow the retreating ice edge north and in summer are usually found along the edge of the pack ice. Walruses are benthic feeders and are thus restricted to areas where the pack ice is over relatively shallow water. In years when the pack ice retreats far to the north over deep water, large numbers of walruses haul out on land. Portions of Wrangell Island are common hauling out areas. As a result of deep water occurring relatively close to the coast in the Beaufort Sea, this area is less suitable as summer habitat for walruses than is the Chukchi Sea. Although a few walrus can usually be found east of Point Barrow in summer, they represent only a small fraction of the total population which is now estimated at about 200,000 animals.

Gray Whales (*Eschrichtius robustus*)

Gray whales make an extensive migration from winter calving grounds off Baja California to summer feeding grounds in the Bering and Chukchi Seas. The majority of animals spend the summer between St. Lawrence Island and Point Hope. Animals are occasionally seen nearshore as far north as Point Barrow and east into the Beaufort Sea. Feeding is done in shallow water on or near the bottom. Invertebrates, frequently amphipods, are ingested (Rice and Wolman, 1971; Zimushko and Lenskaya, 1970).

Arctic Foxes (*Alopex lagopus*)

The Arctic fox population in winter tends to be concentrated in the nearshore region. Numbers fall off rather quickly seaward and landward of this region. Thus, normally, a significant portion of the Arctic fox population spends the winter months on the sea ice, the number probably varying with the availability of food on land. On the ice they feed on polar bear kills and other carrion and sometimes prey heavily on ringed seal pups in spring (Smith, 1976). Movements on the ice are little understood. In the spring most foxes return to land to den and bear their young. It is unknown whether the few animals that remain on the ice in summer survive or successfully raise young during the summer. During the period of land residence, foxes prey primarily on small mammals, especially lemmings and birds. Arctic fox impact on birds appears to be inversely proportional to the availability of lemmings. In years (such as summer 1977), when the lemming population is low in coastal areas of the North Slope, predation on ground nesting birds is high.

Others

Several species of mammals occur rarely or in very low numbers in the Beaufort Sea. These are:

Killer whales (*Orcinus orca*)
Harbor porpoises (*Phocoena phocoena*)
Narwhals (*Monodon monoceros*)
Fur seals (*Callorhinus ursinus*)
Northern sea lion (*Eumetopias jubata*)
Hooded seals (*Cystophora cristata*)
Harp seals (*Phoca groenlandica*)

In addition to the above there are several species of mammals occasionally found in the Chukchi Sea which could conceivably enter the Beaufort Sea. These are:

Humpback whales (*Megaptera novaeangliae*)
Fin whales (*Balaenoptera physalus*)
Sei whales (*Balaenoptera borealis*)
Minke whales (*Balaenoptera acutorostrata*)
Sperm whales (*Physeter catadon*)
Ribbon seals (*Phoca fasciata*)

Potential Effects of OCS Development

As the potential effects of OCS development will be dealt with in considerable detail in the interdisciplinary chapters of this report, only a general presentation will be made here.

The first group of potential effects is that associated with a general increase in human activity in the area. Examples are:

1. Establishment of permanent settlements could cause destruction of habitat, for example, polar bear denning areas. These settlements would attract polar bears and Arctic foxes. The animals would become nuisances and probably have to be killed. Human health problems are possible; for example, Arctic foxes are carriers of rabies.

2. The general increase in noise and activity levels could cause reduced use of certain areas by marine mammals. For example, spotted seals are known to abandon haul out areas when frequently disturbed, and belukhas are known to avoid areas with considerable boating activity.

A second group of potential effects includes direct effects of spilled oil including:

1. Contact with oil is known to cause irritation of mucous membranes (particularly eyes) in seals. Slight and presumably reversible liver and kidney damage has resulted from short-term exposure experiments. Similar effects would likely occur in other mammals.

2. Contact with crude oil might cause interference with the feeding apparatus (baleen) of baleen whales. Right whales, close relatives of bowhead whales, are known to skim the surface of the water with the baleen partially exposed (Watkins and Schevill, 1976).

3. Polar bears and Arctic foxes are dependent on their fur for insulation. Oiling of fur would reduce the insulative properties of the fur and large quantities would undoubtedly be ingested during grooming. Possible effects of oiling and ingestion have not been investigated.

4. Ringed seal pups in lairs might be affected in several ways. The lair may become contaminated with oil, resulting in prolonged, constant contact. Pups may be dependent on clean fur for thermoregulation. Pups may be reluctant to suckle on an oiled mother and if they do they may ingest significant quantities of oil. It is imperative for pups to acquire an adequate layer of blubber prior to weaning if they are to survive.

5. Short-term ingestion of crude oil has been shown to cause slight and presumably negligible liver damage in seals (Smith and Geraci, 1975). Effects on other species are not known. Polar bears could conceivably ingest large quantities of oil from seals that have come in contact with it, as they preferentially consume the hides and blubber of these animals. Effects of oil on suitability of seals as bear food are not known.

6. The traditional use of a limited number of dens by Arctic foxes provides a situation where contamination of den sites with oil could cause abandonment of those sites for extended periods, thus affecting survival.

The third category of effects includes indirect, largely trophic, effects. Some of the possibilities are:

1. Avoidance of contaminated food.

2. Reduction of populations of key prey species.

3. Accumulation and possible transmission of hydrocarbons in the food web.

It is important in this respect to remember that coastal residents are dependent on all of these species of mammals for food, clothing, and materials for producing native crafts. As such they will be the ultimate targets of any effects that are transmitted through trophic pathways.

Major Gaps in Information

We consider the following gaps to be of major significance:

1. Information on the foods and predators, including man, of belukha whales, bowhead whales, ringed seals, bearded seals, and polar bears.

2. Information on the distribution, abundance and natural history of key prey species of ringed and bearded seals and belukha and bowhead whales. In addition, we need studies of acute and chronic exposures of these prey species to toxic substances in both laboratory and natural conditions, and it is imperative that these studies include various life stages, larval through adult. We also need information on the behavior of petro-chemicals in the food webs. The species or species-groups that should receive primary attention are *Boreogadus saida*, *Thysanoessa* spp., and *Parathemisto* spp.

3. Basic natural history and ecological information on belukha whales needs to be obtained, especially in areas where they are important to coastal residents.

4. Distribution, abundance, and interspecific relationships of marine mammals along the summer ice edge need to be examined.

5. Research is needed to determine the effects of industrial activities on marine mammals and to develop techniques to minimize these effects. We are specifically thinking of the effects of aircraft, seismic activity, and other equipment operation on seals, bears, and whales, and in developing techniques for reducing problems with foxes and bears in camps and settlements.

6. Basic natural history, migration, and distribution information on bowhead whales needs to be gathered, especially during the summer and fall months.

7. Movements of Arctic foxes to and from sea ice, movements on the sea ice, and extent of predation on marine mammals during spring are not well understood.

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5. BIRDS

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Introduction

The discussion in this report on marine and water birds of the northern Chukchi and Beaufort Sea coasts will be limited to the area north of Cape Lisburne and west of the Mackenzie River delta (except for a short portion on effects of marine transportation in the Southern Chukchi Sea). By limiting geographic coverage, we can present information that deals with relatively similar bird species and habitats.

Overview

Birds are highly visible organisms that provide an indication of the general productivity of various habitats and are of public interest and concern. Their general value is recognized and protected in North America by an international treaty. With few exceptions birds are transient phenomena in the northern Chukchi/Beaufort seas. Seabird colonies are of major importance south of Cape Lisburne; north of that point, they are of minor importance. Most are present only from May through September. Since they come to this area to breed, they are mostly occupied with their eggs and young. This is a crucial phase of the birds' life cycle and they frequently cannot desert a disturbed area during the breeding season without a significant loss of invested energy (in this case, eggs or young). Low densities of nesting birds are typical of this region, but it should be emphasized that there are many birds distributed over a very large area. Birds generally follow a coastal route to the breeding grounds in spring, but are commonly found far out to sea and inland. Small aggregations sometimes occur in river deltas. The largest coastal concentrations of birds occur from late July through September. At this time, large numbers of migrant shorebirds and larids and molting Oldsquaws are found in lagoons and near barrier island chains. Oil spills in such areas would likely be confined and least subject to dispersal by wave action. Since birds are migrating linearly along the coast, it is possible that damage at one point may affect numerous species of birds as they pass that point. Nearly all species depend on the marine environment for food resources at some time during their stay in this region, and thus are likely to be affected (to varying degrees) by incidents of marine pollution.

Four main information gaps are listed in descending order of immediate need:

1. distribution and predictability of post-breeding concentrations of birds ;

2. bird use of unprotected coastal areas (areas away from barrier island chains);

3. comparative studies of disturbed/undisturbed sites;

4. integrated trophic studies.

We recommend that there be no drilling activity at three islands that have unique and unusual bird colonies: Solovik, Cross, and Howe. Also strict precautions should be taken to avoid damaging four specific late-summer areas of bird concentrations: Peard Bay, Plover Islands, Simpson Lagoon, and Teshekpuk Lake.

The Chukchi Sea will be used with increasing frequency as a marine tranportation corridor to the North Slope oil fields. Precautions need to be taken to avoid consequent damage to the seabird colonies at Capes Thompson and Lisburne and in Kotzebue Sound.

Zoogeography

The birds of the Northern Chukchi/Beaufort region are clearly an international resource. Some birds that breed here spend their winter as far away as Antarctica (Arctic Terns, *Sterna paradisaea*) and southern South America (Pectoral Sandpipers, *Calidris melanotos*); individuals of other species may overwinter in the northern Bering or southern Chukchi Seas (Oldsquaws, *Clangula hyemalis*; eiders, *Somateria* spp.). Birds also migrate to this area from wintering grounds on South Pacific islands (Ruddy Turnstones, *Arenaria interpres*; American Golden Plovers, *Pluvialis dominica*) and from Asia (Dunlins, *Calidris alpina sakhalina*) (MacLean and Holmes, 1971; Norton, 1971).

In his review of birds of the Barrow area, Pitelka (1974) listed 151 species. Of these, 22 are species that regularly breed there. At a coastal site near Prudhoe Bay, Bergman et al. (1977) recorded the presence of 71 species of which 25 were breeding. Because there are no shrubs or cliffs on the coast, birds breeding in this area are limited to loons, waterfowl, shorebirds, and ground-nesting passerines.

Seasonal Habits and Distribution

Small numbers of birds are found on the tundra throughout the breeding season. Post-breeding birds leave tundra areas beginning in late June and move to coastal habitats. Peak use of the coastal zone occurs in August, when juveniles join and/or replace adults and prior to outbound migration in September, when birds depart from many areas along the coast. In some areas, such as Simpson Lagoon, Oldsquaws may remain in large numbers throughout September. Very few alcids are seen in the Beaufort Sea, primarily because breeding cliffs are virtually nonexistent - there is one known colony of these birds in the Canadian Beaufort (See Table 5.1, Fig. 5.1).

Spring Migration

Eastbound spring migrant waterbirds follow a coastal route to their breeding areas (Figs. 5.2, 5.3). There is some evidence that many birds migrate primarily within 10 km of the coast (Flock, 1973; Richardson

Table 5.1 Seasonal peak densities of birds in principal habitat types along the Beaufort Sea coast, Alaska.

HABITAT TYPE	Loons	Geese, Swans	Sea ducks	Plovers	Sandpipers	Phalaropes	Jaegers, large gulls	Terns, small gulls	Alcids	Songbirds
Upland dry tundra (per km^2)[1,2]	-	-	-	10	70	-	5	-	-	100
Lowland wet tundra (per km^2)[1,2]	3	6	10	2	80	70	1	<1	-	30
Mixed tundra with ponds (per km^2)[2,3]	3	10	30	10	150	150	5	<1	-	100
Salt marsh (per km^2)[4]	-	1000	10	2	2000	200	2	20	-	200
Mudflat (per km^2)[2,4]	-	-	-	2	2000	50	2	-	-	50
River mouth (per linear km)[1,4]	2	40	10			100	40	20	-	
Spits, bars, barrier islands (per linear km)[1,4]	2	4	330	2	35	500	20	200	<1	6
Mainland beach (per linear km)[1,4]	<1	<1	1	<1	6	25	10	5	-	15
Lagoon (per km^2)[5,6]	<1	-	470	-	-	15	6	2	-	-
Ocean (<1 km from mainland)[1] (per km^2)	1	1	100	-	-	50	3	180	<1	-
Ocean (>1 km from mainland)[1] (per km^2)	1	-	10	-	-	<1	<1	<1	<1	-

[1]Divoky, in prep. [2]Myers, unpublished data [3]Bergman et al. 1977 [4]Connors, unpublished data [5]Johnson 1978 [6]Schamel 1976

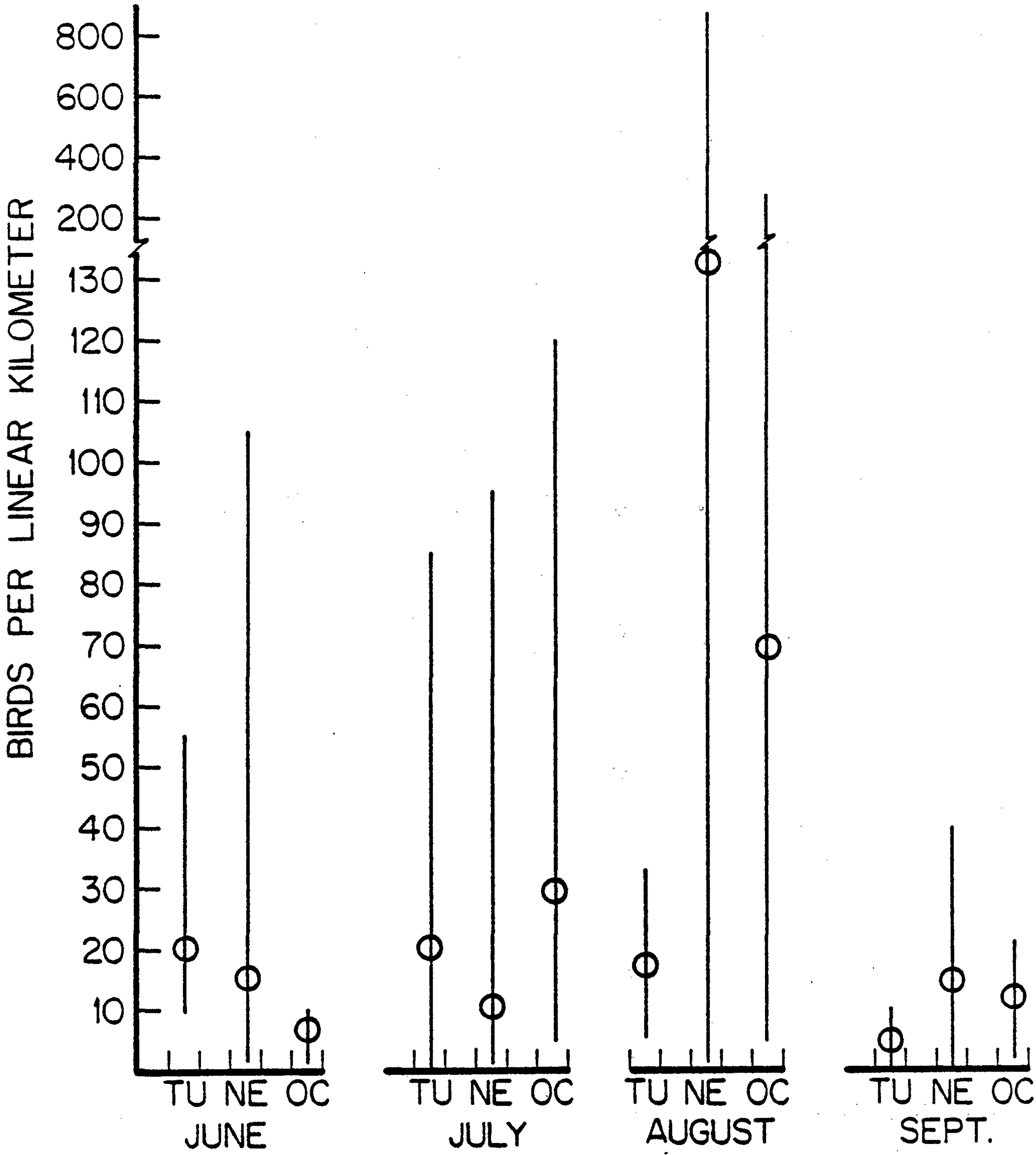

Fig. 5.1 Seasonal bird distribution in major habitat types on the Beaufort Sea coast, Alaska. (modified from Divoky, RU 3/4, in prep.) [Values given are mean (circle) and range (line)].

TU = tundra

NE = nearshore (river mouths, spits, bars, barrier islands, mainland beach, lagoon, ocean < 1 km from mainland)

OC = ocean (> 1 km from mainland or seaward of barrier island)

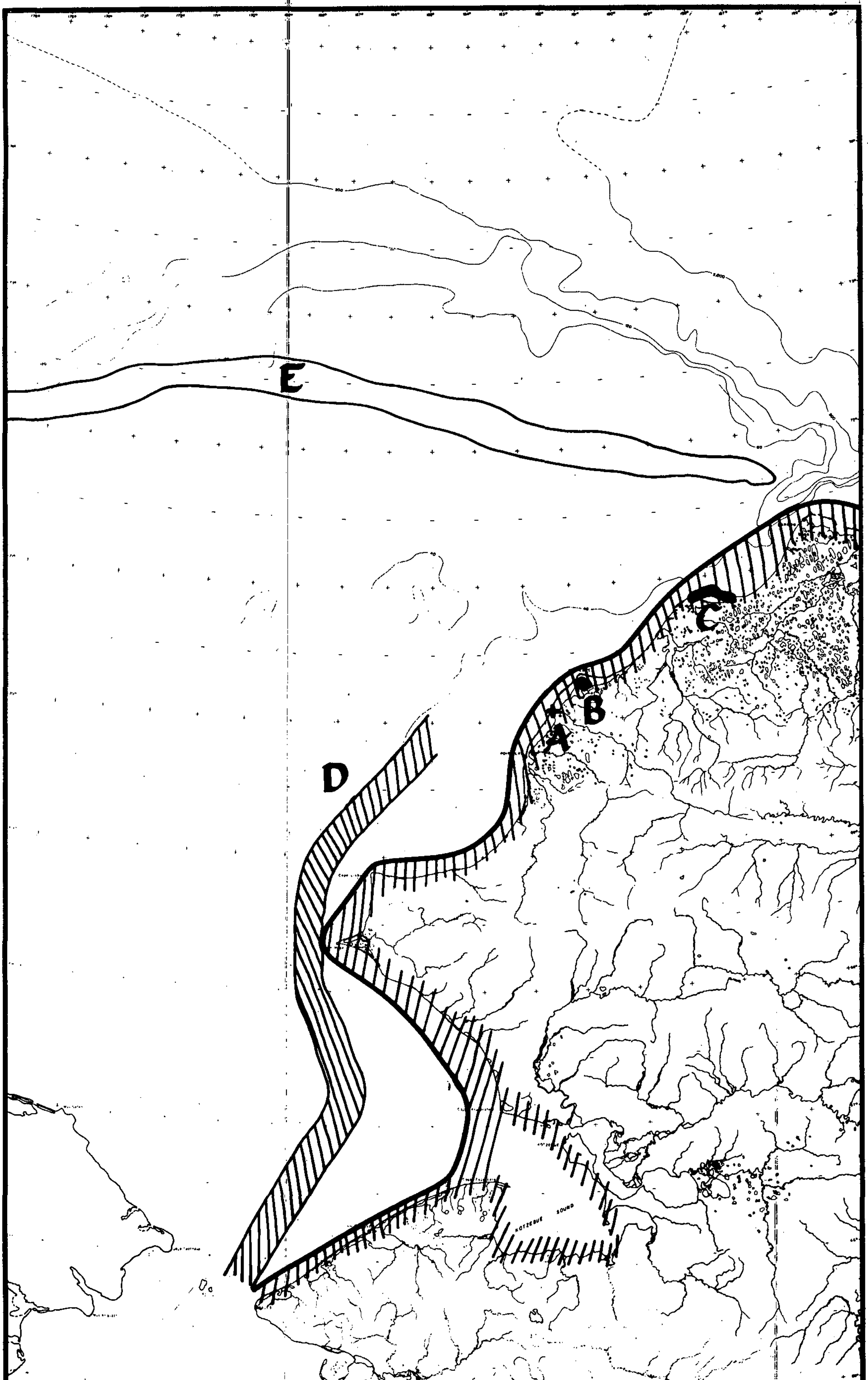

Fig. 5.2

KEY for Fig. 5.2: Breeding, molting and feeding concentrations and migration corridors of marine birds along the Chukchi Sea coast, Alaska.

Breeding concentrations

A Solovik Island: More than 100 waterfowl

Molting and/or nearshore feeding concentrations

B Icy Cape: fall migrant shorebirds

C Point Franklin/Peard Bay: fall migrant shorebirds

Migration corridor

Near coastline

D Offshore

Offshore feeding concentrations

E Seabirds at approximate summer ice edge et al., 1975; Craig Harrison, pers. comm.), but not all migration is restricted to a narrow coastal strip. Migrants are commonly recorded 40 km out to sea, as well as 40 km inland on the coastal plain and in mountain passes (Williamson et al., 1966; Flock, 1973; Richardson et al., 1975; Dean et al., 1976; Johnson, 1978). King Eiders (Somateria spectabilis), for example, probably migrate far out to sea from Point Barrow to Banks Island (Barry, 1968), coming nearshore only when offshore leads close (Stephen R. Johnson, pers. comm.).

Spring migration lasts from late April or early May through mid or late June. In the Chukchi Sea, waterfowl make extensive use of shore leads in May (Bailey, 1948; George Divoky, pers. comm.), while in the Beaufort Sea these leads are used most heavily in early June (Schamel, 1976). At this time, rivers are beginning to flow and open water is forming in river mouths, providing opportunity for birds to rest and feed. A sudden drop in temperature or shift in wind direction at this critical time may close the leads and birds stranded far from feeding areas may starve. This phenomemon has most commonly been noted for eiders; at least 10% of the Beaufort Sea eider population may perish during a single spring migration (Barry, 1968). Not all river mouths receive equal use by waterfowl (George Divoky, pers. comm.). The use of these areas may vary drastically not only between deltas in a single year but also at any given location between years. Contributing factors may include the availability of open water both offshore and inshore, as well as laterally along the coast. At present it is impossible to predict which areas will be critical aggregation areas for birds in a given year as these critical areas may shift from one year to the next. However, the importance of certain larger river deltas may be relatively consistent over succeeding years. Significant numbers of Black Brant (Branta bernicla nigricans) have utilized the Hulahula-Okpilak river delta in May-June each year during 1971-1976 (David Roseneau, pers. comm.).

Similarly, shorebirds use snow-free areas of tundra during spring migration. Such sites may be abundant both along the coast and inland in some springs, or limited to the headwaters of streams in others (James Curatolo, pers. comm.). In any given locality, the pattern of habitat availability may be similar from year to year, but the timing may vary greatly. Once again, this means that critical springtime shorebird habitat may shift localities annually.

Breeding Season

In the northern Chukchi/Beaufort area, waterfowl and shorebirds nest along the entire coastline. They are most abundant in marsh habitat; their greatest concentrations are found in habitats consisting of a "fine-grained mosaic" (MacLean, 1973) of ponds and narrow ridges (Myers and Pitelka, 1976). The greatest concentrations of nesting waterbirds along the Beaufort coast appear to be in the Barrow area (Myers and Pitelka 1976) (Fig. 5.3) and in the Colville River delta (George Divoky, pers. comm.). No comparable areas have been identified along the northern Chukchi coast. It should be emphasized that many other areas of similar habitat exist along both coasts but have been less studied. Many of these areas may also support high numbers of breeding birds.

Key for Fig. 5.3: Breeding, molting and feeding concentrations and migration corridors of marine birds along the Beaufort Sea coast, Alaska.

Breeding concentrations

F Barrow area: 1,000's of waterfowl and shorebirds

G Colville River delta: 1,000s of waterfowl and shorebirds

H Niakuk Islands: ca. 100 Glaucous Gulls
Cross Island: ca. 100 Common Eiders
How Island: ca. 100 Snow Geese

I Mackenzie River delta; ca. 25,000 Whistling Swans; 2,500 White-fronted Geese

J White-winged Scoter and scaup

Molting and/or nearshore feeding concentrations

K Barrow spit/Plover islands: 10,000 post-breeding and juvenile shorebirds, gulls and terns

L Cape Halket/Pitt Point: 1,000s post-breeding and juvenile shorebirds and Black Brant

M Simpson Lagoon/Gwydyr Bay: 10,000s molting Oldsquaws

N Hulahula River mouth: spring migrant Black Brant

O Herschel Island area: post-breeding and juvenile shorebirds; molting Oldsquaws (1,000s)

P Phillips Bay: molting Oldsquaws

Migration corridor

Near coastline offshore

Q Offshore

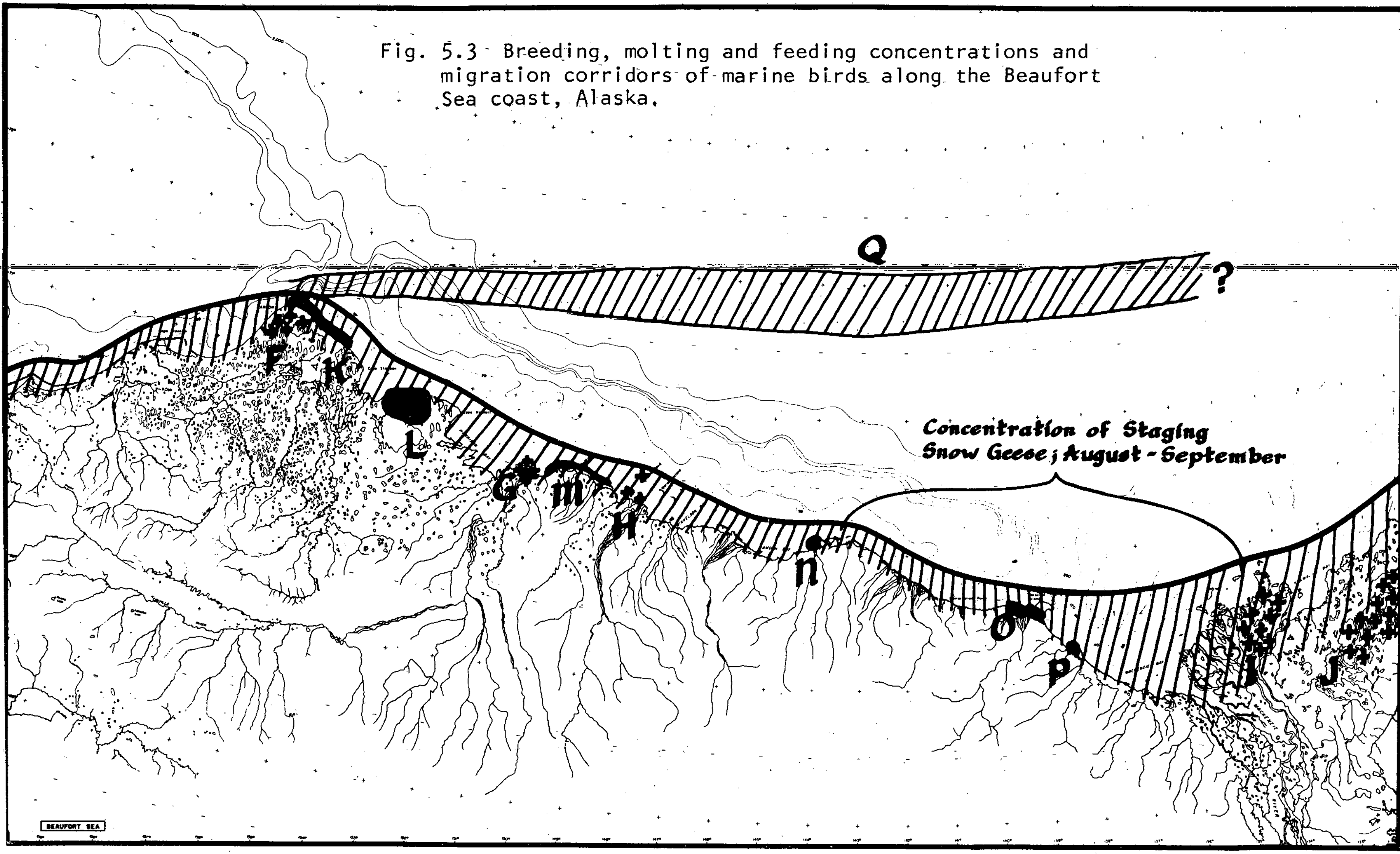

Fig. 5.3 Breeding, molting and feeding concentrations and migration corridors of marine birds along the Beaufort Sea coast, Alaska.

In general, the Chukchi/Beaufort barrier islands support very low numbers of breeding birds (Divoky, 1978a). Exceptions include Solovik Island in the Chukchi Sea, and Cross, Howe, and Niakuk Islands in the Beaufort Sea. Both Solovik and Cross Islands have significant concentrations (ca. 100 or more nests) of Common Eiders (Somateria mollissima). Howe Island supports the only known colony of Snow Geese in Alaska. In 1976 Niakuk Island had a significant concentration (ca. 150 nests) of Glaucous Gulls, Larus hyperboreus (Figs. 5.2, 5.3; Divoky, 1978a). Useful accounts for these and other species are found in Johnson et al., (1975).

Post-breeding Season

The greatest bird use of the coastal zone occurs during the post-breeding season. At this time many tundra species move to the coast to feed prior to migration (Fig. 5.1). Beginning in mid-July Oldsquaws concentrate in bays near the islands, where they feed in shallows and rest on the islands during their feather molt (Schmidt, 1970; Bergman, 1974; Hall, 1975; Vermeer and Anweiler, 1975; Schamel, 1976, 1978; Johnson, 1978; Divoky, in prep.). In late July they are joined by juvenile Red and Northern Phalaropes, which move to the coast from inland marshes (Table 5.1: Connors, 1976; Schamel, 1976, 1978; Johnson, 1978; Divoky, in prep.). Phalaropes are most often found near islands and spits. They appear to be most numerous near the Barrow spit/Plover Islands region (immediately east of Barrow) and in the Peard Bay Spit/Seashore Islands area (Figs. 5.2, 5.3: Connors, 1977; Divoky, in prep.). These areas are also important for juvenile Sabine's Gulls (Xema sabini), Arctic Terns (George Divoky, in prep.), and other shorebirds (Connors 1976, 1977). Johnson (1978) reports Simpson Lagoon to be important for numerous phalaropes, larids, and molting Oldsquaws (Fig. 5.3).

Many birds migrate into the region from breeding grounds elsewhere. They concentrate at various staging areas here before continuing their outbound migration. Black Brant feed in brackish marshes during their migration in August, so numerous river deltas between Prudhoe Bay and the Mackenzie River may be important to substantial numbers of these geese (Koski, 1975; David Roseneau, pers. comm.). West of the Colville River, at Cape Halkett, Pitt Point (near Lonely) and Icy Cape, these birds occurred in large numbers in 1976 (Peter Connors, pers. comm.). The same habitats at Icy Cape and Pitt Point are also heavily used by several shorebird species, especially Dunlins (Connors, 1976, 1977). Approximately 40,000 geese congregate annually in the area north of Teshekpuk Lake to undergo wing molt (Fig. 5.3: Derksen et al., 1977). The majority are Black Brant, but large numbers of Canada Geese (Branta canadensis) and White-fronted Geese (Anser albifrons) are also present. Some of the brant had been banded on Wrangel Island, U.S.S.R.

Between 163,000-400,000 Snow Geese breed on Banks Island, Kendall Island and in the Anderson River area in Canada, then migrate to staging areas along the eastern North Slope of Alaska in and near the Arctic National Wildlife Range (Fig. 5.3: Koski and Gollop, 1974; Patterson, 1974; Schweinsburg, 1974; Koski, 1975, 1977) before returning east and south, down the Mackenzie River to wintering grounds in southern North America.

Another migration pattern is demonstrated by post-breeding male eiders. Beginning in early July, shortly after the females lay eggs, these birds return westward from nesting grounds in Canada and Alaska. There is some evidence that Beaufort Sea male eiders make few, if any, stops before reaching the Chukchi (George Divoky, pers. comm.). Here, at least a few concentrations of molting eiders have been found, one near the mouth of the Noatak River (Craig Harrison, pers. comm.).

Birds in Offshore Waters

During the entire summer, numerous birds are found at the edge of the sea ice (Fig. 5.2, 5.3: Watson and Divoky, 1972, 1974; Frame, 1973; Divoky, 1977). Black-legged Kittiwakes (Rissa tridactyla) and murres (Uria sp.) are the principal species at the ice edge, although numerous jaegers, Glaucous Gulls and Black Guillemots (Cepphus grylle) are also found. In September, Ross' (Rhodostethia rosea) and Ivory gulls (Pagophila eburnea) feed extensively here (Divoky, 1976). Bird densities at the Chukchi ice edge in fall can be exceptionally high (Watson and Divoky, 1972). In the Chukchi, birds forage in moderate concentrations (greater than 30 birds/km^2) in various locations at sea (Fig. 5.2), even after the ice edge has moved northward (Divoky, 1977; Craig Harrison, pers. comm.).

Food Habits

Nearly all bird species rely upon coastal food resources at least some time during their stay along the northern Chukchi/Beaufort coast. Table 5.2 summarizes current knowledge of waterbird food habits in this area. Various species of marine crustaceans are used by many birds. Arctic cod (Boreogadus saida) is important for the larger birds and for birds that feed primarily at sea. Geese are not shown in Table 5.2. They are primarily grazers on plants in brackish marshes. Their specific preferences are currently under investigation by D. V. Derksen and others (USFWS). Glaucous Gulls, jaegers (Stercorarius spp.), and Common Ravens (Corvus corax) scavenge carrion (David Roseneau and James Curatolo, pers. comm.) and rob eggs (Maher, 1974).

Annual Variation and Critical Areas

During post-breeding migration, as well as spring migration, the observed significant year-to-year variation in habitat use makes the delineation of critical areas difficult. In several instances, the data of OCSEAP investigators show trends quite different from the results of earlier studies. The apparent conflict involves annual variation, not faulty data, and signals the need for long-term studies. Because of this difficulty, it seems reasonable to delineate "sensitive" and "critical" areas. "Sensitive" areas refer to locations where a disturbance would probably have a measurable effect on bird numbers. A "critical" area refers to a location where disturbances would result in widespread effects on bird populations. (Concepts developed by John Burns' interdisciplinary group on Biota and Habitats). As such, the entire coast is a potentially sensitive area for birds, especially barrier islands, gravel spits, river deltas, mudflats, and fine-grained mosaic tundra. On the basis of OCSEAP fieldwork, Connors (1977) and Divoky (1977)

Table 5.2 Preliminary list of prey items for selected Beaufort Sea birds.

PREY	Arctic Loon	R-T Loon	Oldsquaw	Common Eider	King Eider	Ruddy Turnstone	Baird's Sdp.	Dunlin	Sanderling	Red Phalarope	Northern Phalarope	Glaucous Gull	Ivory Gull	B-L Kittiwake	Ross' Gull	Sabine's Gull	Arctic Tern	T. B. Murre	B. Guillemot
Mollusca, Pelecypoda	-	-	X[1]	-	-	-	-	-	-	-	-	X[2]	-	-	-	-	-	-	-
Gastropoda	-	-	-	-	-	-	-	-	-	X[2]	-	-	-	-	-	-	-	-	-
Arthropoda, Copepoda	-	-	-	-	-	-	-	-	X[2]	X[2,3]	X[4]	X[3]	-	-	-	X[1]	-	-	-
Mysidacea	-	-	X[1]	-	X[1]	-	-	-	-	-	-	X[3]	-	-	X[1]	X[1]	X[1]	-	-
Isopoda	-	-	-	X[1]	X[1]	-	-	-	-	-	-	X[1,3]	-	-	-	-	-	-	-
Amphipoda	X[1]	-	X[1]	-	-	-	X[2]	-	X[2]	X[2]	-	X[3]	-	X[1]	-	X[1]	X[1]	X[1]	X[1]
Euphausiacea	-	-	-	-	-	X[2]	-	X[2]	X[2]	-	-	-	-	-	X[1]	X[1]	X[1,6]	-	-
Decapoda (zoea)	-	-	-	-	-	-	-	-	X[2]	X[2]	-	-	-	-	-	-	-	-	-
Chaetognatha, <u>Sagitta elegans</u>	-	-	-	-	-	-	-	-	-	X[2]	-	-	-	-	-	X[6]	-	-	-
Chordata, <u>Boreogadus saida</u>	-	X[7]	-	-	-	-	-	-	-	-	-	X[1]	X[5]	X[1]	X[5]	X[1]	X[1]	X[1]	X[8]
<u>Myoxocephalus</u> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X[8]

[1]Divoky 1976 [3]Johnson 1978 [5]Divoky 1976 [7]Bergman 1974

[2]Connors 1977 [4]Connors 1978 [6]Connors 1976 [8]Divoky et al. 1974

concur in nominating the Barrow Spit/Plover Island area and the Peard Bay Spit/ Seahorse Islands area as critical staging areas for juvenile shorebirds and larids. Johnson's (1978) data suggest that Simpson Lagoon is a critical staging and molting area for Oldsquaw ducks. This area also supports thousands of migrant phalaropes and larids during August (see Figs. 5.2, 5.3).

Variation in annual community patterns detected by OCSEAP bird studies has occasionally been wide: Connors (1977) found a strikingly different array and density of zooplankton available for littoral zone birds near Barrow in two successive years. His studies identify some responses of birds to changes in prey, but the system is inadequately understood. In contrast, Connors' work along the shore and Myers' work in the nearby tundra showed the spatial and temporal distribution of the overall bird biomass to be remarkably consistent with the distribution of prey organisms.

Susceptibility to Perturbations

Oil Contamination

Bird species vary considerably in their susceptibility to oil contamination. Susceptibility depends upon: 1) time spent at sea or in littoral areas; and 2) behavior of the bird while in this area. Basically, those bird species that most frequently contact the water's surface (or its path) would be most susceptible to oiling. These criteria are reflected in the oil susceptibility list (Table 5.3).

Major bird mortality would result from oil spills near breeding colonies in the Bering Strait and the Cape Thompson/Lisburne areas. Spills in other open water areas in the Chukchi Sea would possibly cause less immediate mortality to birds. An oil spill in the multi-year ice of the northern Chukchi and throughout the Beaufort may present a complex problem. Oil could remain trapped under the ice for an extended period of time, and in addition to endangering the under-ice prey fauna of birds, it would also threaten birds that feed and roost in the limited open water (Divoky, 1977). Oil contamination of the limited open water nearshore during spring migration would be another hazard. By late June, many of the nearshore waters of the Beaufort are ice-free and birds are able to disperse. However, shorebirds and molting Oldsquaws are especially abundant in lagoon areas, where oil could be confined and less subject to dispersal by wave action.

Gravel Removal, Island Stabilization and Causeway Construction

The importance of barrier island/lagoon systems to migrant birds has been clearly demonstrated by OCSEAP investigators (Figs. 5.1, 5.2 and 5.3: Connors, 1976, 1977, 1978; Schamel, 1976, 1978; Johnson, 1978; Divoky, in prep). Gravel removal from most barrier islands and island stabilization projects would probably have little adverse effect on most birds, unless the integrity of entire island chains was disrupted with concomitant loss of lagoon areas. Loss of nesting habitat would probably be insignificant except on Solovik, Cross, Howe, and Niakuk Islands. In fact, alteration of shorelines may actually increase foraging habitat for fall migrant shorebirds, gulls and terns. However, in such instances, birds might be attracted to areas where contamination is most likely to occur (Connors, 1977). The potential effects of increased turbidity on the foraging efficiencv of birds are not known.

Table 5.3 Waterbird susceptibility to littoral zone oil pollution along the northern Chukchi and Beaufort Sea coasts, Alaska.[1]

High	Moderate	Low
Loons	Geese, Swans	Plovers
Sea ducks	Sandpipers, part	Songbirds
Sandpipers, part	Terns, small gulls	
Phalaropes		
Jaegers, large gulls		
Alcids		

[1]Adapted, in part, from Connors et al. (in prep.)

Aircraft and Other Disturbances

Recent studies have addressed the problems of waterbird reactions to various aircraft and other forms of disturbance. Abandonment of habitat by birds may depend upon season, species, and level and type of disturbance. Gollop et al (1974) reported that noise from aircraft contributed to abandonment of nests and lowered fledgling success of Lapland Longspur (*Calcarius lapponicus*). Schamel (1974) found laying-stage Common Eiders would flush at the approach of aircraft; during incubation, these same birds remained on their nests, even when aircraft approached within 5 m. Similarly, brood-rearing female waterfowl did not relocate or abandon their broods after repeated aerial overflights, although non-breeding birds abandoned such disturbed areas (Schweinsburg et al, 1974).

Post-breeding waterfowl vary considerably in their reaction to aircraft and noise. Snow Geese are perhaps the most sensitive (Schweinsburg, 1974). Salter and Davis (1974) reported that flocks of these birds flushed due to fixed-wing aircraft overflights at altitudes up to 3,000 m. Gas compressor sound-simulators disrupted normal flight behavior of these birds and excluded foraging geese from a radius of 800 m around the noise source (Wiseley, 1974). In contrast, helicopter overflights were found to have little effect on molting Oldsquaws (Ward and Sharp, 1974). On low overflights, birds dived, but this was only a momentary disturbance and birds soon resumed pre-disturbance activities. Moreover, frequently-disturbed areas were not abandoned (Ward and Sharp, 1974; Johnson, 1978).

Oil exploration will certainly lead to the development of additional settlements. In the past, such areas have attracted mammalian predators (arctic foxes, wolves, brown bears) which feed on garbage and handouts. The potential harmful effects of these predators on nesting birds need to be considered.

Information Gaps

The following information gaps are listed in decreasing order of need.

1. Distribution of Post-breeding Birds

A mass of information shows clearly the importance of coastal habitats to post-breeding birds. Connors (1976, 1977, 1978) gathered data over three years which show that the Barrow Spit/Plover Islands region is heavily used. Johnson (1978) estimated a peak of 100,000 post-breeding Oldsquaws using Simpson Lagoon in late summer. This differs significantly from Divoky's (in prep.) estimates from 1976. We need to increase the ability to predict lagoon use in the Beaufort Sea. This requires continued monitoring of the Plover Islands region and Simpson Lagoon, and the implementation of aerial surveys of the island chains between Simpson Lagoon and the Canadian border.

2. Bird Use of Unprotected Coast

All OCSEAP bird investigators have concentrated their efforts near spits, bars, or lagoon systems. Therefore, very little is known about seasonal use by birds of coastal sites located away from lagoon systems. We predict less use of areas away from rather than in the lagoons; however, we have only limited data to support our prediction. To verify this, it would be useful to conduct a study at a site where the mainland coast fronts the open ocean.

3. Disturbed Sites

Most studies to date have been conducted at relatively undisturbed sites. More studies of disturbed sites are indicated. For example, the construction of roadways changes drainage patterns, which affect habitat characteristics. This, in turn, results in a decrease in available habitat for some species and an increase for others. We do not know whether these changes are significant for bird populations. Construction certainly attracts some species (e.g., scavengers), but possible effects on local bird populations are uncertain.

Studies of large waterbirds in Canada documented the high sensitivity of geese and low sensitivity of some sea ducks to aircraft disturbances, as noted above. Decreased feeding time (8.5%) was also calculated for repeatedly-disturbed staging Snow Geese (Davis and Wisely, 1974). These investigations provide an excellent foundation for additional studies. We do not know what flexibility various species may have in using different habitats and staging areas. We also do not know an effective method of dispersing "tame" species, such as Oldsquaws and phalaropes, from oil slicks.

4. Trophic Relationships

Without exception, the life histories, population dynamics and productivity of organisms identified as important to Beaufort Sea birds are poorly understood. These are data gaps that may be of extreme importance. Ideally, such data as well as information on prey selectivity would be gathered during an integrated study of plankton, fish, birds, and mammals.

Recommendations

1. Areas Where Drilling and Surface Activities Should Be Prohibited

There are several areas in the northern Chukchi/Beaufort that are critical and unique in that they support large (for this region) breeding concentrations. Past investigations (Schamel, 1974) suggest that extensive modification of gravel islands or disturbance during the nesting season may be detrimental to these colonies. Therefore, we recommend no drilling or surface activity on the following islands: Solovik, Cross, and Howe. Information on Solovik and Cross is summarized by Divoky (1978a). Howe Island supports the only known colony of Snow Geese in Alaska.

2. Special Precautions Areas

By far the greatest concentration of birds in the coastal zone in this region occurs from late July through September. Birds are not uniformly distributed along the coast at this time. Instead, they congregate in the following areas: Peard Bay/Seahorse Islands, Barrow Spit/Plover Islands, Jones and Return Islands (Simpson Lagoon). We recommend that special precautions be taken to minimize the risks of oil spills in these areas during this time period.

The tundra area north of Teshekpuk Lake is important to migrant and molting geese. Precautions should be taken to avoid disturbances to the birds and the habitat of this area.

3. Tundra Habitats - General

Marsh and salt marsh habitats are important to nesting and post-breeding waterbirds, respectively. Whenever possible, such habitats should not be disturbed.

Addendum: Southern Chukchi Sea - Marine Transportation Considerations
(Principal Author: D.G. Roseneau)

Marine transportation of equipment, fuel oil, and personnel to the Beaufort Sea lease area via shipping lanes through the Chukchi Sea, and potential marine transportation of crude oil or petroleum products from the Beaufort lease area to points south of or within the Chukchi Sea are important considerations within the scope of this report.

Two major seabird colonies, each presently supporting more than 250,000 individuals, are located at Cape Lisburne and Cape Thompson (Springer and Roseneau, 1977, 1978). In addition to several small colonies (up to hundreds of individuals) located in this area, another colony of more than 30,000 birds exists at Cape Lewis (Springer and Roseneau, 1978). Farther south, important coastal habitat for migrant waterfowl and shorebirds is found at various locations in the Kotzebue Sound area (Mickelson et al., 1977; Connors, 1978, pers. comm.). Small seabird colonies (several thousand individuals) are located on Chamisso and Puffin islands and on the north coast of the Seward Peninsula, between Sullivan Bluffs and Cape Deceit.

Seabirds from the major Cape Lisburne and Cape Thompson colonies forage well at sea (Swartz, 1967; Springer and Roseneau, 1977, 1978). Much of the foraging activity may occur as much as 50-70 km offshore (Swartz, 1967; Springer and Roseneau, 1978). Important foraging areas appear to exist south and west of Cape Thompson and northeast and north of Cape Lisburne (Swartz, 1967; Springer and Roseneau, 1978).

In spring, large numbers (at least one million birds) of loons, brant, Snow Geese, Oldsquaws, and eiders migrate northward along the coastline and offshore (Williamson et al., 1966, and pers. comm.). Colonial seabirds, arriving in spring, tend to follow the ice edge as they move northward (Swartz, 1967; Divoky, pers. comm.). These birds probably make extensive use of the large, relatively regular lead system that occurs annually along the late winter edge of the shear zone. Murres have been observed offshore in the lead system by whaling crews (Swartz, 1966). During late summer and fall, large numbers of other species may be present offshore. Large concentrations of petrels, fulmars, and auklets have been observed in August-October (Harrison, 1977, and pers. comm.). During the same time, large numbers of phalaropes move south through this region (Williamson et al., 1966; Harrison, pers. comm.).

Most barge traffic bound for Prudhoe Bay passes through the foraging zones of the Cape Thompson and Cape Lisburne seabirds (Roseneau, pers. comm.). It is assumed that future barge and tanker traffic will follow similar routes. It is also assumed that, during spring and early summer, future ice-breaker tanker traffic would tend to follow the major Bering Strait-Chukchi-Barrow lead system.

Fuel from small but chronic leaks and bilge waste is likely to become increasingly common in Chukchi Sea waters as marine transportation increases. Any major oil spills in the southeastern Chukchi Sea are likely to affect Cape Thompson, Cape Lewis, and Cape Lisburne seabirds. Spills offshore from the Cape Krusenstern-Kivalina-Point Hope-Cape Lisburne coastline would probably cause the greatest direct impact. Furthermore, volumetric water flow and current vector data (Flemming and Heggarty, 1966) clearly suggest that oil spilled even further south, could reach the general foraging zones of these colonies, and the colonies themselves, within days. A large clockwise eddy exists north and east of Cape Lisburne (Flemming and Heggarty, 1966). Oil spilled near Cape Lisburne would be likely to travel toward the major colony there, through important foraging areas.

The sites of onshore support facilities, particularly terminals, along the Chukchi coast must be chosen with caution. The deep waters of the Cape Thompson area, for instance, may make that site particularly attractive for onshore development. Therefore, we suggest that support facilities along the Chukchi coast should be located "downstream" of the Cape Thompson-Cape Lisburne seabird colonies, preferably north of Cape Beaufort.

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6. MARINE BIOTA
(PLANKTON/BENTHOS/FISH)

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Introduction

The organisms within the major ecological groups of phytoplankton, zooplankton, benthic invertebrates and fishes are very diverse in their taxonomy and in their functional role within the oceanic ecosystem. These organisms range from primary producers to herbivores, to omnivores and scavengers, and to animals entrained in the detrital food web. Their habitats include the air-sea interface, the under surface of the sea ice, the water column and the sea floor from coastal waters to the deep sea.

The task of summarizing and synthesizing knowledge of these diverse biotic groups in the Beaufort Sea into a unified and functioning whole is a very difficult one at the present state of development of ecological research. The animal and plant groups together with the decomposers, i.e., bacteria and fungi, form the major structure of the biotic portion of the marine ecosystem and co-function as an interactive food web with integrative biogeotechnical cycles.

The major objective of this interdisciplinary report is the summarization of knowledge and the identification of important research needs for each of the major ecological groups within the context of the potential impact of offshore oil and gas development off the north slope of Alaska and Canada. The unifying thrust behind the marine ecological research has been to describe the natural populations and communities within the ecosystem and their interactions to determine the critical links susceptible to man-made perturbations. This basic knowledge also provides estimates on the limits of natural fluctuations and spatial patchiness of the Beaufort Sea biota.

Individual summaries for each major subdivision of marine biota and plant nutrients are presented with charts, tables and recommendations for research needs, but the scattered and fragmentary nature of the data available for Beaufort Sea organisms does not permit a concise and unified description of the environments that are critical for these groups. However, research has progressed far enough to define zones of mutual importance in loose terms.

BEAUFORT SEA PLANKTON STUDIES

Literature Review

Little is known about the biology of the plankton in the Chukchi and Beaufort Seas. Table 6.1 lists expeditions, collections, and publications on plankton from this area. The earliest collections were made during the Canadian Arctic Expedition, 1913-1918. Major groups of zooplankton reported from this expedition included ctenophores and hydromedusae (Bigelow, 1920), amphipods (Shoemaker, 1920), copepods (Willey 1920), and schizopod crustaceans (Schmitt, 1919). The primary constituents of the zooplankton in these samples were crustaceans, particularly copepods. Diatoms, described by Mann (1925), were primarily benthic forms.

Johnson (1956) reported on zooplankton collected in the Chukchi and Beaufort Seas in 1950 and 1951 and demonstrated, for the first time, the presence of Bering Sea water in the Beaufort Sea based on zooplankton distributions. Hand and Kan (1961) described the hydromedusae from these samples, including breeding ranges and the influence of hydrography on species distribution.

Wing (1974) described the kinds and abundance of zooplankton from the eastern Chukchi Sea in September and October 1970. Quast (1974) reported the density distribution of juvenile Arctic cod (*Boreogadus saida* Lepechin) from the same cruise and considered Arctic cod to be a "key species in the ecology of the arctic sea," important as a major secondary consumer.

Studies concerned with annual cycles, biomass, population dynamics, and production of both phytoplankton and zooplankton have been done primarily at Point Barrow (MacGinitie, 1955; Johnson, 1958; Bursa, 1963; Horner, 1969, 1972; Redburn, 1974). MacGinitie (1955), concerned mainly with benthic invertebrates, included a limited discussion of phytoplankton and zooplankton based on relative abundances and reproductive periods. Johnson (1958) described the qualitative and quantitative composition of the inshore zooplankton community for one month in summer.

Redburn (1974) described the zooplankton community in terms of species abundance and composition, life cycles, and relationship to the hydrographic regime. Copepods were the major constituents of the community along with large numbers of meroplanktonic larvae. The occurrence of Bering Sea water was indicated by the presence of expatriate species of copepods and populations of copepods and hydromedusae that breed from the Bering Sea to Barrow.

Bursa (1963) studied the taxomony, ecology and abundance of phytoplankton from several habitats near Barrow. Horner (1969, 1972) reported a bimodal annual phytoplankton cycle with a spring maximum in June and early July before ice breakup and a fall maximum in August-September.

In the nearshore area of the Beaufort Sea, Alexander (1974) has reported primary production, chlorophyll *a* and biomass data for the phytoplankton community in the Colville River system, including Harrison Bay and

Table 6.1 Expeditions, publications, and subjects of marine biological studies in coastal waters of the Chukchi and Beaufort Seas.

Expedition or Location	References	Subject
Canadian Arctic Expedition, 1913-1918 Chukchi - Beaufort Seas	Bigelow 1920	hydromedusae ctenophores
	Shoemaker 1920	amphipods
	Willey 1920	copepods
	Schmitt 1919	schizopod crustaceans
	Mann 1925	diatoms
CHELAN 1934	Johnson 1936, 1953	zooplankton
BURTON ISLAND 1950, 1951	Johnson 1956	copepods
LCM RIPLEY 1954	Hand & Kan 1961	hydromedusae
	Mohr et al. 1957	fish
Barrow - mainly Chukchi Sea	MacGinitie 1955	mostly benthos, some plankton
	Shoemaker 1955	amphipods
	Johnson 1958	inshore zooplankton (summer)
	Bursa 1963	phytoplankton
	Horner 1969, 1972	phytoplankton
	Horner & Alexander 1972	ice algae
	Matheke 1973	benthic microalgae
	Matheke & Horner 1974	benthic microalgae
	Alexander, Horner & Clasby 1974	ice algae, some phytoplankton
	Redburn 1974	zooplankton
	Alexander 1974	phytoplankton
Oliktok	Alexander 1974	Phytoplankton
Prudhoe Bay	Horner, Coyle & Redburn 1974	phytoplankton, zooplankton
	Coyle 1974	phytoplankton
WEBSEC		
Glacier 1970, 1971, 1972, 1973	Quast 1974	Arctic cod (Chukchi)
	Cobb & McConnell no date	zooplankton
	Wing 1974	zooplankton (Chukchi)
	Horner (unpubl.)	phytoplankton
Staten Island 1974	Horner (unpubl.)	phytoplankton
OCSEAP		
Prudhoe Bay 1975	English & Horner OCSEAP reports	phytoplankton
Glacier 1976 Icy Cape to Prudhoe Bay	English & Horner OCSEAP reports	phytoplankton, zooplankton, ichthyoplankton
Glacier 1977 Icy Cape to Demarcation Point	Horner OCSEAP reports	phytoplankton, zooplankton, ichthyoplankton
Southern Beaufort Sea	Grainger & Grohe 1975	zooplankton
	Adams 1975	primary production, oil under ice
	Hsiao 1976	phytoplankton

Simpson Lagoon. Coyle (1974) and Horner et al. (1974) studied the Prudhoe Bay plankton in terms of primary productivity, standing stock, species composition, and spatial variability, along with local hydrographic conditions.

Cobb and McConnell (unpubl. MS.) have described the species composition, relative abundances, and distributions of zooplankton collected in the Beaufort Sea in summer. Horner (unpubl.) has data on phytoplankton standing stock, distribution, and chlorophyll a concentrations in the Beaufort Sea in summer.

Hsiao (1976) and Grainger and Grohe (1975) have reported on phytoplankton and zooplankton studies in the southern Beaufort Sea (Mackenzie River delta), and Adams (1975) studied light intensity and primary production under sea ice containing oil.

With the exception of Adams (1975), these studies have been concerned with species composition, abundance, and distribution. Few attempts have been made to determine energy flow within the Arctic ecosystem and only Adams (1975) and Hsiao (1976) have studied the effects of oil on phytoplankton productivity in the Beaufort Sea.

Phytoplankton

Carbon fixation by phytoplankton and importation of terrestrial plant-derived detritus provide the energy to maintain the animals living in the marine ecosystem. Knowledge of the distribution, abundance, rate of carbon fixation, and environmental controls on phytoplankton is necessary for an understanding of the ecosystem. Information on seasonal and yearly variability and spatial patchiness is also important for a description of the primary production processes in the system.

1. Standing Stock

Nearly all the species reported for the Chukchi and Beaufort Seas (Bursa, 1963; Horner, 1969; Coyle, 1974; Horner et al., 1974; Hsiao, 1976) are common and widespread in north temperate and subarctic (as defined by Dunbar, 1968) waters. Some species, especially some pennate diatoms and flagellates, occur only in the spring in the community that lives in and on the underside of sea ice, the so-called epontic community. A few species are found in the ice and in the water column, but only one, *Nitzschia grunowii* Hasle, appears to be a major component of both habitats.

In the water column, the diatom genus *Chaetoceros* is apparently the most abundant in terms of numbers of species (ca. 20) and numbers of cells (more than 12 million cells per liter). Other diatoms are also present and may be abundant. Small flagellates (often <10 μm in diameter) may be common and may be dominant at a particular depth or station. Dinoflagellates are also present, but usually contribute less than 5% of the total number of cells. Many of the flagellates and dinoflagellates are colorless and therefore are not photosynthetic.

Based on OCSEAP samples collected in 1975, 1976, and 1977, *Chaetoceros* species were generally the most abundant organisms at most stations in the Beaufort Sea and were especially numerous below the surface at stations near Prudhoe Bay. Small flagellates were generally more abundant at western stations and at the surface at the eastern stations. Dinoflagellates were never abundant, but were present in larger numbers at stations taken in late August and early September 1976. In 1977, *Chaetoceros* species were the most abundant organisms, while small flagellates were generally not as common as in 1976.

It is not possible to separate the phytoplankton into categories based on hydrography because the species present are widespread in the north temperate and subarctic to arctic seas. The only species not previously reported from the Beaufort Sea was *Leptocylindrus minimus* which has been reported from the Bering Sea and was present in Bering Sea water in 1976. Whether this species is an expatriate and indicative of Bering Sea water or just has not been recognized in the Beaufort Sea before, it is impossible to say. Several of the species were more abundant than previously reported.

2. Chlorophyll *a* and Primary Productivity

In general, for OCSEAP 1976 and 1977 samples, high chlorophyll *a* concentrations and high primary productivity occurred at the same depth, and diatoms were the most abundant organisms. Where flagellates were the most abundant organisms, productivity was low (ca. 1 mg C m^{-3} hr^{-1}) suggesting that many of the flagellates were not photosynthetic. Integrated ^{14}C assimilation and chlorophyll *a* is given in Figs. 6.1 and 6.2. Annual production in 1976 was estimated to be ca. 9 g C m^{-2} yr^{-1} in the western Beaufort Sea and 18 g C m^{-2} yr^{-1} in the northeastern Chukchi Sea. In 1977 annual production was 14 g C m^{-2} yr^{-1} in the western Beaufort Sea and 28 g C m^{-2} yr^{-1} in the northeastern Chukchi Sea. The higher estimates for 1977 probably reflect lighter ice concentrations in 1977.

3. Primary Production and Nutrient Dynamics

Seasonal nutrient concentration data are available for only a limited region of the Beaufort Sea coastal zone near the Colville River (Alexander et al., 1975). Nutrient data across the continental shelf are available for several summer seasons from Point Barrow to Demarcation Point (U.S. Coast Guard, 1974; Horner 1977). A recent summarization is available in Section 7 of this Report.

Zooplankton

The zooplankton of the western Beaufort Sea may be grouped into 4 categories:

1. species which are expatriates from the Bering and Chukchi Seas;
2. species occurring throughout the Arctic Basin;

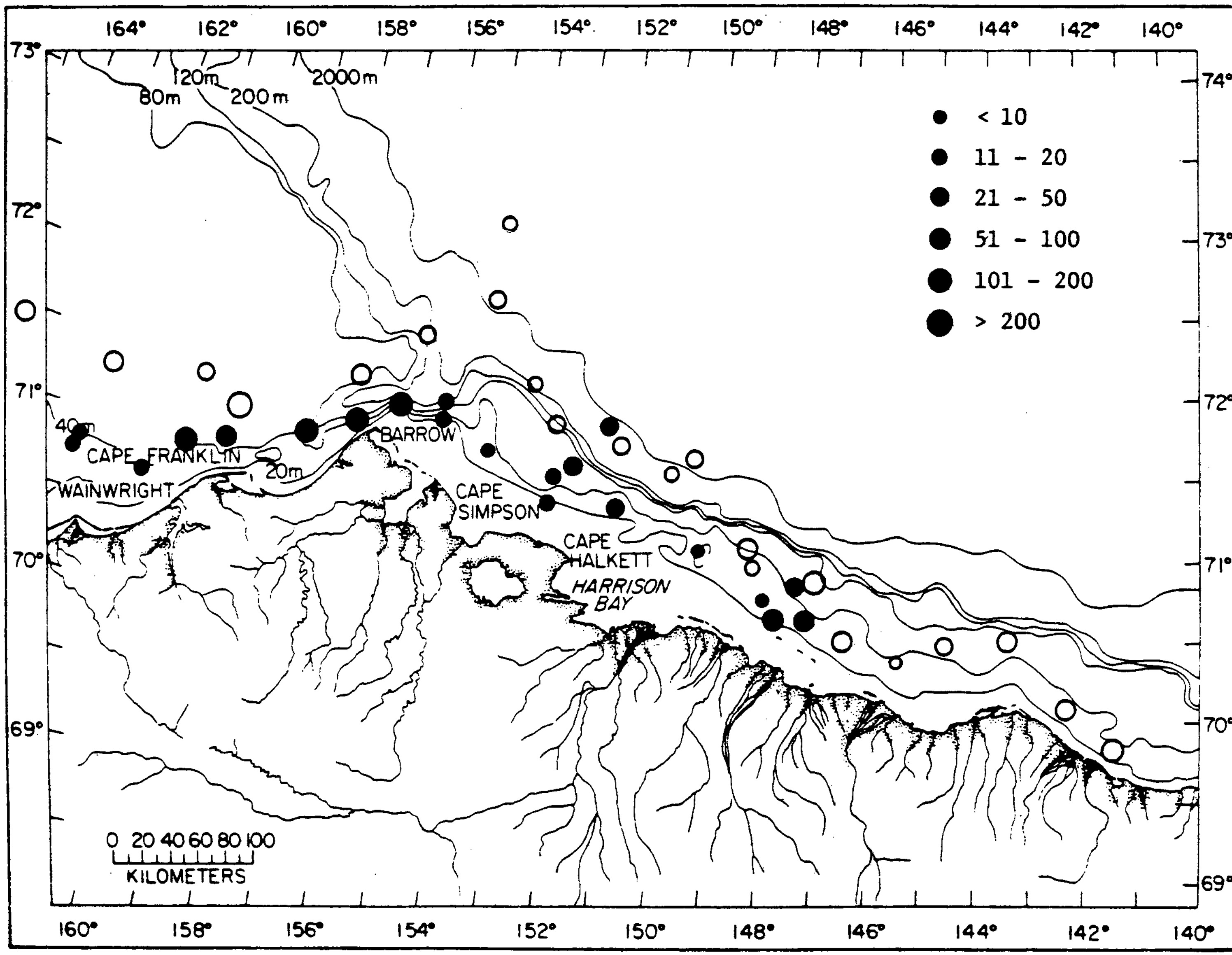

Fig. 6.1. Integrated ^{14}C assimilation (mg C m^{-2} hr^{-1}) for stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ● = 1976; ○ = 1977.

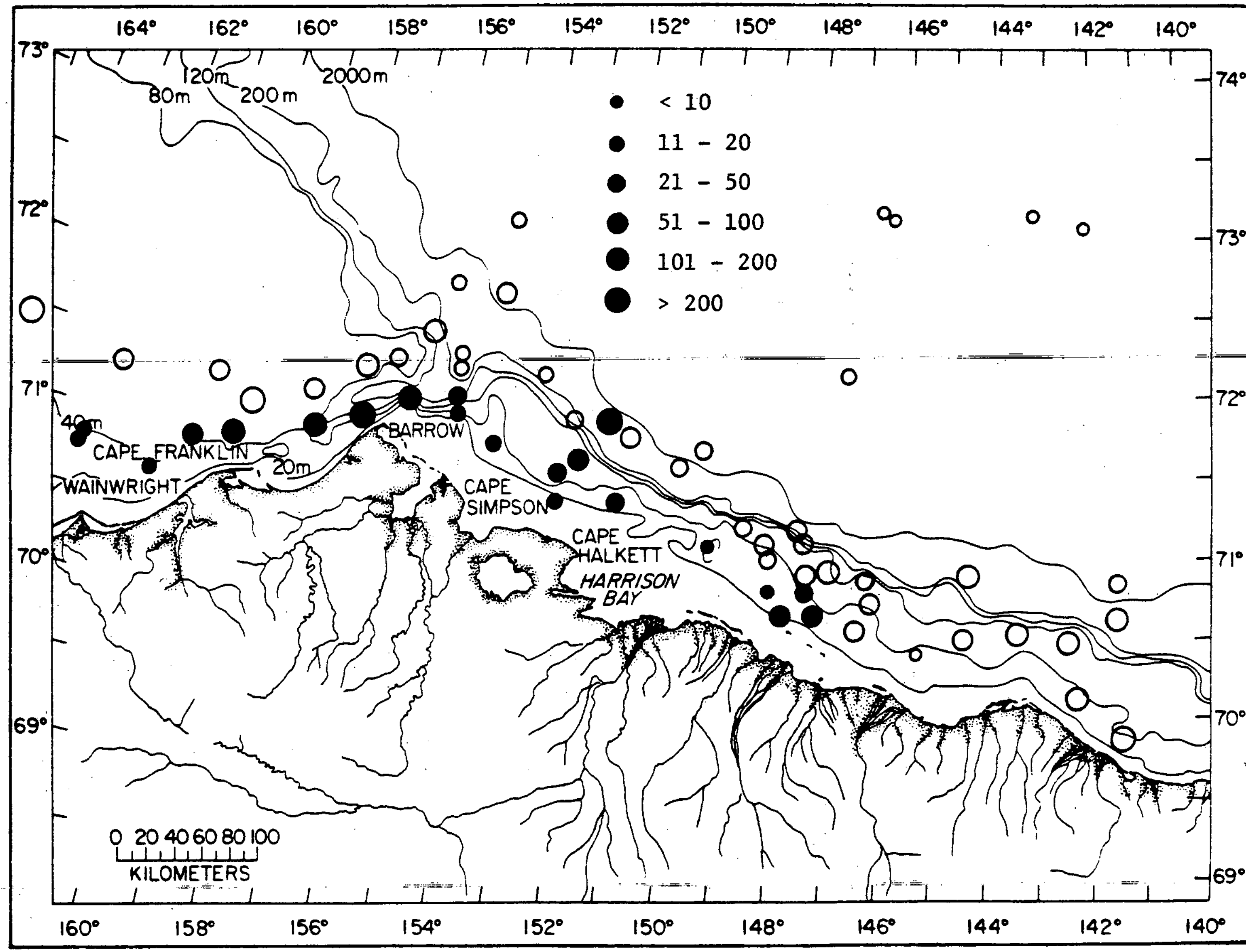

Fig. 6.2. Integrated chlorophyll a (mg m^{-2}) for stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ● = 1976; ○ = 1977.

3. species characteristically found in neritic, less saline environments;
4. species contributing meroplanktonic life history stages to the plankton.

The abundance, distribution, and diversity of these categories is primarily a reflection of hydrographic conditions resulting from the clockwise circulation of the Polar Basin gyre, wind-driven upwelling, and the easterly intrusion of warmer, more saline Bering Sea water.

The northward flow and easterly intrusion of Bering Sea water is not an unusual phenomenon in the western Beaufort Sea (Hufford 1973). Eastward extension of Bering Sea water in 1976 was indicated by the occurrence of the expatriate copepod species Calanus cristatus, and Eucalanus bungii bungii to 151° 47' W.

Copepod species usually more abundant in deeper water, including Calanus hyperboreus, Euchaeta glacialis, Metridia longa, and Microcalanus pygmaeus, were collected in 20-0 m net hauls and at stations near Prudhoe Bay. Many species that occur throughout the Arctic Basin were found in the inshore zooplankton, including the copepods Calanus glacialis, Oithona similis, euphausiids (Fig. 6.3), larvaceans, chaetognaths (Fig. 6.4), and arctic cod (Fig. 6.5). The distribution and abundance of these species is probably more affected by biological interactions, such as predation, food requirements, mortality and sinking rates, and reproductive rates, than by hydrography (Redburn 1974).

Meroplanktonic life history stages of barnacles, polychaetes, hydrozoans, gastropods, and echinoderms comprised the largest part of the zooplankton in the western Beaufort Sea. Johnson (1956) found maximum abundances of barnacle larvae northwest of Point Barrow with diminishing numbers toward the east, suggesting that a sizeable portion of the barnacle larvae in the western Beaufort Sea may be due to advection. In OCSEAP samples, large numbers of barnacle larvae occurred west of 151°W (Fig. 6.6)*.

Amphipods, represented here by Parathemisto spp., were collected at all stations (Fig. 6.7). Shrimp larvae, primarily of the family Hippolytidae, were caught at most stations (Fig. 6.8).

Sampling in 1976 was done with a 0.75 m ring net (mesh size 308 μm), which was lowered to 10-20 m and hauled vertically to the surface. Larger organisms, including amphipods and euphausiids, are difficult to catch with this kind of net, but ice conditions during much of the cruise made it impossible to tow the bongo nets which would have been more efficient in catching larger zooplankton. In 1977, zooplankton sampling was done with a bongo net (mesh size 505 μm). Differences in distribution and abundance between the two years may not be real, but an artifact caused by gear differences.

Conclusions

Based primarily on samples collected in 1976 and the Beaufort Sea literature, the following preliminary conclusions can be made:

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*Editor's note: Barnacles were found in the boulder field near Prudhoe Bay in FY 78 (Broad et al., RU #356).

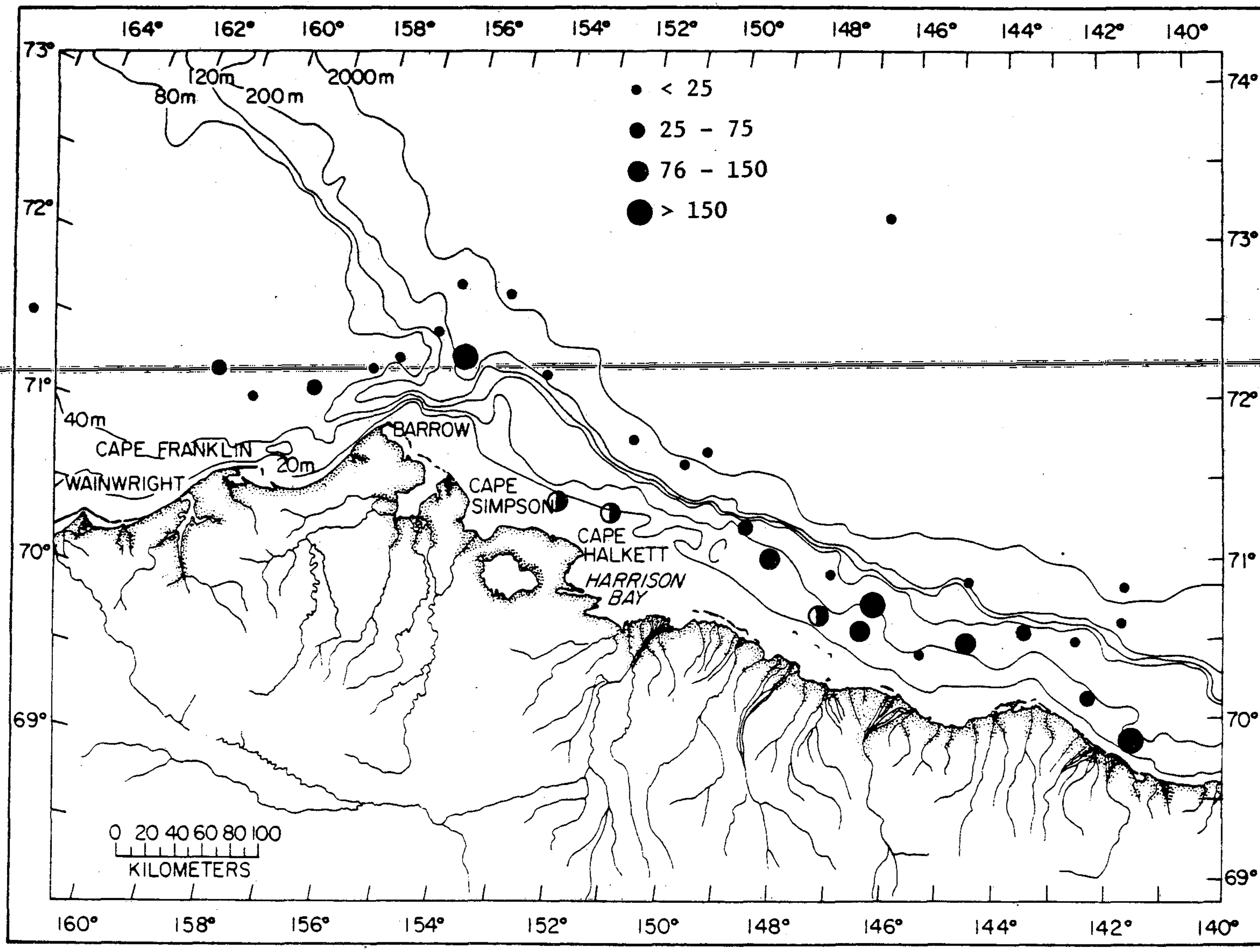


Fig. 6.3. Abundance (number per 1000 m^3) of *Thysanoëssa* spp. adults at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net, 10 - 0 m 1976; ◐ = ring net, 20 - 0 m 1976; ● = bongo net 1977.

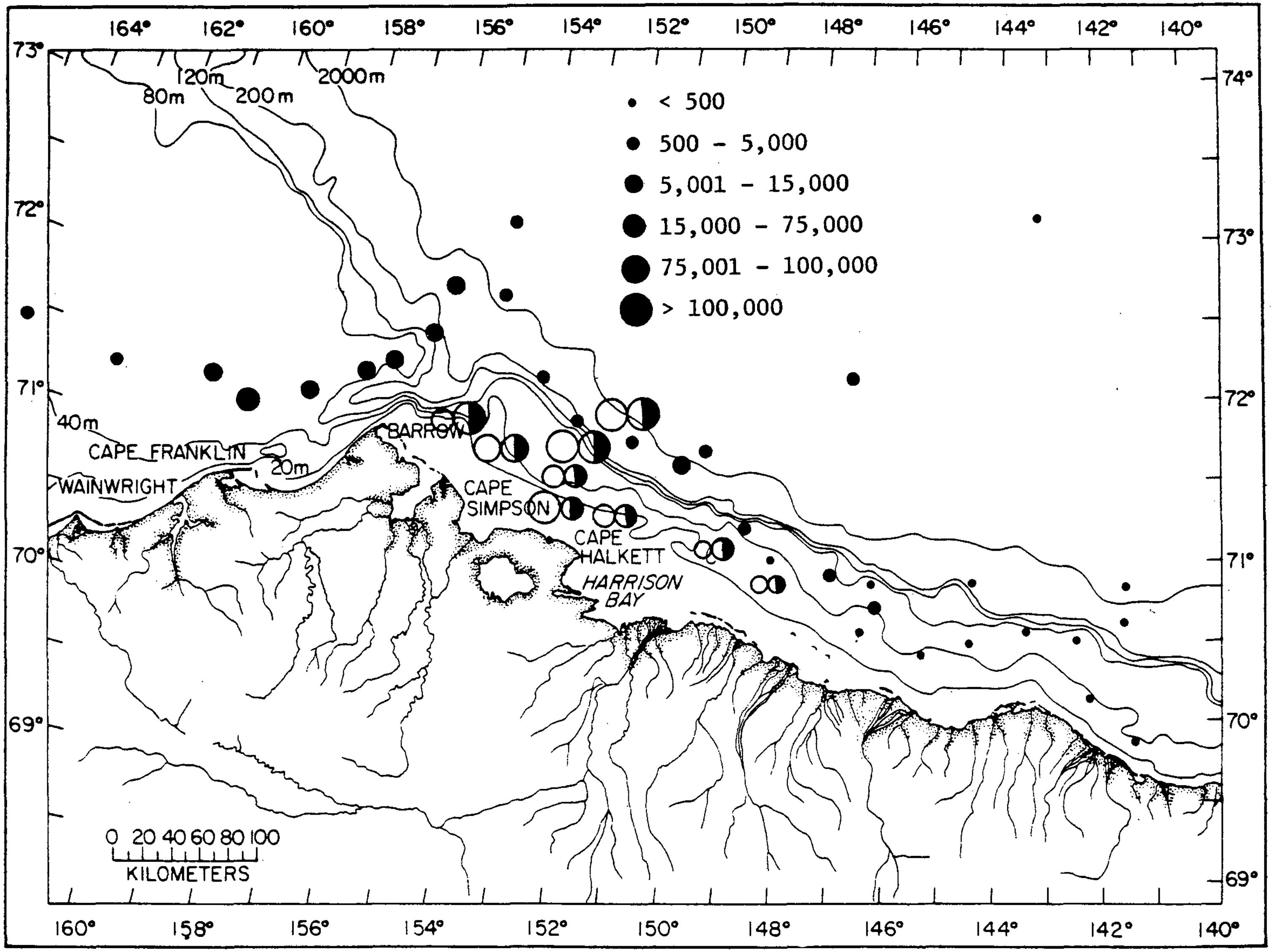


Fig. 6.4. Abundance (number per 1000 m^3) of *Sagitta elegans* at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net, 10 - 0 m 1976; ◑ = ring net, 20 - 0 m 1976; ● = bongo net 1977.

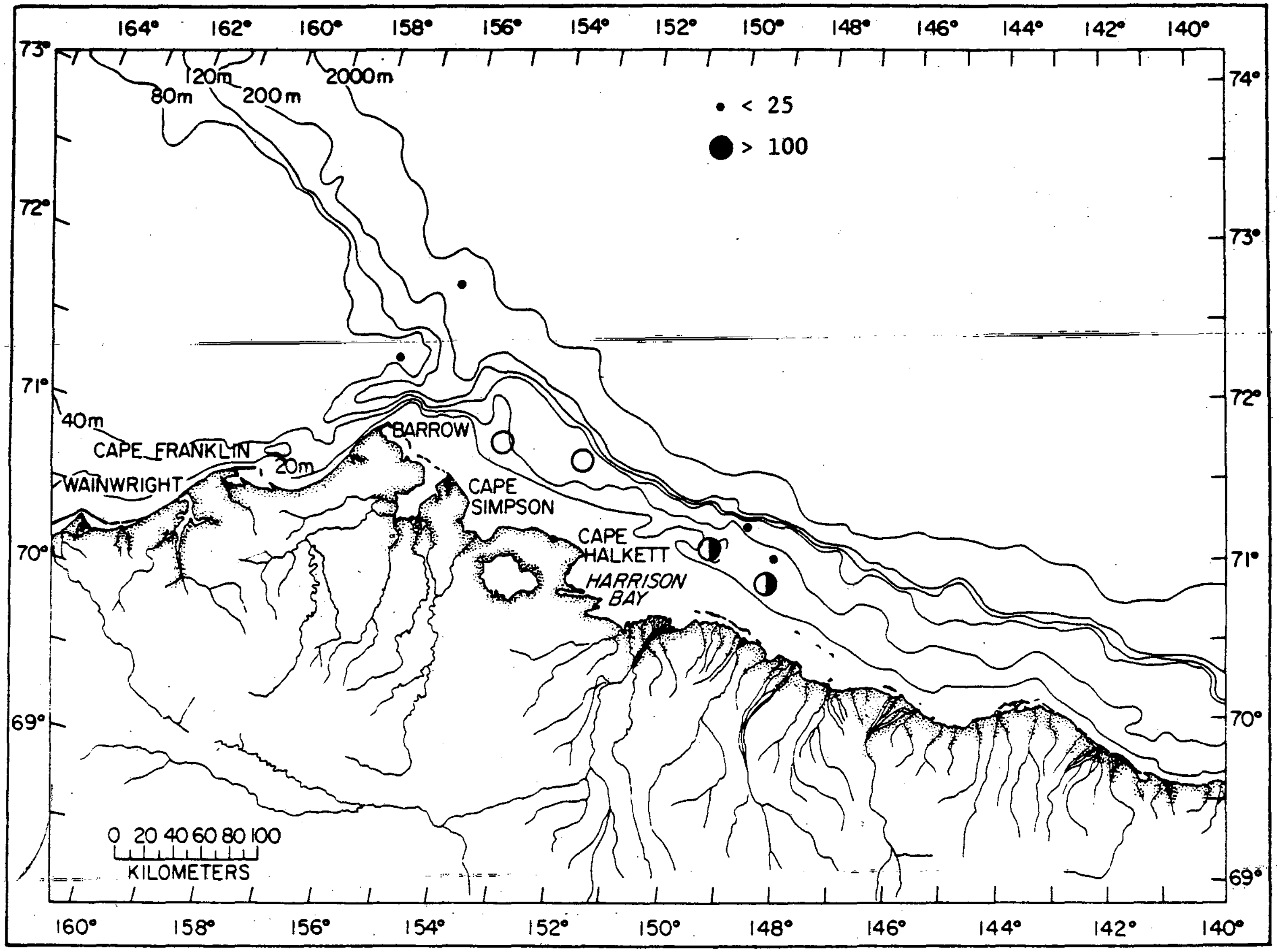


Fig. 6.5. Abundance (number per 1000 m^3) of *Boreogadus saida* at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net, 10 - 0 m 1976; ◐ = ring net, 20 - 0 m 1976; ● = bongo net 1977.

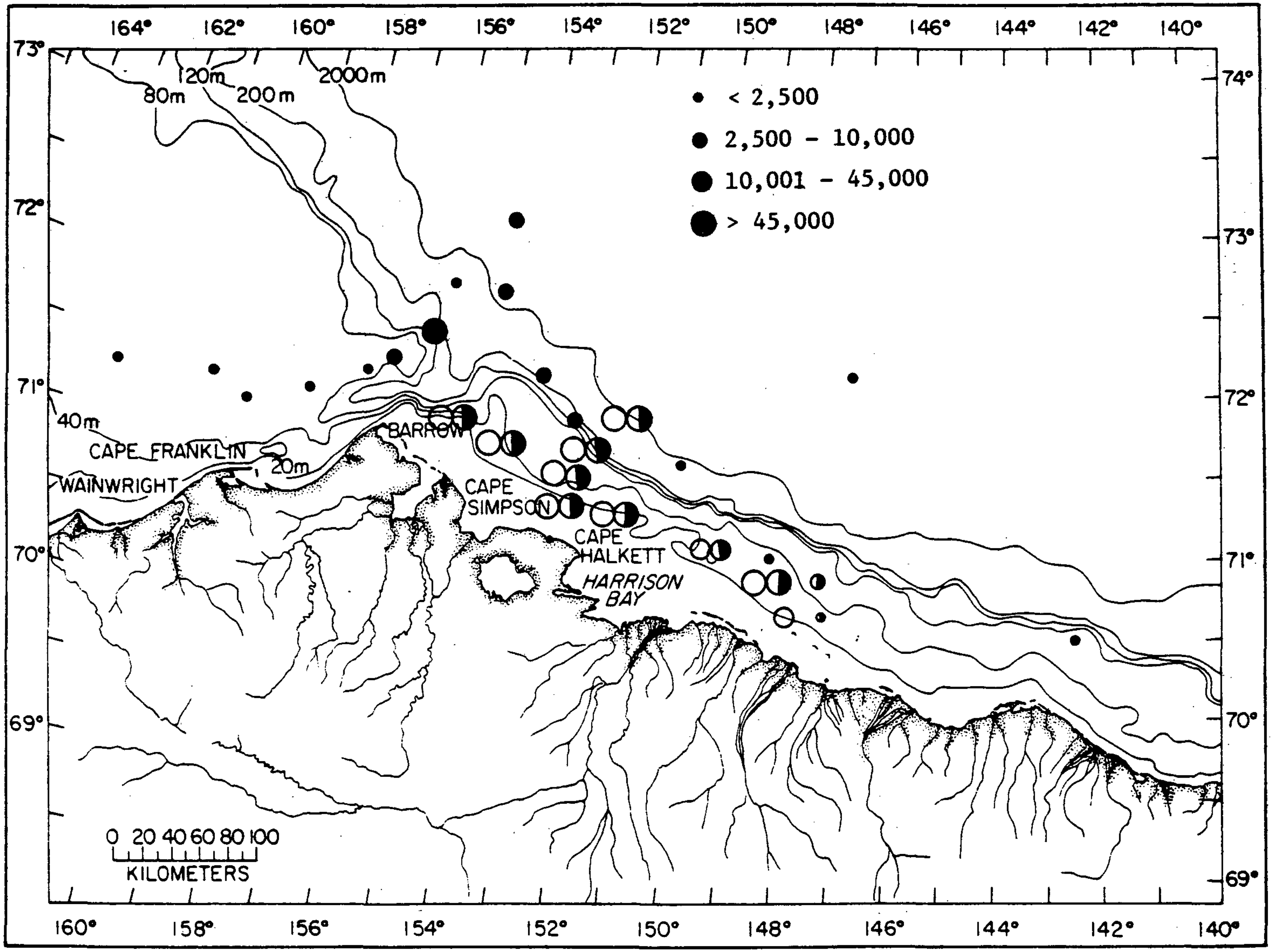


Fig. 6.6. Abundance (number per 1000 m^3) of barnacle larvae at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net, 10 - 0 m 1976; ◑ = ring net, 20 - 0 m 1976; ● = bongo net 1977.

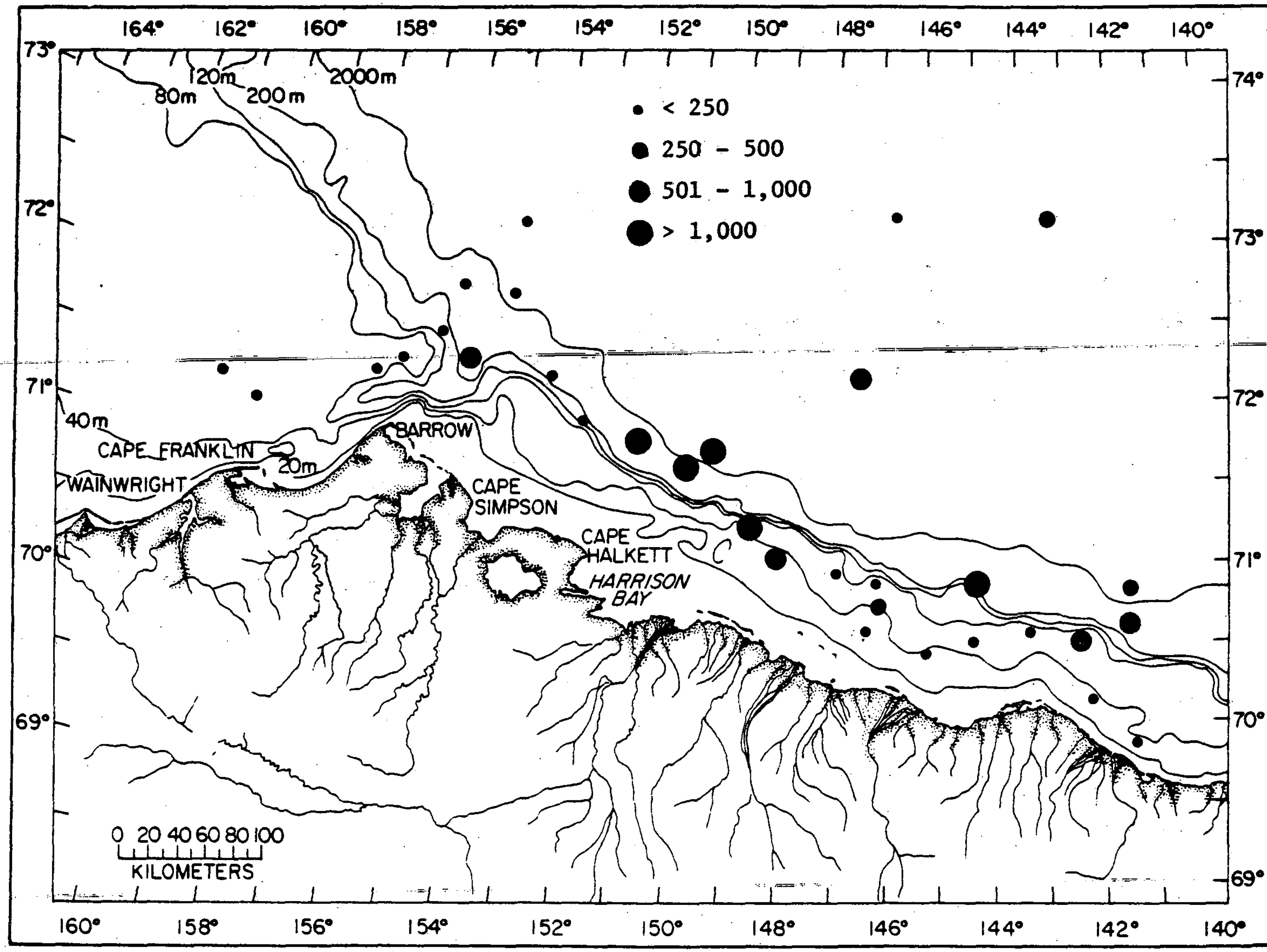


Fig. 6.7. Abundance (number per 1000 m^3) of *Parathemisto* spp. at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net, 10 - 0 m 1976; ◐ = ring net, 20 - 0 m 1976; ● = bongo net 1977.

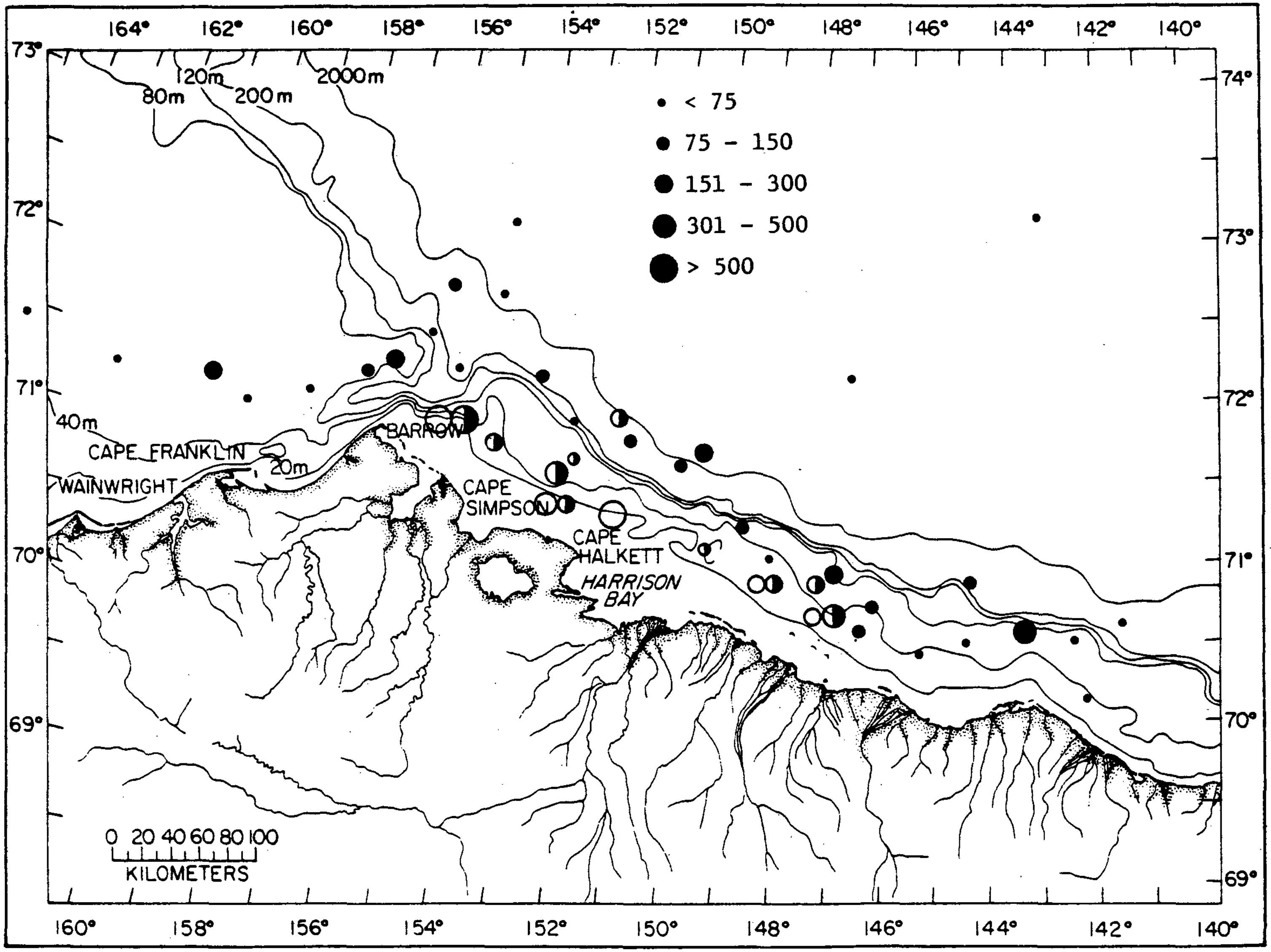


Fig. 6.8. Abundance (number per 1000 m^3) of shrimp at stations in the Chukchi and Beaufort seas, August-September 1976, 1977. ○ = ring net 10 - 0 m 1976; ◑ = ring net 20 - 0 m 1976; ● = bongo net 1977.

A. Phytoplankton

1. Individual phytoplankton species have widespread distributions in the nearshore Beaufort Sea, but standing stocks of phytoplankton are variable and patchy.

2. Some apparently expatriate species occur when Bering Sea water is found in the Beaufort Sea.

3. Primary production is variable and patchy, with highest production usually occurring between 5 and 20 m and where diatoms are the most abundant organisms.

B. Zooplankton

1. Zooplankton species can be grouped into four categories:

   a. Expatriates from the Bering and Chukchi Seas;
   b. Species occurring throughout the Arctic Basin;
   c. Species from less saline, nearshore areas;
   d. Species contributing meroplanktonic stages.

2. Distribution of some species or larval groups is patchy and is influenced by hydrography.

3. Expatriate species occur when Bering Sea water is found in the Beaufort Sea.

4. Meroplankton comprise a large part of the zooplankton in the western Beaufort Sea.

5. Species utilized as food by birds and mammals generally were not caught by our sampling gear in 1976. The presence of ice prevented use of horizontally-towed nets and larger, faster-moving species are able to avoid vertically hauled nets.

Present State of Knowledge

Table 6.2 summarizes the present state of our knowledge of the plankton, ice algae, and benthic microalgae for the Chukchi and Beaufort Seas.

Data Gaps and Needs for Further Study

Information currently available on the phytoplankton and zooplankton of the Beaufort Sea consists primarily of species distributions and abundances during the summer, usually August and early September, and usually west of Barter Island. Sampling was extended eastward to Demarcation Point during the 1977 OCSEAP summer cruise, but there is still no information for the Beaufort Sea during seasons other than summer.

Table 6.2 Present state of knowledge concerning Beaufort Sea Plankton (blanks indicate inadequate information).

Area	Phyto.[1]	Zoo.	Ichthyo.	Ice Algae[1]	Benthic Microalgae[1]
Chukchi Sea					
Icy Cape to Barrow, summer	adequate	adequate	some		
Annual cycle at Barrow	adequate	summer		adequate	adequate
Beaufort Sea					
Barrow to Prudhoe Bay, summer	adequate	some	some		
Prudhoe Bay to Demarcation Point	some	some	some		
Annual cycle at Prudhoe Bay	adequate				
Oliktok, lagoons	some				
Offshore	scattered	scattered			
Eastern Beaufort Sea					
Canada, Mackenzie area	spring, summer				

[1] These categories include standing stock, chlorophyll a concentrations, and primary production.

With the exception of the phytoplankton cycle in the nearshore water at Barrow, there is almost no information on year-to-year variability of plankton populations. The work of Connors (1978) has shown how extreme this variability can be in nearshore waters. Does it occur elsewhere as well?

There is very little information available on trophic dependencies. Some of the important food species for fish and mammals are amphipods, shrimps, euphausiids, and Arctic cod, but distribution patterns, life cycles, and food habits of these organisms generally are not known. No information is available on the vertical distribution of plankton species or on the vertical migrations of zooplankton species in the Beaufort Sea.

It is not known what role the ice algae play in the food web of the Beaufort Sea, although it has been suggested that this community lengthens the growing season by about two months (Horner, 1976). In addition, Schell (see section on Chemistry) has suggested that the ice algae not only serve as food for grazers, but also concentrate nutrients that will be released into the sediments or water column when the algal cells disintegrate, thus increasing the nutrient supply for benthic and planktonic organisms.

Critical species or groups of species have not been defined or identified. These critical species might be important food items, rare species that would be adversely affected by pollution or abundant species.

Little information is available on the effects of oil on plankton in the Arctic. Hsiao (1976) has shown that rates of primary production vary with type and concentration of oil, methods of preparation of oil-seawater mixtures, species composition of the plankton, and duration of exposure. Diatoms, especially, were inhibited by crude oils and mixtures of crude oils and Corexit® (a compound used in oil spill clean-up). Organic pollutants might also contribute to changes in the species composition of the phytoplankton, changing the population from one composed of diatoms to one composed of microflagellates (Fisher 1976, Lee and Takahashi, 1977). This change in structure of the phytoplankton community seriously affects other levels of the food chain. Some life cycle stages have been shown to be more sensitive to pollutants than other stages; in particular, larvae are often more susceptible than adults.

The role of terrestrial plant-derived detritus in the marine ecosystem is not known.

Recommendations for Further Research

Plankton distributions and abundances in the Beaufort Sea during seasons other than summer should be determined. For example, May and June (July), the time just before and during breakup, could be especially important in terms of food availability (ice algal bloom, spring phytoplankton bloom) and reproductive success of zooplankton.

More information is needed on year-to-year variability of plankton populations. This kind of information becomes available as more sampling is done. Can this variability be correlated with environmental factors? with reproductive strategies and life cycle stages?

Information is needed on the distribution patterns (horizontal and vertical), life cycles, and food habits of planktonic species that are the important food organisms for birds and mammals. More intensive zooplankton sampling, using a variety of gear, should be done in areas where seals are abundant, and after their stomach contents are examined. Some knowledge of the biology of the food organisms would help in selecting sampling gear to be used at a particular station.

The importance of ice algal production should be determined for nearshore and offshore areas. Do the ice algae provide significant amounts of food to the benthic community or to the planktonic community? What are the temporal and spatial distributions of the ice algae?

Information on larval fishes is lacking. Small larvae are difficult to identify with the literature currently available. Information on the distribution, abundance, and food habits of the larvae is necessary before decisions on fisheries management and environmental assessment objectives can be made.

BENTHOS

The sea floor organisms associated with the Beaufort Sea continental shelf and slope are generally abundant. Their distributions often can be correlated with aspects of their environment. Data on the large epibenthos associated with the sediment surface and the infauna living within the sediments have been separated for purposes of summarization. Size, relative abundance, position relative to the sediment-water interface and means of collection are used as criteria to separate these faunal groups. Often these classifications are arbitrary, as epifauna can be swimming pelagiobenthos or burrowing infauna depending on environmental factors such as current speed and mode of feeding. In addition, knowledge of the bottom fauna is covered in three ecological zones: (1) littoral or nearshore (<2 m depth) (2) coastal or inshore (5-20 m depth) and (3) offshore (>20 m depth).

The organisms living at the benthic boundary of the oceans comprise a diversified animal group - taxonomically and functionally. They consist of invertebrates spanning a very large size range living within, on, or associated with the sediments and hard substrates, and of demersal fishes that may or may not be predominantly tied to the benthic invertebrates as a food source. Most of the invertebrates are more or less restricted in their movement over and through the bottom substrate; motile organisms such as shrimps and crabs are exceptions. Organisms in this ecological group have distributions that are strongly correlated with environments of particular combinations of characteristics of substrate, bottom water, and food supply; many are highly correlated with depth.

Over the years, the benthos have been studied in the Beaufort Sea from the shoreline to the deep-sea. Though increasing efforts have been placed on this ecological group, only the bare outlines of faunal distributions and abundances are known. At the present time, their functional roles within the Beaufort Sea ecosystem can only be guessed at.

Literature Review

Except for a few early scattered samples collected in the 1880's, extensive sampling of the benthos in the Beaufort Sea did not begin until the early 1950's when MacGinitie began sampling from the Naval Arctic Research Laboratory at Barrow, Alaska (MacGinitie, 1955). This slow start in oceanographic research in the Beaufort Sea can be attributed to: lack of accessibility, lack of early commercial interest (e.g., fisheries), and scientific tradition (Curtis, 1975). Until the advent and availability of modern icebreakers, routine research in the area was not practicable because of the generally heavy sea ice conditions and the very short summer season of variable open water. The dominant factor behind the recent rapid expansion of oceanographic research, including benthic ecological research, has been the potential oil and gas production on the Beaufort Sea continental shelf.

The few early benthic samples in the Beaufort Sea were collected during the cruises of the YUKON (1880) and CORWIN (1884). Some benthic samples were also collected in the area during the International Polar Year Expedition to Point Barrow (1881-83) (Curtis, 1975).

Qualitative but fairly extensive benthic collections were obtained by MacGinitie (1955) during his tenure as director of the Naval Arctic Research Laboratory (NARL). The Naval camp at Point Barrow was established for early oil explorations in the 1940's, but later became the site of the Naval Arctic Research Laboratory, a development that made the Beaufort Sea more accessible for oceanographic research. MacGinitie's samples provide us with the first extensive benthic species lists and scattered natural history notes. The collection locations were mainly west of Point Barrow in the Chukchi Sea. NARL has been used as a base for isolated studies since that time (Mohr, 1969).

During the 1960's, benthic sampling was undertaken in the eastern Beaufort Sea by the Canadians aboard the Fisheries Research Board of Canada vessel, SALVELINUS. This field program was part of the Canadian investigations in the western Canadian Arctic during 1960-65 (Curtis 1975). Deepwater benthic collections by Menzies (1963) and Paul and Menzies (1974) were made in the northern sector of the Beaufort from U.S. ice stations Bravo and T-3 as they drifted through the region.

The 1970's has been a period of rapid development in Beaufort Sea oceanographic investigations, especially in benthic ecology and systematics. The development of oil and gas fields on United States and Canadian coastal lands stimulated scientific investigations of the environment, biota, and ecosystem. Offshore explorations of potentially large oil and gas fields underneath the continental shelf have directly stimulated marine research. The Canadian oceanographic vessel HUDSON obtained quantitative benthic samples from the Beaufort Sea in 1970. The U.S. Coast Guard sponsored a series of ecological baseline cruises (WEBSEC) to the area soon after the discovery of the extensive oil and gas fields on the Alaskan North Slope. Benthic sampling and photography was undertaken by Carey in 1971-72 (Carey et al., 1974; Carey and Ruff, 1977).

Extensive environmental research programs were initiated by the Canadians in the southeastern Beaufort Sea and by the United States in the southwestern sector. The Canadian quantitative benthic sampling concerned the Mackenzie River delta region, the Eskimo Lakes, and much of the Southeastern continental shelf (Wacasey et al., 1977).

Wacasey (1974a, 1974b, 1975) and Wacasey et al. (1977) reported that the diversity and biomass of the benthic infauna in the southeastern Beaufort Sea increased with depth and distance away from the Mackenzie River delta between depths of 3 and 94 m. The number of species ranged from 1-51; the numerical density was from 52-12,444/m^2 and the biomass from 0.1-67.7 g(dry wt)/m^2. Seventeen stations were occupied between Cape Dalhousie and Herschel Island during July 1973.

The Mackenzie River outflow significantly influences the surrounding area, creating estuarine conditions down to 15 meters depth. The freshwater dilution, however, is more marked to the east near Tuktoyaktuk Peninsula. Salinities at the stations ranged from 0.0 o/oo at 3 m depth to 32.8 o/oo at 42 m depth.

Sixteen additional stations have subsequently been sampled by Wacasey on the southeastern Beaufort shelf. The Eskimo Lakes to the east of Tuktoyaktuk Peninsula have also been sampled and preliminary data reported (Wacasey 1974a).

In the western segment of the Beaufort Sea, the maximum macro-infaunal biomass is at 140 m depth on the upper continental slope (Carey et al., 1974). The maximum numerical density, however, occurs at a depth of 700 m; this is considerably deeper than the numerical maxima found in more temperate waters. The standing stocks of inshore fauna at depths of 20 m are depressed in numbers and biomass, perhaps implicating ice scour as a major environmental disturbance (Carey and Ruff, 1977).

The numerical densities of the western Beaufort Sea macrofauna are similar to those from temperate waters, but the biomass reaches higher levels in the Beaufort. The benthic environment near the Mackenzie River, but deep enough (> 33 m) to be below the effect of freshwater dilution, supports considerably larger amounts of benthos than at similar depths in the western portion.

The diverse benthic community data have been summarized in terms of general bio-indices, and these have been evaluated for trends along environmental gradients on the continental shelf and slope. Faunal abundance, diversity, feeding types, and species composition have been reviewed, and where possible, these have been summarized on charts. Sources of data include the work of Broad, Carey, Craig, Feder, and Frost. Readers are referred to the 1977 OCSEAP Annual Reports by these researchers summarizing much of the known literature and data of the Beaufort Sea benthos. Wacasey et al. (1977) have summarized benthic data from the Eastern Beaufort Sea.

The present benthic ecological studies on the continental shelf under sponsorship of OCSEAP include functional, process-oriented research that is built on a strong base of descriptive work on ecological patterns and their relationship to the environment. Seasonal changes in the numerical abundance and biomass of the large macro-infauna (>1.0 mm) are defined at stations across the shelf. The benthic food web and its relationship to bird, fish and mammalian predators are under investigation.

Benthos: Nearshore Environment (0-2 m depth)

In the nearshore environment of Simpson Lagoon, key groups of epibenthic invertebrates and zooplankton include amphipods, mysids, isopods and copepods (Griffiths et al., 1975, 1977; Griffiths and Craig, 1978).

Collectively, these taxonomic groups dominate the invertebrate composition of nearshore environments, though the relative abundance of each group is highly variable from year-to-year. The numerical success of epibenthos in shallow-water environments, compared to the more sessile infaunal species, can be attributed to their mobile life style which allows them to annually re-colonize nearshore areas which freeze solid each winter.

Epibenthos and zooplankton are important links in the transfer of energy from lower to higher levels in the nearshore environment. Detritus, which covers much of the nearshore bottom, may furnish food for most epibenthic invertebrates either directly or indirectly (i.e., it is not yet known whether epibenthos digest the detritus or the organisms living on the detritus). The epibenthos, in turn, provide food for most vertebrate predators in the nearshore system. For example, in Simpson Lagoon (Johnson, 1978; Craig and Griffiths, 1978) epibenthic invertebrates were by far the most important food item in diets of key fish species (Arctic cisco, least cisco, Arctic char, fourhorn sculpin, Arctic [illegible]) and bird species (Oldsquaw, Glaucous gulls, phalaropes). Other studies document a similar utilization of epibenthos by fish (e.g., Kendel et al., 1975; Bendock, 1977). However, birds near Elson Lagoon may differ from the above pattern in that they feed on zooplankton from Bering Sea currents rather than lagoon epibenthos (G. Divoky, pers. comm.).

One reason for the trophic importance of epibenthos is that these invertebrates may be far more common than indicated by traditional sampling gear (i.e., epibenthic trawls). In Simpson Lagoon SCUBA divers estimated that epibenthos densities were approximately 10^2-10^3 times greater than estimates obtained by an otter trawl with a 6.4 mm mesh liner (Griffiths and Craig, 1978) or by an epibenthic trawl with 2.8 mm mesh (Crane and Cooney, 1975). Smaller mesh trawls may also underestimate epibenthos densities since divers observed an avoidance behavior of some epibenthic invertebrates.

The nearshore or littoral infauna in other areas of the western Beaufort Sea has been sampled in 1975 and 1976 with pole-mounted Ekman grabs (0.023 m^2) and, to a lesser extent in 1976, with the 0.1 m^2 Smith-McIntyre grab (Broad, 1977). Fifteen species have been abundant at one or more of the 57 sampling stations, but only five of these were encountered often enough to be considered principal species. The most frequently found animal of the very shallow water is an unknown species (or more than one species) of oligochaete worm of the family Enchytraeidae. The other principal species found in littoral benthic samples are the amphipods, Gammarus setosa and Onisimus litoralis, the isopod, Saduria entomon, and midge larvae (Diptera) of the family Chironomidae. Gammarus, Onisimus and Saduria are actually epibenthic, motile organisms also abundant in epibenthic dredge samples. The enchytraeid worms and chironomid larvae have not been found in deeper water.

The nearshore littoral infauna may be characterized as poor in species (3-29 per station; 7.3 average ± 4.1); poor in biomass (0.1-21.9 g/m^2; 3.1 average ± 4.9); and lacking diversity (Shannon-Weaver indices of 0.000-2.311; average 0.909 ± 0.522).

Epibenthic sampling was done with a sea sled net or dredge towed along the bottom. The mouth of this net is 30.5 cm in diameter and roughly semi-circular. The bag is 1 mm nylon mesh. Data were standardized for a 50 m tow. Biomass data obtained with the epibenthic dredge should not be compared to those obtained with Ekman or Smith-McIntyre grabs because of different efficiencies of gear. Also, different sampling locations may explain the differences between this data set and results shown earlier.

The nearshore epibenthic fauna includes 15 species that are relatively abundant and five that have high enough frequency and numerical abundance to be considered principal species. These are Mysis relicta (by far the most abundant in number), the four-horned sculpin, Myoxocephalus quadricornis, and Gammarus setosa, Onisimus litoralis, and Saduria entomon.

The epibenthos of the littoral zone included from 0-42 species per station (10.0 average ± 6.6). Biomass is low and may reflect the efficiency of the net more than the abundance of animals (0.0-34.1 g/tow; average 4.9 ± 7.0). Species diversity was also low (H of 0.000 -2.133; average ± 0.566). In sharp contrast to these numerical data are the estimates of abundance made by SCUBA divers in Simpson Lagoon (see above).

The nearshore zone of the Beaufort Sea functions as a migration and feeding area for fish. The principal invertebrate species of this region are important fish food.

Benthos: Inshore Environment (2-20 m depth)

In the inshore (2-20 m depth) region, the benthos is strikingly different from the nearshore, and this change probably is associated with the thickness of the shorefast ice. The inner part of this region (> 2 m to 5 m) was sampled in 1976 with the 0.1 m^2 Smith-McIntyre grab (Smith and McIntyre, 1954) and to a lesser extent with the Ekman grab in 1975. Twenty-nine species have been abundant at one or more of the 15 stations sampled. Eleven of these are principal species and include: polychaete worms, Scolecolepides arctius, Ampharete vega, Prionospio cirrifera, and Terrebellides stroemi; the amphipods, Gammarus setosa, Onisimus litoralis, and Calliopus laeviusculus; the isopod, Saduria entomon; two bivalve mollusks, Cyrtodaria kurriana and Liocyma fluctuosa; and the priapulid, Halicryptus spinulosus. Saduria, Gammarus and Onismimus are also principal genera of the littoral zone and of the epibenthos.

The inshore benthos has from 9-43 species per station (23.1 average ± 9.2) and roughly ten times the biomass of the littoral zone (1.0 to 160.6 g/m^2; 30.6 average ± 39.4). The diversity indices of inshore benthos stations are also higher than those in the littoral zone (H of 1.570-2.551; 1.895 average ± 0.244).

The inshore zone is inhabited by many infaunal (animals that live in the bottom sediments) species that are not abundant in the nearshore zone, and the abundant, infaunal oligochaete worms and midge larvae of the littoral are not found (or are quite rare) in the inshore zone. The biomass data from the inshore zone are comparable to those from the inner part of the offshore zone. There is an increase in biomass and species diversity of benthic animals with depth on the inner shelf of the Beaufort Sea.

The coastal large macro-infauna (> 1.0 mm) are generally more abundant inshore at 5 or 10 m depth (Fig. 6.9). Polychaete worms (Carey, 1978) comprise 70-85% of the total infauna in this zone. Biomass, by contrast, does not peak with density indicating that these organisms are small in size on the average (Fig. 6.10).

The minimum numerical abundance zone at 15-25 m depth coincides with the sea ice shear zone between the landfast ice and the polar pack moving in the Beaufort gyral circulation (Barnes and Reimnitz, 1975; Reimnitz and Barnes, 1975). However, studies of the effects of ice gouging on the benthic community are necessary before causality is assigned to this physical phenomenon.

When a grab sample contains a high concentration of peat, it often has a large number of organisms associated with it. It is contended that

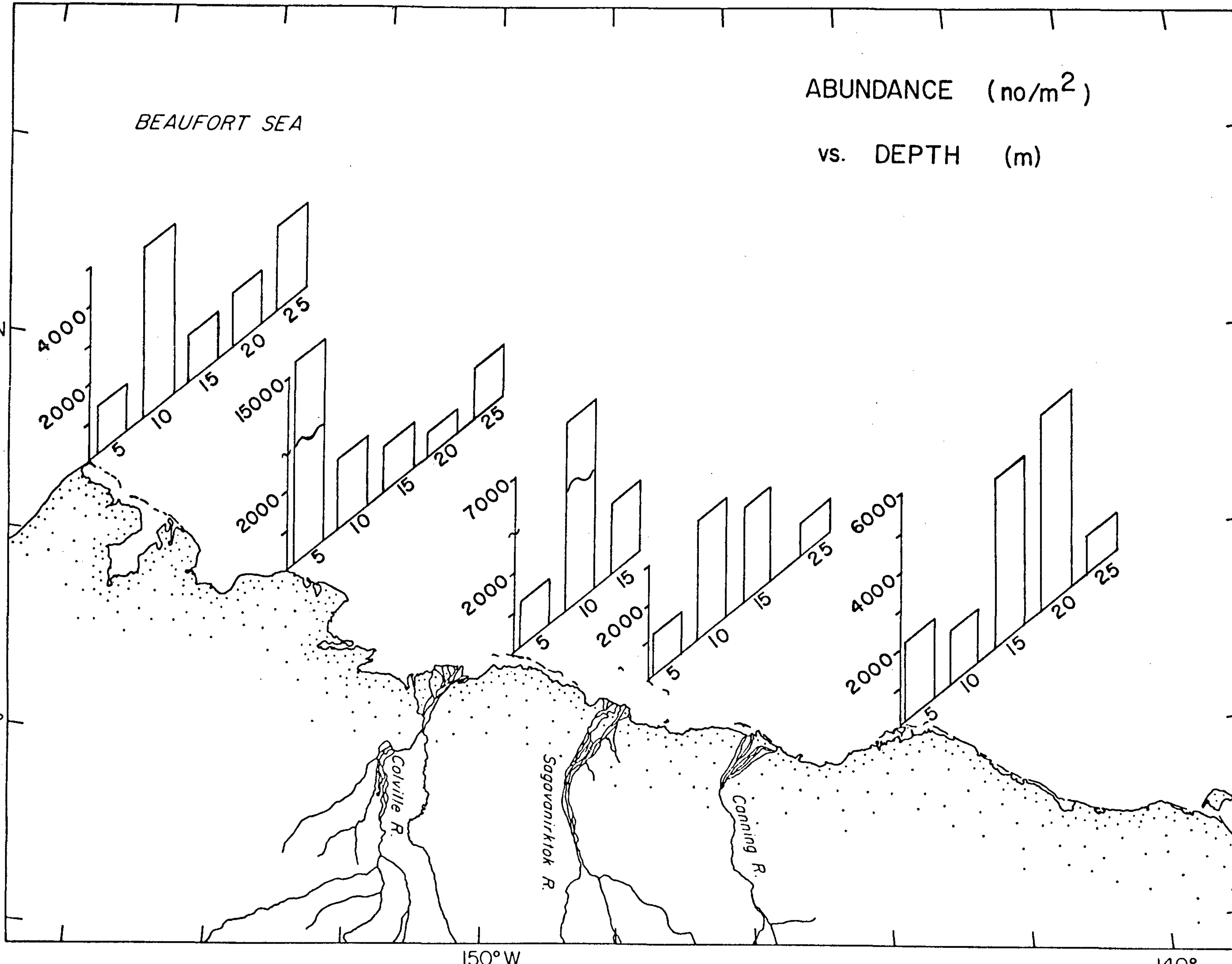


Figure 6.9 Numerical density of coastal infauna (> 1.0 mm) collected during 1976 R/V ALUMIAK cruise.

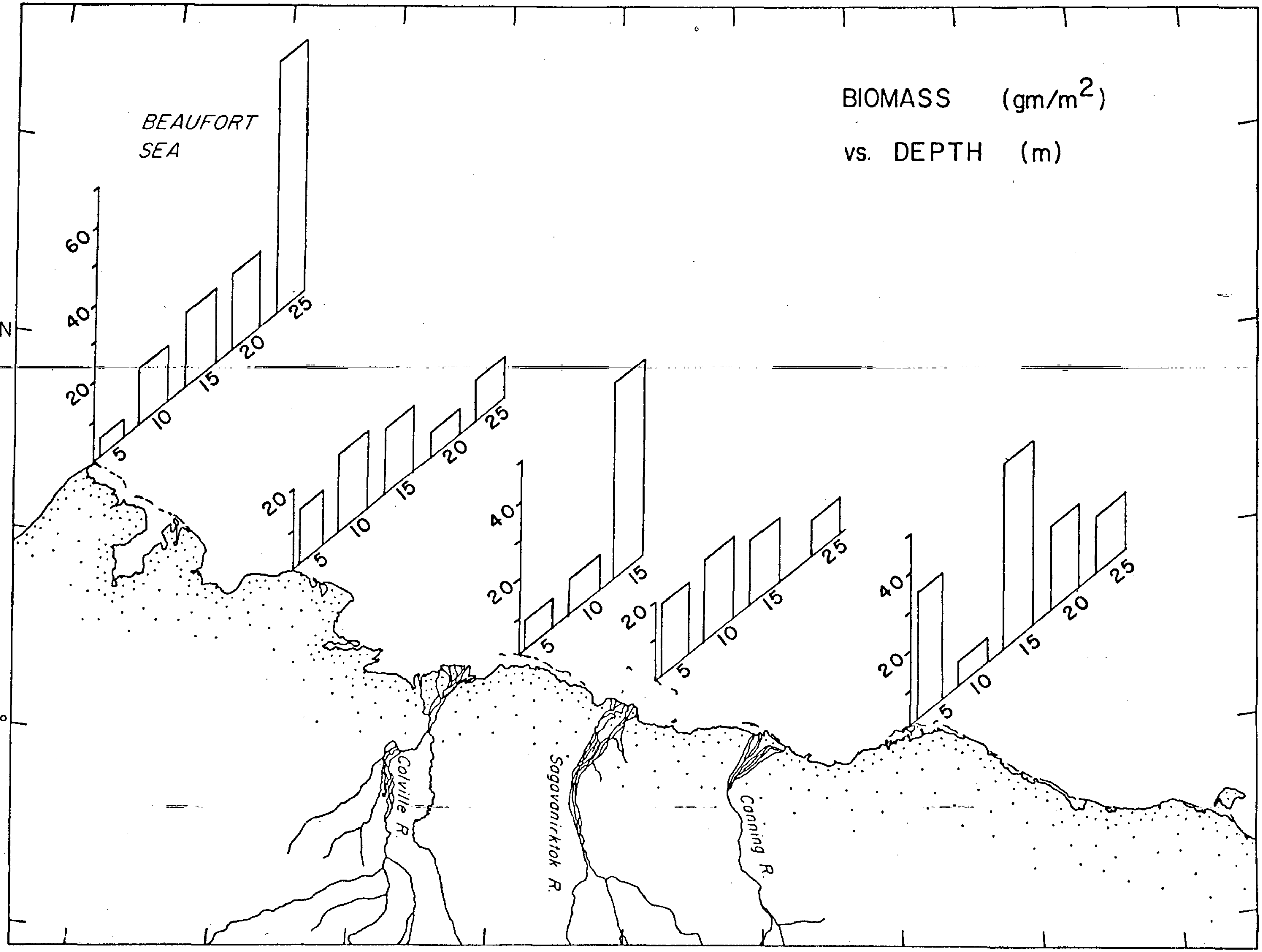


Figure 6.10 Biomass of soft-bodied infauna (> 1.0 mm) collected during 1976 R/V ALUMIAK cruise.

the peat acts as a source of detritus and organic materials for the benthic food web, probably indirectly through the bacterial-fungal and meiofaunal food web.

The range and variability of the biomass for the large macro-infauna (> 1.0 mm) across the continental shelf off Pitt Point are similar to the remainder of the southwestern Beaufort Sea observed from grab samples taken in 1971. The numerical density on the Pitt Point Transect has a much greater variability; the observed temporal variations are probably the cause for this greater range.

The data now at hand on epibenthic animals or epifauna (animals that live on or near the surface of the sea floor) do not show a discontinuity between the fauna of the nearshore and inshore zones. That the available data do not include as principal species some of those invertebrates previously identified by OCSEAP a "critical" (Thysanoessa sp., Parathemisto sp.), probably indicates that the present sampling regime is centered too near the bottom. Our data imply that enchytreid worms, chironomid larvae, Gammarus setosa, Onisimus litoralis, Saduria entomon, Myoxocephalus quadricornis, Scolecolepides arctius, Ampharete vega, Prionospio cirrifera, Terrebellides stroemi, Cyrtodaria kurriana, and Liocyma fluctuosa probably should be added to the critical species list.

Benthos: Offshore Environment (> 20 meters depth)

Infauna

1. Numerical Density

The numbers of benthos collected by quantitative grab samplers are summarized for the whole of the offshore Beaufort Sea shelf (Fig. 6.11); however, the data from the southwestern and southeastern segments should be considered separately, because different screen sizes were used during the processing of the samples. Neverthless, trends in the abundance of the fauna can be demonstrated in both regions.

In the southwestern Beaufort Sea greater numbers of organisms per unit area are found on the outer shelf and the upper continental slope from Cape Halkett eastward to Barter Island, though the inshore maximum in the Barter Island region indicates that this is a different ecological environment. Along the shoreline of the mainland and barrier islands and in the shallow sublittoral zone to a depth of 1 m, few benthic organisms exist. The fauna increases in abundance from an almost depauperate littoral zone to a more abundant fauna beyond the 1 m isobath. The broad distribution of shallow invertebrate species along the alaskan coast indicates that widely dispersed stock is available for the immediate repopulation of ice- and salinity-stressed areas.

To the east in Canadian waters the numerical density of benthos is probably higher than in the southwestern Beaufort Sea because Wacasey et al. (1977) processed the grab samples through a smaller aperture sieve, and the smaller organisms can be very abundant. However, the general pattern of faunal abundance demonstrates high numbers of benthos in:

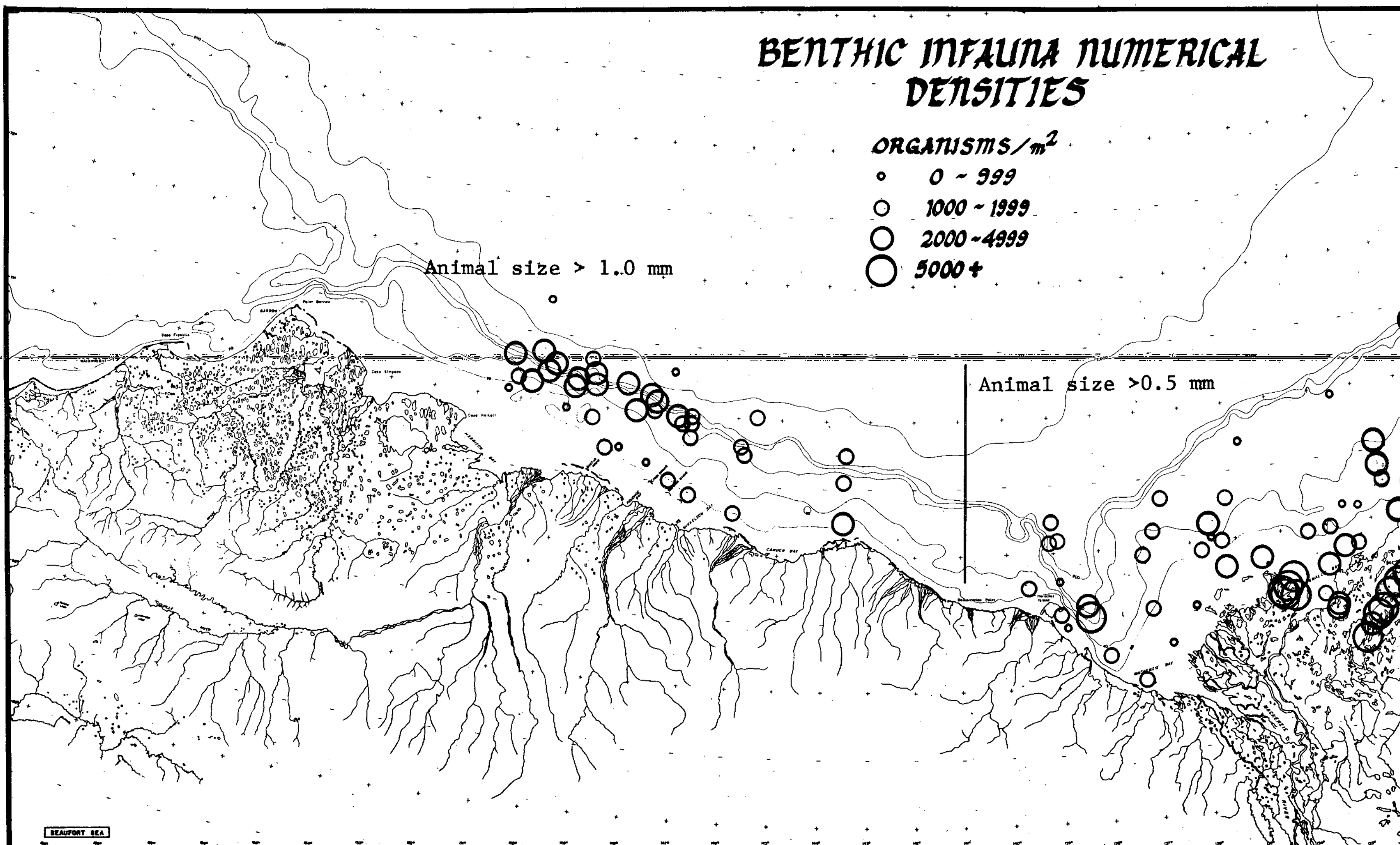


Figure 6.11 Benthic Infauna Numerical Densities

(1) the Mackenzie Trough, which acts as a source of higher salinity water close inshore, and possibly as a trap for particulate material; (2) inshore in the northwestern delta and in the protected Eskimo Lakes region; and (3) offshore near the edge of the continental shelf to the northeast of the Mackenzie River delta. Presumably, the northeastern flow of the Mackenzie River plume transports detrital organic material to the bottom fauna in these areas, and possibly the benthic community is responding to the more stable conditions in the protected waters of the delta and Eskimo Lakes.

The results from different projects generally demonstrate that the inshore fauna from the shoreline to depths of about 25 m are low in number, probably caused by the seasonal environmental stress of highly fluctuating salinities and by the intense ice-gouging of the sea floor to water depths of 30-40 m. Maximum numbers of animals are at the shelf edge. Beyond the upper continental slope the numerical density of the benthic infauna decreases rapidly with depth. These levels are comparable with other arctic and subarctic regions.

2. Biomass

Similar trends can be defined in the biomass data for the Beaufort Sea, as with the numerical density, though the trends appear to be more clearly defined. Generally, the standing stock of benthic infaunal invertebrates is low inshore and increases offshore across the continental slope. Beyond about 700 m depth the biomass decreases with depth to very low values. The coastal lagoon and shallow subtidal environment also support very low standing stocks.

The region northeast of the Colville River and north of Barter Island are two ecologically aberrant areas that can only be explained by further sampling and data analysis including correlations with physical characteristics of the environment. In these two areas, the standing stock maximum is fairly close to shore in shallower water. Perhaps the Colville River exports a significant amount of detrital material during ice break-up and the Barter Island region is a focal point for coastal upwelling under the proper open water and wind conditions during certain summers.

Though the benthic standing stock data in terms of weight of organisms per unit area can be summarized for the Beaufort Sea (Fig. 6.12). Once again a mismatch of data sets should be noted between the eastern and western portions of the Beaufort. Though screen size has much less effect on this bio-index, the Canadian data are reported in terms of dry weight per unit area versus wet-preserved weight per unit area. An average conversion factor of about 20% (wet to dry weight) converts the three data sets into comparable units. The outer continental shelf to the northeast of the Mackenzie River delta and the inner protected bays of the Eskimo Lakes are the regions supporting the highest benthic infaunal standing stocks.

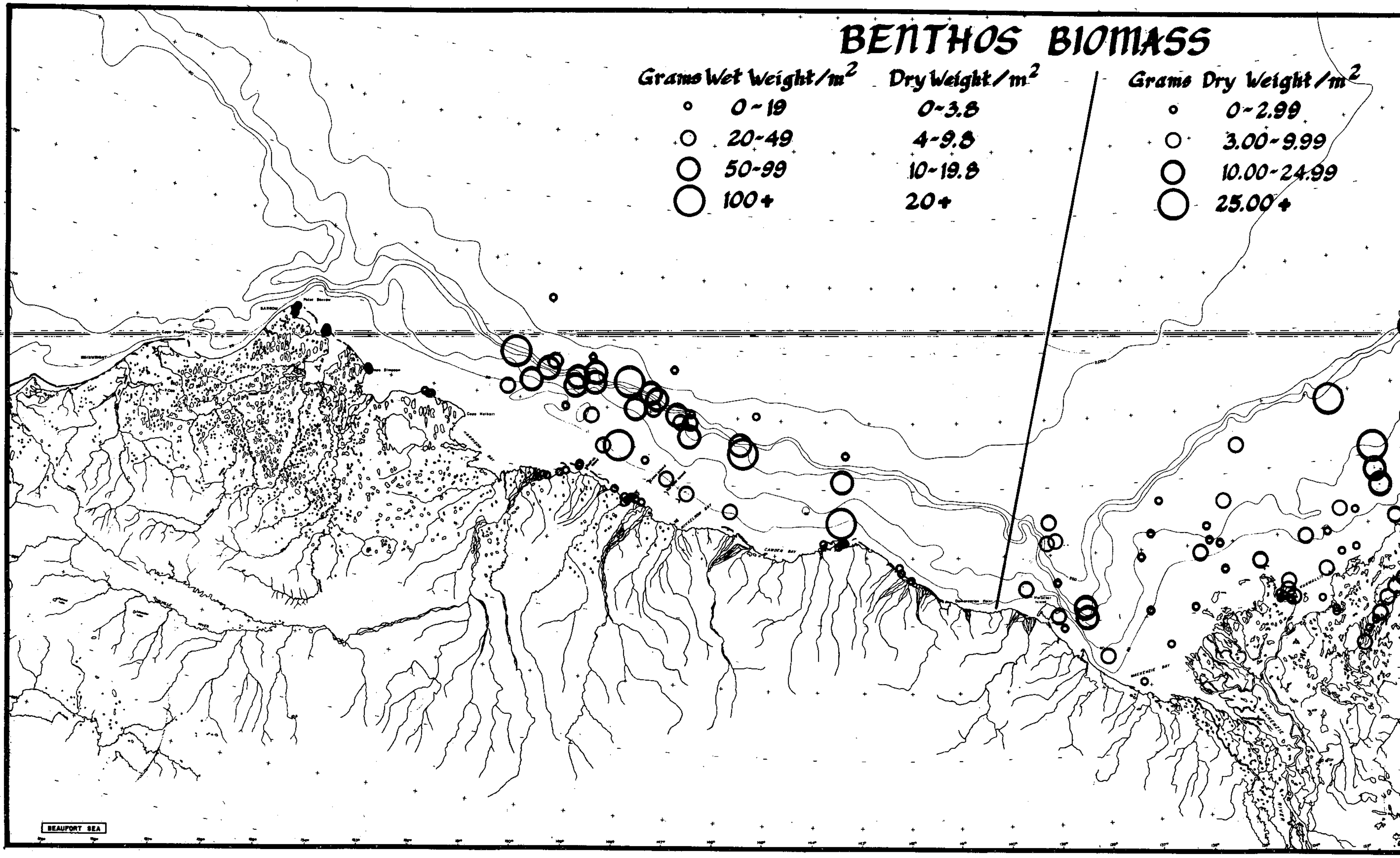


Figure 6.12 Benthic Biomass

3. Diversity and Feeding Types

Fewer species of benthic organisms live in the extreme environment of the coastal zone that is subjected seasonally to intense salinity stress and to sea ice impingement and gouging. For example, there are fewer species of gammarid amphipods living in the coastal region, while there are many species in offshore waters (Fig. 6.13). This is a general relationship reported for low salinity, estuarine environments elsewhere. The fauna of the Barrow region appear to be slightly less diverse than in the nearshore areas further to the east.

The concentration of ophiuroids (brittle stars) along the northwestern continental shelf edge (Fig. 6.14) is correlated with a region of sediment deposition. These organisms are probably detritus-deposit feeding animals that survive best in this area of sedimentations and presumed organic input to the benthic boundary. This is also an area that is affected by the Bering Sea-Chukchi Sea water mass intrusion into the Beaufort Sea (see section on Physical Oceanography).

4. Temporal variability of benthic infauna across the continental shelf on the Pitt Point Transect

Large standing stocks of macro-infauna, equivalent to those of many temperate environments, have been found across much of the Beaufort Sea continental shelf off the Alaskan north coast (Carey et al., 1974; Carey and Ruff, 1977). It has been generally assumed that this arctic environment, in contrast to analagous regions in the shallow Chukchi Sea to the west and in the Antarctic, supports a very low energy ecosystem. Low standing stocks and production rates have been recorded previously in the Beaufort Sea for both phytoplankton and zooplankton (Dunbar, 1968; English, 1961; Hsiao, 1976). The large populations of benthic invertebrates encountered on the shelf were, therefore, expected by us to exhibit low biological activity and to be in energetic equilibrium with the low inputs of nutritive material (Carey and Ruff, 1977). It was anticipated that the biomass and total numerical abundance of the benthic community would not vary signficantly throughout the year.

Based on the amplitude and temporal pattern of total numerical abundance the benthic communities along the Pitt Point line can be classified into an inner- and outer-shelf group. This abundance index varies within narrow limits at the innermost stations while it exhibits a broader range with distinct maxima and increasing statistical significance for seasonality at the three deepest stations. Since the shallowest station lies within the active ice gouging zone, this inner-shelf community could be adapted to episodic destruction and could be characterized by the presence of opportunistic species with asynchronous reproductive cycles that are not closely coupled to the other biological cycles around them. It is suggested that the reproductive capacity of animals at the shallow station is influenced by the physical disturbances and that at the deeper stations it is accommodated to a seasonal food input. The benthic community at PPB-40 at the outer edge of the ice gouging zone is a transitional environment and could be expected to comprise a spectrum of species with a mix of life histories.

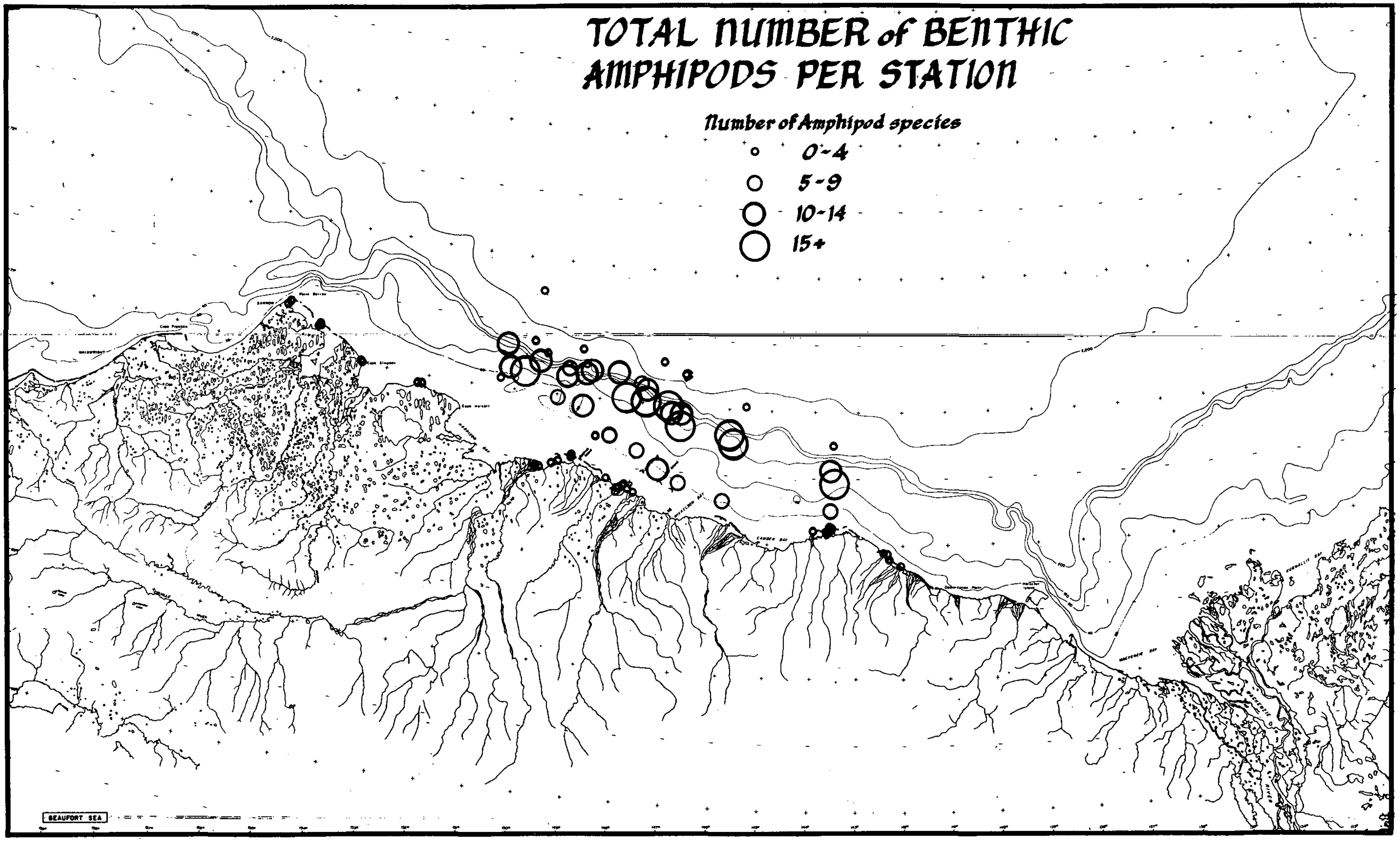


Figure 6.13 Benthic Amphipods

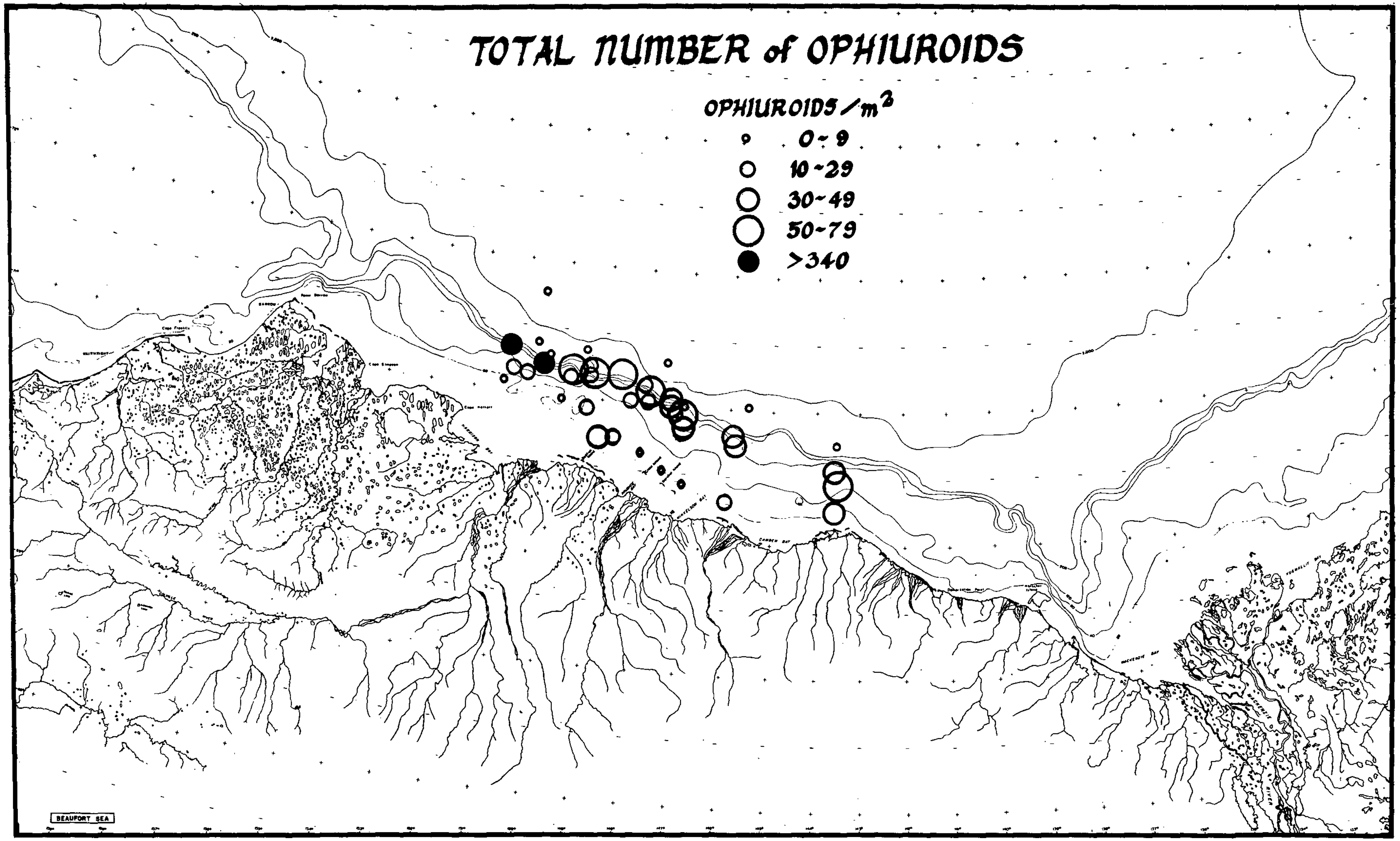


Figure 6.14 Ophiuroids

Food sources available to the continental shelf ecosystem could include: coastal benthic diatom production (Matheke and Horner 1974), tundra and peat erosion and continental run-off, localized phytoplankton blooms induced by occasional coastal upwelling (Hufford et al. 1977), diffuse and low level neritic phytoplankton production, advection of fauna and organics with the Bering Sea-Chukchi Sea water mass (Johnson 1956), and under ice epontic diatoms (Horner, 1976). Except for the intrusion of the southern water mass, the neritic phytoplankton and the ice algae, these food sources are localized and influence only shallow lagoon or nearshore coastal environments. Though its areal extent and overall contribution to the ecosystem are unknown, carbon fixation by ice algae appears to be a likely energy source for the outer shelf biotic system. To account for the dynamic trends encountered within the benthic community, both a seasonal cue and an energy source capable of supporting annual benthic reproduction and recruitment are required. These conditions are met by ice algae. In the nearby Chukchi Sea, populations of these epontic diatoms begin to increase in April under very low ambient light intensities, reach maximum population densities and productivity in May, and decrease during the early summer. This underlayer of diatoms and associated biota sloughs off during the initial stages of ice melt and possibly sinks to the sea floor. Carbon fixation of ice algae per unit area during May can be ten times that of the later phytoplankton bloom in the water column (Horner, 1976; Clasby et al., 1976). Annual production is about 5 g C/m^2 off Point Barrow. Though not high when compared with more southern coastal areas, this may represent a major portion of the primary production in the offshore Beaufort Sea. Rapid sinking of the "inverted benthos" ice epontic community could carry much of this food rapidly through the pelagic zone and make it available to sea floor organisms during their period of recruitment.

Average temporal changes in basic community structure in the benthos are probably caused by the collective annual reproductive cycles of the fauna. To drive these dynamics of offshore benthos, larger sources of energy are required than have been previously reported for the Beaufort Sea. Ice algae are suggested as a likely cyclic food source that could make this Arctic ecosystem productive (Carey, Ruff, and Montagna, unpublished MS.).

Findings from samples taken seasonally across the Beaufort Sea continental shelf in 1975-76 indicate that changes were encountered in both the total numerical density and the soft-bodied infaunal biomass within the benthic population at stations on the middle and outer shelf. The magnitude and periodicity of fluctuations in numerical abundance are indicative of an annual reproductive cycle with a large peak in recruitment, and the temporal variability in biomass suggests possible seasonality. Similar changes are not found at the shallowest shelf stations, indicating that different processes are operating there. The seasonal changes exhibited by the Beaufort Sea benthic community have compelled us to re-evaluate our concept of the productivity of this Arctic ecosystem.

At Stations PPB-55, PPB-70, and PPB-100 on the outer portion of the continental shelf the benthic assemblages showed marked variations in numerical density (Fig. 6.15). Though these are not synchronous trends at all three depths, they appear to be periodic and are indicative of annual reproductive cycles. The average trends for stations demonstrate an increase in animal numbers through the spring with a maximum of 8,500/m^2 reached in May and a subsequent decline occurring through the summer and fall. Presumably the spring increase in density is caused by recruitment to the (> 1.0 mm) benthic community beginning early in the season. During the picking/sorting phase in the laboratory, we observed a much greater proportion of small individuals in the May samples than at any other time of the year. The summer-fall decrease in numerical abundance implies high mortality rates, caused perhaps by predation and/or competition.

Temporal changes in biomass were not as marked as those in numerical abundance, but the trends were strongly suggestive of seasonality (Fig. 6.16). The biomass maximum appeared in August, not in May when peak densities occurred. This increase could be caused by growth of individuals after their recruitment to the benthic populations in the spring. The high growth rates that would have to exist to cause this seasonal increase are in contrast to the slow growth rates reported for Antarctic invertebrates (Pearse 1976).

Average trends in gross structure suggest that the benthic communities on the outer continental shelf of the Beaufort Sea are dynamic and undergo distinct seasonal cycles. Numerical density and biomass return to similar levels from one year to the next. Further research on the life histories of individual species will be necessary to test this hypothesis.

In contrast to the outer shelf, the total yearly range in infaunal abundance at the shallowest station PPB-25 varies within narrow limits (Fig. 6.16). The amplitude of range for both indices is low, variances are high, and no seasonal trends are evident. The numerical densities of macro-infauna at the 40-meter station are similar to those at PPB-25, but because of the lack of fall samples from either year, it is difficult to determine whether these changes in gross structure are random or cyclic at 40 m.

5. Ecological Zones and Benthic Faunal Groupings

Four broad environmental zones can be defined for the benthic environment off the Alaskan North Slope and off the Candian coast (modified from Wacasey, 1975) (Fig. 6.17).

1. Estuarine Zone - characterized by lowered nutrient values and unstable temperature and salinity conditions. This nearshore region is greatly influenced by freshwater runoff from coastal rivers.

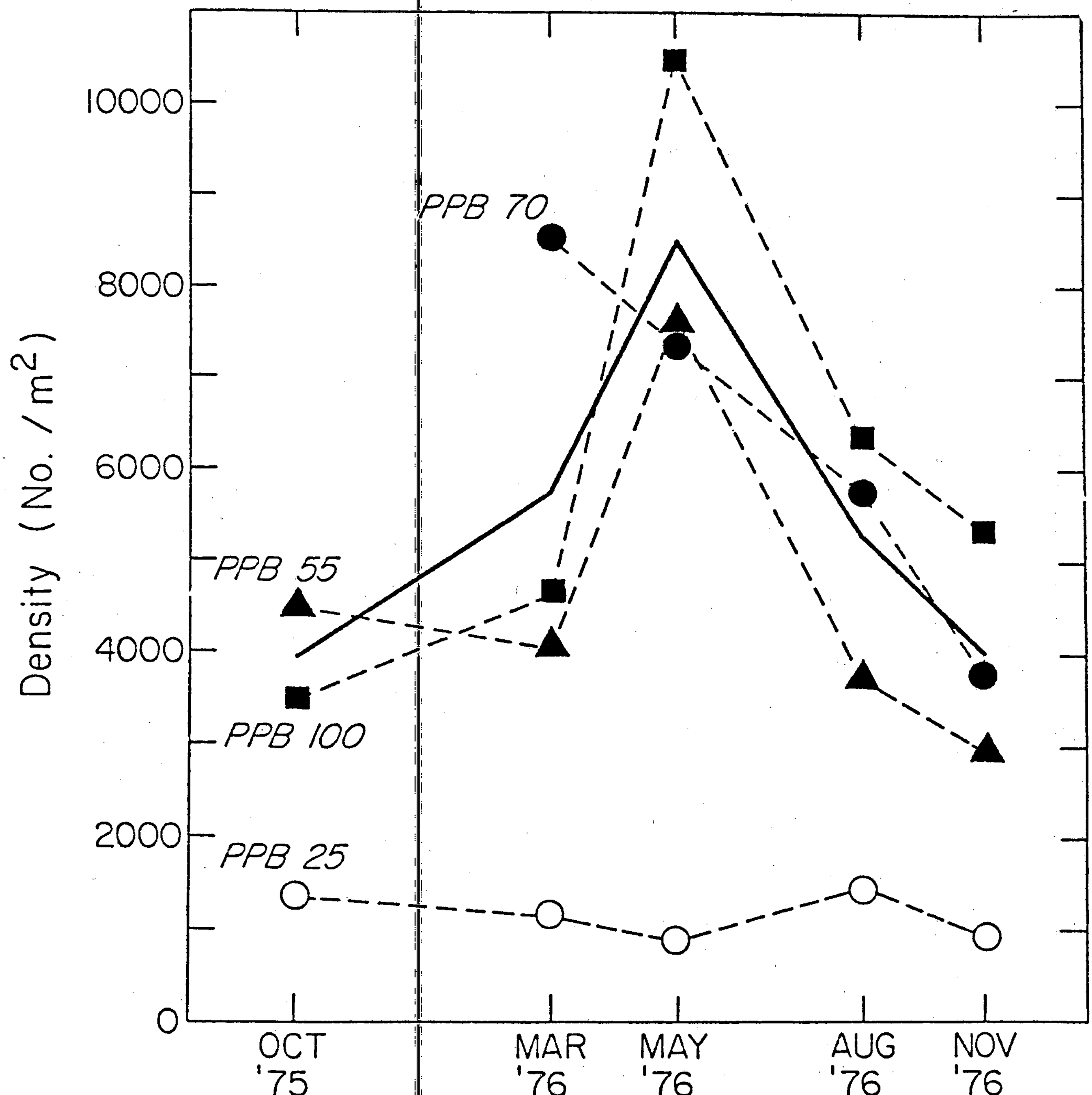


Figure 6.15 Numerical density of macro-infauna (1.0 mm +) at standard stations at 5 sampling periods. Station PPB-40 is considered transitional and consists of 3 data points; it has been omitted for clarity. Each point represents an average of 5 samples. The solid line is the mean trend for the 3 outer stations.

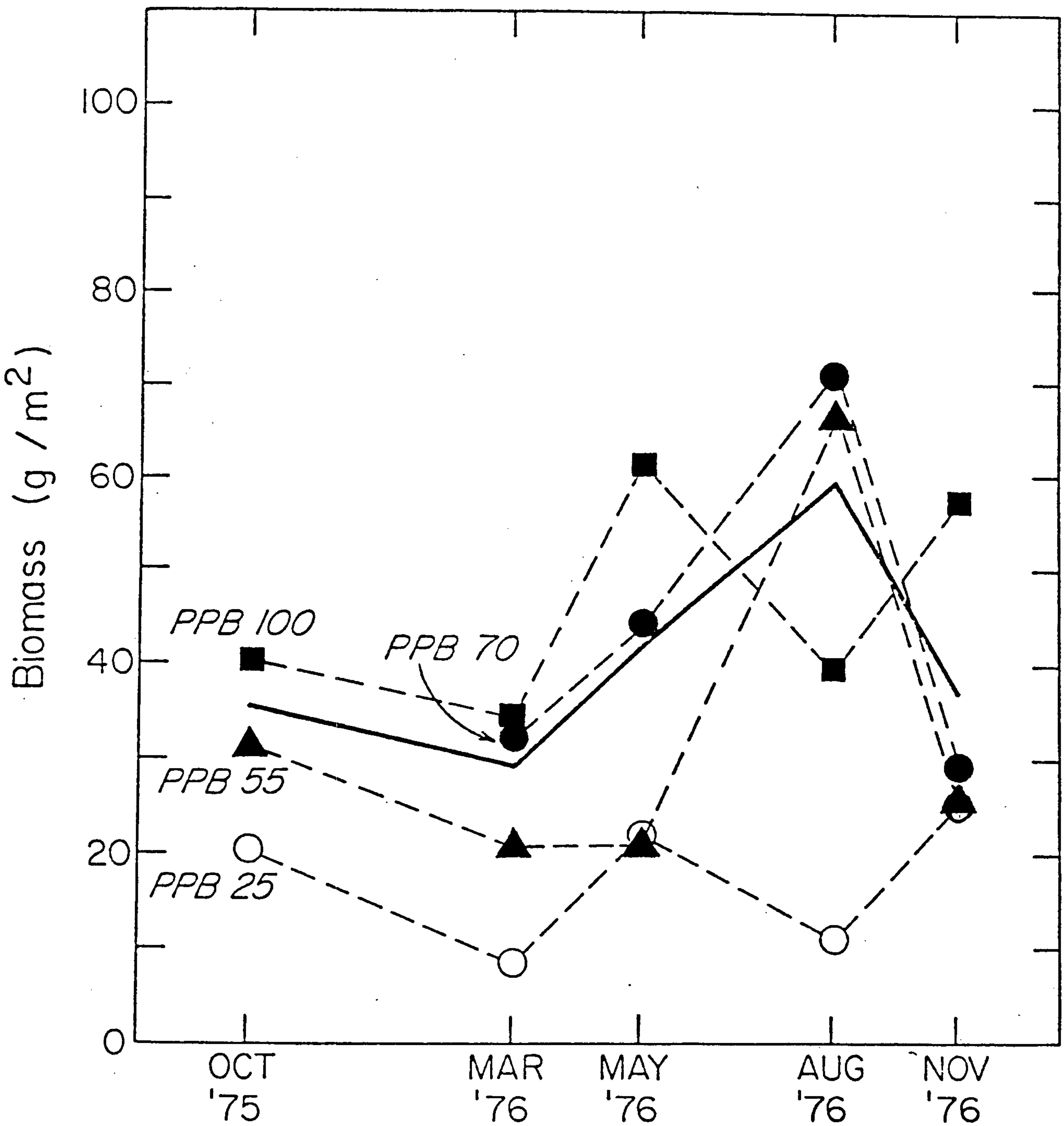


Figure 6.16 Biomass of soft-bodied infauna (grams wet-preserved weight) at standard stations at 5 sampling periods. Station PPB-40 is considered transitional and consists of 3 data points; it has been omitted for clarity. Each point represents an average of 5 samples. The solid line is the mean trend for the 3 outer stations.

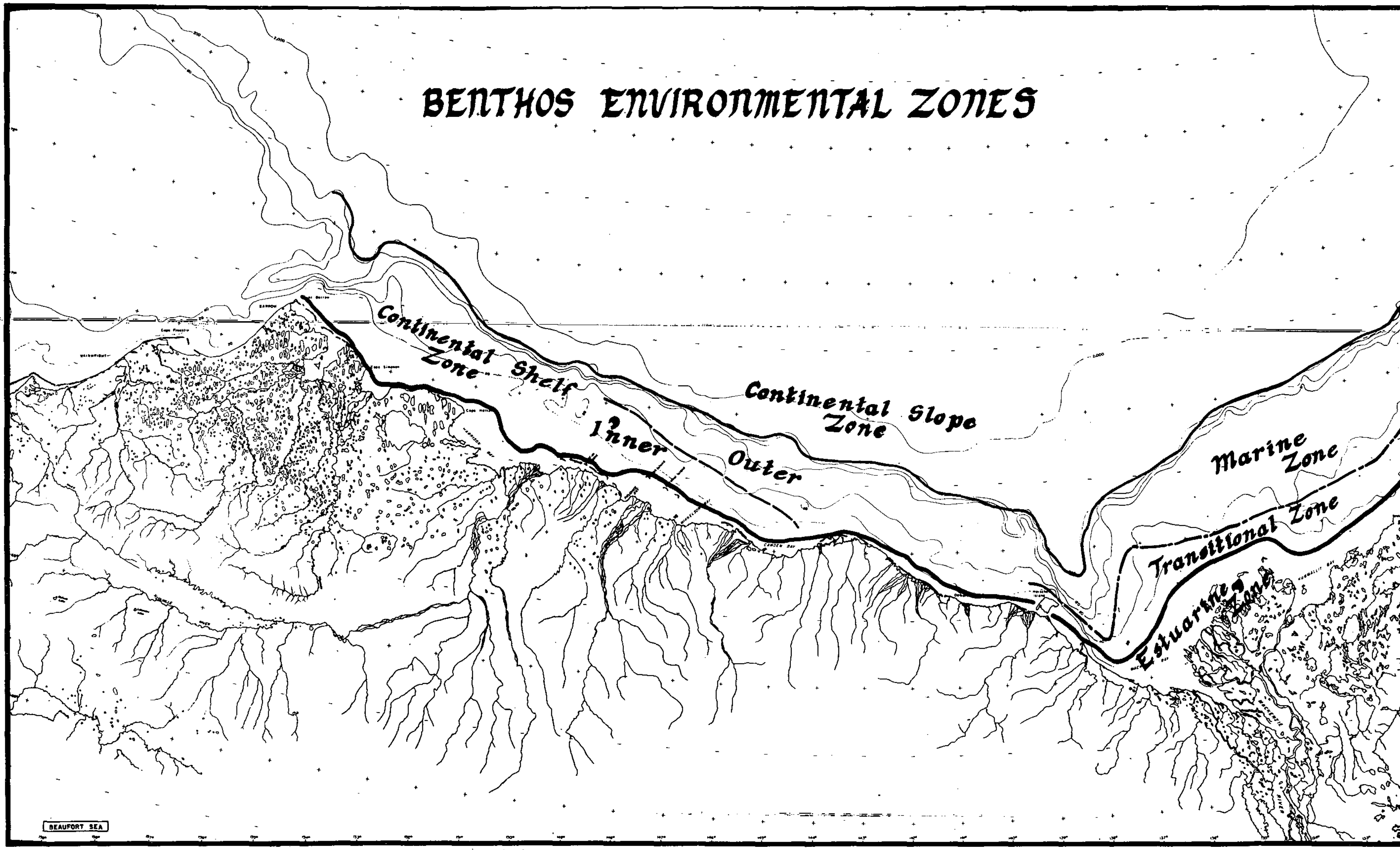


Figure 6.17 Benthos Environmental Zones

2. Transitional Zone - exhibits smaller temperature and salinity fluctuations, but is the area of most intense ice scour.

3. Marine Zone - occupies the outer portion of the continental shelf, and is a region with much more stable environmental conditions.

4. Deep-sea Zone - occurs beyond the shelf break and down the continental slope. This zone is defined by the presence of benthic species that are rare or absent from the shallow zones. The depth extends beyond the seasonally-changing continental shelf environment.

Although these ecological zones undoubtedly extend across the Beaufort Sea, the significant influence of the Mackenzie River in the southeastern portion greatly extends the estuarine zone offshore. To the west of the Mackenzie, the low salinity estuarine zone is narrow and remains close inshore except at the mouth of Alaskan rivers, where the isohalines bow seaward. A transitional zone cannot be defined in Alaskan waters at this time, as there are few data for the depth interval most probably concerned.

To define further the ecological groupings of benthic fauna, we grouped species of selected organisms and stations sampled by the Smith-McIntyre grab; these were analyzed for similarity and clustered according to their similarity. Several subgroups can be defined on the continental shelf with these statistical techniques. Essentially, there is an inshore group of species and an offshore assemblage on the shelf. The individual subgroups indicate closely associated species and station groups that tend toward the southeast to the Barter Island area. We do not have an explanation for these groupings and their distributions at this time. Invertebrate species along the southwestern shelf tend to cluster into bands which roughly parallel the coastline. Similar bands are described from the southeastern sector around the Mackenzie River delta. It remains to be seen whether the species composition within these bands are the same for the two areas. The anomalous regions around the Colville River and Barter Island are indicated by differences in the structure of the benthic communities.

The species groupings indicate that the southwestern continental shelf can be divided into a western area off the Colville River, and an eastern region. The only species found with any regularity near the Colville River were cosmopolitan species and those only associated with the Colville River region. To the east, the area is again divisible into shallower and deeper benthic faunal groups. The stations on the deeper shelf have a more cosmopolitan composition, and include more of the total species present. Further study is required to clarify the processes occurring in these environments.

6. Benthos: Trends in Infaunal Abundance across the Shelf

By compiling stations taken during the two summer 1976 cruises (OCS-4 and OCS-5), two shore to shelf-break transects can be constructed. On the Pitt Point Transect, the trends in numerical density of the large macro-infauna indicate a maximum in abundance at the shallowest and the deepest depths (Fig. 6.18). A bimodal pattern is also evident on the shorter transect off Narwhal Island near Prudhoe Bay. These two transects accentuate a minimum numerical density occurring at intermediate depths around 15-20 m.

It is evident that several processes are probably in operation across the shelf. The nearshore zone often has concentrations of peat-like detritus. The minimum lies within the sea ice shear zone, the most active area of ice pressure ridging and bottom gouging. Ice encroachment on barrier islands may also depress the abundance of the nearshore fauna. The Narwhal Island data may be a result of this scour, as the pack ice generally rides up over the shoreline of the island.

Epifauna

This segment of the benthic communities has been sampled on three icebreaker cruises to the Beaufort Sea. Though only 58 stations have been sampled by otter trawl to collect these large and generally scarcer organisms living on or associated with the sediment surface, preliminary conclusions on distribution and species associations can be drawn.

Epifauna are important components of offshore ecosystems. Identification of epifaunal communities and species interactions is necessary before larger scale system interactions can be understood. Benthic food webs and, therefore, key species are poorly delineated at present and cannot be traced until interactions between major infaunal and epifaunal species are known. Some marine fishes feed on epifaunal species and several species of marine mammals, especially bearded seal, feed almost exclusively on epifaunal invertebrates.

During the 1971 and 1972 U.S. Coast Guard cruises to the Beaufort Sea (WEBSEC-71 and 72) twenty-five bottom otter trawls were collected between Cape Halkett and Barter Island (Carey et al., 1974; Carey and Ruff, 1977). Thirty-four mega-epifaunal species (10 arthropods and 17 echinoderms) were large enough (> 1.3 cm) and abundant enough to be captured by the net at twenty trawling stations. These species were generally distributed in zones parallel to depth contours off the northern Alaskan coast between 24 and 464 m depth (Fig. 6.19). Stations along depth contours have the greatest affinity, sharing larger numbers of species. The area off Barter Island, east of about 144° appears to have an epifaunal community that differs from the environments to the west.

An analysis of species groupings (Fager, 1957) demonstrated three main interrelated and two independent groups. The largest species group consisted of species widespread across the continental shelf, while one

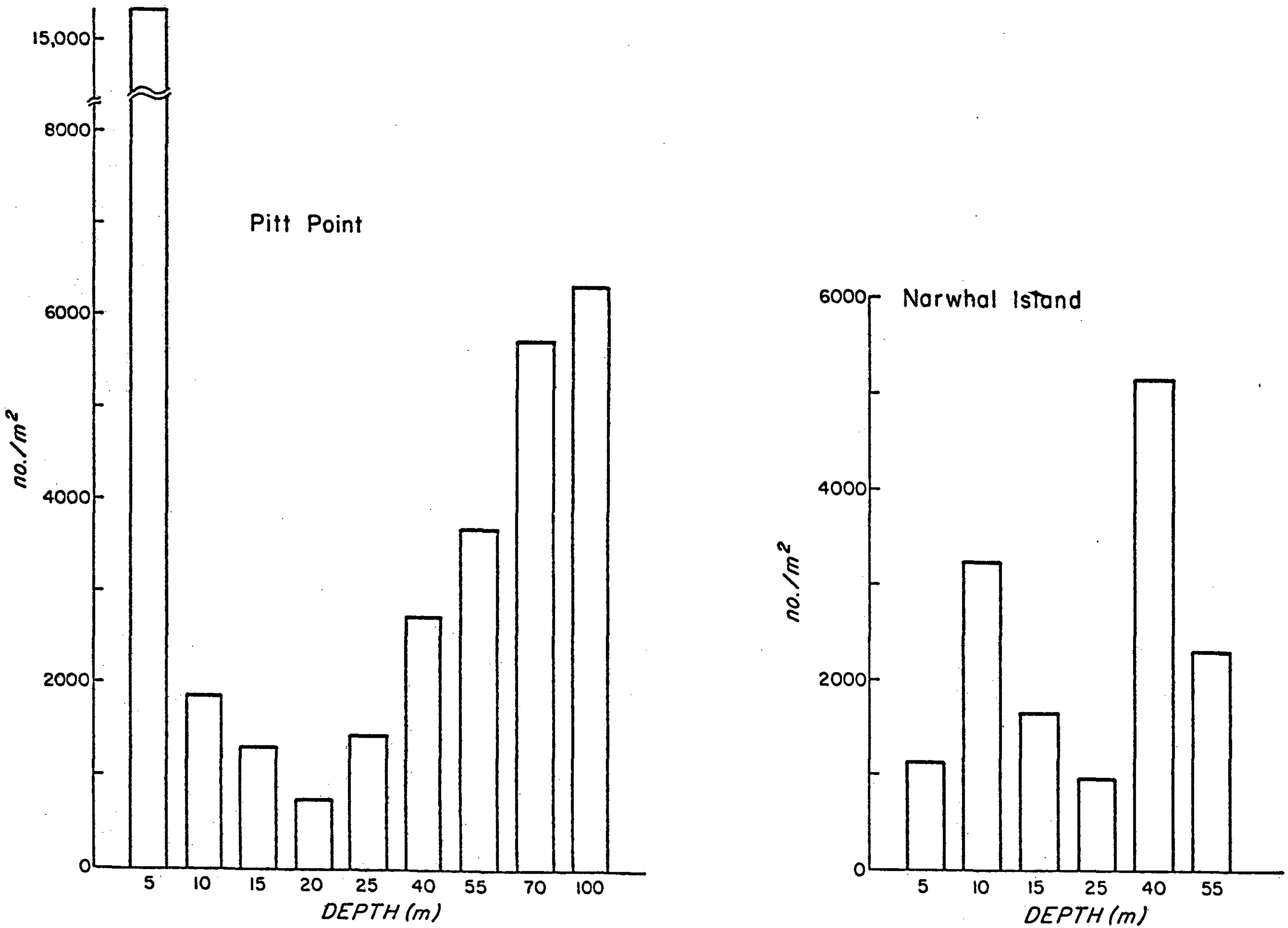


Figure 6.18 Numerical density of large macro-infauna (> 1.0 mm) across the continental shelf.

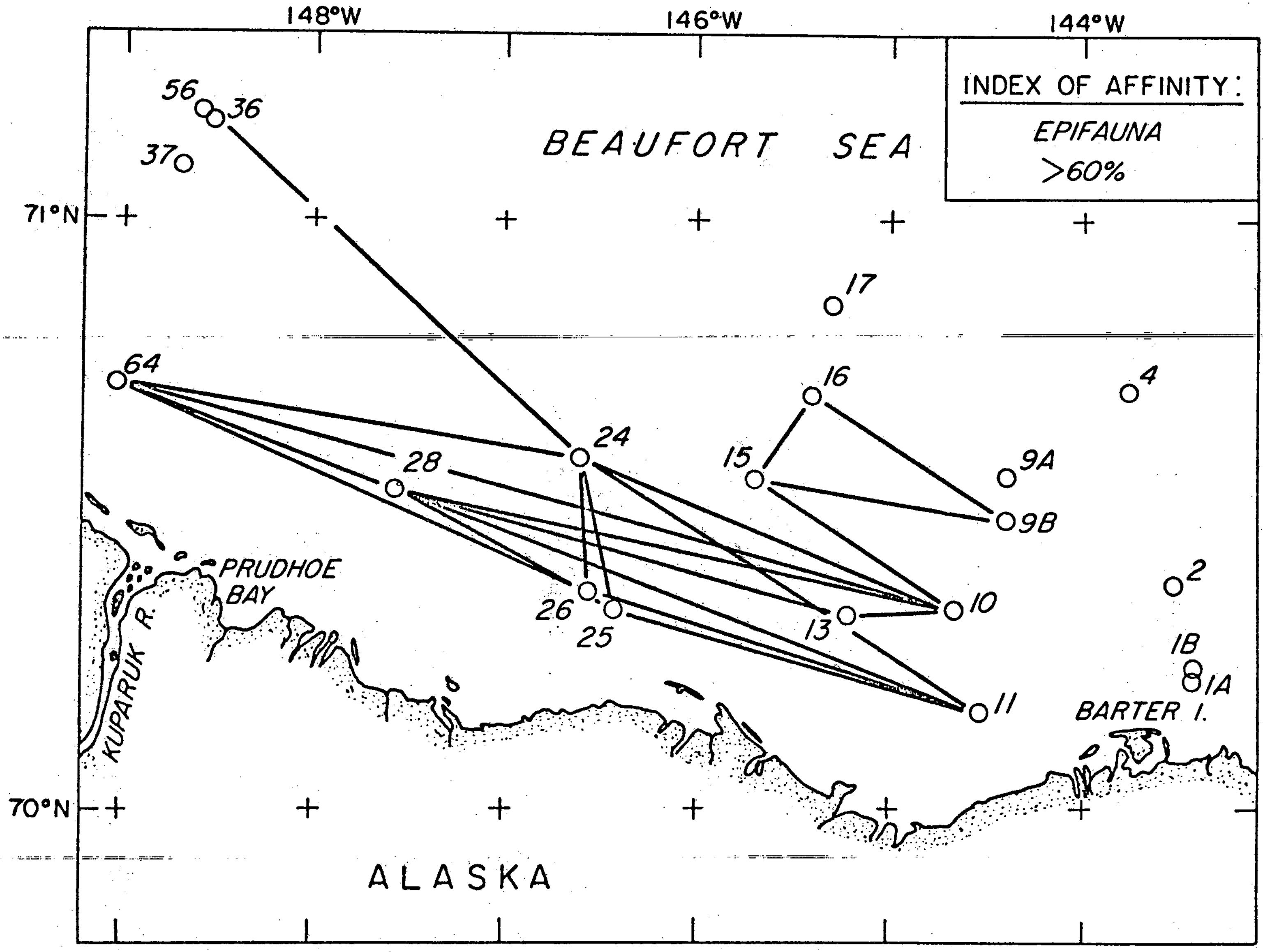


Figure 6.19 Similarity of mega-epifauna between stations at the 60% level, i.e., those stations connected by lines have 60% of their abundant large epifaunal species in common.

group was located on the inner half of the shelf and one with the deeper stations sampled on the upper slope. Another species group was comprised mostly of attached epifauna and was associated with gravels found near the edge of the shelf. These species grouping techniques also demonstrated that the Barter Island region is different faunistically and, therefore, probably environmentally from the areas to the west.

During the interdisciplinary OCSEAP Trophics cruise in the summer of 1977 a series of trawls was conducted to provide additional data on distribution and abundance of epibenthic invertebrates and demersal fishes. Trawl locations are shown in Fig. 6.20 (Frost et al., 1978, Appendix to OCS Annual Report).

Although 33 trawls are inadequate to characterize Beaufort Sea continental shelf epifauna, some generalizations can be made. A total of 238 species or species groups of invertebrates was identified from the 33 trawls. 49 of those species were gastropods, 34 were amphipods, 28 were polychaetes, 25 were bivalves, 27 were echinoderms, and 14 were shrimp. Only 14 species occurred in more than 20 trawls. 41 species occurred in 10 or more and almost half of the 241 were found in less than 5 trawls. At 26 of the 33 stations echinoderms were the most abundant invertebrate group. In most cases they comprised more than 75% of the total trawl biomass.

At least two major community types seem to exist. West of 154° brittle star communities are predominant. Associated species vary within a wide range. Other characteristic species seem to be soft corals and two kinds of sea cucumbers. At all stations where the brittle star community exists, the bottom type was mud. West of Harrison Bay (150°W.) a very different community exists. This one seems to be characterized not by a single species but by a group of abundant species. The two most abundant and widespread are a small, clear-shelled scallop, and sea lilies (crinoids). In addition, sea cucumbers, sea urchins, several species of brittle stars (not the same species as in the western brittle star communities), and a crangonid shrimp are usually among the most abundant species. Most trawls in which this species assemblage occurred were in rocky areas.

Although most of the areas trawled contained substantial numbers of organisms, few of them were either major predator or prey species. Echinoderms with the exception of sea stars, which are usually carnivores or scavengers are, in general, filter feeders, detritovores, suspension feeders, or deposit feeders. They utilize organic fallout from the water column or organic material within the sediment. Almost nothing eats adult echinoderms (except sometimes other echinoderms). Thus, their only input back into the system is excretion, decomposition after death, and release of reproductive products.

Some trawls fell into neither of the above patterns. Those trawls were generally in rocky areas between 158°W. and 162°W. and between 150°W. and 154°W.

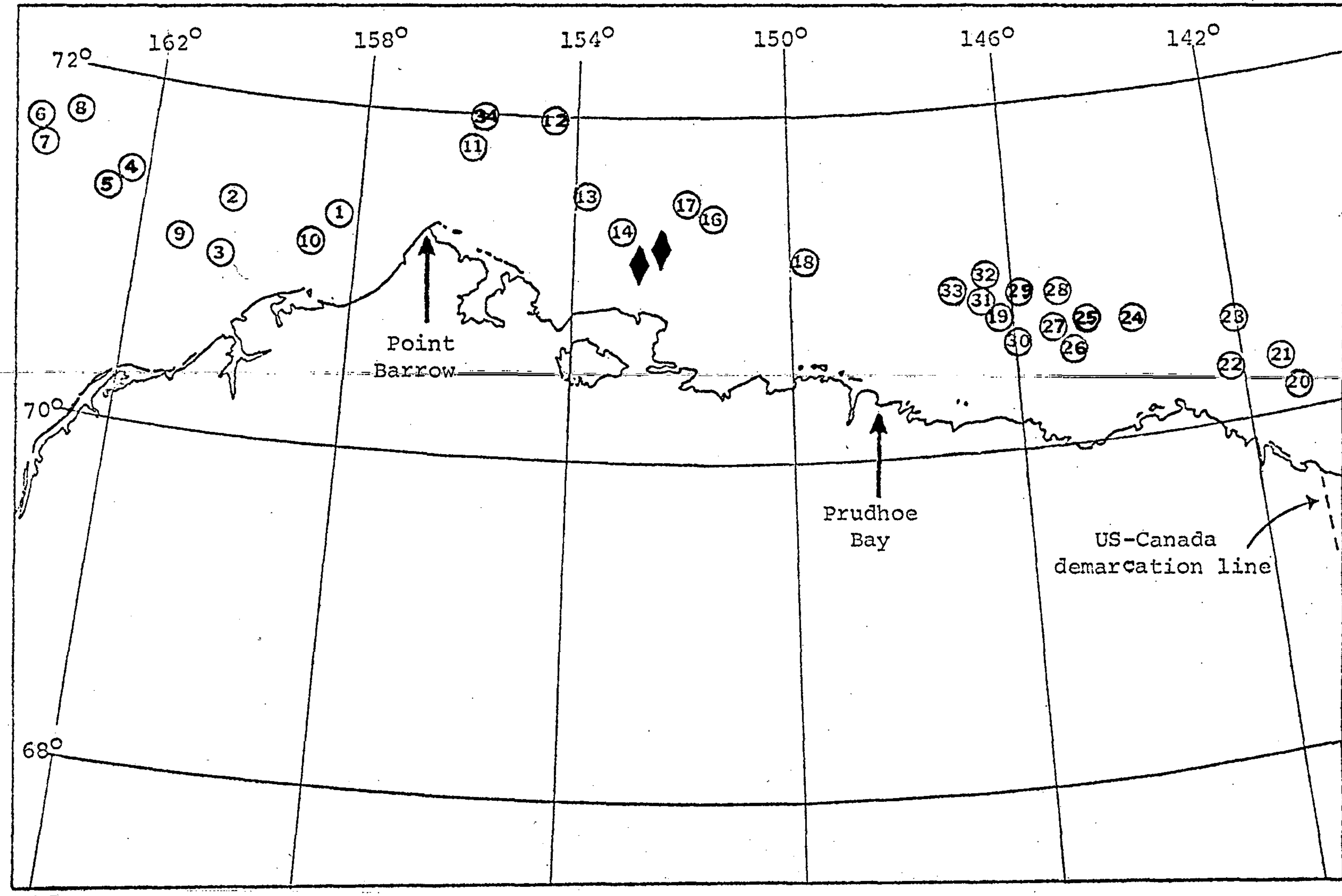


Figure 6.20 Locations of otter trawl stations in the northeastern Chukchi and Beaufort Seas. Numbers refer to stations trawled in 1977. Stations trawled in 1976 are indicated by ♦

What is sometimes termed "food benthos" is relatively much less abundant in the Beaufort Sea epifauna. Food benthos includes primarily crustaceans, polychaetes, and molluscs. Polychaetes are not adequately sampled by otter trawls. Of the crustaceans, shrimp was the most abundant group, followed by crabs and then amphipods. Shrimp biomass was about twice that of fish in the trawls, crab biomass was about half that of crabs or fishes. Species composition of crustaceans in the Chukchi and western Beaufort Sea varies noticeably from that in the eastern Beaufort Sea. Major species of shrimps, crabs, and amphipods change from west to east.

Of the molluscs, bivalves were the most abundant, especially east of Harrison Bay. This was due to scallop-dominated communities of that area. No patterns in gastropod abundance were evident. Biomass was relatively constant although species composition changed from west to east.

Benthos: Research Needs

1. General Comments

The second phase of benthic ecological research should be the elucidation of energy pathways within the benthic food web and the maintenance of community structure through the population dynamics of dominant species. When the major pathways of carbon flow within the benthic food web to major marine mammals, bird and fish predators are known, then critical pathways (e.g., dominant prey species) can be evaluated for their sensitivity to oil and other forms of pollution caused by man's activities off the northern Alaskan coast.

The measurement of rates and processes within the food web is ultimately a more difficult task, but one that would allow more accurate estimates of environmental impacts. Changes in the metabolism, assimilation, growth and reproductive rates of species populations can be used to determine the extent of chronic effects of pollution. The partitioning of energy production and use in the benthos and ecosystem would provide a clearer understanding of the functioning of the ecological units and the degree to which they may be affected by oil exploration and production.

Benthic research on year-round reproductive activity of dominant benthic species seeks to define some of the functional interactions among the community components. These must be known before the effects of environmental impacts can be predicted.

The benthic invertebrates constitute a major source of food for the top level carnivores, including birds, seals, and occasional walrus. Any decrease in benthic populations caused by oil pollution might eventually be reflected in the populations of these larger animals. Nearshore areas would be most sensitive since it would be in these regions that pollutants would be most likely to mix to the benthic boundary.

The timing of environmental disturbances in this strongly seasonal environment may be extremely critical in determining the stresses experienced by the benthic community. For example, an oil spill in the winter on top of the pack ice could be cleaned up with little or no resultant damage to the marine benthos, while a spill of the same magnitude during a summer of open water might have significant effects. It remains to be determined if the bottom-dwelling invertebrates are more or less sensitive to oil-related pollution during the summer months, but the pelagic larvae and juvenile stages of the benthic organisms would be vulnerable to spills during periods of open water conditions.

It seems likely that the development of the oil and gas resources will bring about changes in the marine environment, but the extent of degradation in the benthic environment still cannot be predicted. There remains a great scientific need for long-term studies on the dynamics of the benthic populations, including year-round sampling with measurements on growth, metabolism, and reproductive activity.

2. Infauna

(a) Trophic interactions.

The major food pathways should be defined for the benthic invertebrate communities on the inner and outer shelf environments during the summer and winter seasons. Predation rates by mammals, birds and fish should be determined. The small epifauna should be assessed as a food source.

(b) Temporal variability.

Studies should continue on the reproductive biology of dominant species at standard stations across the continental shelf to define the degree of seasonal and yearly variability. The reproductive activity and the species population size structure should be studied with the objective of defining reproductive rates and cycles and growth rates.

Additional samples should be obtained from the same locations to assess yearly variability of the benthic communities across the continental shelf.

Winter and spring samples should be obtained from lagoons and offshore in the landfast ice zone to determine the seasonal changes within the benthic communities in these areas and to determine if unfrozen topographic lows form refugia for the epibenthic fauna.

(c) Benthic repopulation rates.

Repopulation and growth rates of benthic invertebrates should be studied by conducting natural experiments on repopulation, perhaps of aged ice gouges on the inner continental shelf.

3. Benthic Epifauna:

Despite their important role in the nearshore/inshore food web, little is known about the ecology of epibenthic invertebrates. We lack basic information regarding life cycles of key epibenthic species and their use of nearshore and inshore habitats in summer and winter. Studies are needed to determine epibenthos densities, movements and food sources. Research should address the following questions: (1) How productive, through growth or immigration, is the epibenthic community? (2) How would bird and fish populations respond to reduced densities of food organisms due to perturbations in the nearshore environments?

Specific needs for the epifauna are:

a) Additional trawl data to provide distribution and abundance information.

b) Distribution and abundance information to determine species associations or communities and within those communities key species, either because they structure that community or because of their heavy use by higher trophic levels.

c) Delineation of determining factors, e.g., temperature, salinity, sediment types, etc. for key species. If critical habitat needs are determined, it should be possible to evaluate potential effects of at least some kinds of habitat alteration.

d) Examinations of food habits of key species and their interaction with the infauna. Also determination of the importance of key species to demersal fishes, birds, and marine mammals.

e) Sensitivity to hydrocarbon contamination should be determined for key species.

f) Resolution of the different estimates of abundance that come from trawl and dredge data on one hand and observations by SCUBA divers on the other.

FISH

In this section, fish resources are described for nearshore, inshore and offshore zones of the Beaufort Sea.

Nearshore Zone (<2 m depth and enclosed or protected coastal waters)

Petroleum discoveries in the arctic have prompted a variety of fisheries studies over the past decade, and a general picture of fish use of nearshore waters has emerged. Craig and McCart (1976) summarized much of the work prior to 1976; more recent studies include Bendock (1977), Doxey (1977) and Craig and Griffiths (1978). Portions of the present description of nearshore fish resources have been abstracted from reports by Craig and McCart (1976) and Craig and Griffiths (1978).

Over 30 species of fish have been recorded in nearshore habitats between the Colville and Mackenzie rivers. Areas of greatest species diversity tend to be the deltaic environments of the largest North Slope drainages (Fig. 6.21). Species occurring in nearshore waters can be classified in three broad categories:

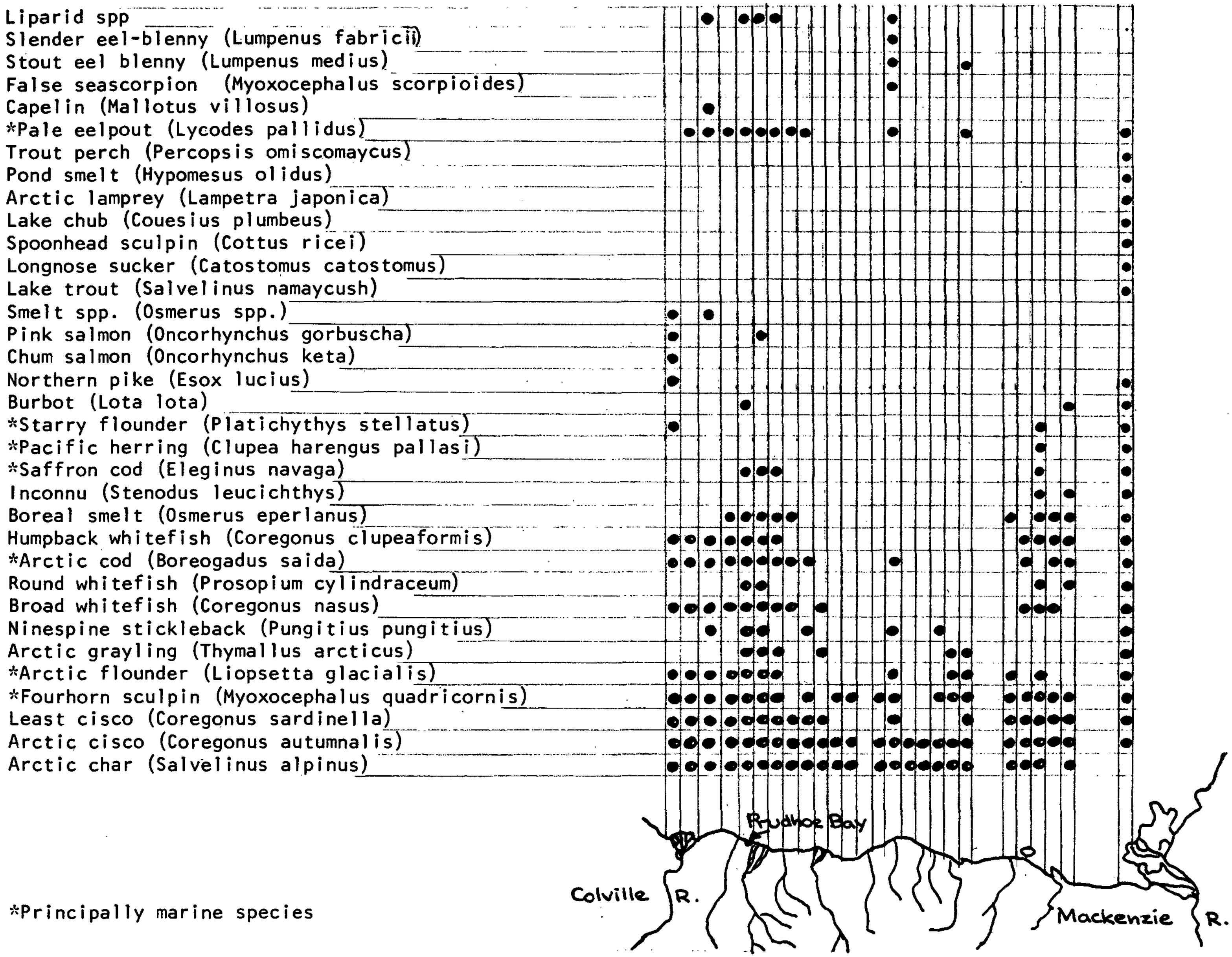
(1) Freshwater species, which are occasionally present when salinities are low;
(2) Anadromous species, which are tolerant of saline water and undertake seaward migrations during their life cycle;
(3) Marine species, which remain in brackish or marine waters throughout their lives.

Despite the variety of species indicated in Fig. 6.21, very few species account for the vast majority of fish present in nearshore waters. In terms of numerical abundance or use by humans, the following fishes are considered "key" species in nearshore waters of the Alaskan Beaufort Sea:

Species	Anadromous	Marine
Arctic cisco (*Coregonus autumnalis*)	x	
Least cisco (*C. sardinella*)	x	
Arctic char (*Salvelinus alpinus*)	x	
Fourhorn sculpin (*Myoxocephalus quadricornis*)		x
Arctic cod (*Boreogadus saida*)		x

Though proportions of these five species vary from site to site and according to sampling gear used, these species account for 91-98% of all fish enumerated at Simpson Lagoon (Craig and Griffiths, 1978), Prudhoe Bay (Doxey, 1977), Kaktovik Lagoon (Griffiths et al., 1977), Nunaluk Lagoon (Griffiths et al., 1975) and along the Yukon Territory coastline (Kendel et al., 1975). Anadromous broad and humpback whitefish (*Coregonus nasus* and *C. clupeaformis*) may also be important species in some localities.

Figure 6.21 Distributions of fish species recorded in nearshore areas between the Colville and Mackenzie Rivers. Species records are approximate, since sampling efforts varied throughout the area. Most samples shown here were taken in nearshore, brackish water areas less than 3 m in depth. (Modified from Craig and McCart, 1976).



*Principally marine species

1. Summer Distribution and Movements

During the open-water season, anadromous and marine fish utilize nearshore habitats extensively as feeding and rearing areas. Some fish arrive with the first signs of spring break-up (approx. June 5-20) and some are still present when surface ice forms on nearshore waters in early winter (approx. Sept. 20-Oct. 10). As a generalization, most anadromous fish which enter coastal waters tend to be immature fish or mature fish which will not spawn that year. Spawners either enter coastal waters for a brief period or remain in the rivers for that year.

For the anadromous species, two prominent trends describe their spatial distribution in Beaufort Sea coastal water: (1) most fish are found nearshore rather than offshore waters, and (2) within the nearshore environment fish numbers are highest along mainland and island shorelines as opposed to lagoon centers or other areas distant from any shoreline (Fig. 6.22). Reasons for this habitat preference are not known although shoreline waters tend to be slightly warmer and less saline than other areas.

Once in coastal waters, Arctic char move actively along the coast, and stocks from several river systems intermix (Fig. 6.23). Arctic and least cisco from the Colville and Mackenzie rivers, the two major sources of these fish, also migrate considerable distances along the coastline, and perhaps these stocks overlap as suggested in Fig. 6.24. (Note that in both Fig. 6.23 and 6.24 the fish do not venture as far offshore as is graphically shown -- see previous paragraph). Thus it can be seen that anadromous fish from major Beaufort Sea drainages utilize a large portion of the Alaskan coastline, and conversely, the anadromous fish present at any particular coastal location have probably originated from several different drainages.

2. Winter Distribution

Although there has been an on-going effort to locate where fish overwinter in North Slope rivers (Craig and McCart, 1974; Bendock, 1977), the use of coastal areas for fish overwintering is virtually unknown.

Anadromous and marine fishes differ in their overwintering habits (Fig. 6.25). In general, anadromous fish leave coastal waters and return to overwinter in rivers and lakes; however, the possibility that some anadromous fish overwinter in select coastal areas needs examination. Arctic and least cisco have recently been found overwintering in the brackish waters of the lower Colville Delta (Craig,pers. comm). In river deltas, overwintering habitats are sometimes limited to a series of discontinuous unfrozen pools under the ice. These nonfrozen habitats become critical environments for anadromous fishes such as Arctic char, Arctic cisco, least cisco, and freshwater fishes such as grayling and round whitefish.

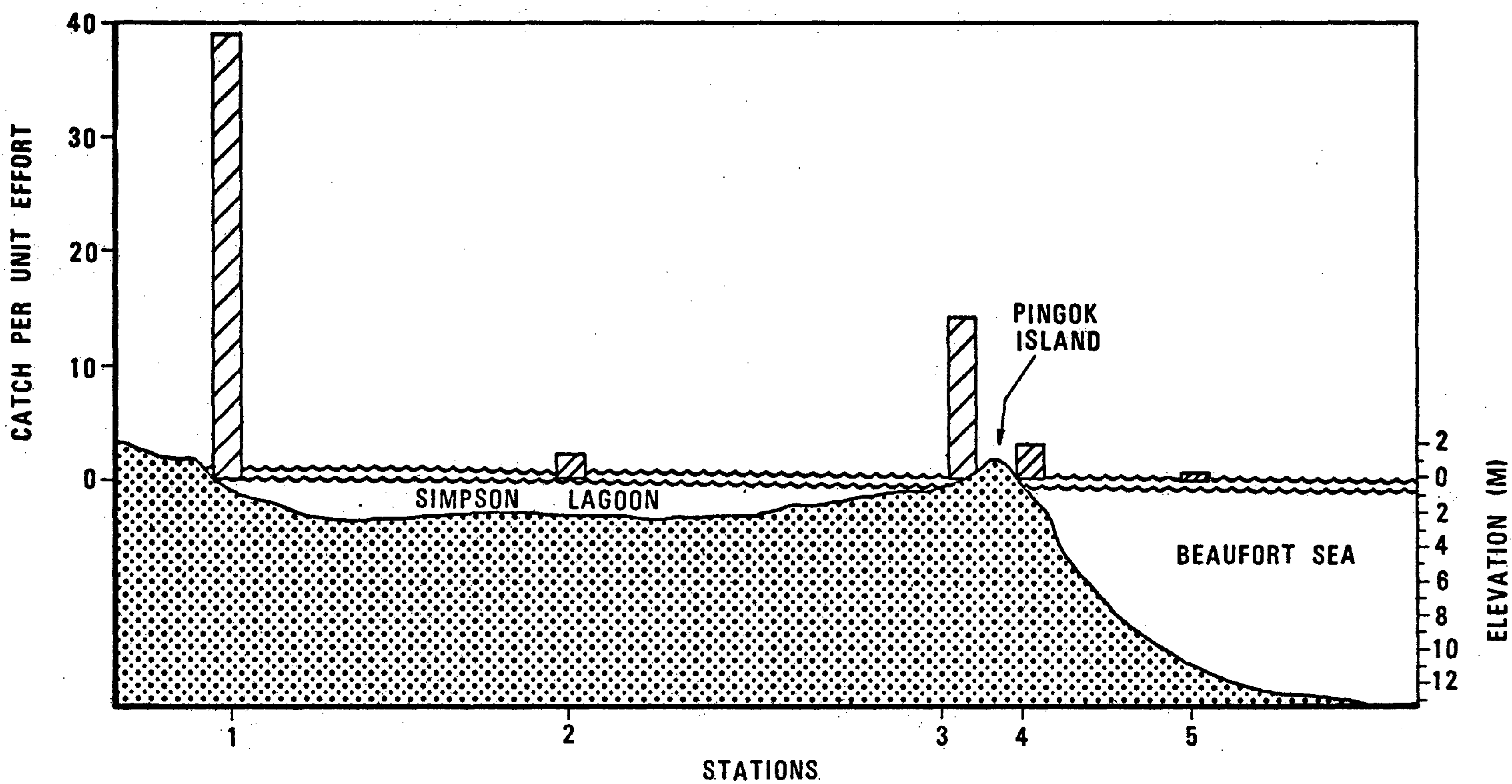


Figure 6.22 Cross-section of Simpson Lagoon study area showing relative numbers of fish caught at 5 sampling stations. Numbers of fish represent a seasonal average for combined species caught in a standardized 24 hr. gill net set. (From Craig and Griffiths, 1978).

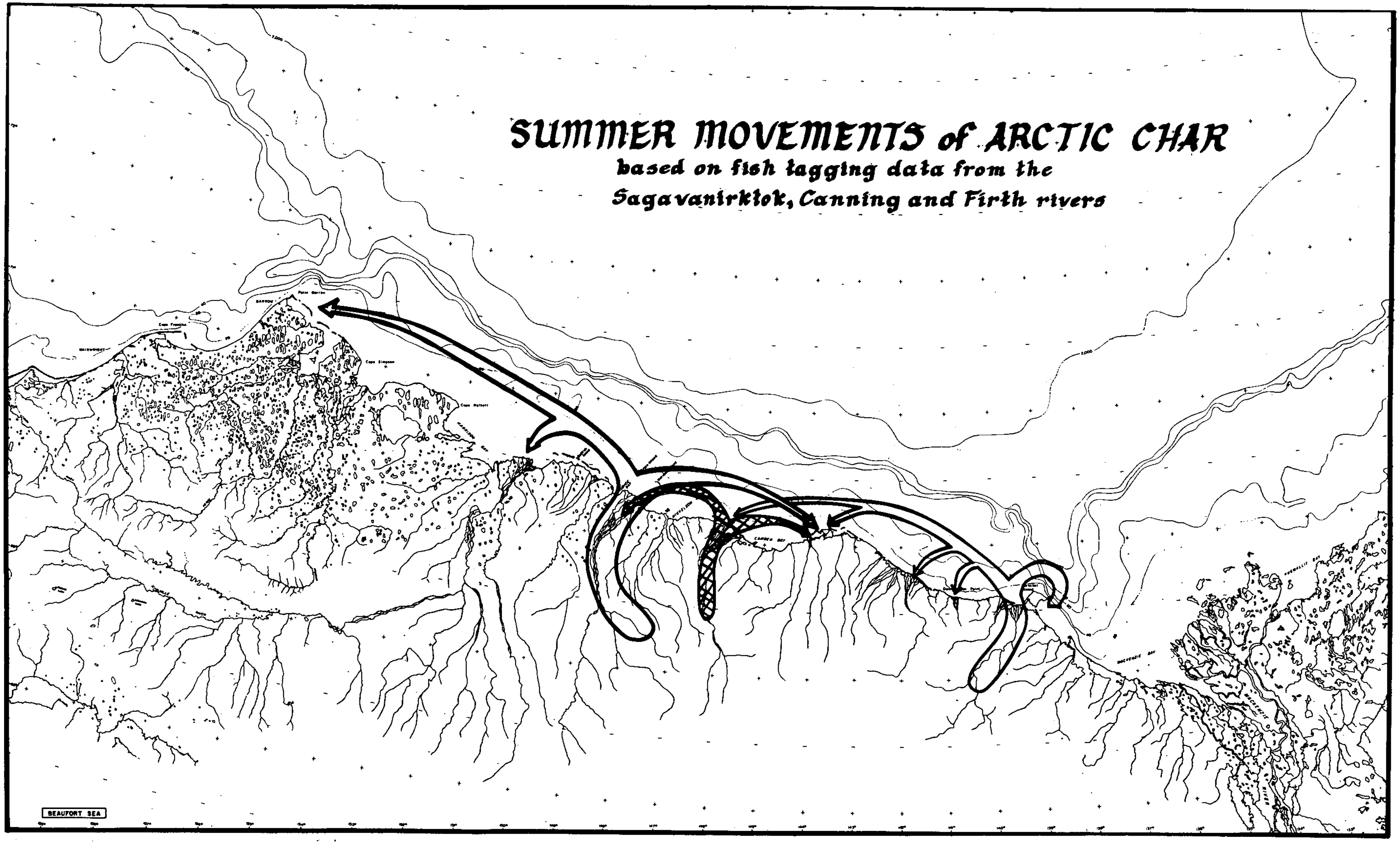


Figure 6.23 Summer Movements of Arctic Char

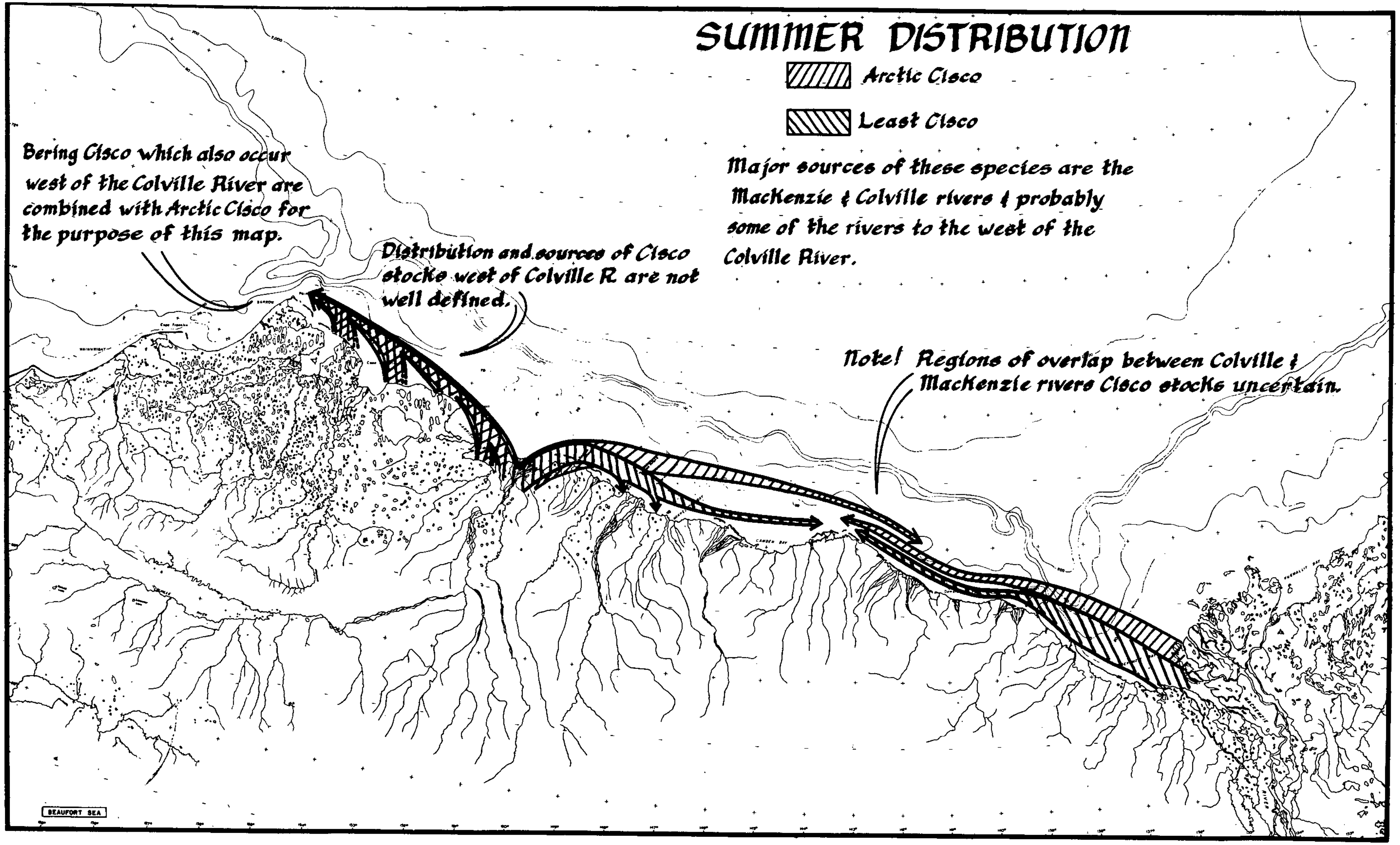


Figure 6.24 Summer Distribution

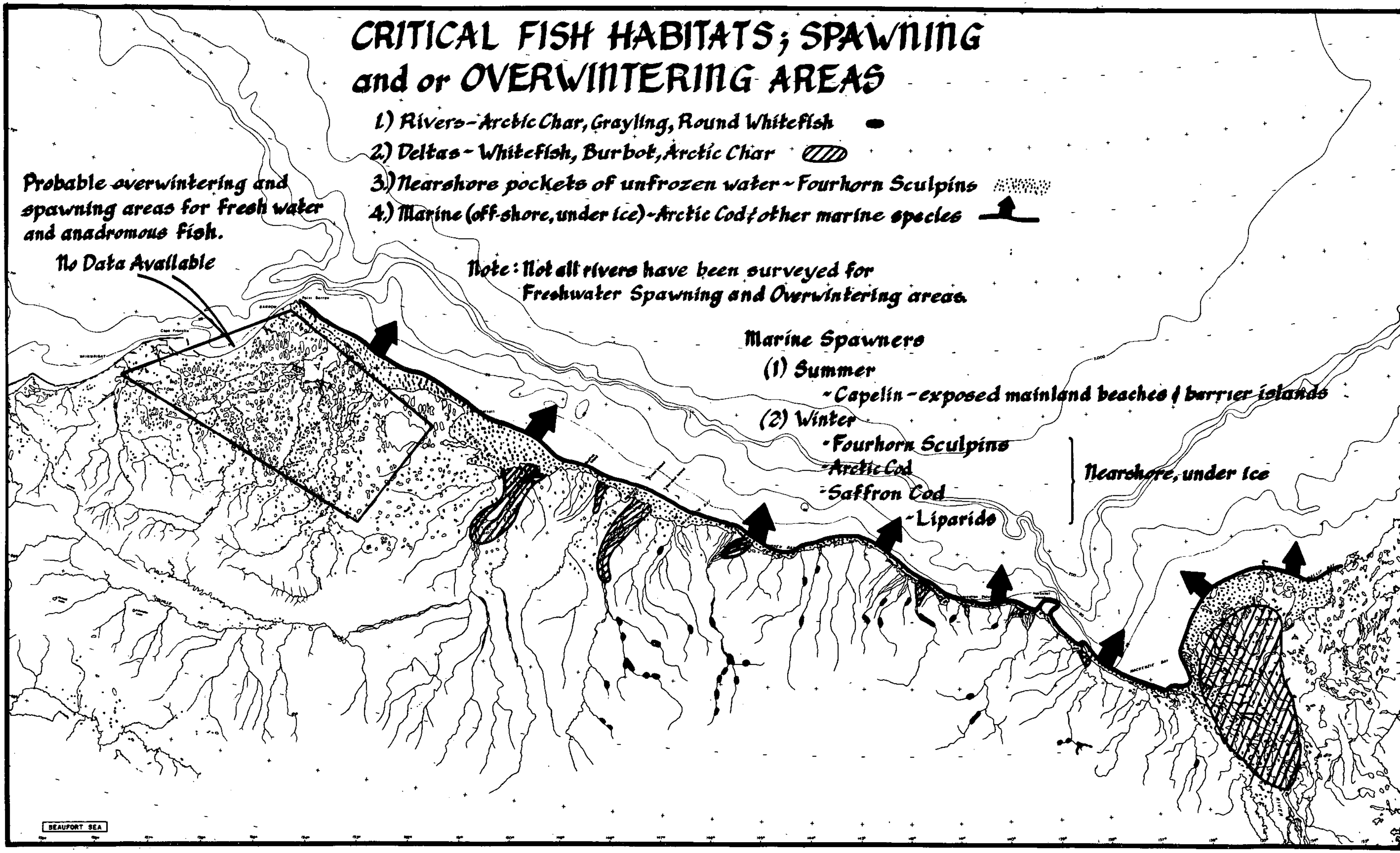


Figure 6.25 Critical Fish Habitats

Marine species presumably migrate further offshore during the winter or overwinter in the deltas of large rivers. The Colville Delta is used by fourhorn sculpin, but no other overwintering sites are known for marine species. Arctic cod, a key marine species, is also present in winter but its under-ice distribution is unknown.

3. Food Sources

Food habits of key fish species are surprisingly similar. While in nearshore waters, the fish feed extensively on epibenthic invertebrates (organisms living on or near bottom substrates) and zooplankton. Major food items include amphipods, mysids, isopods and copepods. Large anadromous fish, particularly Arctic char, may also feed on small Arctic cod or fourhorn sculpin. Benthic infauna (organisms living within bottom substrates) are not commonly eaten.

In Simpson Lagoon the important epibenthic food items for both anadromous and marine fishes were mysids (Mysis litoralis and M. relicta) and amphipods (Onisimus glacialis and Apherusa glacialis). Not only was there a high degree of dietary overlap between the fish species, but there was also a significant overlap between the diets of these fish and Oldsquaw, one of the major bird species using Simpson Lagoon. Food overlap indices and caloric calculations of available epibenthos for estimated numbers of predators indicate little competition for an apparently abundant food supply. However, it also appears that densities of epibenthic organisms in the nearshore environment are maintained by a continual immigration or dispersal of these organisms into shallow water. A disruption of this dispersal rate might affect the availability of food for vertebrate consumers.

4. Human Use of Fish Resources

Anadromous fish, particularly ciscoes, whitefish and char, are the focal point of several fisheries along the Beaufort Sea coastline in Alaska. Arctic cod are also an important food item in late fall and winter. Principal areas where fish are taken include: (1) domestic fisheries in the vicinity of Barrow, Colville Delta (Nuiqsut Village) and Barter Island (Kaktovik Village), (2) a commercial fishery in the Colville Delta (Helmericks), and (3) sport fishing at villages, DEW Line stations and oil camps.

5. Information Needs

More information on the ecology of nearshore fish stocks must be acquired in order to increase our understanding and predictive capabilities of OCS-related impacts. Locations of fish overwintering areas and fish use of under-ice areas in winter are priority requirements. Process-oriented studies (e.g., trophic relationships, factors limiting population numbers, relative importance of various nearshore habitats, response of fish to changes in temperature, salinity or water circulation patterns resulting from causeways, etc.) and studies of the biology of key fish species are also needed. Data regarding population numbers, fishing pressure and stock identification are necessary for fisheries management and environmental assessment objectives.

Inshore Zone (2-20 m depth)

Few data are available to describe fish resources in the inshore zone. The scant information available suggests that (1) fish densities are lower in the inshore zone compared to the nearshore zone, and (2) marine fishes rather than anadromous fishes account for the species composition in inshore waters (McAllister, 1962; Griffiths et al., 1977; Craig and Griffiths, 1978). However, very few sites in the inshore zone have ever been sampled.

Arctic cod, a key species in the Beaufort Sea food web, are presumably abundant in inshore waters. Spawning occurs under the ice in mid-winter. Ring seals, also present in the inshore zone, feed extensively on Arctic cod in winter months (L. Lowry, ADF&G, personal communication).

Since many OCS leases lie within the inshore zone, it is recommended that fish resources in this zone be examined in both summer and winter periods.

Offshore Zone (> 20 m depth)

Little information is vailable on fishes inhabiting the offshore zone of the Beaufort Sea. In offshore areas, demersal marine fishes are important components of benthic and of pelagic food webs. They are probably the major predators of many benthic infaunal and epifaunal organisms. Some species consume large numbers of planktonic crustaceans and are thus tied into the planktonic food web. The importance of Beaufort Sea demersal fishes to higher level consumers is poorly documented. They are probably not utilized to any great extent by marine birds. Two species of seasonally resident marine mammals, bearded seals and spotted seals, feed to some degree on demersal fishes. Arctic cod (Boreogadus saida), more properly termed a bentho-pelagic species, is probably the single most important fish in offshore Beaufort Sea waters. Arctic cod in offshore waters eat copepods primarily. They are in turn eaten in large numbers by marine birds and ringed seals. Belukha whales associated with the offshore pack ice during summer months may also eat arctic cod. A subsistence fishery by coastal residents has traditionally existed for arctic cod, which are caught under the ice during winter months.

During the 1972 U.S. Coast Guard WEBSEC cruise to the Beaufort Sea, Carey sampled offshore demersal fishes by otter trawl over a depth range of 27-464 m. The collections from the 25 trawls contained a total of 22 species of fish, including some new distributional records. A manuscript on Marine Fishes of Arctic Canada including these species is under preparation (McAllister, unpublished manuscript). These species lists and ecological analyses will be available at a later date.

In August 1977, as part of an interdisciplinary cruise on the USCGC GLACIER, sampling was undertaken to provide additional information on the species composition, distribution, abundance, and food habits of offshore demersal fishes.

A total of 17 species (or species group, e.g., Liparis spp.) were identified (Frost et al., 1978). A list of these species with a summary of abundance and distribution is given in Table 6.3. Of the 17 species found in offshore areas and the 34 nearshore species (Fig. 6.21), only 3 species (Boreogadus saida, Lumpenus medius, and Liparis spp.) were found in both areas. The nearshore and offshore fish faunas are obviously very distinct.

The mean number of species per tow was 4 (range 1-9) with, in general, more species per tow in the eastern Beaufort Sea than in the Point Barrow and northeastern Chukchi Sea region. A total of 497 fishes were caught and examined. Three species (B. saida, L. polaris, and I. bicornis) accounted for 68% of those fishes. 39% of all fishes caught were arctic cod, which occurred in 85% of the tows. Several species (B. saida, L. polaris, Liparis spp., A. scaber, and G. viridis) were found throughout the sample area, two (I. bicornis, and E. derjungini) were found only east of Barrow and one (A. olriki) was found only in the vicinity of Barrow. Sufficient samples are not available to examine depth distribution patterns.

The most striking difference between Beaufort Sea epifauna and that of other Alaskan waters was the paucity of fishes in the offshore Beaufort Sea. Not only were the absolute numbers of fishes extremely low in the 1977 collections, but so was the fish biomass relative to invertebrate biomass. In only 8 of 33 trawls was fish biomass greater than 2% of the total catch. In only 4 of 33 was it greater than 3% of the total catch.

Food items of the major species of fish caught in the 1977 trawl survey are shown in Table 6.4. Two species (B. saida, and E. derjugini) fed primarily on planktonic and nektonic crustaceans. All other species fed on infaunal and epifaunal benthos. Gammarid amphipods, polychaete worms, mysids, and caprellids were the primary prey of benthic feeders.

Information Needs

1. A considerably larger number of bottom and mid-water tows is required to delineate geographical and depth distribution of offshore fishes. Major gaps are in the region from the barrier islands to 40 m water depth and in waters over 110 m deep.

2. Food utilization in relation to availability should be investigated for major species (B. saida, L. polaris, I. bicornis).

3. Seasonal changes in distribution, feeding, and reproductive status of B. saida should be investigated. This species is a major trophic link between zooplankton and other vertebrate consumers.

Table 6.3 List of species of demersal fishes collected in bottom trawls in the northeastern Chukchi and Beaufort Seas. Species are listed in order of decreasing abundance as judged by the number of individuals of each species caught, total biomass of each species, and frequency of occurrence.

Scientific Name	Common Name	# Fish Caught	# Stations Sampled	Depth Range (m) of Sea Floor
Boreogadus saida	Arctic cod	194	28	40-400
Lycodes polaris	Canadian eelpout	74	13	40-150
Liparis spp.	Snailfish	28	18	40-400
Icelus bicornis	Twohorn sculpin	68	12	50-130
Eumicrotremus derjugini	Leatherfin lumpsucker	29	11	50-110
Artediellus scaber	Hamecon	30	10	40-70
Gymnelis viridis	Fish doctor	23	11	43-130
Icelus spatula	Spatulate sculpin	14	3	56-64
Lycodes raridens	Eelpout	7	2	64-105
Aspidophoroides olriki	Arctic alligatorfish	19	4	64-400
Gymnocanthus tricuspis	Arctic staghorn sculpin	2	2	50-58
Triglops pingeli	Ribbed sculpin	2	2	105-110
Eumesogrammus praecisus	Fourline snake blenny	2	2	50-62
Arctogadus glacialis	Polar cod	1	1	150
Lumpenus medius	Stout eel blenny	1	1	40
Lycodes mucosus	Eelpout	2	2	50-105
Lumpenus maculatus	Daubed shanny	1	1	44

Table 6.4 Food items of major species of offshore demersal fishes collected in the northeastern Chukchi and Beaufort Seas during August 1977. Items are ranked in terms of importance from 1 (most important) to 5 (least important).

	FOOD ITEMS				
Species	1	2	3	4	5
Boreogadus saida	Copepods	Gammarid Amphipods	Hyperiid Amphipods	Mysids	Chaetognaths
Lycodes polaris	Gammarid Amphipods	Polychaetes	Caprellids	Cumaceans	
Liparis spp.	Gammarid Amphipods	Caprellids	Polychaetes	Hyperiid Amphipods	Isopods
Icelus bicornis	Gammarid Amphipods	Polychaetes	Mysids	Isopods	Euphausiids
Eumicrotreums derjugini	Hyperiid Amphipods	Gammarid Amphipods	Mysids	Polychaetes	
Artediellus scaber	Gammarid Amphipods	Polychaetes	Mysids	Cumaceans	Isopods
Gymnelis viridis	Gammarid Amphipods	Caprellids	Polychaetes	Mysids	
Icelus spatula	Mysids	Gammarid Amphipods	Shrimp	Polychaetes	
Aspidophoroides olriki	Gammarid Amphipods	Polychaetes			

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7. CHEMISTRY AND MICROBIOLOGY

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Introduction

The topics considered in this section on the chemistry and microbiology of the Beaufort Sea include a wide range of subject matters. Predevelopment measurements of hydrocarbon concentration are, of course, quite important, as in an understanding of the ultimate fate of spilled hydrocarbons. In this latter respect the microbiological aspects of the Beaufort Sea come into consideration— particularly because microbial activities, population levels and ratios here are quite different from those elsewhere. The effects on the Beaufort Sea ecosystem as a result of petroleum development will depend largely on food chain or path of energy flow, which must be quantified. Finally, the ambient concentrations of metals and possible increased levels from activities both onshore and offshore need to be considered. Consideration of such a wide range of subjects is obviously difficult, and synthesis of this information in the Beaufort Sea leaves many questions concerning concentrations, extents and processes. These questions have been liasted as "data gaps."

Hydrocarbons

Hydrocarbons in the water column and the sediments of the Beaufort and Chukchi Seas were investigated by Shaw (1977). As yet there are no data from OCSEAP concerning hydrocarbons from petroleum in biota for these areas. Limited information about hydrocarbons in fish (cisco, char, sculpin, etc.) is available from measurements by Shaw of animals collected in Prudhoe Bay in 1974 and 1975 for ARCO. Work showed no evidence of contamination of fish tissue by petroleum.

The analysis of sea water for hydrocarbons is not sufficiently precise to permit detailed comparison of the results for individual stations. Three of 14 surface water samples (BS-1, BS-2, BS-3)collected in the Beaufort Sea showed arrays of petrogenic hydrocarbons characteristic of distillate fuel oil (Table 7.1). The most likely source of this oil is the diesel fuel of the ship from which the samples were collected. These data have been included to emphasize the difficulty of collecting uncontaminated samples from ice-choked waters where even an ice breaker's headway can be insufficient to avoid her own contamination. Eleven other water samples from the Beaufort Sea reveal no evidence of petrogenic hydrocarbons. The analyses of surface water hydrocarbons from the Chukchi Sea were similar. Total extractables were analyzed by gas chromatography and ubiquitous components identified by mass spectrometry. The results obtained in this way do not appear markedly different from those for other Alaskan OCS areas: total concentrations are generally 1μg/kg or less and the compounds present appear to be biogenic.

Earlier work had indicated the presence of aromatic hydrocarbons in the sediments of the Beaufort Sea. This finding was investigated in detail by the analysis of a suite of 20 nearshore sediment samples collected between Barrow and Barter Island. The aliphatic hydrocarbons of these sediments are dominated by biogenic compounds with few abiotic and no anthropogenic compounds.

Table 7.1

HYDROCARBON CONCENTRATIONS IN SURFACE WATER FROM BEAUFORT SEA

Station	Position Latitude	Position Longitude	Date	µg/kg Fraction 1	µg/kg Fraction 2
BS1	70°36.0'N	148°11.0'W	8/23/76	27.16	0.43
BS2	70°36.65'N	148°21.43'W	8/24/76	6.92	0.08
BS3	70°31.28'N	147°31.22'W	8/25/76	0.17	0.19
BS4	70°39.03'N	147°40.54W	8/26/76	1.49	0.10
BS5	70°47.59'N	149°04.35'W	8/27/76	0.27	0.20
BS6	70°57.31'N	149°31.81'W	8/27/76	0.41	0.90
BS7	71°07.99'N	151°19.45'W	8/28/76	0.17	0.07
BS8	71°43.16'N	151°46.72'W	8/29/76	0.14	0.25
BS9	71°34.99'N	152°16.60'W	8/30/76	0.48	0.28
BS10	71°22.14'N	152°20.09'W	8/30/76	0.42	0.04
BS11	71°19.04'N	152°32.40'W	8/31/76	0.42	0.69
BS12	71°07.63'N	152°57.97'W	9/1/76	0.11	0.45
BS13	71°23.5'N	154°23.0'W	9/2/76	0.05	0.83
BS14	71°34.6'N	155°35.2'W	9/2/76	0.18	0.14

µg/kg = µg of sample detected per kg surface water extracted

This is indicated by the dominance of odd chain length alkanes with 23-31 carbon atoms. These compounds, important constituents of higher plant waxes, typically occur in nearshore marine sediments; their source is terrigenous detritus. Biogenic origin is also indicated by the present of heptadecane and pristane, two compounds characteristic of many species of marine plankton.

All samples analyzed were found to contain a complex mixture of aromatic hydrocarbons including 3, 4, and 5 ring systems and 1-10 alkyl carbon substituents. This great complexity suggests that the source of these compounds is abiotic rather than biotic. Their wide geographic distribution and fairly uniform concentration indicate that they are probably not associated with modern industrial development. The detailed distribution of individual compounds within each sample and potential source materials from the North Slope indicate that these aromatic hydrocarbons do not represent an unaltered accumulation from a single source, such as crude oil, coal or diesel exhaust, but instead a mixture with contributions from these and other sources. Assessment of aromatic hydrocarbons in this environment is particularly important because the occurrence of this molecular class is often associated with polluted but not with undisturbed environments. If these aromatics had not been observed prior to further OCS development, their presence might have been attributed incorrectly to that development. A suite of offshore sediments was collected in 1976 by Kaplan (1977). Analyses of these samples were not available for inclusion here.

Nutrient Chemistry

Considerable data have been acquired on seasonal nutrient concentrations and related parameters in the Beaufort Sea coastal waters and in the river water draining into the coastal zone (Alexander et al., 1975). The large pulsed input of nutrients to the nearshore region by spring break-up of the Colville River has been documented by Hamilton (1974) and the accompanying sediment load has been the object of other studies (Arnborg et al., 1967; Walker, 1974).

The coastal marine waters of the Beaufort appear to be a strongly nitrogen-limited system with the maximum standing stocks of inorganic nutrients occurring immediately prior to the onset of the spring ice algae bloom. At this time N:P ratios average about 5:1-7:1, indicating the deficiency of nitrogen since biological assimilation usually requires N:P ratios of approximately 15:1. In contrast, the terrestrial runoff in summer is extremely low in phosphate (often nearly undetectable) and large quantities of dissolved organic nitrogen. Upon mixing with nearshore marine waters, the inorganic nitrogen is rapidly assimilated by phytoplankton populations. able) and large quantities of dissolved organic nitrogen.

The winter season is accompanied by active regeneration of nutrients beneath the ice cover in spite of very low temperatures and high salinities. Ammonification and nitrification rates have been measured in the Colville Delta and Simpson Lagoon waters, and evidence of nitrification processes has been described in Elson Lagoon and Dease Inlet near Barrow (Schell, 1974). An anomalously active zone of nutrient regeneration occurs in the relatively deep and saline delta channels of the Colville River where high organic nitrogen concentrations are biologically mineralized over the winter months to ammonia and nitrate. Oxygen depletion accompanies this microbial activity and Schell (1975) identifies this estuarine habitat as potentially sensitive to disturbances that would alter the organic loading of the waters. It is unknown if similar under-ice environments exist in other river mouths along the Beaufort Sea Coast.

It is suspected that much of the regenerated nitrate and ammonia in coastal waters is transported offshore by thermohaline convective processes during the months of November through March. After the onset of the ice algae bloom on the under-ice surface, however, the removal of nutrients by the attached plants serves as a mechanism by which a net increase in nitrogen and phosphorus stocks occurs in the nearshore zone. An estimate of the magnitude of unpublished algal particulate nitrogen data (Alexander, pers. comm.) and chemistry data (Schell). Standing stocks of ice algal-nitrogen were found to be approximately double and amount expected if assimilation of nitrogen were dependent solely on the underlying water column in the lagoon (194 vs. 90 mg N/m^2). The validity of extending these findings to other areas of the Beaufort Sea coastline needs to be ascertained.

Energy Flow in Beaufort Sea Ecosystems

As in most coastal and estuarine systems, the secondary production in nearshore areas of the Beaufort Sea is dependent upon in situ primary production, augmented by detrital carbon derived from terrestrial sources. In most temperature waters, this secondary production is very closely coupled to the inputs by primary producers, and detritus sources and cycling of carbon and nutrients is relatively rapid. In contrast, there is growing evidence that a sizable fraction of secondary production in the nearshore Arctic is a "fossil fuel economy" with the energy supply being derived in part from modern detrital material and in part from eroded and transported peat. Estimates by Schell (unpublished manuscript) on the significance of peat carbon to the Simpson Lagoon ecosystem showed that between 25-50 percent of the fixed carbon input to the lagoon was in the form of eroded peat from the shoreline. The availability of this carbon source in winter is detrital particulate material may further increase its significance as an energy source on a year-round basis.

Microbiology

Knowledge of microbiology in the Beaufort Sea (Atlas, 1977; Morita and Griffiths, 1977) is primarily limited to the region between Point Barrow and Prudhoe Bay. During summer 1975, when the sea ice cover persisted, microbial populations were found to be higher in the Prudhoe Bay area than in the Point Barrow area (Table 7.2). This geographic pattern was not detected in the winter of 1975 or the milder summer of 1976 (Table 7.2). Bacterial numbers and activity were higher in the sediment than in the water during all seasons. Winter water showed a marked drop in numbers of viable bacteria. Numbers of bacteria in ice were similar to those in the underlying water.

Bacterial population levels in the Beaufort Sea have been described (Kaneko et al., 1978). The numbers of viable bacteria in surface waters are several orders of magnitude higher in the Beaufort Sea than in southern Alaskan OCS areas. Numerical taxonomic studies have shown that the bacterial populations in the Beaufort Sea are distinct from those in temperate areas.

Table 7.2 Microbial Populations in the Beaufort Sea

Station Number	Direct Counts ($x10^6$) Water Winter 76	Water Summer 76	Sediments Winter 76	Sediments Summer 76	Hydrocarbon Degraders Ice Winter 76	Sediments Winter 76	Sediments Summer 76	Water Winter 76	Water Summer 76
1	0.15	0.37							1
2	0.13								
3	0.17								
4									
5	0.22		1,000			17	15		
6	0.19		770				30		
7	0.10				0.1	25		0.1	4
8	0.14		50			0.1		0.2	
9	0.15		230		0.3	3.7		0.2	
10	0.17		1,900		0.4	1.0		0.2	2
11	0.27	0.35		9,900	0	0.4	17	0	
12	0.17				0	4.7		0.3	
13	0.12	0.16	1,300	9,800	0.1	7.8	16	0.2	4
14	0.12	0.16	1.300	7,500	0.2	1.6	26	0.2	5
15	0.17	0.30	1.600	6.700	9.0	0.7	45	20.2	5
16	0.18	0.46			19.5			0	3.1
17	0.14	0.32		26,300	0.1		15	0.1	20
18		0.47		11,100			55		2,100
19		0.61		13,500					
20		0.50		12,800			430		
21	0.26	0.34	2.200	2.400	2.2	16	400	0.6	33
22					1.1	11			
23	0.13		1,600		0.3			0.4	
24		0.44		4,800			210		
25	0.14		1,700		0				
26		0.37		26,700		3.3	470		1,000
27	0.11		1,700		0.3	0.1			
28	0.12				0.1			0.1	

Beaufort Sea bacteria are clearly adapted to growth at low temperatures. Orange and yellow pigmented bacteria, tentatively identified as flavobacteria species, are dominant in surface waters during summer. Pigmentation appears to be an important adaptive feature of bacterial populations during periods of constant sunlight.

Addition of petroleum hydrocarbons results in rapid and major shifts in bacterial populations. Numbers of hydrocarbon-utilizing and heterotrophic bacteria increase in response to hydrocarbons (Horowitz and Atlas, 1977). The diversity of bacterial populations decreases in response to petroleum hydrocarbons; the dominant bacterial populations in surface water, after exposure to petroleum hydrocarbons, are different from the normal unperturbed dominant bacterial populations (Horowitz and Atlas, in prep.). Pseudomonas species appear to dominate the hydrocarbon-utilizing populations two months after introduction of Prudhoe Bay crude oil in nearshore surface waters near Point Barrow.

Most of the work that has been completed by Morita and Griffiths on relative microbial activities in the Beaufort Sea has been summarized in a recent article (Griffiths et al., 1978). Microbial activity in the sediments of Prudhoe Bay was higher than that found in Barrow when measured using glutamate uptake. Within Prudhoe Bay, the microbial activity in water was inversely related to the distance from shore. Relative microbial activity in offshore waters showed no significant geographical trends. In the bays and the areas behind the barrier islands, the sediment had about 400 times the activity of the entire overlaying water column. On an equal volume basis, the activity in the sediment was, on the average, four orders of magnitude greater than that found in water. A comparison of microbial activity in the winter was roughly one-tenth of that found in summer. In the winter the percent respiration was much higher than that found in the summer. These data, along with the incubation temperature studies, suggest that quality and/or quantity of nutrients available in the water column are significantly different during these two seasons. Studies on melted ice and field observations in the ice pack suggest that melting ice has very little effect on microbial activity in surface waters under natural conditions.

Beaufort Sea sediments from the 1977 USCGC GLACIER cruise, collected between Point Barrow and the Canadian/US border, were analyzed for microbial activities. It was found that both the rates of nitrogen fixation and relative microbial activity were highest in the area near Point Barrow. It was also observed that crude oil degradation potentials were highest in the area to the east of Prudhoe Bay. In general, the levels of microbial activity that we have observed in the Beaufort Sea are as high or higher than those observed in more temperate marine waters.

Hydrocarbon-degrading microorganisms enumerated by Atlas and Roubal (1977) were found in higher numbers in summer than winter (Table 7.2). During winter high numbers of hydrocarbon utilizers were found in an area of Pitt Point. In summer, numbers near Prudhoe Bay were higher than for other regions. Numbers of hydrocarbon degraders determine in part the ability of an ecosystem to tolerate input of hydrocarbons and may also reflect previous exposure of the ecosystem to hydrocarbons. Oil spilled under ice shows depressed rates of loss of even "volatile" hydrocarbons (Atlas et al., 1978). Light hydrocarbons remain in the oil under ice for weeks. No biodegradative changes have been detected during a one-month exposure under ice. Little is known as yet about the fate of oil in Beaufort Sea sediment. Also, little is known about incorporation rates of oil into sediment from surface or subsurface oil spills.

Metals

Metal distribution in the sediments of the Beaufort Sea has been mapped by Barnes (1974), but data are sparse and qualitative, especially within the 20 20 m contour. The distribution of metals would seem to have close correlation with sediment type.

Concentration of Fe, Cu, Zn, Ni, V and Cr have been measured on gross sediments as well as on the non-lithogenous or the "readily mobilized" (acetic acid-hydroxylamine hydrochloride extracts) phases of sediments from deltaic, continental shelf, continental slope and abyssal regions of the Beaufort Sea by Naidu (1977). The "readily mobilized" phase consists of the absorbed, exchangeable and ferrimanganic hydroxide components of the sediment. To impart further understanding of the heavy metal geochemical partitioning patterns of the sediments, additionally Mg, K, Na, Rb, Li, grain-size distributions, organic carbon, carbonate and clay mineral composition of these sediments were determined (Naidu et al., 1972).

The average concentrations (μg/g) of Fe, Mn, Cu, Zn, Ni, V, in the Beaufort Sea sediments are 22000, 394, 30, 90, 42 and 98, respectively. It would seem that there is a progressive enrichment of all the metals in the sediments from the deltaic to the deep-sea region through the continental shelf and slope. The average total concentration (μg/g) of Fe in the deltaic deposits is 18900, and those of Mn, Cu, Zn, Ni, Co, Cr and V are 289, 26, 91, 36, 29, 57 and 55, respectively. Further analysis of Fe, Mn, Cu, Ni, and Zn on 10 short box-core samples do not indicate any significant stratigraphic variations in the metal concentrations in all but one of the core samples (Naidu, 1976).

A few tentative conclusions have been reached on the relative quantities of various heavy metals that can be readily mobilized from sediments of the Beaufort Sea (Naidu, 1976). These conclusions are based to a large extent on the "circumstantial evidence" manifested by the correlation coefficient data and existing knowledge on the geochemical behavior of metals. They are, therefore, tentative and must be applied with caution while speculating about the chemical impact of perturbations relating to oil development activities in the shelf region of Beaufort Sea.

A variety of environmental materials collected in 1972-73 from the north slope slope region were analyzed for Hg content by neutron activation (Weiss and Crozier, 1972). Studies of Hg distribution have been performed by Burrell et al. (1977). The Hg concentration in zooplankton was 37 ppb (parts per billion). Concentrations in snow ranged from 4 to 46 ppt (parts per trillion) with an average of 13 ppt. For water gathered 40 km upstream of the Sagavanirktok River mouth and the Umiat and Gubik sections of the Colville River, Hg concentrations of 17 and 19 ppt were determined.

The Hg content of Beaufort Sea water was determined for samples collected between 146° - 151° W. Of interest is the greater concentration of Hg in the water recovered from stations occupied at 151° W (21 ppt) as compared with the stations eastward of this longitude (13 ppt). Temperature data (Hufford, personal communication) indicate that the water from the Chukchi and Bearing Seas also had penetrated to 151° W at the time the stations were occupied. The difference in Hg concentrations may, therefore, reflect varying concentrations of this element between the more eastern part of the Beaufort Sea and the Chukchi-Bering Sea water masses.

The Hg content of sediments from the Sagavanirktok and Colville Rivers was 112 and 119 ppb. Marine sediments collected on the shelf, the slope and in the basin between 143° and 154° W, with the exception of an area on the shelf between 143° to 146° W, averaged 100 ppb in Hg. These values are reasonably consistent with the river sediments that drain into the general area. The concentrations were only 40 ppb on the shelf between Barter Island and the Canning River. These lower concentrations probably reflect input from this river.

Another set of water and sediment samples collected from the Chukchi and Beaufort Seas (1975) were analyzed for their Hg content by cold vapor atomic absorption spectrophotometry with emphasis upon speciation. The concentration of reducible Hg in these waters ranged from 6 to 32 ppt. Photooxidation did not result in further increases in Hg content. The range of Hg values for Chukchi Sea sediments was between 10 and 31 ppb with a mean of 17 ppb. Results for the Beaufort Sea sediments were consistent with the values for the samples previously collected. The Hg concentration ranged from 60-169 ppb (average 100 ppb).

For all samples, elemental and readily reducible Hg in the sediments accounted for less than 2% of the total. The fraction of reducible and organically bound Hg released into seawater was less than 5%. Thus, if the sediment was reworked, as in a dredging process, probably only this fraction of Hg would be mobilized into the receiving sea water.

To estimate the atmospheric influx of elements into the north slope region, snow deposits were analyzed by Weiss for a suite of metals. The samples were collected (February, 1974) in a north to south transect with the Barrow gas well as reference point. Seven samples were gathered, and but for a single 30-mile span from 60-90 miles from Barrow, all were collected in 15-mile increments. Samples were neutron irradiated and instrumentally analyzed for activation products of Na, Mg, Al, Ca, V, and Mn. Zn and Cd were analyzed directly by atomic absorption spectrometry and Hg by an activation technique involving a radiochemical separation (Weiss and Crozier, 1972).

The average concentration (μg/l) for Na, Ca, Al, V. Mg, Mn, Zn, Cd and Hg were 107, 71, 39, 0.99, 1.11, 0.09 and less than 0.010, respectively. Variations in the concentrations of elements occurred from site to site accompanied by a decided covariation between the Ca, Mg, Mn, Al and V. The pattern for Na suggested a maritime effect; the concentrations decreased with the distance from the coast. For Zn, Cd and Hg the patterns were dissimilar.

A crustal encrichment factor (EF), defined as the concentration ratio of an element to Mn in the sample compared to this same ratio in crustal material, was calculated on the basis of average crustal abundances. For Mn, Ca, Al and V whose spatial deposition pattern was comparable, the EF's ranged close to unity. The relationship was taken as evidence of their common lithospheric origin. On the other hand, the enrichment factors for Zn, Cd and Hg suggested significant input from other sources, possibly induced by man's activities. An analysis of data derived from ice deposited in Greenland and the Antarctic before this century (Weiss et al., 1971, 1975) indicates that the relationship holds for this instance as well (Weiss, in preparation). Thus the atmospheric enrichment of certain elements occurs as a natural process and demands accountability in interpretation of the chemical composition of contemporary reprecipitation.

Information Gaps

Data gaps identified were:

1. Long term fate of oil in the Beaufort Sea, especially in sediments or trapped under ice. Studies have been initiated to examine the rate of oil degradation under ice and in sediments.

2. The effects of various treatment methods, such as burning or dispersants, on the eventual fate of petroleum hydrocarbons in the Beaufort Sea. This is in addition to questions about the effects of dispersant-petroleum mixtures which need to be answered in order to evaluate the usefulness of the former in the Beaufort Sea. To our knowledge there is no available dispersant which has been formulated for optimum performance at Beaufort Sea temperatures. Some dispersants must be diluted with hydrocarbon solvents for use at low temperatures. Clearly, sea trials of dispersants in the Beaufort are necessary.

3. The role of microorganisms in the food web in the Beaufort Sea and the effects of crude oil on energy transfer from microorganisms to higher trophic levels.

4. Long and short term effects of crude oil on heterotrophic bacterial populations and nitrogen cycling in marine sediments.

5. Knowledge of microbial distribution and activity east of Prudhoe Bay.

6. Knowledge of natural nitrogen cycling in the sediments of the Beaufort Sea.

7. Effects of dispersants alone and in combination with petroleum on microbial populations in the Beaufort Sea.

8. Effects of drilling muds with bactericides on essential microbial activities.

9. Background information about hydrocarbons in Beaufort Sea biota. The need for this information is greater than previously thought because of the finding of aromatic hydrocarbons in nearshore sediments. It is important to determine whether these compounds (some of which are known to be carcinogenic) are accumulating in animals or whether mechanisms to remove the aromatics are present.

10. Knowledge of effects of petroleum on Beaufort Sea organisms. Very little information is presently available concerning the lethal and sublethal impacts of oil on these organisms. Effects work from lower latitude studies is not necessarily indicative of the situation in the Beaufort and more information is needed about quantative aspects of the sensitivity to oil of Beaufort Sea organisms.

11. Knowledge of the distribution of the following metals in the Beaufort Sea: a) Cd and Pb in sediments; b) V, Mn, Cr, Cu, Cd, Pb, Ni and Zn in biota; c) V, Mn, Cr, Cu and Cd in the water column.

12. Detailed inorganic and organic geochemical studies relating the Beaufort Sea sediments to individual heavy metals, with special reference to the physiochemical and biological conditions of the depositional environments.

13. Role of clay-sized particles as a source or sink for heavy metals, especially as these particles move from fluvial to nearhsore environments, through water columns.

14. Areas of intensive nutrient regeneration under winter ice cover with accompanying oxygen depletion that are sensitive to disturbance which might significantly alter the biological oxygen demand of the system. In particular, areas such as the deep channels of the Colville, Meade, and other river deltas may be susceptible, and the hydrography of these areas is poorly described or unknown.

15. Spatial and temporal variability of ice algae populations and the magnitude of "nutrient pumpint" by these populations as yet unknown. This data gap is being addressed.

16. Importance of detrital carbon in the energy flow of the nearshore ecosystem is unknown, but under investigation. Shoreline stabilization and causeway construction effects which would alter the shoreline erosion rates or affect the input of freshwater-transported detritus to areas of currently high detritus-based production need to be examined carefully.

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PART II

INTERDISCIPLINARY ASPECTS OF LIKELY OCS IMPACTS

8. SPECIES, HABITATS AND PROCESSES SENSITIVE TO OCS DEVELOPMENT

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Introduction

The Alaskan Beaufort seacoast is a mosaic of marine, shoreline and tundra habitats distributed over a length of several hundred kilometers. These habitats differ in abundance, in importance to wildlife and humans, and in resistance to disturbances arising from development. Some habitats, such as saltmarsh, are very important to wildlife and are easily damaged by OCS development, but are limited in areal extent and are dispersed in many small patches along the coast. It is not possible to depict all the locations of sensitive habitats on a simple map. Instead, we have assigned different sensitivity ratings to a list of habitats, and have noted the seasonal variations in sensitivity within each habitat.

In several cases, specific areas can be designated as especially important to wildlife and humans, and these are noted in Figures 8.1 and 8.2. Within these areas, habitats designated as more heavily used than others should be excluded from disturbances whenever possible. In the event of compelling cultural or economic reasons, development within these sensitive areas should proceed with regard to priorities set by reference to the lists of sensitive habitats, species and seasons. Some disturbances (noise, transport over lagoon ice) are limited in duration; others (gravel removal, drainage changes) may last through many seasons. Our notes on seasonality of sensitive habitats refer to seasons in which the effects of a disturbance may be felt, rather than just the season in which the original disturbance occurs. More detailed descriptions of the high sensitivity areas in Figures 8.1 and 8.2, with the justifications for their inclusion, are presented in the earlier disciplinary sections of this report and in the OCSEAP annual report series.

Under the separate discussions of key biota, we list species which merit special attention in research and management. These are chosen for a variety of reasons, including high population concentrations along the Beaufort coast, vulnerability to potential disturbances such as oil spills, scarcity in North America, or importance to humans for subsistence use.

Finally, we summarize several biological processes, discussed more fully in earlier sections of this report and considered to be important in determining the productivity of biological systems along the Beaufort coast. These also are difficult to localize on maps and our understanding of some of them is marginal; they suggest important areas for continuing study.

Table 8.1 Sensitivities of Beaufort Coast Habitats

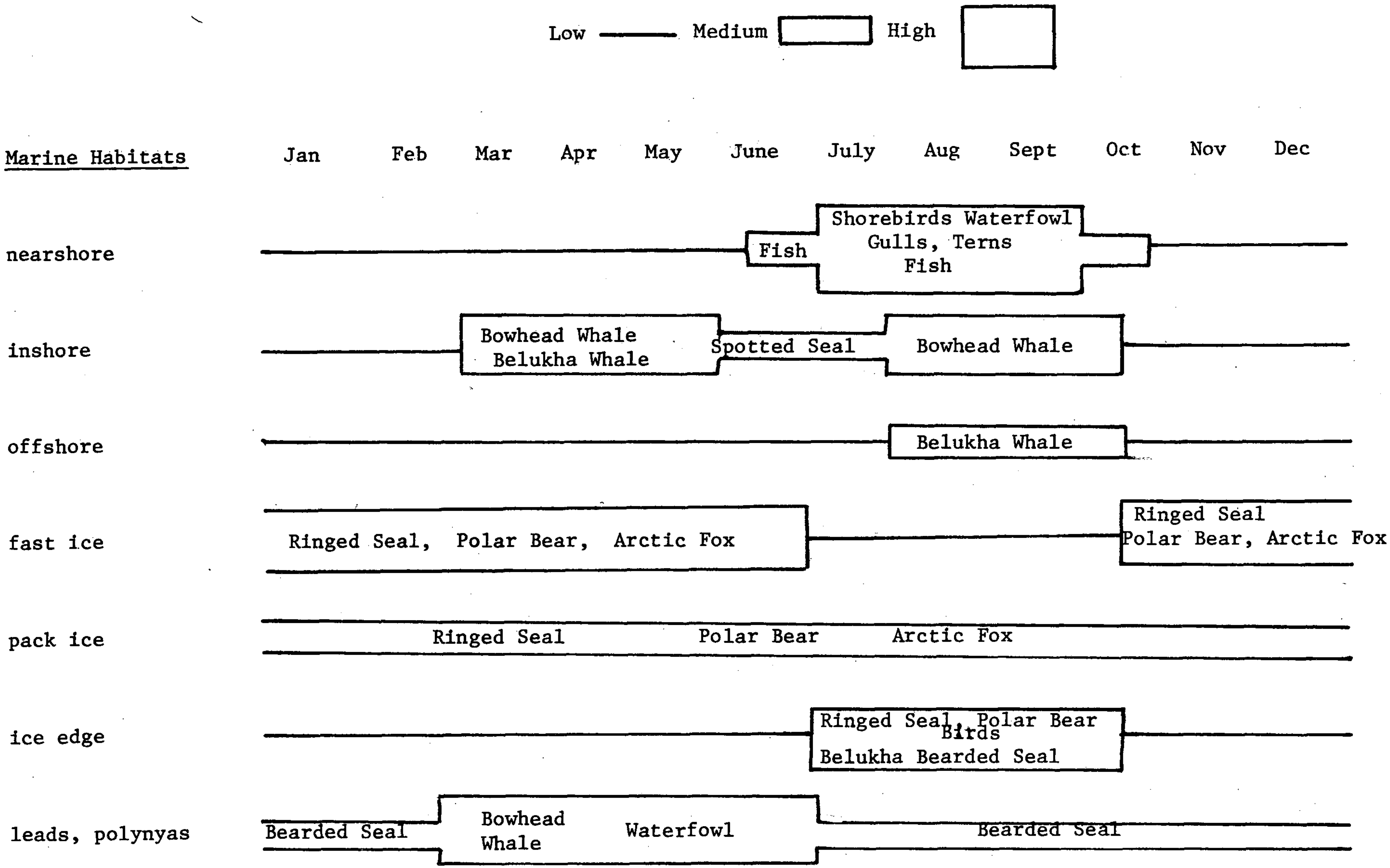
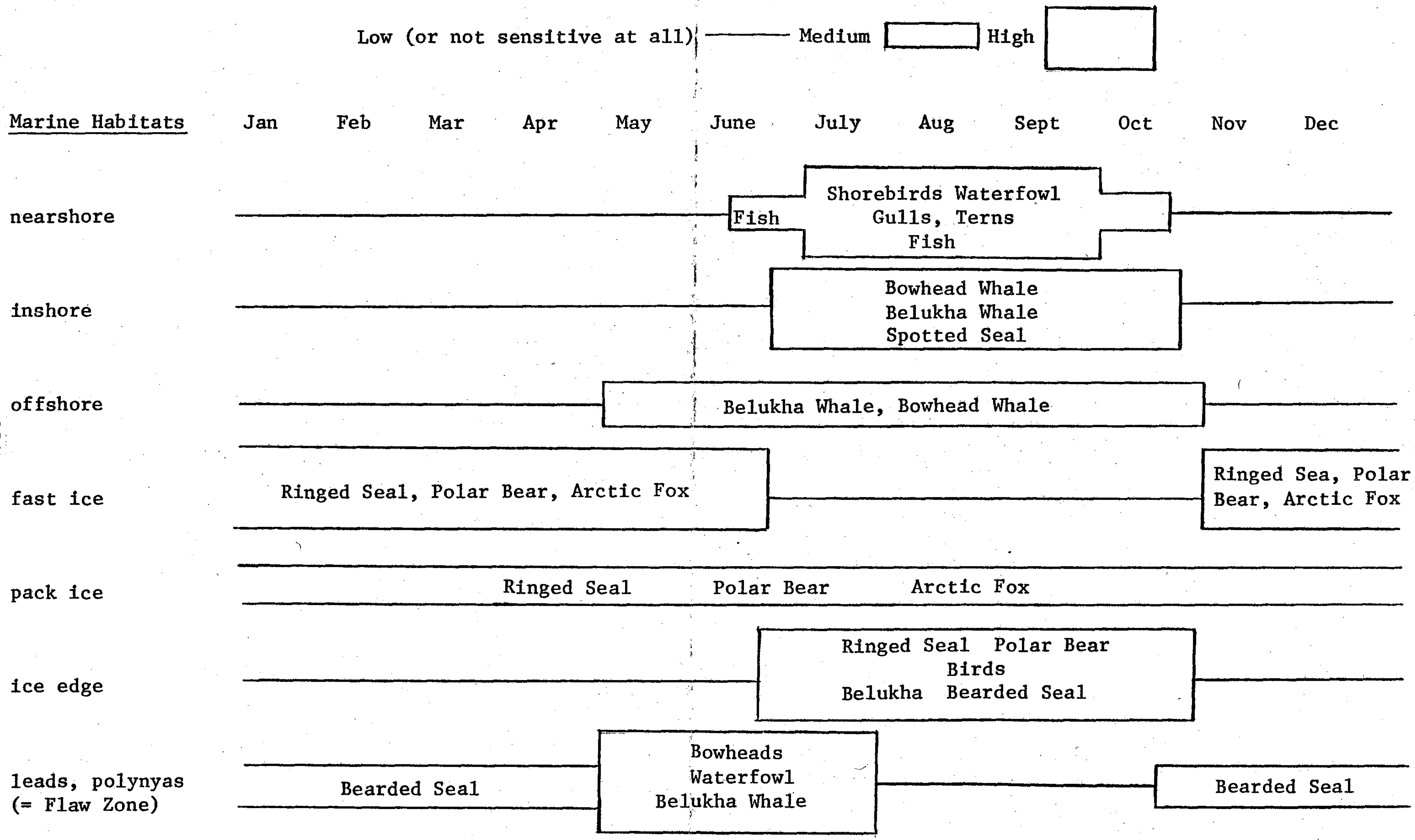


Table 8.1 Idealized Sensitivities of Beaufort Coast Habitats



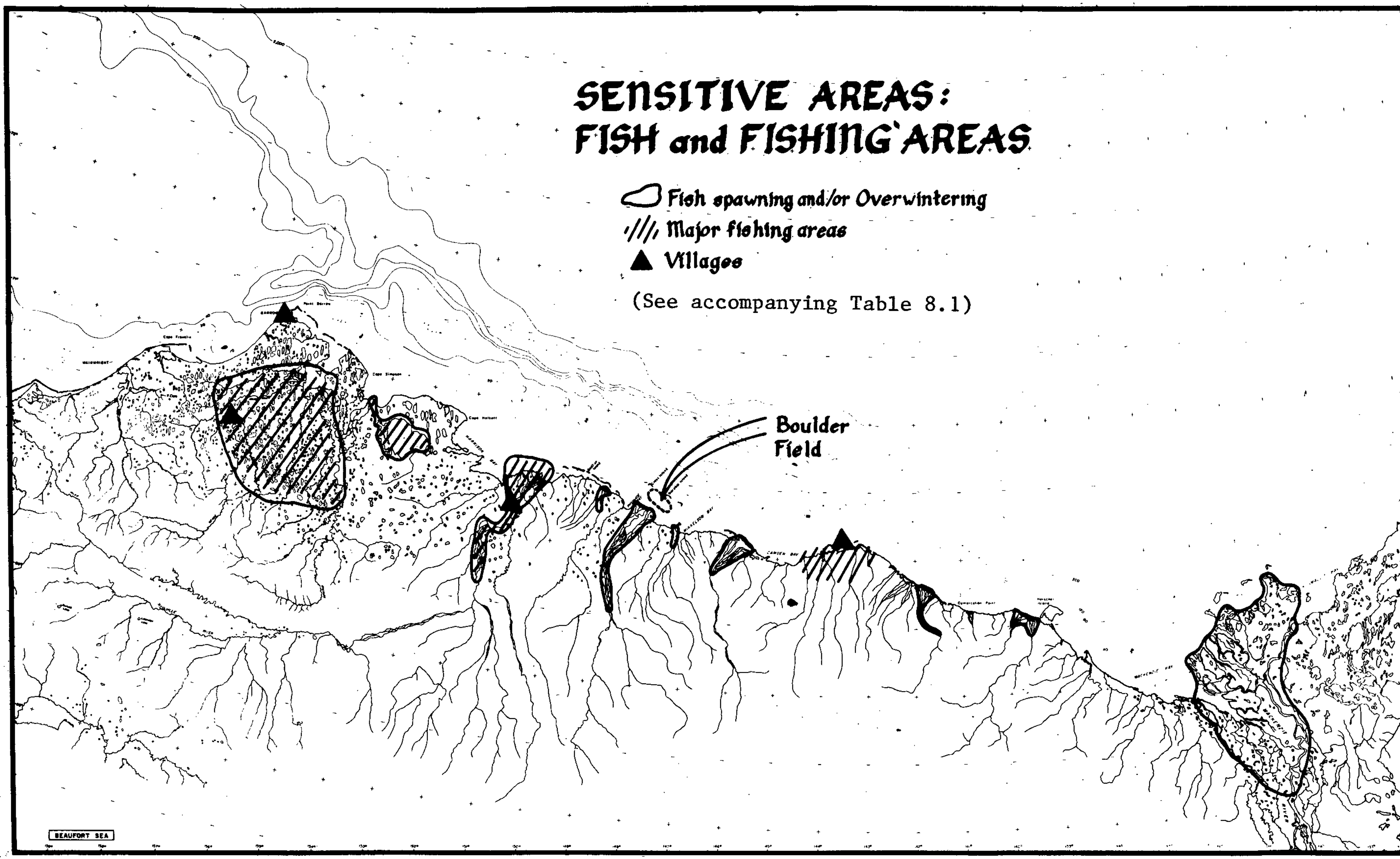
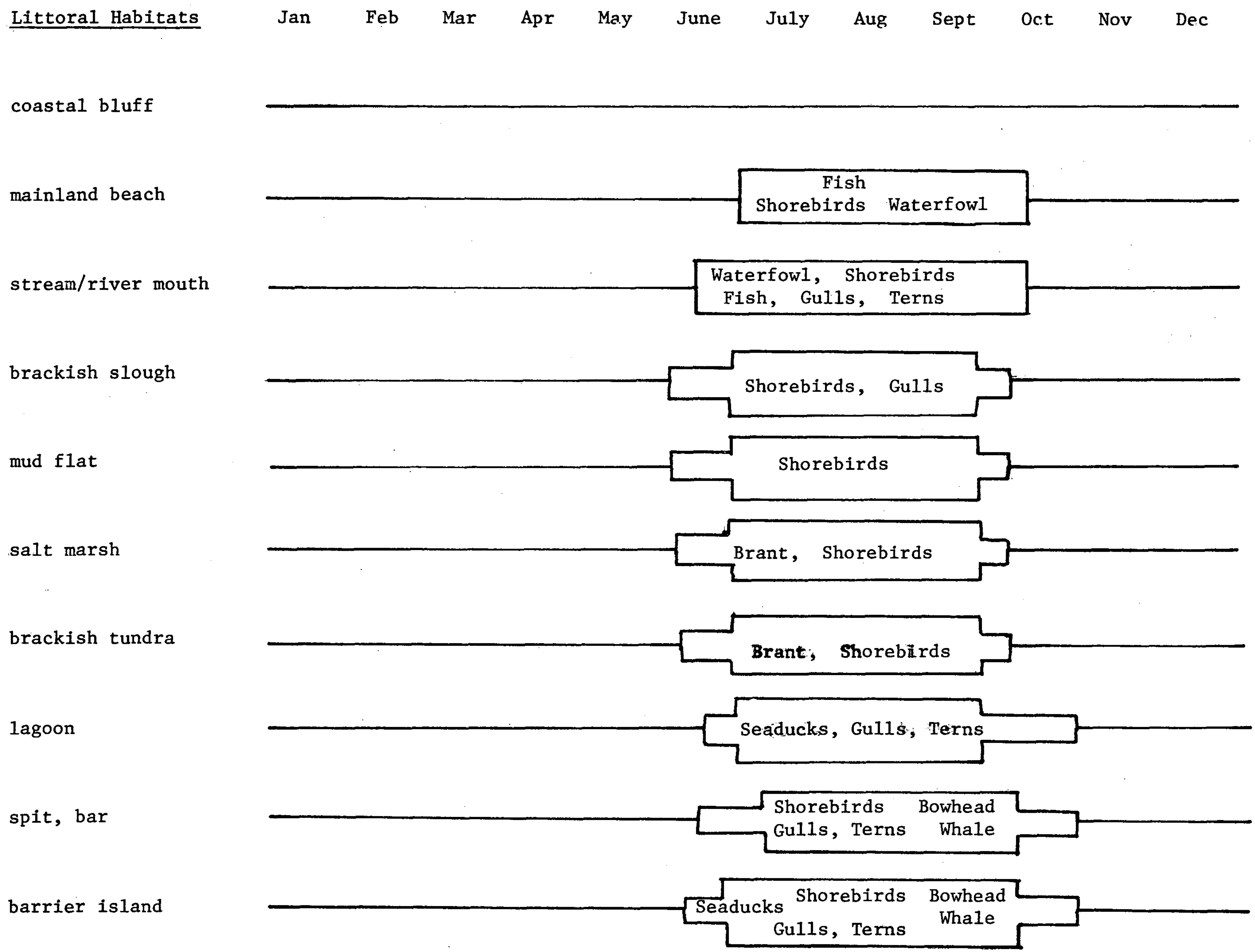
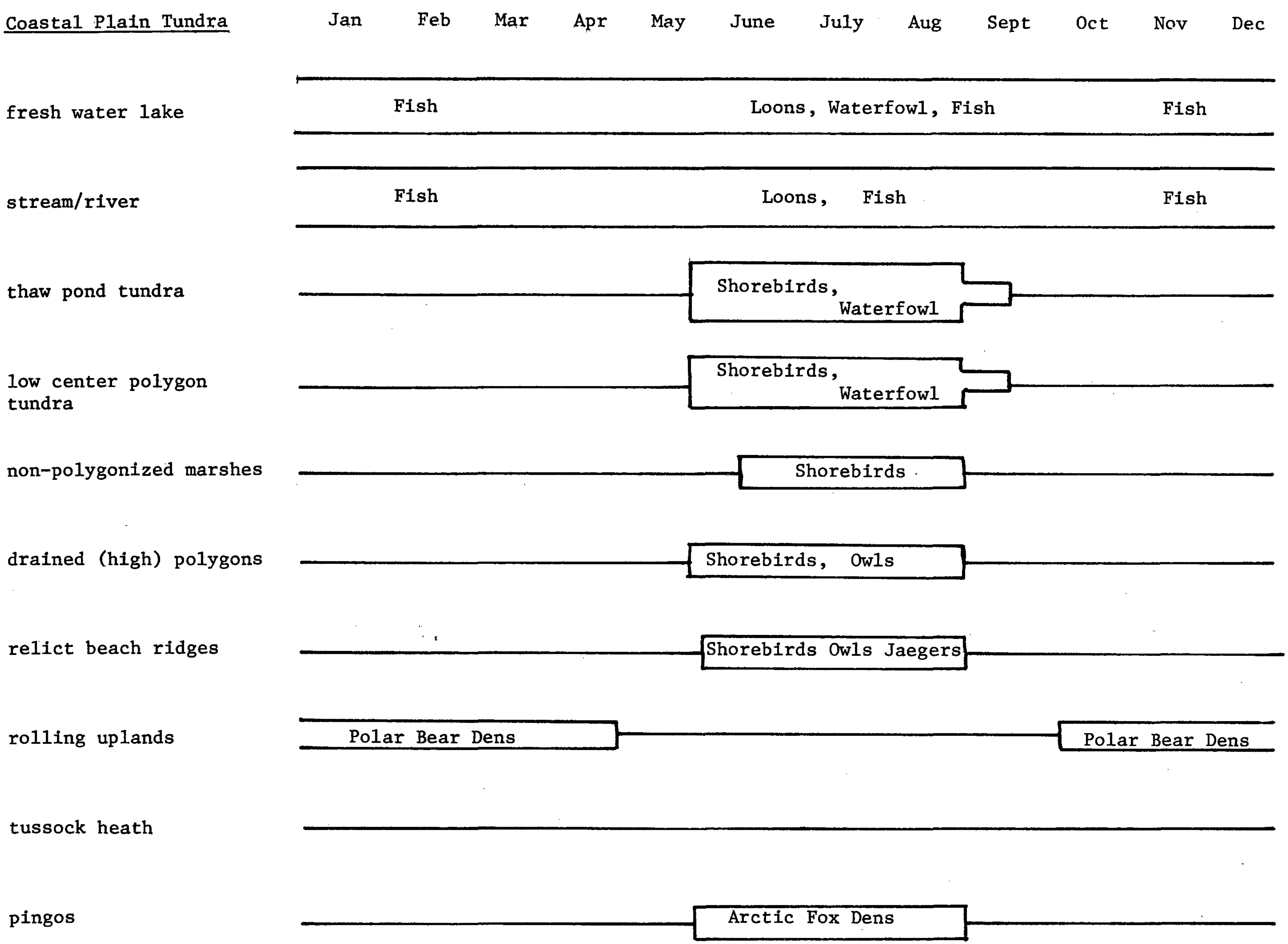


Figure 8.1 (Bendock et al.)


Littoral Habitats
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
coastal bluff
mainland beach
Fish
Shorebirds Waterfowl
stream/river mouth
Waterfowl, Shorebirds
Fish, Gulls, Terns
brackish slough
Shorebirds, Gulls
mud flat
Shorebirds
salt marsh
Brant, Shorebirds
brackish tundra
Brant, Shorebirds
lagoon
Seaducks, Gulls, Terns
spit, bar
Shorebirds
Gulls, Terns
Bowhead
Whale
barrier island
Seaducks
Shorebirds
Gulls, Terns
Bowhead
Whale


Coastal Plain Tundra
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec
fresh water lake
Fish
Loons, Waterfowl, Fish
Fish
stream/river
Fish
Loons, Fish
Fish
thaw pond tundra
Shorebirds, Waterfowl
low center polygon tundra
Shorebirds, Waterfowl
non-polygonized marshes
Shorebirds
drained (high) polygons
Shorebirds, Owls
relict beach ridges
Shorebirds Owls Jaegers
rolling uplands
Polar Bear Dens
Polar Bear Dens
tussock heath
pingos
Arctic Fox Dens

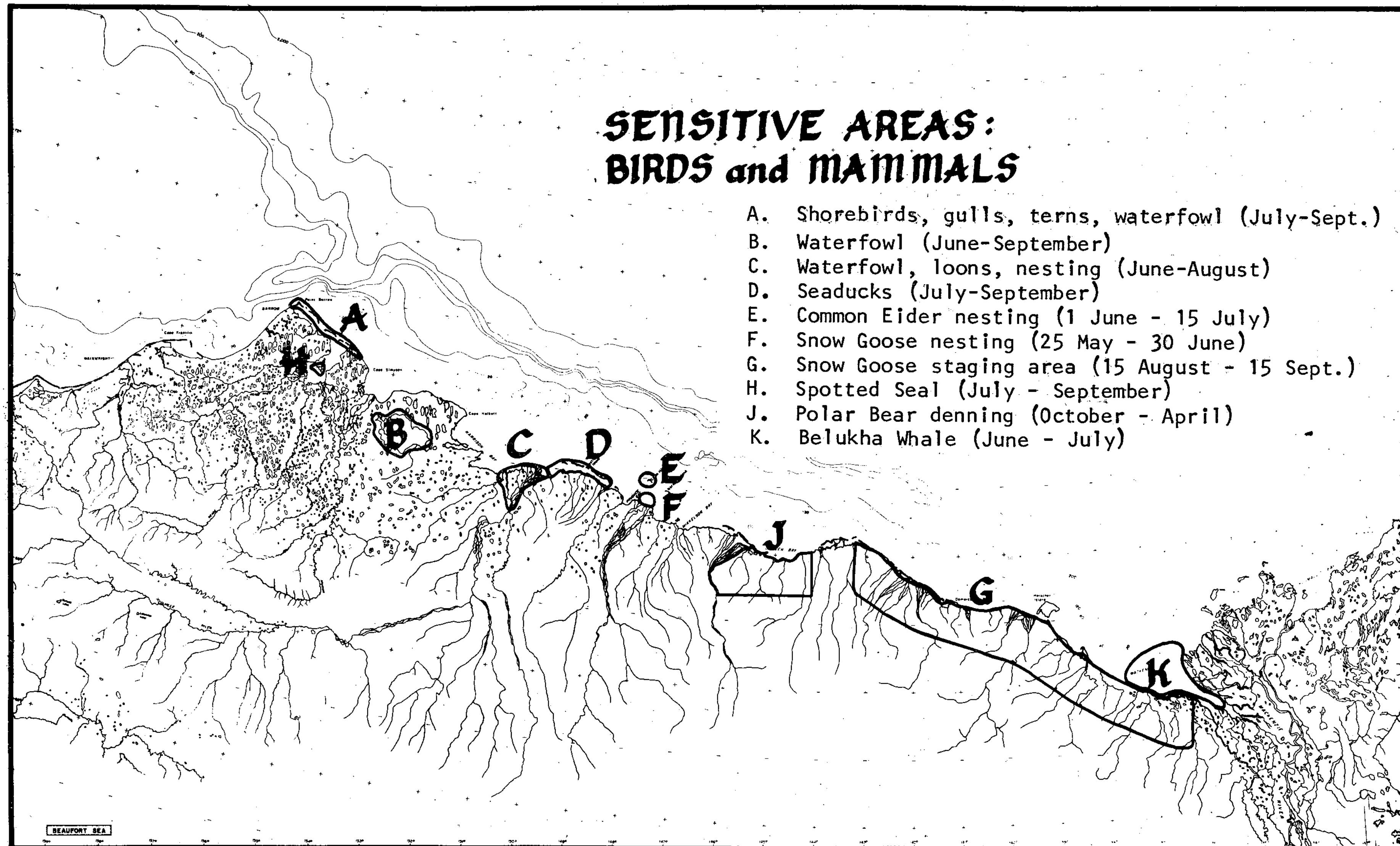


Figure 8.2 (Burns et al.)

Essentially no area or habitat within the Beaufort Sea coastal region is completely insensitive, as any major development would affect some species. We suggest three categories to convey a scale of relative sensitivity so that the impact of development may be minimized. High sensitivity implies that perturbations within an area or habitat are likely to affect relatively large numbers or proportions of one or more species (usually fish, birds, marine mammals or humans). The magnitude and importance of the effects depend on the same considerations as discussed below for key species, as well as the extent of the region or habitat in question, its resistance to disturbances, and the timing of the disturbances. Moderate and low sensitivity are two lower categories on the same scale.

Benthos

On a large scale, the entire coastal zone from the shoreline out to about 30 m depth can be considered sensitive with respect to benthic invertebrates and therefore to the waterfowl and marine mammals which utilize this food source. The nearshore (0-2 m depth) and inshore (2-20 m depth) benthic environments are potentially very susceptible to oil pollution. In shallow open water, wave dynamics can mix suspended oil down and into the sediments. Under-ice movement of oil may bring it into contact with the shallow sea floor. We do not know the probable effects on arctic benthic invertebrates or on recruitment and repopulation rates of different species in disturbed areas under different conditions of depth, substrate and oil exposure.

We identify one area in particular as a region of high sensitivity with respect to benthos (Figure 8.1): the shallow water area near Narwhal Island is unusual along the Beaufort coast in that the bottom is a boulder field supporting considerable beds of algae (Barnes et al., 1977). Preliminary surveys indicate that the invertebrate fauna associated with this substrate is unusually rich compared with other segments of the Beaufort coast*, compelling us to believe that more information is required before development proceeds. Other areas found to have high abundance of benthic invertebrates within the nearshore and inshore zones include the Barter Island regions, Mackenzie River delta, northeastern continental shelf, and the Eskimo Lakes in Canada.

Microalgae and Plankton

Ice algae in the shallow coastal zone provide a major component of primary production in April and May. This constitutes a key resource in the entire trophic structure of the Beaufort coast ecosystem, providing food for grazing amphipods which become prey of fish and birds. Environmental perturbations which affect circulation or solar radiation reaching the ice algae might reduce the productivity of this system.

Phytoplankton in the water column will be affected by local oil spills but impacts may not be long-term, with populations probably recovering within one season after the original disturbance dissipates. Potential changes in species composition of the phytoplankton could be detrimental to herbivorous zooplankton.

* Editor's note: OCSEAP studies in this area are in progress by A.C. Broad et al. (RU #356).

No areas of high sensitivity for zooplankton are known. Yet areas where large concentrations of birds forage on zooplankton (especially Barrow Spit, the Plover Islands and Simpson Lagoon) may be sensitive in that higher trophic levels are especially dependent on zooplankton in these areas. Key species groups of zooplankton, based on abundance and use by fish, birds and marine mammals, include several species of copepods, amphipods, mysids and euphausiids (Connors and Risebrough, 1976, 1977; Divoky, 1977; Lowry et al., 1977; S. Johnson, pers. comm.; see also 1978 OCSEAP annual reports by the same authors). Many vertebrate predators are flexible and opportunistic when confronted with changing species composition in a prey community, switching primarily to those prey species which are most abundant. They may depend closely on a sufficient population of zooplankton as a group of species; however, identification of any particular "key" species is difficult and may be misleading.

Fishes

The overwintering areas of fish provide some of the best examples for certain habitats or locations to be designated "critical" to the survival of the population in question. Freshwater and anadromous fish can successfully overwinter only at specific locations where there is an adequate and dependable supply of unfrozen low salinity water throughout the prolonged arctic winter, usually in deep or spring-fed channels in North Slope rivers (Craig and McCart, 1974; Kogl and Schell, 1974; Mann, 1975; Craig, 1976; Bendock, 1976, 1977). For anadromous fish, which frequent coastal waters in summer, overwintering generally occurs in deltas of the larger Beaufort Sea drainages (Figure 8.1), but specific sites within these deltas are generally not known.

Overwintering areas are extremely vulnerable to industrial activities such as gravel mining, water removal and seismic testing. Since overwintering areas are few in number, it is conceivable that the numerical size of anadromous and river-dwelling fish populations in the Arctic may be determined by the extent and availability of suitable overwintering habitat. The high densities of fish in overwintering areas also make them vulnerable to deleterious effects of hydrocarbons and other pollutants.

Overwintering and spawning areas for marine fishes have received little attention to date. It is not known whether these species are widely dispersed in winter or restricted to particular habitats under nearshore ice.

During the open-water season, anadromous and marine fish utilize nearshore habitats extensively as feeding and rearing areas. Although we do not know if particular sites along the coastline are more sensitive than other sites during this season, some generalizations regarding the relative importance of various habitats can be made. First, habitat preferences differ between species: some important anadromous species (arctic char, whitefish and ciscos) are restricted to nearshore waters (typically less than 2 m water depth), while arctic cod, an important marine species, is widely distributed in offshore waters. Second, within the nearshore and inshore environments, preferred habitats for fish are generally the mainland and island shoreline, with lower densities occurring in lagoon centers or other areas distant from shorelines. Third, while large fish migrate considerable distances along the coastline, it appears that small juveniles of the anadromous species remain near their rivers of origin. Thus nearshore densities of small anadromous fish are greatest near large rivers such as the Colville.

Birds

Habitat use by bird species is an important criterion in determining the sensitivities of habitats listed in Table 8.1. In general, removal or degradation of any habitat will affect birds using the habitat. In most cases, if the perturbation is limited in extent, it will not produce a critical impact on Beaufort Sea or world populations of any species. However, local populations of breeding birds or concentrations of migrating or molting birds might be seriously affected. We do not know how flexible most species may be with respect to choice of areas for nesting, molting or migrational staging; many factors may determine the greater suitability of one area over another.

In selecting sensitive areas, we must note that the Beaufort coast to date has been unevenly studied. Areas chosen as highly sensitive are in many cases the areas best known. Although these now represent our best judgment of the most sensitive regions, further work may identify additional, equally vulnerable sites. Seven sensitive areas for birds are shown in Figure 8.2, selected for reasons of unusually high densities of breeding, molting or migrating birds during part of the summer. Specific reasons for each choice are summarized in the table accompanying Figure 8.2. Three of these areas (E, F, G) require additional explanations.

Acknowledging that waterfowl, gulls and terns may be able to change nesting sites to alternative islands in the event of development, we do not know what changes in nesting success may follow, and therefore consider Howe Island and Cross Island to be especially sensitive (Figure 8.2) because they currently support the largest concentrations of nesting Snow Geese and Common Eiders among the Alaskan Beaufort islands (Gavin, 1976). To avoid disturbance of these nesting colonies, we recommend that airplane and helicopter overflights be restricted to minimum elevations of 1500 feet near these island from 20 May to 20 July.

In late summer, Snow Geese numbering up to a few hundred thousand birds leave nesting grounds in Canada, and in some years feed for several weeks on the coastal tundra as far west as the Arctic Wildlife Range in eastern Alaska (Koski, 1977). Precise locations of staging areas within this large region are variable from year to year. The geese are extremely sensitive to disturbance at this time (Schweinsburg, 1974). We recommend restricting aircraft overflights in this area to minimum elevations of 3000 feet between 15 August and 15 September.

Farther east, in Canada, large areas of the Mackenzie River delta support high densities of nesting waterfowl of many species (Barry, 1976). Although it is not depicted in Figure 8.2, we consider this extensive region an area of high sensitivity for birds.

Several species of Alaskan Beaufort coast birds can be emphasized as particularly sensitive because of the large numbers, relative to total populations, occurring in situations which render them especially susceptible to potential effects of oil development. We provide the following list of species which should be monitored closely as development proceeds.

Brant
Eiders (4 species)
Oldsquaw
Red Phalarope
Nothern Phalarope
Ross' Gull
Sabine's Gull
Arctic Tern

Mammals

Habitats and areas considered sensitive for mammals of the Beaufort Sea and the Beaufort coast differ considerably between species. Seasonal habitat information is summarized in Table 8.1, and 3 sensitive areas (H, J, K) are shown in Figure 8.2. Brief discussions of principal Beaufort species follow.

Ringed Seal

The fast ice zone is a sensitive habitat for ringed seal populations, with a substantial part of the Beaufort Sea population spending the months when there is sea ice cover in this zone. Extensive feeding occurs during winter months under the ice. (Concentrations of arctic cod, an important prey species, also occur there.) Pregnant females establish lairs under the snow in March and April. Pups spend the first 4-8 weeks in these lairs, and are potentially very sensitive to oil under the ice. Principal sensitivity in ringed seals therefore arises from: (1) displacement from preferred stable breeding habitat; (2) direct oiling of pups; (3) trophic disruption of key prey species.

Spotted Seal

Oarlock Island in Admiralty Bay (Figure 8.2) is used as a hauling-out ground by up to 350 Spotted Seals during open water months. Since this represents the largest concentration of this species known in the Beaufort, we designate Oarlock Island as a high sensitivity area.

Belukha Whale

Concentrations of this species peak in mid to late July, feeding and possibly breeding in an area of the Mackenzie Delta from Herschel Island to just east of Kugmallit Bay.

Bowhead Whale

During late April through early June, Bowheads pass Barrow heading east toward Canada. At this time they are restricted to leads in the flaw zone and are susceptible to spilled oil in the leads. Other leads in the flaw zone farther east are probably similarly sensitive areas through August, when the whales are migrating westward. Migration corridors in this area are not well known. In September, concentrations have been observed near shore from Cape Simpson to Point Barrow.

Arctic Fox

Concentrations of traditional den sites occur in: (1) river delta areas (sand dunes, gravel-sandbar banks, terraces and beaches); (2) pingos; and (3) beachlines (in coastal banks or under driftwood). Arctic foxes are adaptable to human presence, but development should avoid den concentrations and minimize physical destruction of den sites.

Attraction of foxes to shore-based facilities, principally due to refuse as a food source, may produce elevated concentrations of this efficient predator. This could exert a serious predation pressure on local populations of nesting birds and on ringed seal pups. (There are also human health and safety risks associated with locally elevated concentrations of Arctic foxes, as explained in the earlier section on mammals.)

Polar Bear

Denning occurs during winter months in three habitat types: landfast ice, drifting pack ice, and on land usually within 30 km of the coast. Denning in landfast ice is probably distributed widely along the Beaufort coast, whereas land dens appear to be concentrated in river banks and bluffs along rivers draining into Camden Bay (Moore and Quimby, 1975). We recommend that this land denning area (Figure 8.2) be considered highly sensitive from October through April, with all activities controlled by stipulation during this period.

Caribou

Post-calving concentrations of caribou utilize beaches and spits for relief from insects from late June through August. In recent years approximately 90,000 individuals of the Porcupine herd have summered along the coast between the Canning River and Barter Island, and portions of the arctic herd have occurred in the Cape Simpson-Harrison Bay area. During this period, caribou wade and swim in coastal waters off beaches and spits, in lagoons, and in stream mouths. The consequences of contact with oil spilled on the water surface are unknown.

Human Subsistence Use

The villages of Barrow, Atkasook, Nuiqsut and Kaktovik (Figure 8.1) form the centers of regions in which development activity might affect the subsistence use of wildlife resources. Since subsistence hunting and fishing cover extensive areas of the North Slope, and deal with many migratory game species, sensitive areas are difficult to localize on the map. The heavily used fishing areas shown in Figure 8.1 are especially sensitive for the reasons discussed in the section on Fishes. In general, the areas and habitats described as highly sensitive for populations of fish, waterfowl and marine mammals can be considered especially sensitive for the people who depend on these resources for food. Historic subsistence sites are listed by Nielson (1977).

Archaeological Sites

Sites of former village settlements and camps of various ages occur at many points along the Beaufort coast and on some of the barrier islands. The North Slope Borough has compiled an atlas of known sites (Nielson, 1977). These should be considered sensitive, and disturbance from development activities should be avoided.

Sensitive Coastal Processes

The major trophic relationships (food chains) involving birds, mammals and man represent key processes in the Beaufort Sea ecosystem and are discussed elsewhere in this report. Several important and more narrowly defined processes dealing with the lower levels of these trophic systems are at present poorly understood and potentially sensitive to the effects associated with coastal oil development. We list four, and stress that more information is required concerning all these processes:

1. Thermohaline convective nutrient pumping

This process, also described earlier in this report, provides nutrients to the under-ice algal community in shallow water areas, thereby enhancing primary productivity and incorporation of nutrients in these areas during the spring season. Habitat perturbations which affect circulation (causeway construction, channel dredging) or changes in solar radiation reaching these algal populations (oil spills on or under the ice), may greatly reduce primary productivity in the shallow water areas. At present the quantitative importance of this process in the entire trophic system is poorly understood, making the sensitivity of the process difficult to evaluate.

2. Peat detritus energy base

Studies in Simpson Lagoon are beginning to suggest the importance of peat, eroding from the tundra, as a possible energy base of a lagoon trophic system involving many invertebrate species, fish and birds. Here also we lack measures of the quantitative importance of this process. Disruption may arise from changes in current patterns in the lagoons, stabilization of presently eroding shorelines, or incorporation of spilled oil into the detrital mat on the lagoon floor.

3. Marine phytoplankton energy base

Outside barrier islands, or in more open marine lagoon systems (Elson Lagoon), birds and mammals may rely more on a food base of marine zooplankton, which is in turn dependent on phytoplankton productivity. This system may differ markedly in its sensitivity to current changes and other habitat alterations, but at present we do not understand the conditions which govern its pronounced annual variation.

4. <u>Brine pools under fast ice as winter refugia</u>

Salt is exuded into the water column during freeze up. In the irregular deep pockets under fast ice, a high salinity brine forms which at least on occasion harbors high densities of invertebrates, mainly crustaceans (Sellmann, pers. comm.). When salt concentrations do not increase to highly toxic levels, these brine pools may serve as winter refugia for invertebrates, which would be sensitive to contamination by drilling muds or oil. We know virtually nothing about location, extent or formation of such winter refugia.

We have chosen to emphasize these four processes at risk because of their uniqueness to the arctic nearshore systems, and because they are less immediately obvious to non-specialists in arctic dynamics. Other more obvious processes at risk (spawning, migration, erosion, etc.) are discussed in other sections of this report.

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9. TROPHIC INTERACTIONS

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Introduction

In this chapter we will attempt the overwhelming task of specifically exploring the trophic interactions of the food web in the Beaufort Sea and the potential environmental impacts of petroleum exploration and development on this ecosystem. Arctic ecosystems, especially Beaufort Sea systems, are not well understood. Our present understanding of the short- and long-term consequences of environmental perturbation is inadequate. Ecological ignorance of arctic systems makes it difficult to realistically assess either environmental disaster or environmental resilience.

Arctic oil spills have not been adequately studied. Baseline data have rarely been available for areas where spills have occurred. In most cases basic ecological and physiological data do not exist even for key arctic species. Any predictions based on past experience must therefore rely on data from spills in temperate waters where considerable followup has occurred. But one must be careful. Not only are arctic organisms different from temperate ones, but so is the behavior of oil in cold arctic waters, and in the presence of ice.

In making predictions or assessing impacts of petroleum exploration and development, it is not enough to look at only the highly visible or economically important components of the system, i.e. marine mammals, birds, and in some cases fish or shellfish. One must go farther and look at the apparently inconspicuous organisms upon which more visible species depend. It is not enough to examine discrete parts of the system as separate entities; one must study the connections and dependencies among parts.

Those connections and dependencies are central to the study of trophic interactions. Trophic studies deal with the flow of energy and materials within a biological system, more exactly how that flow is broken into discrete levels or quanta. Food habit studies are part of trophic investigations, but a true study of trophic relationships goes beyond food habits to explore interdependencies among many species and many levels, and to assess such things as competition for resources among species.

Through a study of trophics one can identify key species in the Beaufort Sea. Identification of key species and important species interdependencies will make it easier to develop predictive models or to assess ecological effects. Trophics studies are a means of ordering and simplifying systems, of reducing them from lists of hundreds of species to smaller sets of key species and interactions. They should provide a focus of attention which might otherwise be hard to determine.

The argument has been made that for an organism utilizing a wide variety of prey items, the removal of a single prey species should not seriously affect survival of the predator. While it is true that utilization of a variety of prey is some evidence for adaptability, variety does not obviate the importance of single species. Ringed seals may survive on shrimps and amphipods if arctic cod or euphausiids are absent, but they may be in poor physical condition, more susceptible to predation, not able to bear young, or they may bear smaller, less fit young.

If we understand something of the trophics of a system we may be better able to interpret redundancy. Many environmental perturbations are in the form of small-scale local insults. The question becomes, how much is enough to matter? How many small insults constitute a large one? To a great degree the answer will always remain a value judgment, but a study of trophics and any interpretation of the redundancy it allows will provide necessary input into decisions that must be made.

For scientists and user agencies alike, a complete understanding of all links within the system would be ideal. Such understanding would allow the development of a model that could give predictability of the consequences of petroleum-associated development. Obviously, such an understanding is not within reach. Desirable, although less than ideal, would be identification of at least the major links within the system, measurement of the effects of natural variation on those links, and an ability to predict the effects of human-caused perturbations. Even this is probably unattainable. What the study of trophic interactions within a system can do is provide partial understanding of small parts of the system and actual or hypothetical interactions among some of those parts. With this understanding of parts we can make educated guesses as to probable results from disruptions to the system. We cannot make absolute statements about what will happen. We can identify potential differential sensitivity of parts of the system, evaluate which times or places or species appear to be most or least vulnerable, and make recommendations as to how to minimize potential detrimental effects of OCS development.

The interdisciplinary trophics session at the 1978 Beaufort Sea Synthesis Meeting was an outgrowth of the need felt for further trophics work and for synthesis of existing trophics-related data, in order to address these questions. As an outgrowth of the 1977 Synthesis meeting, trophics studies had been conducted during summer 1977 in offshore areas and in nearshore barrier island lagoon systems of the Beaufort Sea. The group's task was to distill available trophics information to a product useful in evaluating effects of petroleum development, and to identify data gaps which must be filled before such evaluation can be made.

The Beaufort Sea is an area of extremes. Many biological subsystems exist within the "Beaufort Sea ecosystem," and yet characteristics of all those subsystems are ultimately determined by the same factors that regulate all arctic systems - great seasonal fluctuations in light, ice cover and nutrients. The discussion that follows attempts to show how these factors affect interactions within major subsystems of the Beaufort Sea.

Nearshore Coastal Waters

Nearshore* coastal waters include lagoons inside barrier islands and those areas near river mouths or along the coast where water is very shallow, generally less than 10 m deep. During breakup and in ice-free months these areas are subjected to large influxes of fresh water and thus widely varying salinities. During winter months, most of these areas are covered by shorefast ice.

Nutrients

The section on microbiology contains a discussion of nutrient cycling in nearshore Beaufort Sea waters, which we will not repeat here.

Carbon Flow in Nearshore Beaufort Sea Ecosytems

As in most coastal and estuarine systems, secondary production in the nearshore Beaufort Sea is dependent upon *in situ* primary production, augmented by detrital carbon derived from terrestrial sources. In most temperate waters, this secondary production is coupled to the inputs by primary producers and detritus sources, and cycling of carbon and nutrients is relatively rapid. In contrast, there is growing evidence that a sizable fraction of secondary production in the nearshore Arctic derives its energy supply in part from modern detrital material and in part from eroded and

*Editor's note: Nearshore is given a different definition here from that in sections on fish and habitats.

transported peat. Personnel of the barrier island study group (Truett et al., 1978) have found a high density of benthic epifauna associated with the flocculent detrital peat material that covers large areas of the bottom of Simpson Lagoon. Feeding studies by Broad (1978) have documented active feeding on peat by Beaufort Sea gammarid amphipods and it is reasonable to assume that the heterotrophic microflora and microfauna associated with detrital peat could provide a ready food source to these invertebrates. Estimates by Schell (pers. comm.) on the significance of peat carbon to the Simpson Lagoon ecosystem showed that between 25-50% of the fixed carbon input to the lagoon was in the form of eroded peat from the shoreline. The availability of this carbon source in winter as detrital particulate material may further increase its significance as an energy source on a year-round basis.

Trophic Interactions

Most trophics work in nearshore Beaufort Sea waters has occurred within lagoon systems, particularly Simpson Lagoon (Truett et al., 1978). Therefore, the following discussion will be primarily of Simpson Lagoon, with the realization that other nearshore areas may or may not be the same.

During summer months lagoon waters support large numbers of zooplankton, birds and fishes, and small numbers of marine mammals. High densities of zooplankton have been observed. Amphipods and mysids were the most abundant groups in 1977. Predominant species were Onisimus glacialis, Apherusa glacialis, Gammaracanthus loricatus, Gammarus setosus, Mysis littoralis, and Mysis relicta.

Principal species of fishes include arctic and least cisco, arctic char, fourhorn sculpin, and arctic cod. With the advent of spring breakup, there is a large influx of anadromous fishes (ciscos and char) from overwintering areas. Euryhaline marine fishes (fourhorn sculpin and arctic cod), presumably excluded during winter months by bottom fast ice, also move into the area. Lagoons serve as nursery areas for juvenile fishes, especially for anadromous species, but also perhaps for arctic cod (Bendock, 1977).

Principal bird species making use of barrier island lagoon systems are Oldsquaw, Red and Northern Phalaropes, Glaucous Gulls, Arctic Terns, and Common Eiders. Arctic Terns and Common Eiders breed and raise their young here. Migrating Oldsquaw and phalaropes use these areas to rest, molt, and feed.

Marine mammal use of nearshore Alaskan Beaufort Sea waters is limited and seasonal. Inside the barrier islands where ice in winter is frozen to the bottom seals are excluded. During summer months spotted seals and perhaps belukha whales use river mouths and estuaries. Both species feed in these areas, probably on anadromous fishes (Percy, 1975). Ringed seals are found primarily outside of the barrier islands, associated with the pack ice. Their use of nearshore areas probably depends on ice conditions during a particular year. Polar bears frequently cross the nearshore zone and sometimes feed on carrion on the beaches.

People are also major users of lagoon resources. North coast residents utilize large numbers of the anadromous fishes and waterfowl found here during summer months.

There is an apparent reliance of zooplankton on detritus for a significant portion of their diet (Truett et al., 1978). Detritus, principally in the form of peat, is derived largely from coastline erosion and river runoff. The fate of peat in the lagoon system, i.e., the seasonal distribution, storm driven movements in and out of the lagoon, etc., is largely unknown. The manner in which zooplankton utilize peat, whether directly or by consumption of microorganisms existing on that peat, is unclear.

Gammarid amphipods and mysids were consumed by virtually all carnivores in the lagoon during 1977. To a large degree, fishes and birds utilized the same prey species, i.e., *Onisimus glacialis*, *Apherusa glacialis*, *Mysis littoralis* and *M. relicta*. Food overlap among predators, and caloric calculations of energy available to consumers indicate that the food resource is not a limiting factor for key fish or bird species in the nearshore environment during the open water season.

Essentially nothing is known about the distribution, abundance, and trophic interactions of species found in the nearshore zone during winter.

Offshore Waters

Offshore waters of the Beaufort Sea are ice covered for much of the year. Freeze up occurs in the fall, usually October. Several distinct ice zones exist: the fast ice, the grounded ridge zone, and the pack ice (see Sea Ice section, this report). In most years ice cover disappears briefly during summer months. Breakup takes place in June or early July and some open water exists until fall. The extent of open water varies considerably from year to year; in some years the ice hardly moves offshore at all. Meteorological conditions are the major factor determining extent of open water areas.

1. Planktonic/Pelagic System

Primary producers in the form of phytoplankton support the pelagic food web. Light and various nutrients, especially nitrogen and phosphate, are required for these plants to convert carbon dioxide into "usable" organic carbon in the form of sugars and starches. Light and thus photosynthetic primary productivity is absent in offshore Beaufort Sea waters for much of the year. During some of the months when light does exist it still may not reach the plants that require it to reproduce. Incident radiation may be adequate but snow and ice are highly reflective. Thus, most productivity is restricted to periods when snow and ice are melted and dispersed.

Two types of primary productivity occur in offshore waters: that by ice-associated or "epontic" algae and that by phytoplankton in the water column. Ice algae live on and in the underside of the ice. They are present in brine pockets within the ice as early as March (Meguro, 1966). Their numbers peak later in the spring, while there is still snow on the ice and before other phytoplankton blooms occur. The bloom disappears with decreasing ice cover and increasing light intensity (Horner and Alexander, 1972; Alexander, 1974; Mansfield, 1975). Ice algae have been estimated to contribute greater than 10 percent of annual phytoplankton production in arctic waters (Grainger, in press, cited in Mansfield, 1975) and they serve to extend the growing season and thus food availability to herbivores and benthos.

Production in the water column is restricted to a few months of the year when open water occurs. Blooms generally do not occur until July and are over by August or September. Spring bloom may be advanced by as much as two months in open water leads (Bursa, 1961). There are suggestions in the literature that in heavy ice years carbon fixation by phytoplankton may be reduced by as much as 50% (Grainger, in press, cited in Mansfield, 1975). Little is known about nutrient cycling in offshore waters. Nitrogen may be limiting during peak bloom conditions, especially in areas of deep water beyond the shelf break.

Winter

The offshore pelagic system during ice-covered winter months is a relatively simple one. Primary production apparently does not occur. Herbivorous zooplankton species, abundant during the phytoplankton bloom, are much reduced in number (Grainger, 1959). Zooplankton consists mostly of a variety of copepods, gammarid and hyperiid amphipods, most of which are detritivores or carnivores. Stored energy reserves may be crucial for overwinter survival of some species (Dunbar, 1953).

Pelagic fish fauna in winter is limited to two genera of cods, Boreogadus (arctic cod) and Arctogadus (polar cod). Arctic cod appears to be by far the most abundant. They are present year-round; however, seasonal fluctuations in distribution and abundance seem to occur (Frost and Lowry, unpubl. observ.). The extent of these fluctuations is unknown. Movement in winter into shallower onshore water for spawning has been reported for arctic cod in other parts of the arctic (Ponomarenko, 1968). Subsistence fishers on the Beaufort Sea coast jig for arctic cod during the winter in apparent response to an increased winter abundance.

Arctic cod are of direct and major importance to two of the four top-level consumers (ringed seals and people) present in the Beaufort Sea during winter months, and of indirect importance to the other two (polar bears and arctic foxes). Ringed seals feed extensively on arctic cod (Lowry et al., 1978a). During winter months over 95% of their diet is comprised of this fish. Other prey items are taken, such as shrimps, gammarid amphipods, mysids, and Parathemisto spp., but in much smaller quantities. If arctic cod are concentrated in shallower waters in winter, they should provide a large, predictably available food source during the months that ringed seals are located in the same shallow water zone.

The other two top consumers present during ice-covered months are polar bears and arctic foxes. The relationship between polar bears and ringed seals is simple and direct: polar bears eat ringed seals (Stirling and Archibald, 1977). Arctic foxes also utilize ringed seals, sometimes through direct predation on pups and sometimes through scavenging remains of kills made by polar bears.

Spring

The complexity of this relatively simple winter system increases dramatically with the onset of spring and the open water period. Early in spring, as light increases, ice algae begin to grow and multiply. The ice algae are present in and on the lowest few centimeters (usually less than 5 cm) of ice as early as March. The peak of the ice algal bloom takes place in late May before the phytoplankton bloom in the water column. The ice algae disappear about mid-June, their disappearance caused by a combination of melting ice and brine drainage, along with currents that wash away the soft bottom ice (Horner, 1976). Ice algae have been estimated to provide at least 25-30% of the annual primary production in northern coastal regions, or about 5 g C m^{-2}/yr (Alexander, 1974).

The fate of the ice algae when they leave the ice is not known, but they do not cause the spring phytoplankton bloom in the water column and are not found in large enough numbers in the water column to provide much food for zooplankton consumers (Clasby et al., 1973; Horner, 1976). The importance of the ice algae appears to be that they lengthen the productive season by about two months, providing food for herbivores, especially amphipods, long before the phytoplankton are available.

The phytoplankton bloom in the water column begins when the ice algae leave the ice. The bloom is apparently triggered by increased light reaching the cells in the water column, not by an influx of ice diatoms into the water column. Primary production in the water column is restricted to the months of open water, and is highest at about the time of ice breakup when nutrient levels, especially nitrogen, are high and sufficient light is available. Diatoms are usually the most abundant components of the phytoplankton bloom, although small, non-photosynthetic flagellates may also be common (English and Horner, 1977).

Reproduction of some key zooplankton species, notably copepods, occurs when the phytoplankton are available as food (Dunbar, 1968). Those benthic invertebrates that have pelagic larvae also spawn in the spring during the phytoplankton bloom (Thorson, 1950).

In May and early June, offshore leads open and there is a mass influx of migrating seabirds concentrated along these leads. Arctic cod larvae hatch, at least in other parts of the Arctic, and feed extensively on small plankton, as do larger arctic cod (Rass, 1968). Bowhead and belukha whales move into and through the area on their eastward migrations. Shortly thereafter bearded seals move north and some of enter the Beaufort Sea. Additional numbers of ringed seals enter the Beaufort Sea as ice in the southern portion of their range disappears. Few Pacific walrus enter the area. Bearded seals and walrus are benthic feeders, but all others rely primarily on a pelagic food web.

Summer

By July, phytoplankton is present in the water column and large numbers of euphausiids (Thysanoessa spp.), copepods, mysids, and amphipods (Parathemisto spp.) may be present. Herbivorous species have a ready food supply of diatoms. Their reproductive products, as well as themselves, provide a rich food supply for carnivorous zooplankton such as Parathemisto. Arctic cod collected in offshore areas in August feed extensively on copepods, particularly Calanus glacialis, C. hyperboreas, and Euchaeta glacialis, and on the amphipod Parathemisto libellula (Lowry et al., 1978a).

Major species of birds in offshore waters include gulls (Sabines and Glaucous), Arctic Terns, jaegers, and Black Guillemots, among others. These birds feed on zooplankton in nearshore areas and overwhelmingly on juvenile arctic cod in areas more than 2 km offshore (Divoky, pers. comm.).

Food habits of belukha whales in the offshore Alaskan Beaufort Sea are entirely unknown. As they are fish and cephalopod eaters in other areas, they may feed in a similar manner here and eat arctic cod and squid or octopus.

Although detailed food habit studies of bowhead whales have not been done, it is known that they feed on zooplankton such as copepods, euphausiids, mysids, and amphipods (MacGinitie, 1955; Lowry et al., 1978b). Tremendous quantities of zooplankton must be present to meet the energy requirements of these animals. If a 40-ton bowhead consumes 5% of its weight per day, that amounts to 2 tons of zooplankton per animal per day (as opposed to about 8-11 lb. per day for a ringed seal).

During summer months ringed seals feed almost exclusively on zooplankton. Depending on the year and the area, they utilize Parathemisto spp., Thysanoessa spp., or Mysis spp. In areas where arctic cod and zooplankton occur simultaneously, seals seem to prefer zooplankton. This may relate to the relative concentrations of the two types of prey. Sometimes smaller amounts of other items, including epibenthic gammarid amphipods and shrimps, are eaten. This probably occurs when preferred prey are unavailable and in these instances the stomach is seldom filled. In contrast, seals eating arctic cod or zooplankton frequently have very full stomachs (Lowry et al., 1978a).

The late summer/early fall foraging period is extremely important to ringed seals as this is the time in which they regain weight lost during the spring molt. During the molt, seals may lose as much as 30% of their body weight.

Some groups of zooplankton, for example, chaetognaths, pteropods, hydromedusae, and ctenophores, have not been treated in detail in this section. At times and places these groups are present in great abundance and may structure a substantial part of the food web. Chaetognaths are voracious carnivores and may substantially influence the availability of copepods to other zooplankton, arctic cod, or bowhead whales. Parameters determining pteropod abundance and their effect on other plankton are unknown in the Beaufort Sea, although MacGinitie (1955) reported that they were utilized as food by whales. Both chaetognaths and pteropods are sometimes utilized by birds (Connors, pers. comm, 1978). Hydromedusae and ctenophores are occasionally extremely abundant in the Beaufort Sea, their distribution and abundance sometimes regulated by hydrography (Hand and Kan, 1961).

Fall

Fall is a time of year when sampling has been very infrequent, so that generalizations are difficult. It is the time when phytoplankton populations decrease because low light and low nutrient concentrations limit production. Dinoflagellates, while never very numerous, are more abundant than previously, but many of these are not photosynthetic. Their utilization by herbivores is not known.

Many zooplankton species, including some amphipods and euphausiids, produce eggs and breed during the fall and early winter. Dunbar (1957) reported Parathemisto libellula carrying hatched young in brood pouches in December. Perhaps some of the zooplankton is able to use dissolved organic material as food in winter, thus explaining how some species are able to produce eggs and young when other food is in short supply.

As food availability declines and sea ice cover increases, those species of birds and mammals not adapted to overwintering in the Beaufort Sea migrate from the area. Bowhead whales taken on their fall migration near Point Barrow have at times been eating euphausiids (Lowry et al., 1978b). Ringed seals collected in the Barrow and Prudhoe Bay areas in November had eaten arctic cod and Parathemisto (Lowry et al., 1978a).

Summary

Although our knowledge of the offshore pelagic system is far from complete, it does provide us with focal points in the form of key species and species interactions. The relationship of primary productivity to copepods and euphausiids is basic to the system. Copepods, euphausiids, mysids, and hyperiid amphipods are critical prey species of arctic cod, ringed seals, birds, and bowhead whales. Arctic cod are important to virtually all seabirds feeding offshore in summer months and to ringed seals and people in the winter. Ringed seals are the primary food source of polar bears and a major food source of arctic foxes in winter. Ringed seals, polar bears, arctic foxes, and bowhead whales have been traditionally utilized by coastal Eskimo residents for food and income.

2. Benthic System

Energy input into offshore benthic systems is largely in the form of detrital (including phytoplankton, which sinks) or animal material. During winter months when biological activity in the water column is greatly reduced, organisms must rely primarily on organic material present in or on the sediment, or on other benthic organisms. As spring and summer approach, ice algae bloom and as the ice melts they are released into the water column and sink to the bottom. Later, open water phytoplankton and zooplankton blooms also provide detrital material. In the Gulf of St. Lawrence, molted carapaces of crustaceans have been found to supply substantial amounts of detrital carbon to the benthos (Sameoto, 1976). Detrital input from onshore sources is unknown but is undoubtedly significant, at least in some areas. The release of reproductive products by members of the benthic community may provide a major input into some portions of the system. Key species within the benthos are difficult to define. There are many species and many connections. Much remains to be learned about community structure before we can hope to identify key species as we have in the pelagic system.

The benthos can be divided into two components, the infauna and the epifauna. Species diversity is great in both. Major groups in the infauna are polychaete worms and bivalve molluscs (Carey, 1977). Members of these groups are predominantly filter feeders, deposit feeders, or detritivores. Some polychaetes are carnivorous.

In general, the most abundant groups in the epifauna are echinoderms, such as brittle stars, sea cucumbers, crinoids, sea urchins, and sea stars (Lowry et al., 1978a). As with the two major infaunal groups, most are filter feeders, deposit feeders, or detritivores. Some of the sea stars are carnivores, eating other members of the epifauna or infauna. Few of these species are eaten by organisms at higher trophic levels as adults. Their major energetic contribution to the system, other than decomposition upon death, is probably the release of reproductive products into the water. Larval forms are utilized by a variety of filter feeders and carnivorous zooplankton.

Other groups comprising much of the epifauna at some places are sea anemones, soft corals, bryozoans, and tunicates. They also appear to be seldom eaten by other consumers. They interact with other benthic species primarily by competition for available food and space.

The remaining fraction of the epifauna constitutes the "food benthos" and consists primarily of bivalve and gastropod molluscs, polychaetes, amphipods, shrimps, and crabs. These groups are the major food source for a variety of demersal fishes, bearded seals and walruses.

Nineteen species of demersal fishes have recently been identified from offshore Beaufort Sea waters (Lowry et al., 1978a). This fish fauna is almost entirely discrete from the fish fauna of nearshore lagoonal waters. Arctic cod, sculpins, eelpouts, and snailfish are the most abundant fishes. Almost all demersal fishes were found to feed on gammarid amphipods and polychaete worms. The major exceptions were arctic cod and a species of snailfish which fed on zooplankton.

The benthos is utilized in a major way by only two high-level consumers, bearded seals and walruses (Lowry et al., 1978a). Both are resident in the Beaufort Sea only during summer months and neither species is present in large numbers. Major summering areas for bearded seals and walrus are in the Chukchi Sea. Bearded seals eat mainly epifaunal invertebrates. Crustaceans and molluscs are the two most important groups. Important species are spider crabs, *Hyas coarctatus*, crangonid shrimps, *Sclerocrangon boreas* in the vicinity of Barrow, and *Sabinea septemcarinata* further east, snails especially of the genus *Buccinum*, and clams, Serripes groenlandicus and Spisula sp. Walruses eat infauna as well as epifauna. Major prey items are bivalves and gastropods, although a variety of other groups, including tunicates, sponges, and priapulids are sometimes eaten. Ringed seals and bowhead whales connect to the benthic food web through their occasional eating of gammarid amphipods and shrimps. Beaufort Sea coastal residents utilize the benthic system indirectly through harvest of marine mammals.

As a whole, the benthic system is probably much more stable through time, both on a seasonal basis and an annual basis, than is the pelagic system. Its components are much less susceptible to "boom and bust" cycles than are members of the plankton community. Invertebrates in general have slow growth rates and are relatively long-lived. Many of the larvae develop directly from large yolky eggs; many species brood their young (Thorson, 1950). In combination, these factors favor survival of young. Demersal fishes also tend to grow slowly. They tend to have few large yolky eggs that hatch in an advanced state and are therefore more mobile and able to feed (Marshall, 1953).

Pelagic/Benthic Connections

In many ways pelagic and benthic systems appear to be independent of each other. Fish and many of the invertebrate species are different, most high-level consumers are different, and most species interactions are among species within the same system. There are, however, connections and some of these may be important.

1. Much of the food of benthic organisms originated from phytoplankton or zooplankton. This includes not only the organisms themselves but also such things as feces and molted exoskeletons.

2. Some species of demersal fishes feed on planktonic crustaceans. Some snailfish feed on Parathemisto and sculpins sometimes feed on mysids.

3. Bearded seals sometimes feed on arctic cod. Polar bears sometimes eat bearded seals and walruses.

4. Ringed seals sometimes feed on gammarid amphipods, shrimps, isopods, and demersal fish.

   Because the benthic community tends to be more stable, these benthic prey items may moderate the effects of low productivity, low zooplankton years.

Nearshore/Offshore Connections

Much as benthic and pelagic systems appear discrete, so do nearshore/offshore systems at first glance. Some possible nearshore/offshore interactions follows:

1. The source of zooplankton in nearshore lagoons is unknown. Zooplankton is probably transported in by means of onshore or longshore currents. This seeding effect would be very important in recolonization if lagoon zooplankton were extirpated for some reason.

2. Arctic cod utilize both nearshore and offshore systems. They are the most abundant fish offshore and one of the most abundant nearshore. Although data are far from conclusive, there are indications that juvenile arctic cod may spend much of their time in shallow waters (Bendock, 1977). Lagoon areas may serve as protected "nursery" areas where food is abundant. Predation appears to be relatively light in these areas, as seals don't commonly enter lagoons and birds seem to prey exclusively on zooplankton in these areas.

3. Some species of marine birds (such as Oldsquaws and Common Eiders) utilize both systems. They may breed and fledge young in one and migrate and feed through the other.

4. Coastal detritus may be transported to offshore benthic communities and provide energy input to those communities.

5. People utilize both systems. They harvest marine mammals and arctic cod from offshore waters. They take large numbers of anadromous fishes and waterfowl from nearshore systems.

Hydrocarbons in the Food Chain

Almost any discussion of the impacts of petroleum development includes mention of incorporation of hydrocarbons into the food chain and concentration of those hydrocarbons by higher trophic levels. Such incorporation and biomagnification are highly contested by some. The trophics interdisciplinary section at the 1978 Beaufort Sea Synthesis meeting discussed this problem, examined the evidence available, and decided as a group that the problem of hydrocarbon incorporation and magnification is a valid concern.

Not all organisms incorporate or accumulate hydrocarbons. Animals with gills are generally at or near chemical equilibrium with the water around them. They do not for the most part accumulate hydrocarbons. In those cases when they do, accumulation is often short-term because enzymatic depuration (clearing) occurs. Problems with accumulation are most apt to occur in birds and mammals which are not in chemical equilibrium with the environment, and frequently have no means of depuration. However, the ability to depurate hydrocarbons is not easily determined. The presence or absence of aryl hydroxylase, an enzyme that breaks down some hydrocarbons, is not enough to predict whether an organism can clear hydrocarbons from its tissues.

Accumulation of hydrocarbons has been demonstrated in filter feeders (Blumer et al., 1970). Some bacteria sequester pools of hydrocarbons (Atlas, pers. comm.). In Lower Cook Inlet incorporation of hydrocarbons from detritus by clams has been shown (Shaw, pers. comm.). The Beaufort Sea also supports relatively large numbers of detritus-utilizing clams and it seems plausible that they too might incorporate hydrocarbons. An arctic species of amphipod, Onisimus glacialis, is known to clean rocks of asphaltics (the tar residue from oil). To our knowledge asphaltics do not transform and their fate once ingested by the amphipods is unknown. Whereas clams are utilized by relatively few higher level consumers, gammarid amphipods are a regular food of numerous birds, fishes and ringed seals.

Folk wisdom often suggests that hydrocarbons inevitably accumulate progressively up the food chain. That is not the case. However, the possibility of biomagnification exists. If biomagnification is to occur at least the two following prerequisites must be met:

1. The hydrocarbon must be a lipid-soluble fraction that is not soluble in water.

2. The organism must be one with no mechanism adequate for the active removal of hydrocarbons.

Seasonality

Seasonal cycles in the Beaufort Sea have been discussed above as various systems have been described. However, the implications of marked seasonality with respect to petroleum exploration and development merit some additional discussion. Particularly, the question of whether a winter shutdown of biological activity takes place requires re-examination.

It is easy to assume a biological standstill during winter. The ocean is sealed away under a lid of ice. The organisms that live there become invisible to us and difficult to reach. Many of the most visible summer residents are absent. Birds migrate south with the approach of freeze up to more hospitable areas where water, and thus food, is accessible. Bowhead and belukha whales, spotted and bearded seals, and walruses all abandon Beaufort Sea waters for areas where the winter ice conditions are more favorable. Most anadromous fishes move from coastal marine waters to fresh water overwintering areas. Primary production essentially ceases and concentrations of zooplankton decrease. In nearshore areas less than 2 m deep, ice freezes to the bottom precluding access by swimming organisms.

Yet some species do remain and are active. Polar bears are active on the ice. Many arctic foxes move from land to the sea ice during winter. Ringed seals are present and they feed, breed, and bear their young during winter months. Arctic cod, their primary food source, are also active during months of heavy ice cover. They apparently feed throughout the winter and spawning occurs at this time. Demersal fish in the Canadian arctic are reported to feed actively throughout the winter (Green and Steele, 1975) and presumably also do so in the Alaskan arctic. Diver observations in Elson Lagoon near Barrow (Atlas, pers. comm.) and in Resolute Bay, N.W.T. (Green and Steele, 1975) report actively swimming amphipods, mysids, and copepods.

This activity, although much reduced from summer months, appears far from a biological standstill. Two species important to people, ringed seals and arctic cod, perform critical reproductive activities at this time. Although winter is still the preferred time for exploratory drilling, caution should be exercised to protect those species which remain active, and also those areas where less visibly active species gather to overwinter. Some species seem to concentrate and overwinter in very limited areas or pockets of abundance. Some of these pockets may serve as reservoir populations from which summer blooms are seeded. Contamination or physical disruption of these relatively small areas could affect a large portion of a population.

Resilience

Arctic ecosystems have long been considered fragile. Many predators depend on the same few prey species. Production to support the entire system must occur in a few short months. If something happens during those months to reduce production, the ramifications may be great.

In spite of all this, the arctic may actually be very resilient. Few systems undergo such extremes of temperature, light and salinity, such inconstancy from year to year in ice cover, and length of the growing season. A partial explanation for this resilience may be in redundancy throughout the system in the form of many small population centers. Local extirpations may be accommodated by the existence of reservoir populations elsewhere.

One example is the existence of many small interconnected lagoon systems across the Beaufort Sea coast. If one lagoon is unproductive or experiences a catastrophe in one summer, it may be possible for birds or fishes to shift to another similar lagoon. The benthos is patchy and many species are widely distributed. If local extinction occurs, repopulation, albeit slow, can occur from other areas.

A redundancy of energy sources may dampen the effects of widely varying production. Particularly in lagoon systems, detritus from river runoff and eroded peat may supply adequate carbon to supplement, or in years of poor production largely replace, phytoplankton input.

Some resilience is built into the system by the ability of many species to utilize a variety of resources. Euphausiids (Thysanoessa spp.) in the Gulf of St. Lawrence are able to shift from diatoms in the spring and summer to dinoflagellates and crustacean material in fall to substantial amounts of crustacean material and "mud" in winter, as species composition of the plankton changes (Berkes, 1976). Arctic cod in nearshore areas eat mysids and gammarid amphipods, the most abundant species available (Craig, pers. comm.). In offshore areas in summer they eat a variety of copepods (Lowry et al., 1978a) and in the late fall Parathemisto (Lowry, pers. comm.). Ringed seals vary their diet seasonally and apparently in relation to prey abundance. Extreme prey specificity would not seem advantageous in a system where the dominant plankton species vary greatly by season, place, and year.

Despite this apparent resilience, the system is still sensitive. Arctic species are generally long-lived and slow to reproduce. Disturbed benthic communities will repopulate, but it may take a long time. Ringed seals can eat a variety of prey, and most individuals will probably make it through years when zooplankton or arctic cod numbers are drastically reduced. However, less abundant prey may lead to poorer physical condition, causing increased susceptibility to disease or predation, production of fewer or smaller young, or migration from the area. This situation seems to have existed in the heavy ice years of this decade and we are now witnessing a reduction in the number and productivity of ringed seals in the Beaufort and Chukchi Seas. It is unknown how long it will take populations to recover from such events. Compounding natural events with human-caused perturbations could have even greater ramifications.

A variety of zooplankton exists in any one year and the dominant species seem to vary from year to year and place to place. There is the possibility that if one species were severely reduced, as the result of an oil spill, for example, that another would increase to take its place. In this case, consumers might shift to the alternate prey with no ill effect. It is equally possible that replacement species, especially in the case of phytoplankton, might be of lesser food value, and the effects would then be considerable. Perturbation could happen after reproduction by major species had occurred for the year, and then there would be no mechanism for a second species to replace the original one.

The questions remain - how much redundancy is necessary to maintain the resilience of the system as a whole? How many small perturbations can the system withstand before the effects become large? What happens to resilience if rates of dispersal and interconnections among systems are disrupted?

Petroleum Exploration and Development

Numerous concerns exist with relation to petroleum exploration and development in the Beaufort Sea. Some of them are as follows:

1. What effect will interruption of longshore currents (e.g., by causeways) in the nearshore area, have on:

    a) transport of detritus? Terrestrial carbon sources (detritus from coastal erosion, river runoff) probably provide the principal energy source to nearshore systems. Detritus may provide a buffer against years when primary productivity is low and a means by which zooplankton populations are sustained through winter months. It also may enable zooplankton blooms to start early in the spring before primary productivity is at its peak. Any development that changes the amount of detritus entering the system by interrupting longshore transport of materials or by altering erosion rates of coastlines may seriously affect the nearshore ecosystem.

    b) movement of anadromous fishes along the coast? Most anadromous fishes are known to overwinter in fresh water. They reenter the marine environment at breakup and disperse along the coast. They appear to remain extremely close to the shore. These fishes are utilized by coastal residents and some marine mammals. Dispersal along the coast may be blocked by causeways, affecting their availability to people and seals.

c) dispersal of zooplankton? The source of zooplankton found in lagoons is unknown. It is probably not local, as many lagoons are frozen to the bottom during winter, but is carried in by currents. Interruption of these currents could reduce or delay zooplankton repopulation of lagoons in spring.

2. Is crude oil toxic to the major species of zooplankton, epibenthos, and fishes? Invertebrate species of particular concern for the nearshore area are gammarid amphipods, especially Apherusa glacialis, Onisimus spp., Mysis relicta, and Calanus spp. Some toxicity tests have been run on Onisimus glacialis and Calanus hyperboreas by Percy and Mullin (1975). Onisimus was found to be sensitive to oil-contaminated sediments and dispersions of oil in water. Calanus on the other hand was found to be "remarkably resistant". To our knowledge no toxicity tests of any kind have been run on Mysis spp.

Offshore, important zooplankton species are Thysanoessa spp., Parathemisto libellula (and probably P. abyssorum), Mysis littoralis, Calanus glacialis and C. hyperboreas, and Euchaeta glacialis. To our knowledge the toxic effects of hydrocarbons on all of these species except C. hyperboreas are unknown.

Of the abundant nearshore fish only Myoxocephalus has been tested. Larvae were found to be extremely sensitive to crude oil (Percy and Mullin, 1975). There is no information available on the sensitivity of arctic cod to petrochemicals. Larvae of cod species other than arctic cod have been reported to be quite sensitive to hydrocarbons (Kuhnold, 1970).

Pollutant levels high enough to cause large-scale die-offs of individuals will probably occur only on a localized basis, in close proximity to the pollutant source (except where oil or pollutants are trapped under the ice and transported long distances in a relatively unweathered state). Perhaps the greatest concern, however, is not with local die-offs but with long-term sublethal effects of pollutants. Individuals may not be killed outright, but very low concentrations of pollutants may affect locomotion, metabolism, or reproduction and lead to substantial reduction or extermination of populations over several generations (Percy and Mullin, 1975). These long-term reductions are of special concern in considering food availability to consumers. Short-term local reductions would most likely be of major consequence when they:

a) occurred during a time of year when food was otherwise scarce, for example, a die-off of arctic cod during winter months when ringed seals have little else to feed on;

b) affected a very productive area during a period of peak utilization, for example Simpson Lagoon in August, when approximately 30,000 Oldsquaw are feeding and molting in the area, and large numbers of anadromous fishes are present.

3. In nearshore areas are pockets of deeper water important as overwintering areas for zooplankton and anadromous fish? If so, discharge of drilling muds into these "holes" or pumping water from them for the construction of ice islands should be avoided.

4. Oil lenses under the ice may destroy ice algae and associated invertebrate fauna. These ice communities appear to be important food resources of arctic cod and in some instances birds and ringed seals.

5. Extensive oil slicks will restrict light penetration to the water column and reduce or eliminate primary production in those areas. Such reduction could be especially critical in high productivity areas that support large numbers of zooplankton and thus birds, fishes, and mammals.

Most concerns over the impact of petroleum exploration and development on trophic interactions in the Beaufort Sea relate to prey availability. The Beaufort Sea is an area of limited productivity, most of which occurs during a very few months of the year. Many consumers are dependent on ephemeral blooms of prey populations. Some take in a major portion of their annual consumption during a few short months while others are dependent on this abundance for their young to survive. Any substantial decrease in prey abundance will undoubtedly affect predator populations.

Data Gaps

1. There is a need for an assessment of the sources of production, as related to ice, oceanographic, and meteorologic conditions. Magnitude and causes of natural variation, relative rates of production in open water versus under sea ice, contribution of ice algae, and the possible effects of heavy or light ice years on total production should be explored. With this information one should be able to delineate areas and/or times in which oil spills would be most detrimental to production, i.e., under the ice or in open water, during winter or summer months.

2. The importance to nearshore systems of detritus from river runoff, peat erosion, and water column fall-out is unclear. The extent to which coastal detritus reaches offshore areas is unknown. Both of these inputs should be better defined in order to understand the implications of human-caused alterations of input routes or rates.

3. A seasonal basis of data is needed for the distribution and abundance of key invertebrate prey species, the factors determining their presence or absence, and the timing of important life history events in the Beaufort Sea.

   These species are:

   Pelagic amphipods - *Parathemisto libellula* and *P. abyssorum*
   Mysids - *Mysis relicta* and *M. littoralis*
   Euphausiids - *Thysanoessa raschii* and *T. inermis*
   Copepods - *Calanus glacialis*, *C. hyperborea*, and *Euchaeta glacialis*

Gammarid amphipods - Apherusa glacialis, Onisimus spp. Many other species of gammarids are also abundant and important.

Some information on these species is available in the literature. It should be compiled and analyzed in light of questions pertaining to petroleum development. This research should begin immediately. If critical feeding areas for high-level consumers exist in the Beaufort Sea they will be determined by the distribution of these organisms.

4. Distribution and abundance of arctic cod, Boreogadus saida, are virtually unknown in the Beaufort Sea. Limited data are available for summer months and no winter data exist. Spawning time and locations are unknown. Very limited data are available on feeding; prey specificity, seasonal variation in prey, availability of alternate prey items, and sensitivity of prey to hydrocarbons should be examined. With this information we can evaluate the sensitivity of this link. Arctic cod constitute one of the most important forage species in the Beaufort Sea. Research should be undertaken immediately to fill in these data gaps.

5. There is a lack of focus in the benthic data. Key species have not been identified. Characteristics of the epifauna are poorly known. If epifaunal communities could be defined it should be possible to begin to name key species and key interactions with infaunal species. Such information is useful, for example, in identifying areas suitable for bearded seal or walrus foraging. With information on geographical distribution of those communities we can delineate sensitive areas where, for example, the sinking of oil or perturbation of the bottom would be most damaging.

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10. PROBABLE IMPACTS AND CONSEQUENCES OF OIL DEVELOPMENT

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Introduction

Our attempts to predict the possible impacts and consequences of oil development on the biota and habitats of the Beaufort Sea involved two separate and intensive meetings which took place one year apart. It is important to be somewhat aware of the background which led us to this version of our group report.

The general objectives of this interdisciplinary group were essentially presented during the first Beaufort Sea Synthesis Meeting (7-11 February 1977). At that time the workgroup was chaired by J. Burns and group members included: T. Bendock, P. J. Cannon, A. Carey, G. Divoky, K. Frost, R. Griffiths, R. Horner, G. Hufford, B. Krogman, P. Myers, D. Roseneau and L. Shapiro. Each member of this group at the 1977 meeting was a scientist involved with OCS research in the Beaufort Sea. We had essentially no information about how the oil industry would proceed in developing OCS leases, the technology likely to be employed or the actual problems of human and mechanical failures which occur during various phases of development under arctic conditions. Additionally, in 1977 there was a rather minimal input of current information pertinent to the historical, anthropological, cultural, sociological, subsistence and economic values advanced by long-term residents of the Beaufort Sea Coast. Nonetheless, we proceeded to try and predict the impacts which would result from a series of hypothetical but probable situations which might arise during the course of OCS petroleum development.

During the 1977 Synthesis meetings the work of this group was conducted in three different phases: during the first phase we explored the kinds of impacts which would result from planned and controlled human endeavors as well as unplanned (accidental) occurrences. The second phase was an exercise in which we developed probable sequences of events and impacts resulting from three different hypothetical happenings: (1) orderly construction of a coastal settlement, (2) chronic but localized releases of fuel, and (3) a major discharge of crude oil resulting from structural failure at a producing offshore oil well. The third phase of our work was devoted primarily to delineating geographic areas which were "sensitive" in the sense that perturbation within them would have a significant impact (based on attributes of the area) on one or more kinds of animals. Additionally, we addressed the multi-dimensional questions of sensitive species of animals, critical species of fishes and invertebrates (mainly commonly shared prey species used by fishes, birds and mammals) and critical habitats of birds and fishes. The time available for this exercise allowed for only cursory consideration.

In the present synthesis report, two sections, one on sensitive species and habitats and another on trophic interactions, have been singled out for separate discussions preceding this section. Our charge during the 1978 Beaufort Sea Synthesis Meeting was to reexamine and reevaluate predictions of the possible consequences of hypothetical situations which would probably occur during development of the Beaufort Sea. To the extent possible, all new information obtained from OCSEAP and other research was to be used to update our predictions. A significant and extremely beneficial improvement at the 1978 meeting was that local residents of coastal communities, as well as knowledgeable representatives of the oil industry, were in attendance. These participants were able to provide specific information which helped our group to understand the importance of fauna and habitats to human residents of the arctic coast, and to be aware of the probable construction and engineering methods to be used in the Beaufort Sea, and the hazards which they may entail.

This working group was concerned with attempting to recognize and discuss those species, geographical areas and habitats considered to be sensitive or critical. For purposes of our discussions, sensitivity was usually viewed in the context of some probable impact of OCS development. In other words, if a species of animal is considered sensitive, its sensitivity is to oil spills, disturbance, dislocation or other impacts generated by the processes of exploration, development or production of gas and oil fields. The animal could be adversely affected while the capability of its habitat to support that animal remains essentially unchanged. Thus, for example, although an oil slick in the open sea may result in the loss of great numbers of birds, it may drift out of the area without causing significant damage to bird habitat, per se. Sensitive and critical, as these terms relate to habitats along the Beaufort and Chukchi Sea coasts, connote something different. In this case, the basic capability of the geographical habitat to support the naturally occurring fauna and flora is impaired. "Sensitive areas" are considered to be those in which biological productivity is relatively high and which would probably be adversely impacted by major disturbances resulting from OCS development, particularly oil spills. Adverse impacts in a significant portion of a sensitive area would result in a "critical impact" to one or more species of plant or animal.

The ability of this working group to use available information (sometimes only suggestive or fragmentary) to predict the possible consequences of oil development is more apparent than real. It is a constructive and helpful exercise to produce tangible and useful predictions. However, our understanding of the Beaufort Sea ecosystem is far from complete and our predictions remain just that - predictions. Additional information will certainly modify them. Some of the predictions will be empirically tested. Only at that time can they be validated or discarded.

Probable Impact-causing Planned or Controllable Activities

Planned and controlled (or controllable) activities associated with OCS development were considered to include:

1. establishment of settlements and support sites;

2. establishment of utility or transportation corridors including roads, piers, pipelines, utility lines, airfields, storage areas, etc.;

3. on-site development and production structures (platforms, rigs, ice islands, etc.);

4. marine transport.

Probable Impact-causing Unplanned Activities

1. fuel spills;

2. losses and discharge of drilling muds (also including disposition of drill cores and escape of formation water);

3. well blow-out (gas);

4. petroleum facility fires;

5. major spills of crude oil, including well failures.

With regard to accidents, a concensus of the participants at our work sessions was that under the rigors of arctic conditions more accidents are likely to be caused by human error than might be true in other areas. Compounding the problem of rigorous working conditions, there is possibly a higher risk of accidents resulting from the psychological attitudes of workers. Some mishaps (such as leaks in fuel lines buried under snow) may involve a longer than average time before detection.

All of the above were examined from the standpoint of their probable impacts on food webs, on higher trophic level animals and on habitats. The general kinds of impacts resulting from both planned and unplanned activities are listed in outine form, below.

Impacts Resulting From Planned and Controllable Activities

1. Establishment of settlements and support sites:

   Impact on food webs, from the establishment of new settlements and camps would result from:

   - concentration of scavengers such as gulls, ravens and white foxes;
   - increased predation on wildlife species surrounding a settlement or camp;
   - increased exposure of some species (i.e., white foxes) to disease such as rabies and distemper;
   - increased impact of people on the surrounding fauna and flora;
   - eutrophication of surrounding areas due to waste disposal;
   - decrease of species diversity (i.e., phytoplankton);
   - introduction of harmful exotic animals (dogs, cats, rats).

Direct physical or physiological impacts on organisms resulting from the orderly establishment of settlements would include:

- death of birds resulting from the presence of obstacles (towers, poles, wires, drill rigs);
- entrapment and subsequent death of some species, such as caribou by various kinds of cables or fish by water removal;
- mortality of larger animals taken in defense of life and property (occasional bears, wolves, foxes);
- increased taking of fish and game resources.

Impacts of settlements on plant and animal habitats would include:

- significant local changes in phenological events (natural phenomena that recur periodically, as thawing, blossoming, nesting, egg laying);
- reduction in air quality as a result of smoke, smog and ice fog;
- seasonal elimination of important fresh water aquatic habitats through water removal;
- destruction or alteration of habitats through extensive gravel mining;
- changes in habitats by alteration of natural drainage patterns;
- appropriation of habitat due to construction and occupancy of settlements;
- displacement of acoustically sensitive animals, such as some birds and marine mammals by noise pollution;
- various effects of erosion, thawing of permafrost, etc. on habitats;
- alteration of habitat by petrochemical pollutants.

2. Establishment of utility or transportation corridors, including roads, piers, pipelines, utility lines, airfields, storage areas, etc.:

Effects on trophic structure would include:

- restructuring of biological communities by piers, causeways, artificial islands, etc.;
- increased vulnerability of some organisms to predation;
- alteration of feeding efficiencies in various organisms;

Direct physical and physiological effects on animals would include:

- increased accessibility of living resources to appropriation by man;
- higher mortalities through the presence of increased numbers and more widespread distribution of lethal obstacles;
- disturbance and dislocation of animals by aircraft, heavy

equipment on shorefast ice, etc.;

- avoidance responses of some birds and mammals.

Effects of utility corridors on habitats would, in many instances, be similar to those resulting from settlements. However, these impacts would influence a much broader area. They would include:

- changes in habitat due to disruption of natural drainage patterns;
- local changes in phenological events due to dusting;
- changes in habitat due to alteration of the snow cover, etc.;
- direct appropriation of habitats;
- alteration of habitats by gravel removal;
- alteration of habitats through removal of water from streams;
- various impacts of erosion and surface subsidence on habitats;
- changes in habitat due to physical alteration of sea floor;
- increased accessibility of scavengers and predators (e.g., white foxes) to island colonies of breeding birds;
- creation of anerobic embayments during winter;
- changes in water quality and characteristics of habitats;
- presence of barriers restricting or inhibiting animal movement.

With regard to physical alteration of the Beaufort Sea ocean floor it is suggested that trenching, as used for the placement of buried pipes, would not have a significant or large scale impact. The effect of dredging, for instance to obtain gravel for an artificial island, could be quite variable. In shallow water areas (less than 15 m) protected from natural ice gouging, dredging would significantly affect established benthic communities. However, in unprotected shallow water areas, benthic communities are also affected adversely by natural ice gouging. Dredging may also result in release of hydrogen sulfide. Large man-made depressions in the sea floor could possibly act as nutrient sumps through entrapment of detritus. More information is needed about the effects of large, man-made depressions in the sea floor (see also section 2 of this report).

3. On-site development and production structures (platforms, rigs, ice islands, etc.

Many of the impacts from structures placed in marine areas were judged to be similar to those already mentioned.

Impacts on trophic structures would result from:

- alteration of biological communities resulting from change in substrates (the structures themselves resulting in new substrates);
- effects of discharges into surrounding waters. Two different aspects of the problem have come to light. These are the

direct releases (accidental or planned) and the leaching of accumulated petroleum wastes. Island facilities may be a special problem in which accumulated petroleum wastes are leached into the gravel, apparently to the level of the summer permafrost or water table. Lateral leaching results in the release of petroleum wastes at waterline, during late summer and fall. This could be a significant problem to migrating shorebirds. During summer 1977, chronic release of petroleum compounds, as described above, occurred at the Flaxman Island drilling site.

Direct physical or physiological impacts of offshore structures would result from:

- presence of obstacles lethal to birds (particularly affected would be red phalaropes, eiders and murres). Structures may serve as lethal attractions under some conditions, thus intensifying the problem (examples include lighted towers and airfields).

Effects on habitat would be significant although perhaps only localized. They would be caused by:

- restriction of normal sea ice movements;
- development of flat shore-fast ice through protection from impingement of heavy drifting ice;
- changes in salinity;
- presence of artificial "barrier islands" and causeways which alter water circulation patterns and surface movements of sea ice;
- increased noise and waste pollution from a source situated in the marine environment;
- alteration of air quality and increase in surface dusting from fallout of soot, ash, etc.;
- changing patterns of sediment deposition;
- changing patterns of ice breakup.

4. Marine Transport:

A concensus was that shipping will probably be minimal and not pose a significant threat to the biota in the Beaufort Sea.* In view of the time of year and prevailing conditions when marine shipping is feasible, it would probably have little impact other than that associated with discharge of pollutants into surrounding waters. These discharges would range from relatively small amounts, as in the case of spillage during transfers and bilge wastes, to large amounts (resulting from damage to vessels). The problems associated with shipping are anticipated to result chiefly from petroleum releases into the marine system.

*Editor's Note: Oil movement by tanker from Canadian or U.S. production was not considered.

Impacts Resulting From Unplanned Activities (Accidents)

1. Fuel spills.

In most cases, the effects of fuel spills (a chronic problem) would be localized. The area of impact is related quite logically to the size of a spill, success of recovery efforts and time of the year.

Effects on trophic structure would result from:

- increased volume and availability of dead and dying organisms to scavenger, including coastal migrating birds dying because of exposure.
- reduction in survival of organisms on lower trophic levels of food webs, including phytoplankton (of pelagic, under-ice, benthic and surface melt pond communities), zooplankton, benthos and larval or juvenile stages of fishes;
- change in species composition of lower organisms, particularly bacteria and algae;
- incorporation of petroleum into bottom sediments or beaches, the slow degradation of petroleum, reworking of sediments, and possible slow re-release of petroleum over time;
- increased concentration of contaminants in higher trophic level consumers;
- selective consumption of petrochemicals by some organisms and active absorption by oleophilic (with an affinity for petroleum) substances such as peat and organic detritus.

An important aspect of arctic ecosystems to be kept in mind is that the growing season is very short, although biological activity is intensified. Anything that interferes with or further reduces primary production during this brief period can have serious implications.

Physical and physiological impacts on organisms would include:

- direct mortality to many kinds of organisms, from phytoplankton to seal pups in lairs;
- destruction of epontic phytoplankton and grazers associated with this community;
- oiling of birds and mammals (significant mortality of birds during summer to early fall period);
- possible, although largely unknown, effects on whales and mature pinnipeds;
- initiation of physiological or behavioral imbalances in a wide array of organisms;
- morphological anomalies as recorded for some invertebrates;
- changes in growth rates, time to maturity, etc.;
- suppression of reproduction, at least in some invertebrates;
- synergistic intensification of pathogens affecting some kinds of organisms.

Discussion at the 1977 Synthesis Meeting indicated a concern that crude oil released into the sea would result in the production of significant amounts of SO_2, HCl, H_2SO_4 and other toxic compounds. Reevaluation of this point indicates that dilution and the great buffering capacity of sea water would not permit accumulation of these substances.

Effects of an oil spill on habitats would be caused by:

- eventual accumulation of large amounts of oil on beaches (see comments below);
- incorporation of nonvolatile components into sediments;
- long-term re-release into marine system from beaches and sediments;
- concentration of oil in leads, cracks and other openings in the sea ice;
- long-term entrapment and entrainment of oil by ice;
- long-term floating oil slick;

The localized effect of fuel spills on habitats was thought to be mainly that of rendering them temporarily unfit for some organisms. Since fuels have a large component of volatile fractions, impacts on habitats from individual fuel spills would be short term. Continuous losses of fuels would have a cumulative and perhaps intensified impact.

2. Losses and Discharges of Drilling Muds.

The subject of drilling muds was discussed at great length during both the 1977 and 1978 Synthesis meetings. In 1977 our group concluded that drilling muds were a significant environmental problem and muds must be disposed of in a manner that would not introduce significant amounts of a variety of toxic substances into the nearshore marine environment of the Beaufort Sea. The concerns about drilling muds included those of increased turbidity, toxicity, heavy metals, changes in pH and bacteriocidal components, among others, in shallow waters of restricted areas.

Drilling muds may present a special problem as far as habitat degradation goes. In areas where this mud accumulates on the sea floor, it may set up and form an effective seal, resulting in significant but localized disruption of habitats. Ice action on the sea floor would prevent this in unprotected nearshore waters of the Beaufort Sea.

At the 1978 Synthesis meeting it was pointed out that the U. S. Environmental Protection Agency had conducted a conference dealing with the question of drilling muds. Although we did not have access to the documents produced at the meeting, the general conclusion was reported to be that the impact and effects of muds released directly into the marine environment were negligible. We felt, however, that further consideration of this question, particularly as it relates to the special problems in the Beaufort Sea, was required. Our findings follow.

It is anticipated that offshore production facilities in the Beaufort Sea will have between 10 and 20 directionally drilled wells, to depths in excess of 10,000 feet. The drilling process will release about one cubic foot of drill cuttings per foot of well in addition to the planned and unplanned releases of drill mud amounting to 2,500-3,000 barrels per well. These will accumulate in the immediate vicinity of production facilities, especially since most of them will be in shallow water where there is little current. The seasonal presence of sea ice allows several options for disposal of muds and cuttings. These include: transport to disposal sites on shore; direct release into the water column (very restricted and with low flow rates during winter); deposition on the drilling platform; release onto the ice surface over deep water with subsequent disposal during seasonal ice melt and disintegration.

Disposition of drilling muds on shore, where they may reach fresh water aquifers, would be less desirable than release into the marine system. The sea water can further dilute the small volumes of toxic compounds and, perhaps more importantly, chemically neutralize them more effectively than fresh water. It was suggested that drilling muds be released into the sea where water depths are sufficient for adequate dispersal, and be dumped on top of the ice when the latter is present.

Finally, it should be noted that no participant of this interdisciplinary workgroup has had first-hand experience with environmental problems associated with drilling muds. We consider this question, as it relates to conditions extant in the Beaufort Sea, to require further consideration.

3. Well Blowout (Gas):

It appears that a gas blowout per se would not have a great impact on habitats of the Beaufort Sea or the organisms which they support. Almost all the gas would be released into the atmosphere. Some water soluble components would be incorporated into sea water but these are considered to have a low toxicity. Associated occurrences such as cratering at the blowout site, destruction of rigs, loss of muds, and intensified repair and reconstruction activities would be the most serious consequences to the immediate area where such an occurrence took place.

4. Petroleum Facility Fires:

It was the opinion of this group that the probability of facility fires is higher in arctic Alaska than it is in more temperate climates, due mainly to the additional requirement to use a variety of heat sources for men and machines. Most facility fires involve gas or gas with low volumes of crude oil. Occasionally a fire will involve mainly crude oil. A facility fire in which gas is the major flammable component would probably not have a great impact on the marine system, beyond that indicated for a gas blowout.

If crude oil is involved, impacts would be greater and geographically more extensive. According to some participants, the burning of crude oil may actually intensify problems associated with large spills, by localizing concentrations of nonflammable but toxic components in the immediate vicinity of a fire. These heavier components sink rapidly and would become incorporated into sediments in concentrations much higher than those resulting from a dissipated oil spill.

At the surface (water or ice), a large "fall-out" plume would be produced, consisting largely of asphaltic compounds. As these particles fall on the sea surface, or are released by seasonal melting of ice, they would sink and also become incorporated into sediments, with eventual incorporation into living components of the system. The effects on food webs, organisms and habitats would be of a similar nature to many of those indicated for fuel spills. However, larger amounts of environmental contaminants would be released over a wider area.

The question of oil fires, either accidental or as a means of containing a spill, deserves a great deal of additional study. In the minds of some investigators it may be more desirable to allow crude oil to dissipate "naturally," attempting to clean it up in areas where it accumulates. However, certain occurrences, such as timing of bird migrations, must enter into such a decision.

5. Major Spills of Crude Oil (including Well Blowouts):

Major oil spills are, without doubt, serious calamities that have far-reaching impacts. Our subgroup was not able to adequately address all of the potential effects of a major spill. However, likely impacts are listed below.

From the standpoint of trophic interactions (food webs and energy transfers) we would expect the following occurrences to be of concern:

- an oil layer greatly altering light transmission in the upper water column and thus, at certain times, influencing the rate of primary production;
- a significant change in albedo, especially as oil is incorporated into the ice structure;
- changes in percent species composition of the lower organisms due to changes in water chemistry;
- incorporation and active upward transfer of oil in the ice;
- production of oil melt puddles;
- chemical alteration of aquatic environments.

Each of the above would probably have a significant effect on the survival of organisms, alter migratory behavior (i.e., fishes), or otherwise displace organisms which are mobile and physiologically irritable.

A recent report on possible containment measures for future oil spills in the eastern Beaufort Sea (Logan, 1975) provides some information about probable impacts of a major spill and, more directly, about the feasibility of containment. In general, it is concluded that with the exception of a spill in essentially open water during periods of calm sea surface conditions, the chances of effectively containing and removing a sizable portion of a spill are presently very low.

Petroleum industry representatives expressed the opinion that at the 1977 Synthesis meeting this subgroup did not give adequate consideration to the effectiveness of oil spill cleanup procedures. They were of the opinion that cleanup efforts would recover a significant portion of any spill. In many instances, cleanup procedures applied at sea do not appear to be very effective even under favorable conditions of weather and sea state, however. For example, in the relatively recent Buzzards Bay spill, which occurred in temperate zone conditions of winter ice in a protected bay, only 10% of the spill was removed by cleanup procedures.

Additional general comments about cleanup of spills which were expressed at the Synthesis meetings follow:

Under some conditions where a spill of crude oil is localized and the oil is in pools, burning might, under ideal conditions, remove a significant portion (50-75%). However, the remaining residues will rapidly sink in a localized area and remain for a longer period of time, perhaps resulting in an asphaltic "pavement" of the sea floor.

Regarding dispersants, efficient compounds and technology for use under arctic conditions do not presently exist. There appear to be significant problems associated with low salinity water (as in melt or runoff water) which dominates the surface layer of the Beaufort Sea during breakup. Dispersal of petroleum may cause as many problems as it solves. The main result of dispersal may be that an oil slick, though it would not inundate a specific area, would no longer be visible. This might well eliminate the possibility of mechanical cleanup or burning.

Mechanical cleanup procedures involving small boats, skimmers, booms, mats, etc. can only be utilized under favorable conditions of open water and calm seas. These procedures may be applicable for only a very short period of time during the open water season. They are ineffective in the "average" sea state conditions that exist in the Beaufort Sea (normally 1-2 foot seas).

The question of various spill containment and cleanup methods requires evaluation of the tradeoffs which may be involved. Dispersal may protect a beach but sacrifice larval fishes and zooplankton. Burning may deposit asphaltic compounds in a localized area which persist for a long period of time.

Given the present state-of-the-art and the conditions existing in the Beaufort Sea, we remain of the opinion that cleanup efforts would not recover a significant proportion of petroleum released into the sea. Such efforts should nevertheless be attempted, and we make the following recommendations:

1. When possible, immediate mechanical containment and physical cleanup is the key to minimizing damage.

2. As a general operating procedure we recommend against methods which promote the sinking of or dispersal of oil. There may be situations when this is desirable (i.e., to prevent an oil slick from inundating a biologically critical shoreline area). However, it is probably more desirable to keep track of, and possibly mechanically clean up, a relatively thick viscous layer of crude oil, as opposed to exposing more organisms to petrochemical toxins over a much wider area than a spill would normally cover.

3. Under most circumstances crude oil spilled in large quantities at sea should not be burned. Other petroleum compounds, which burn more completely, could probably be disposed of in this manner. The burning of crude oil in contact with ice and/or sea water is very incomplete. The unburned heavy fractions will sink. These fractions are detrimental to a variety of plants and animals and would remain in the marine system for a comparatively long period of time.

There is a definite need to identify, in a spatial and temporal context, the biologically significant (and certainly critical) areas and events as part of any contingency plans for cleaning up spilled oil. It is these considerations which will probably indicate the best cleanup procedures to be used.

An Evaluation of Events Associated with Petroleum Development in the Beaufort Sea

In the exercise assigned to our group we attempted to amplify the considerations addressed above by incorporating them into sequences of events likely to result from four different hypothetical occurrences, including: (1) the occurrence of a significant oil spill; (2) the establishment of a camp-type settlement; (3) chronic releases of relatively small volumes of fuel oil and gasoline into the Beaufort Sea system; and (4) the establishment of a production facility on one of the natural barrier islands.

Occurrence Number One: A Significant Oil Spill

Situation: Underwater blow-out, northwest corner of lease area, between Thetis and Spy Islands. Water depth about 10 m. On May 1 an underwater blow-out is initiated due to a poor bottom cementing job. 50,000 barrels of crude oil are released over the next week. Success is achieved in arresting the blow-out. Cleanup measures are relatively ineffective, although some identifiable oil pools under the ice are drilled and tapped. The probable sequence of events would be:

During May

Movement of oil: The oil is initially dispersed under the ice into pools of uneven thickness depending on under-ice topography. Assuming an average oil thickness of 1 cm, an initial area of 1 km^2 would be affected. Some of the gas and soluble fractions of the petroleum would be distributed into the water column. The ice would immediately begin to sponge up some of the oil through brine drainage holes and cracks, such that oil would appear on the ice surface within a few hours. The relatively weak under-ice currents would have minor effects on the spill dispersal; however, a slight net movement toward the west (Harrison Bay) might be expected.

Disturbance:

1. Some microorganisms closely associated with the ice are killed as a result of direct contact with the oil, e.g., bacteria, ice algae.

2. There would be little or no initial effect on benthic communities.

3. Some ringed seal pups might be killed due to oiling as a result of mothers' periodic entries of lairs through oil slick under the ice.

4. Adult ringed seals surfacing within the slick would develop sub-lethal but significant pathological conditions including eye and nasal irritations and skin lesions.

In early June

Movement of oil: The Colville River floods during the first week of June and the runoff fans out over and under the fast ice, dispersing the oil in a fan-like pattern further offshore. The oiled area would be greatly enlarged by this process. The heavy bentonite load of the Colville would cause substantial settling of oil to the bottom by clay particle adhesion. Dark patches of sediment and oil finding their way onto the ice surface might greatly increase the ice melting rate. Rapid weathering of surface oil would be expected. Some oil would now start to appear as slicks in open-water leads. Formation of "chocolate mousse" would be common.

Disturbance:

1. Oil would adhere to Colville River peat which is consumed by amphipods. These, in turn, would affect seals, fishes, and birds.

2. Microfauna would be affected over a larger area, but the effects would be less intense.

3. Seals and polar bears would still be contaminated by oil; some might die, others would suffer increased susceptibility to cold temperatures, predators, etc.

4. Much of the oil would concentrate in the limited open-water leads which are heavily utilized by eiders and oldsquaws. Significant deaths among these species might be expected.

5. Larval stages of fishes (especially polar cod) and zooplankton would be subjected to very high direct mortality within the affected area. Abnormal and/or arrested development of immature organisms subjected to sub-lethal doses of petroleum compounds would occur.

At the time of breakup and formation of open water

Movement of oil: Oil would now be present in four general locations: in the bottom sediments, in the water column, on the water surface, and incorporated in the sea ice. The distribution area would extend for some kilometers to the north and west of the original spill site. The oil might be emulsified, some would form thick layers against the ice edge, some would form thin irridescent slicks, and some would move as tar balls. The open-water slicks might move to the west at a typical speed of 15 cm/sec, i.e., about 10 km/day. There is a possibility that some oil would ultimately be detectable on the shores between Cape Simpson and the Kogru River after a few weeks of open water.

Except for the oil retained on some of the beaches and that incorporated into the sea floor sediments, the effects are judged to be largely over by midsummer.

Disturbance:

1. Some impact on phytoplankton (peak production occurs in this period) through nutrient uptake and possibly reduced light.

2. Effects on mammals, e.g., whales, bears and seals, are expected. However, the nature of the impact is largely unknown at this time.

3. Continued impact on migratory birds using the oiled open-water leads. The spill area occupies major migration corridors.

4. Nearshore birds would be impacted in areas of fouled mainland beaches and barrier islands. Dieoffs of shorebirds, gulls and terns could result from direct oiling or ingestion of oil. The mudflats west of Cape Halkett could be critical because they would be likely to retain any oil which entered for a long time. The area is heavily utilized by ruddy turnstones, black-bellied plovers, dunlins, semipalmated sandpipers, phalaropes, sanderlings, and others.

5. Where significant amounts of petroleum compounds are present in the sea, expecially in nutrient-rich nearshore regions, they would continue to cause mortality and especially abnormal development of immature fishes and zooplankton.

Long-term effects:

Reintroduction of oil from beaches and bottom sediments could cause long-term disturbance to the shelf and nearshore ecosystems. Also, spill monitoring and sporadic cleanup efforts would lead to increased activity by humans, aircraft, and marine equipment.

Occurrence Number Two: Establishment of a Camp-Type Settlement

Situation: Establishment of a year-round oil industry facility at Oliktok to house a maximum of 1500 residents in summer and 700 in winter.

There are, of course, many ways to proceed with the orderly development of an oil industry facility. A reevaluation of the situation explored at the 1977 Synthesis meeting indicated that if the same assumption were made then as now, the effects would also be the same. However, things can and most likely would be done in a much different way. As a means of comparing probable impacts we present the situation as envisioned in 1977 and as modified, based on probable design and construction changes that would likely be utilized by the oil industry.

The situation as envisioned in 1977:

Facility Requirements: Airfield and connecting road; gravel pads for all construction on land; gravel for concrete; 25 acre construction site; all-weather road to Prudhoe Bay (dock facilities are there); 20 miles of winter roads on fast ice to drill site; winter ice roads to land-based drill sites; control tower, power plant; gas turbines; solid waste disposal facilities; sewer system; central fuel supply depot; requirement for 200,000 gallons of fresh water per day, year round, for all uses.

Events:

1. Gravel removal from marine beach with northeast exposure. 1.0 million m^3 removed with no obvious damage. In summer begin to see slumping and rapid melt of newly exposed permafrost after 1.3 million m^3 is removed. Strip mining at this site, and development of another borrow pit for additional 700,000 m^3 gravel. Effect of the latter is slight modification of drainage patterns and intensification of polygonization. No major effects on biota.

2. Construction of the airfield, storage and living areas. Effects include: displacement of all locally nesting geese and cranes due to human activity and disturbance. General reduction in other waterfowl. Alteration of drainage patterns with resulting changes in localized habitats. Localized changes in phenology as previously defined. (It is recommended that construction occur only on well-drained sites and out of areas with a mixed mosaic of habitats).

3. Operational secondary treatment sewage facility with outfall into bay. Result is minor eutrophication (artificial nutrient enrichment) of restricted area. Impact is negligible.

4. Solid waste landfill. Results: Restricted appropriation of bird, ground squirrel and microtine (rodent) habitat. Significant attraction of scavengers including gulls, ravens, arctic foxes, grizzly bears, ground squirrels and occasional polar bears and wolves. Effects: Increased survival of juvenile gulls and ravens and locally increased densities of same. This would increase the significance of predation on eggs and young of smaller bird species in surrounding area within a 5-10 mile radius. Arctic foxes would be greatly concentrated and provided with more denning areas (berm piles, outbuildings, storage yards, etc.). Foxes would take 35% of all newborn ringed seal pups in a 25 mile radius, 35-40% of waterfowl nests and 5-15% of shorebird nests. Foxes themselves would be subjected to periodic reduction efforts because of diseases transmissible to man. Two grizzly bears, one wolf and one polar bear would be taken by accident or purposefully in defense of life or

property. (It is recommended that feeding of wildlife not be permitted and that such a compound, including dump, be fenced to exclude animals.)

5. Presence of structures and human activity would result in death of some birds (i.e. red phalaropes and eiders) from flying into obstacles, exclusion of denning polar bears in vicinity of continuous activity (probably for a considerable area around it); reduction of ringed seal density within one mile of the entire over-ice haul road. No remedial steps could be taken.

6. Water requirements would initially remove almost all water from deep holes in adjacent streams thus killing all overwintering fishes. (Recommendation: construct water pit adjacent to stream with fish barrier between pit and flowing channel.)

The Situation as Modified in 1978

Camp Requirements: This facility will use the Deadhorse Airport, which is about 30 road miles distant, and either the Oliktok Point DEW line site (POW-2) landing strip or a comparable small strip adjacent to the camp; gravel pads for all construction on land; gravel for concrete; 25 acre construction site; all weather road to Prudhoe Bay (dock facilities are there); 20 miles of winter roads on fast ice to drill site; winter ice roads to land based drill sites; control tower; power plant; gas turbines; solid waste disposal facilities; sanitation systems; central fuel supply depot; requirement for 150,000 gallons of fresh water per day, year-round, for all uses.

Events:

1. The gravel source for this camp probably will be the existing gravel pits of the Kuparuk and Putulagayak Rivers. The road to Oliktok would, most likely, start at the Kuparuk River (which must be bridged) and extend to the camp site. Gravel will first be used to build the road, and the road will then serve for transportation of gravel for construction pads, drill pads, etc. Assuming a need for two million yards of gravel (estimates of gravel used at Prudhoe Bay are generally below eight million yards), the Kuparuk and Putulagayak River beds and abandoned channels probably can supply what is needed. An alternative source, albeit one that will require slightly more gravel, is the Colville River which contains "at least 35,000,000 cubic yards of sandy gravel and gravelly sand" (Labelle, 1976).

   Regardless of the source of fill material, the amount of fill required represents a mound (or, alternatively, a hole or several holes) about one mile long, as wide as a football field is long, and 50 feet high. For the purpose of this hypothetical situation, this excavation is made outside the main river channel or channels and creates a large lake or lakes. It results in local depression of permafrost but provides both water storage and waterfowl habitat. The biological effects are negligible.

2. Construction of the airfield (if necessary) and camp. Effects include: displacement of all locally nesting geese and cranes due to human activity and disturbance. General reduction in other waterfowl. Alteration of drainage patterns with resulting changes in localized habitats. Localized, minor changes in such seasonal events as snow melt, flowering of plants, duration of growing season, etc. (phenology).

3. Each camp or cluster of buildings will be required to construct its own sewage treatment facility. These facilities will include primary, secondary and, if necessary, tertiary treatment. Effluent may be discharged into tundra ponds and lakes. Sludge will be incinerated.

   Environmental effects will include minor heat enhancement of the atmosphere and of receiving ponds. Biological effects of discharge of treated sewage will be minor or, if tertiary treatment is part of the system, virtually nonexistent.

4. Solid waste will be collected and incinerated, probably at a central garbage treatment plant. Kitchen wastes may, as an alternative, be ground and introduced into sewage treatment plants. After incineration the solid residue, along with nonburnable materials will be stored above ground in a garbage dump. Periodically, salvagable materials will be shipped out.

   If required by law or by the nature of materials being burned, the incinerator may be equipped with a precipitator or scrubber. The dump area will not be an attraction to birds and mammals and will have minor or negligible environmental effects. The garbage incinerator will add some heat and moisture to the atmosphere and may be a source of air pollution.

5. Presence of structures and human activity would result in: the death of some birds (e.g., red phalaropes and eiders) from flying into obstacles; exclusion of denning polar bears in vicinity of continuous activity (probably for a considerable area around it); reduction of ringed seal density within one mile of the entire over-ice haul road. No remedial steps could be taken.

6. At Prudhoe Bay, domestic water use is generally less than 100 gallons per man per day. We estimate domestic usage of 150,000 gallons per day at this camp plus, during drilling, 20,000 gallons per drill rig per day. Annual consumption of water will be on the order of 70 million gallons (0.26404 x $10^6 m^3$ per year. During peak runoff, the Colville River discharges about 2.29 trillion gallons a day (8.64 x $10^6 m^3$) (Walker and McClay,1969). If the Colville River were used as a water source, the problem would not be supply but storage.

   A catch basin would be constructed adjacent to the main channel of the Colville and a reservoir (or reservoirs) capable of storing about 2/3 of the annual water required by the camp (177,148m^3) will be constructed near the water treatment facility. This reservoir should be deep enough to allow for 2-3 m of ice during the winter (most of which will become usable water before breakup) and still provide 3-4 m of unfrozen water beneath the ice. A single reservoir 172 m x 172 m (29,584m^2) in area and 6 m deep would suffice, but it is more likely that several smaller lakes would be better.

The impact of construction of such a water supply system would be that associated with excavation of the catch basin and reservoirs: some thawing of permafrost beneath the enlarged lakes; and that of road construction to the Colville River. The amount of water removed from the river during the summer would be insignificant.

Occurrence Number Three: Chronic Releases of Small Volumes of Fuel Products

Situation: Continuous losses of fuel products associated with transit and transfer. Involves a settlement on the mainland, a causeway to the barrier islands and drill sites, and the drill sites of production wells.

Comments: This hypothetical situation was considered at both the 1977 and 1978 Synthesis meetings. The frequency of fuel losses indicated in 1977 were considered by several participants of the 1978 meeting to be too high. In fact, we have no real way of determining if these rates of fuel spills are too high. We have therefore chosen to consider this hypothetical situation using two sets of values for the frequency and amounts of fuel spilled.

Frequency of Losses (High):

Hypothetical Location	Frequency of Spills	Amount of Spill	How Lost
Pingok Island	Once every 2 wks	50 gals/spill	Transfer
Causeway	Once every 2 mos	2,000 gals/spill	Accident
Thetis Island	Once every 2 mos	2,000 gals/spill	Accident
Oliktok	Once every 2 wks	50 gals/spill	Transfer

Results of Small Transfer Spills:

In the winter: spilled oil will remain on the surface of the ice and snow and will be covered and absorbed partially by snow drifts, except where cleanup removal is attempted. Effects on biota will be negligible.

By spring several thousand gallons of spilled oil will locally accelerate melting and some of this oil will flow into the water moats forming around the coast and barrier islands. Amphipods and later mysid populations may be affected by the oil, as well as birds which are concentrated in the moats. Other effects involve local populations of invertebrates and fish, their eggs, young and larval forms. These effects will all be extremely localized along the moats and be most pronounced at breakup.

During fall, flightless oldsquaws, which molt and feed in the lagoons, are probably the most severely affected, both directly through contact with the oil, and indirectly by eating molluscs which assimilate hydrocarbons.

Results of Larger, Accidental Spills:

Assuming a spill of 2,000 gallons every two months (well within the realm of possibility, judging from similar accidents along the TAPS road) about 8,000 gallons will have been spilled at our hypothetical site during the winter months. Early melt ponds formed by the oil will attract incoming birds. When breakup occurs on the streams and rivers, flooding on top of and under the ice can carry the spilled fuel about five miles in every direction from the spill site. The following will probably be affected during the summer, open-water period:

- spawning and nursery areas of anadromous fish along the beach;
- zooplankton, phytoplankton and larval forms of invertebrates;
- nearshore fauna (impingement of the oil on the mainland coast, but less so on the islands, is likely);
- birds (oiling, egg mortality and feeding interference, although shore areas are primary feeding areas only at stream mouths).

Effects would be quite localized, but numerous. Similar spills at many locations along the coast could lead to more serious consequences.

Frequency of Losses (Minimal):

Hypothetical Location	Frequency of Spills	Amount of Spill	How Lost
Pingok Island	Once every 2 wks	10 gals/spill	Transfer
Ice Road	Once every 6 mos	2,000 gals/spill	Accident
Thetis Island	Once every 6 mos	2,000 gals/spill	Accident
Oliktok	Once every 2 wks	10 gals/spill	Transfer

Results of Small Transfer Spills:

In winter; spilled oil will remain on the surface of the ice and snow and will be covered and absorbed partially by snow drifts, except where cleanup removal is attempted. Effects on biota will be negligible.

During spring; these small transfer spills on gravel pads are negligible in amount and occur on land (Pingok Island and Oliktok). They would have little adverse effect. Some seepage from frequent small spills such as around fuel storage facilities and pumps may occur at particular sites and fuel will quickly flow into gravel. Cleanup by removal of gravel is not recommended unless to reduce fire hazard. The nature of refined fuels is such that the most toxic components of these small spills will evaporate.

Results of Larger Accidental Spills:

Results of a large spill on gravel at Thetis Island would be similar to small spills on gravel discussed above, except that the probability of seepage into the ocean is high, therefore prompt cleanup is necessary. If fuel reaches tundra plants they will be killed, but cleanup of tundra is not recommended; it is ineffective and only of cosmetic value.

For the hypothetical spill on an ice road we assume that mechanical cleanup is 75% effective. Recovered oil might be trucked to Prudhoe, put through an oil/water separator and subsequently reprocessed. Of the 500 gallons that are left in snow and ice most will remain until breakup. Subsequent behavior is well described in the previous spring scenario for small transfer spills.

In summary, if minimal losses of fuel occur and mechanical cleanup methods are utilized, adverse environmental impacts would be slight and reversible in a short-term perspective.

Occurrence Number Four: Establishment of a Production Facility on a Natural Barrier Island

Situation: A production facility on one of the natural barrier islands (Cross Island) is being developed. Three production wells have been completed and 17 additional wells are planned. All wells are being directionally drilled to an average depth of 11,000 feet. One drill rig is being used and 4 wells per year can be completed. The dimensions of this natural barrier island are approximately 1/2 x 3 km. The island is about 10.5 nm from the mainland and surrounded by shallow water.

Comments: Consideration of this not-so-hypothetical situation was an exceptionally fruitful exercise because of the composition of our work group. Suggestions for engineering design and operational criteria were provided by petroleum industry experts, eliminating some of the guess-work. We examined the possible alternatives in design and construction as well as the possible environmental impacts. Characteristics of the hypothetical production facility during the 3.5 years required for completion are indicated below.

Size of Cross Island Facility:

50-75 inhabitants during the drilling stage. An area 400 x 400 ft. for living quarters and drilling rig.
An area 400 x 400 ft. for storage depot of materials required, especially during summer (for mud, casings, drill pipe, cement, water, fuel, sand and gravel, construction materials).
An area 200 x 200 ft. for a "flow collection facility" (gas and oil separation) on Cross Island.

Transport Support Facilities:

Helicopter landing pad (year-round on island).
Ice runway 3,000'in length for fixed wing aircraft (winter).

Ice haul road connecting island to mainland during winter and spring.

Landing area for barges during summer. This requirement is optional.

It is suggested that marine-borne freight be unloaded at present Prudhoe Bay facilities and trucked to the island during winter. This eliminates the requirements for barge landings, movement of heavy freight on the island during summer and the necessity of a large storage area on Cross Island.

Estimated extent of traffic to the facility will be 2-3 helicopter flights/day, year-round; the equivalent of 4.5 barge loads of equipment per summer; 1 small fixed wing aircraft landing per day and 1 large fixed wing landing per week during the period when the ice runway is usable; two large truck and 12 pickup truck round-trips per day during existence of ice road.

Engineering Requirements:

Fresh water: 60 gallons per day per man and 4,000 gallons per day for drilling (i.e., approximately 500 barrels per day).

Gravel: 100,000 yards^3 required to raise the surface of working areas on the island (400,000 sq. ft.), 9 ft. above present level.

Fuel supplies: require the storage of 30,000 barrels of fuel (1,260,000 gallons) on the island for use at the facility. Note: This would not be required if utility pipe lines are installed (see below).

Sewage disposal of 60 gallons per person per day (i.e., 4,500 gallons per day for 75 persons). Disposal into sea after secondary treatment.

Solid waste disposal facility (no estimates derived). Drill cuttings (a cumulative total of 220,000 cubic feet) will be used to increase the elevation of Cross Island itself, or will be used to form an extension of it.

Drilling muds will be released in water deeper than 60 feet. Volumes amount to about 2500-3000 barrels (105,000-126,000 gallons) per well.

Possible design considerations:

Trenched pipelines to mainland facilities including pipelines for fresh water, for fuel (both would reduce transport and storage requirements to and on the island), for crude oil and for gas. It may be possible to put all pipes in the same trench.

Levees would be be required around fuel depots on the island.

Insulation and an impermeable barrier would have to be installed under the entire work pad.

Possible gravel sources include the island itself; mining of marine deposits or mining on shore and transport to the island over winter ice road. The latter is suggested as the most desirable.

Actual facility could be constructed on the ground or be a 3-story modified platform type structure constructed on piles. The latter may be more desirable than the former.

Protection of the facility from wave and ice action would require construction of protective barriers in certain locations, and stabilization of beach in others.

Trenched pipeline utilidor to the mainland (as previously mentioned).

Environmental Impacts: Most of the potential environmental impacts have been discussed previously. Potential mishaps range from large-scale production facility fires, blow-outs and spills to the continuous, chronic, low level disturbances and releases of contaminants. For this discussion we are assuming that no major mishaps occur and that environmental impacts will be those resulting from "normal" operations of an adequately designed production facility.

Adverse impacts of one degree or another can be expected to result from:

- appropriation of surface area occupied by facility;
- presence and activity of men and machines on the island;
- periodic small (but cumulative) spills of fuel during transfer operations;
- minor transportation accidents;
- flushing of pollutants from area of facility, resulting in presence of petroleum products in the moat surrounding the island in spring and on the wave-washed beaches during the open water season -- leaching is intensified because of increased snow accumulation around facility during winter;
- physical presence of a drill rig (obstruction to birds which are especially vulnerable in certain weather conditions;
- attraction of scavengers;
- increased air pollution and deposition from burning and flaring;
- noise disturbance of marine mammals sensitive to sounds transmitted through water.

Adverse impacts of the hypothetical Cross Island facility on marine birds would probably result from displacement of breeding birds to the point of nest or colony desertion, to the following extent:

Common Eider - 100 nests
Arctic Tern - 10 nests
Sabines' Gull - 5 nests

Limited numbers of eider may continue nesting if areas of the island are off limits to humans. The nests listed above are all clumped in the northwest corner of the island. If at all possible, activities should be limited to areas on the island where breeding birds are known not to occur. In mid-July post-breeding concentrations will start to form along the shoreline. These peak in early August when up to 1000 birds per km will be present. These are not open to disturbance directly from drilling activities. Impacts would occur from spills or any contamination of nearshore water that would affect nearshore zoolankton concentrations. Oldsquaw concentrate in the bay behind the island in August with as many as 1000 being found regularly (G. Divoky, pers. comm.). A small number of eiders would occasionally be killed from striking the derrick and facility.

Physical environmental impacts of this hypothetical facility would include:

- the deterioration of permafrost, at least around the drilling site;
- destruction of archeological sites present on Cross Island; alteration of sediment transport processes;
- physical alteration of surface topography of the island;
- introduction of a considerable volume of well cuttings (1 cu. ft. per ft. of well x 20 wells); impact of gravel removal at source.

The adverse effects on mammals would probably include:

- elimination of the seasonal use of habitat between the island and mainland by belukha whales during the open water season (avoidance);
- displacement of an estimated 5 breeding female ringed seals and their pups because of use of an ice road and ice runway;
- attraction of increased numbers of arctic foxes to the habitation and subsequent increased predation of foxes on newborn seals within a 15 mile radius of facility;
- attraction of one nuisance polar bear every other year which would have to be immobilized and moved;
- temporary elimination of Cross Island as a potential bear denning site;
- probable elimination of Cross Island as a hunting and camping site for subsistence hunters.

The adverse effects on fishes and marine invertebrates are unknown. Invertebrates would be especially susceptible to the effects of increased sediment deposition, resulting from drill cuttings and muds. Sessile and other benthic (bottom dwelling) organisms would probably be destroyed and because of micro-environmental changes, different communities would evolve after cessation of drilling.

In summary, it was the concensus of this group that barring any major mishaps the environmental impacts of a single island facility would be biologically insignificant and reversible upon termination of the facility. However, the cumulative effects of numerous facilities of this type, operating simultaneously, would result in significant adverse, short-term impacts. The time required to reverse these impacts would be longer. (Answers are needed to questions such as: How many areas can belukha whales be displaced from and still maintain a stable population level? How long would it take for a depressed population to increase?) The bowhead whale population has not recovered in 60 years even though carrying capacity of their environment has probably not been altered at all.

Perhaps the most significant permanent loss which would be accelerated by the hypothetical facility on Cross Island would be loss of archeological sites.

A Re-evaluation of Spills, Transport and Effects of Oil

As part of the 1977 Synthesis meeting a working group, chaired by K. Aagaard, was asked to consider the probable transport mechanisms and effects of major spills of crude oil. The results of that exercise have been re-evaluated by this group and are summarized as follows:

In considering oil as a potential environmental pollutant in the Beaufort Sea, we constructed two hypothetical spills. With the exception indicated below, we feel that these concepts are realistic. We have been fairly conservative in our estimate of environmental impacts. The first spill was an instantaneous release of 25 thousand barrels of crude oil inside the barrier islands during an ice-free period in summer. The second was also an instantaneous spill of the same size, but in early January, beneath fast ice. In both cases the water depth was assumed to be 6 m, corresponding to a point between Prudhoe and Cross Island.

Two obviously simplifying assumptions in hypothetical events are: (1) that the spill was an instantaneous event, and (2) that only oil would be released. A time-release, rather than an instantaneous spill would significantly complicate consideration of movement, and the inclusion of gas among the spilled hydrocarbons might alter the nature of the water column uptake. Too little is known, however, of the effects of either of these to permit reliable assessment of the impact. With these reservations, we proceed to construct the rather simple but instructive conceptual framework of the two hypothesized spills.

Sequence of Events Following a Summer Oil Spill

In the summer spill, the oil would initially be on the ice-free sea surface, subject to wind influence and degradation. There would be an immediate loss of birds in direct contact with the surface oil slick. This loss would continue as long as the oil slick persisted. The immediate slick area, of an initial size of about 10 km across, would be abandoned by marine mammals.

We note that it is possible to get the oil, including low molecular weight aromatics, into the sediments very rapidly under certain conditions, e.g., through adhesion to clay minerals or by the action of breaking waves in shallow water. Should oil be introduced into the sediments, there might be local loss of benthos.

On a time scale of two days, the low molecular weight aromatics would disperse rapidly through evaporation and dissolution. The dissolution would be accompanied by loss of fry and larvae, as well as the reproductive capability of arctic cod and sculpin, zooplankton and epibenthos.

Within 1-2 weeks, the effects of weathering and biodegradation of the oil would be visible. While further portions of the oil would enter the water column, most of the material would be piled against the shoreline and/or continue as free-floating slicks. The populations of phalaropes and shorebirds would suffer their principal losses during this period. In fact, it is during this period that overall mortality in the entire system would peak. One would by this time also see a large increase in oil-degrading bacteria. The oil that remains in slicks, i.e., that which has not been trapped on the shoreline, would disperse both along and off the shore, with a net horizontal displacement of approximately 2-5% of the mean wind vector. The net drift would be toward the western shores of Prudhoe Bay and the entrance to Simpson Lagoon. An effort might be made to prevent oil entry into the lagoon by blocking the relatively narrow straits by booms.

The distribution of material in both slicks and shore doposits would, by the end of this time, have become quite patchy. The toxic effects of this ever-widening area of contamination would be limited to organisms coming into direct contact with the oil.

On a time scale longer than two weeks, the nature of the contamination would change. For one, the oil would sink through both physical and biological processes. It could also become incorporated into offshore ice, or move onto the land via storm surges and windblown aerosols, or become part of the large-scale circulation (e.g., move eastward with the Bering Sea water or westward with the Beaufort gyre). In any case, the surface slicks would have disappeared. The biological consequences might include the effects on benthic habitats which come into direct contact with the oil.

Other biota that could be affected include the marine mammals, certain birds (notably brandt, white-fronted geese and snow geese) and, if there were large storm surges, possibly some other tundra life. On this larger time scale the oil would become incorporated into the food web in various ways, but the long-term toxic effects of this are largely unknown.

An all-out effort to mechanically remove the oil cannot be recommended as this would cause destruction, in many cases, of much larger coastal habitats than would be caused by the oil spill itself. Cleanup techniques should be evaluated on a case-by-case basis.

Sequence of Events Following a Winter Spill Under Fast Ice

In the winter spill under fast ice, oil would initially be subject primarily to gravitational spreading, including the filling and possible overflow of holes and cracks in the ice. Some additional spreading could be expected from tidal and surge currents. Biodegradation and weathering would be very much reduced from the summer situation. Some loss of seals might accompany the initial rapid gravitational spreading, and certainly the seal population would be displaced.

We note that, in contrast to the possible summer situation, rapid incorporation of oil into the sediments is not likely, assuming, of course, that the spill does not occur below the sea bed. As suspended sediment is by no means absent from the water column in winter, some bentonite adhesion and oiled sediment settling might be expected.

On the two-day time scale, the low molecular weight aromatics would move down through the water column, but evaporation would be nil. A certain amount of oil would be incorporated into the skeletal layer of the lower ice surface. The aromatics would cause some loss of zooplankton, invertebrates, and fish larvae, e.g., arctic cod. Well within two days, the gravitational speading would have been completed, the oil occupying a relatively thin layer beneath the ice, extending over perhaps 0.5 km^2. The lateral dispersion would be controlled primarily by the under-ice topography. On the largest scale of ice morphology, the oil might well be prevented from reaching offshore leads by ice ridging at the edge of the fast ice.

Within 1-2 weeks, the continuing freezing process would trap the pools of oil between horizontal ice sheets. The oil would remain trapped until spring.

In early April, when photosynthesis by ice algae normally begins, there would locally be a delay or reduction in this process, primarily due to reduced light at the underside of the ice. In late April, brine channels in the ice open, and this would allow the oil to move upward from the under-ice trapped pools and appear at the surface. The resultant albedo reduction would accelerate the local melting process and the oil would, in due course, be spread onto melt ponds. As the oil came to the surface it would increasingly be subjected to weathering and biodegradation. The effect on marine mammals during this period is likely to be small.

Beginning in late May the eiders arrive, and they might suffer some loss by being attracted to the oil-covered melt ponds and therby coming in direct contact with the oil.

If the oil were in a region of river overflow, it would be rapidly dispersed, both laterally and downward through drain holes, probably mixing with river-borne sediments and organic material and then sinking. It is conceivable that if the oil were to enter the water during the early melt season, it would interfere with the production of euphausiids and thereby also with the grazing of the baleen whales. Away from rivers the oil would also be dispersed as the melt ponds expanded and their water eventually drained into the sea.

By late June to early July, any remaining oil would end up in open water or near the retreating ice edge, the oil distribution being very patchy. Much of this oil would be in slicks, but some would also be contained within the ice. At this point, the further movement and degradation of the oil would follow the summer sequence.

In regard to containment and cleanup, we note that this would be extremely difficult for a winter spill, but that the same basic rules apply as for a summer spill.

Transport of Spilled Oil in Pack Ice

Several variations and extensions of these two hypothesized spills are also instructive. A possible variation is one in which oil is introduced into the main shear zone or moving pack ice off Prudhoe sometime after the fall freeze up. The oil would undergo a net westward translation together with the ice, but the movement would probably not exceed 50 km through February. Some of the oil would be trapped by the ice topography as in the previous inshore sequence, but some would also appear at the surface of both the leads and the ice as the ice field was constantly deformed. We note that as the oil comes to the surface, it becomes extremely viscous at temperatures below its pour point, which for Prudhoe crude is about -10?C. Nonetheless, it would not be unreasonable to expect some lateral oil dispersion in association with blowing snow. This would continue intermittently throughout the winter and spring. Once at the lead surface, the oil might be transported long distances downwind, as some of these leads are very long indeed. However, except for windblown material, the oil would not appear inshore of the grounded ridge zone. Since the leads in the shear zone are of fundamental importance to ringed and bearded seals, polar bears and foxes, these animals at least would be displaced. One would also expect some impact on under-ice biota.

In April the westward ice drift would increase, moving the oil some 100-150 km to the west of the spill site by late May. Brine channels would bring oil to the ice surface, which, as before, would promote melting and drainage back into the water. Biodegradation would also be underway at this time, although the rate would still be relatively slow. As in the case of the inshore spill, one would expect some local physical and toxilogical effects on ice algae and under-ice fauna. Eiders, seals, whales, and arctic cod may encounter oil in leads, as might polar bear sows and cubs crossing from the coast to the pack.

By late June, oil transported with the ice could be expected as far as Cape Simpson. The remaining oil fractions would by then have become quite dense, and some sinking should be expected. Oil within the water column over the outer shelf would probably move eastward with the Bering Sea water. In general, the oil would be very widely dispersed.

Some of the oil would probably have encountered the Colville River plume. As a result, some oil might have been moved further offshore due to the currents, and some would have settled to the bottom by bentonite adhesion.

Finally, any oil in open water in July and August is capable of coming onto the western Beaufort Sea beaches under the influence of summer winds. Ice with oil still entrained would move relatively rapidly northwest and become part of the pack ice.

Other Transport Considerations of Pollutants

Briefly, some other sequences are as follows: In the case of a minor leak within the sediment, oil would probably move only some tens of meters laterally, but within this zone it would effectively be fatal to life and habitats, possibly for decades. There would be a very slow release of oil into the water. If the surface temperature were less than the pour point, the lateral extent of the congealed oil would be relatively small and cleanup fairly easy.

In the case of a winter spill on the surface of the ice, oil volatilization would be rapid, but dissolution and biodegradation would be nil.

We point out that the probable movement of spilled oil depends to some extent on the spill meridian as well as on the season. If the spill is to the west of Prudhoe, the oil could conceivably be carried with the ice well south into the Chukchi Sea. On the other hand, a summer spill east of Prudhoe could end up either west or east of the spill site, depending on the wind regime.

If ethylene glycol is introduced into the marine environment, temporary local toxicological problems should be expected. The material would, however, dissolve and dissipate relatively rapidly. We note that the TAPS line at one stage contained antifreeze for test purposes, and the disposition of this material must be controlled.

We wish to emphasize that our Canadian colleagues have made considerable efforts to ascertain the effects of oil development in the eastern Beaufort Sea. In particular, the Beaufort Sea Technical Reports No. 31a by Logan, Thornton and Ross (1975), and No. 39 by Milne and Smiley (1976) consider problems similar to those which we have just addressed.

Additional Information Gaps

We have been unable to resolve the various questions related to drilling muds. In the Beaufort Sea, direct releases into the marine system would be into very shallow water adjacent to drilling sites. Comparisons with other offshore oil fields are inappropriate as water depths and currents are greater in these areas (dilution, transport, sediment rates, etc.). Additional information about the toxicity and settling rates of these muds is required, as is information about the best ways to dispose of them. We still consider drilling muds to be a potential hazard in the nearshore Beaufort Sea system.

The leaching of petroleum at facilities on natural and man-made islands appears to be a problem because of its potential presence in critical places (beach lines and moats) during summer and fall. Methods for eliminating this problem should be developed.

Effective methods for cleaning up spilled oil in the Arctic should receive continued study.

Possibilities for the enhancement of barrier islands for breeding marine birds should be explored. There may be a possibility of accommodating birds displaced from islands that have production facilities.

The significance and impact of disturbance caused by the transmission of noise in waters around oil facilities is essentially unknown. The impact of such disturbance on marine mammals, particularly belukha whales, should be investigated.

Lethal and especially sublethal effects of petroleum on all life stages of key plant and animals species should be evaluated. Adverse effects on eggs and larvae of polar cod may be especially significant.

Considerable discussion about the possible synergistic intensification of pathogens in combination with the presence of petrochemicals in plant and animal tissues has been discussed at length. This question remains unresolved and should be investigated further.

The archeology of the Beaufort Sea coast remains inadequately known. Archaeological assessment of sites which may be developed by the oil industry should be undertaken, and a program of salvage archaeology instituted.

Studies of selected species of phytoplankton and animals recognized to be of importance in the Beaufort Sea system should be continued for the purposes of determining annual and longer-term variations which occur naturally as well as in response to development.

Marine areas between the barrier islands and mainland, from Oliktok Point to Flaxman Island should be studied during the period when ice is present, in order to determine the importance of this region to over-wintering fishes.

We also point out some transport and containment mechanisms in the Beaufort Sea which are at present not very predictable, well understood, or well known.

> First, there is a general lack of detailed information on inshore currents, whether related to wind, tides, river runoff, storm surges or freezing. This is true for both summer and winter.
>
> Second, the morphology of the under-ice surface (particularly nearshore) and its role in trapping oil is not well known. The same can be said for the time of formation and the extent of the grounded ridge zone and the possible role of this ice barrier in influencing water and oil motion.
>
> Third, a great many questions about the importance of sediments to oil transport remain unanswered. These include the movement of river-borne sediments during early summer flooding and underflow, the role of ice in mixing and moving sediments, and the movement and fate of oil within the sediments.

Fourth, the movement of oil and its many components in the food web is very poorly understood. This is an issue which is extremely complex and probably includes rather long time scales.

Fifth, there is not as yet a satisfactory understanding of how fast or by what means oil might be expected to move significant distances across the shelf, e.g., from the nearshore area to the shelf break.

Finally, we wish to point out that the entire question of the cumulative effects of numerous production facilities in the Beaufort Sea has not been adequately considered. The multiplication and perhaps compunding effects of "minor" adverse environmental impacts will be proportional to the extent of development associated with the production of gas and oil. The extent of "natural redundancy" which is part of the Beaufort Sea ecosystem is unknown and we have no indications about how much redundancy can be eliminated without posing serious threats to components of this ecosystem.

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11. EFFECTS OF GRAVEL MINING AND CONSTRUCTION OF GRAVEL ISLANDS AND CAUSEWAYS

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Introduction

Exploration for and production of petroleum on the Beaufort Sea shelf will require construction of large, stable platforms capable of resisting the pressure of moving ice. Construction of artificial islands, modification of existing islands, and construction of jetties and causeways will probably be called for. Large amounts of gravel will be needed for these structures. Gravel mining, island modification or construction, and causeway construction will alter the natural physical environment and affect the biota of the Beaufort Sea to some degree. It is important to anticipate adverse effects and to consider ways in which they can be minimized or mitigated.

The possible effects of gravel mining and of island and causeway construction were considered at length by a panel of biologists, oceanographers, and geological scientists during the first OCSEAP Beaufort Sea Synthesis meeting in February 1977. However, at that session we were handicapped by inadequate knowledge of the availability of gravel, of the processes affecting the natural offshore islands, and of industry requirements, capabilities, and economics. These same effects are reconsidered here, following new discussions which benefited greatly from participation by geologists and engineers from the petroleum industry, enabling us to make a more realistic appraisal of what might be proposed and what could be done. Furthermore, we now have the benefit of a considerable amount of more recent OCSEAP research, designed to fill some of the critical environmental information gaps made obvious at the first synthesis meeting.

Assumptions as to Probable Needs for Structures, Construction Materials, and Construction Techniques

The artificial structures needed, the potential flexibility of scheduling, and the resulting environmental impacts vary considerably during the different phases of petroleum development. During exploration phases, drill sites may be occupied for periods of only a few weeks, but development and production sites must be occupied for several decades. An exploratory well can be completed in a few months, and thus exploratory drilling can be confined to a favored season. However, industry spokesmen indicate that development drilling must go on more or less continuously year-round, because damage can result if wells are left seasonally idle. Needs for causeways are minimal and largely avoidable during the exploratory phase but may be essential during development and production phases.

Industry sources indicate that directional drilling can reach points 2 or 3 km distant from a given drill site and that as many as 20 wells can radiate from a single pad or platform. Thus, much of the proposed 1978 Beaufort Sea lease area could be reached by directional drilling from shore, from natural islands, and from artificial islands spaced 6 to 10 km apart. However, drilling of obliquely directed holes is said to be much more time-consuming than drilling of vertical holes; this reduces the potential for drilling to be scheduled during the autumn, winter, and spring months of low biological activity.

A surface area of 7,500 to 8,000 m^2 is needed to accommodate the drill rig, work area, living quarters, and the stock piling needs of an exploratory well. The drill pad can be circular and about 100 m in diameter, or it can be a rectangle as narrow as 50 m wide and 150 or 200 m long.

Most of the natural Beaufort Sea islands are of adequate width and length, but are low-lying. If they were used as drill sites, their freeboard would have to be raised by the addition of several meters of gravel. If exploratory drilling were confined to the winter months, little shore protection might be required, but use of the islands as long-term production platforms would require that their shores be stabilized and defended in some fashion from wave erosion and deformation by moving ice.

Sea ice can be and has been artificially thickened for use as an artificial island for exploratory drilling. Experiments thus far have been in sheltered waters covered by shorefast ice; ice islands can only be used in areas of limited ice movement. The water depths in which ice islands can be built are limited by the trade-off between time required for island construction and time left for drilling. The ice island constructed in Harrison Bay in winter, 1976-1977, was built in water 3 m deep and was available for drilling in early January. Future technological developments may make it possible to preserve an artificial ice island through the summer; this would permit an ice island to be constructed in sheltered waters perhaps 8 or 10 m deep during one winter, for use as a drilling platform during the next. However, ice islands may not be satisfactory as long-term production platforms.

Sunken barges have been used as exploratory drilling platforms in water less than 4 or 5 m deep. Protection against moving ice is needed, and a common solution has been to construct a barge-cored gravel island.

Artificial islands of silt have been constructed in Mackenzie Bay in water less than 2.5 m deep. The islands were constructed during summer and allowed to freeze, providing a hard working surface for exploratory drilling during the following winter. Frozen silt islands can be used only in areas of limited ice movement, and they are not suitable for use as development-drilling or production platforms.

Artificial islands constructed of gravel are likely to be proposed for use as exploratory drill sites and later as production platforms in many parts of the 1979 Beaufort Sea lease area. The maximum number of artificial islands that might be required probably would be on the order of

15 or 20. The amount of gravel needed, and thus the cost of an artificial island, increases geometrically with increasing water depth. The 20-meter isobath is probably the economically limiting depth for gravel islands. Perimeters of artificial islands must be protected against wave erosion and moving ice. There is a wide choice of designs and materials for island perimeters, and some are ecologically preferable to others.

Causeways provide dependable, year-round, all-weather access to drill and production sites and also can provide the medium through which pipelines can be brought through the hazardous nearshore and beach zones. The availability of a causeway can permit a smaller drilling pad because of reduced necessity for stock-piling of supplies. Causeways are too costly to use for access to exploratory drill sites, but they become attractive for both economic and safety reasons during the development and production phases.

Exploration and development of an oilfield in the Arctic requires large quantities of gravel. Industry participants indicated that a single Prudhoe Bay onshore drill pad required about 30,000 m^3 of gravel and that nearly 10,000,000 m^3 of gravel has been quarried thus far in the Prudhoe Bay oilfield.

Gravel for construction of causeways and artificial islands or modification of natural islands may come from onshore or offshore sources. Gravel can be moved from an onshore quarry to an offshore fill site by loading it onto moored barges, by trucking it over ice during winter, or by end-dumping from trucks on a causeway building out from land. Transportation is a major cost element in gravel use, and economic considerations favor quarrying of gravel as near as possible to the use site. High cost makes loading moored barges with gravel mined onshore a nearly prohibitive alternative. Gravel structures in water less than 1.5 m deep are, in some cases, most easily built by hauling gravel by truck over grounded ice, because dredges and barges cannot work in these shallow water depths. Trucking gravel over floating land-fast ice, however, is extremely hazardous as well as excessively costly. On the other hand, causeways are quite likely to be built with gravel truck-hauled from an onshore source.

Gravel can be excavated offshore by clamshell or by suction dredge and can be placed by dump-barge or by barge-mounted clamshell. The Beaver Mackenzie dredge, currently in use in Canadian waters, can operate in water depths greater than 1.5 m and can excavate about 13.5 m below the sea floor, if water is not excessively deep. The economic and practical limit for excavating gravel from the sea floor evidently lies somewhere landward of the 20-m isobath. The soft Holocene marine mud and clay overburden of the Beaufort Sea shelf can be handled by a suction dredge. However, heavier and more costly dredging equipment will be required if gravel is to be quarried in the large areas of the shelf where it is overlain by 5-10 m of overconsolidated silt and clay and in areas where the gravel is frozen and ice-bonded immediately beneath the clay.

Subsea tunnels and chambers have been proposed for use as access routes and drill sites for offshore drilling on the Beaufort Sea shelf (Lewis et al., 1977). The irregular depth to the top of offshore permafrost and the presence of thawed, incoherent, permeable, brine-soaked gravel to depths of 50 to 100 m throughout much of the lease area poses very serious design problems in planning tunnels and drilling chambers. Consequently, tunneling does not appear to be a realistic alternative for offshore petroleum development in the Beaufort Sea lease area.

Construction Materials

1. Availability of gravel and riprap:

Small supplies of gravel are present in the beaches and barrier islands of the Beaufort Sea (Hopkins and Hartz, 1978). Thin patches of sandy gravel are also present locally on the sea floor. Much larger and more significant supplies are available in a sheet of Pleistocene gravel that lies buried beneath the coastal plain and the continental shelf eastward from the Colville River Valley and central Harrison Bay. The buried Pleistocene gravel is at least several tens of meters thick and lies beneath a 3-10 m thick overburden of Holocene mud, sand, and peat and the overconsolidated clay and mud of the Flaxman Formation. The gravel grows finer seaward, grading into sand and then probably into marine silt on the outer shelf. The seaward limit of shallow gravel seems to lie about 20 km offshore and somewhere between the 15 and 20 m isobaths in the Prudhoe Bay area.

Ice-bonded permafrost affects the cost of gravel-mining on land and may limit the areas in which gravel can be dredged offshore. Some onshore gravel pits in the Prudhoe Bay area have been excavated to depths of many meters in ice-bonded gravel, but we know of no attempts, thus far, to quarry ice-bearing or ice-bonded gravel on the continental shelf. On the coastal plain, the permafrost table generally lies within the overburden, and the gravel is perennially frozen everywhere except beneath wide river channels and beneath lakes deeper than 1.5 m. In deeper water, the top of the ice-bonded layer is very irregular, lying in some places at depths of 8 or 10 m within or just beneath the clay overburden of the Flaxman Formation and, in others, at depths greater than 50 or 100 m within the underlying gravel (Sellmann and Chamberlain, 1978; Rogers and Morack, 1977).

Little or no gravel is present in the subsurface on the continental shelf westward from western Harrison Bay, and supplies on the coastal plain are available only in the chain of mounds and ridges representing a former Pleistocene island chain extending discontinuously from Barrow across the National Petroleum Reserve/Alaska to the peninsula north of Kogru River (see Geological Sciences, Section 3; also Hopkins and Hartz, 1978).

If available, coarse rock would be useful for riprap to protect the flanks of causeways and drill pads from wave erosion. Unfortunately, bedrock outcrops are lacking, and boulders are generally very sparsely distributed on the Beaufort Sea shelf and in adjoining coastal areas. Also, where they do occur as outcrops of the

Flaxman Formation, they appear to harbor an abundance of life forms, which may well make them critical habitats, as discussed later in this section.

2. Consequences of gravel mining - mainland beaches and islands:

Because mainland beaches are thin and narrow, they are generally unattractive as gravel sources. If they were quarried, the result in most places would be an acceleration of the already rapid rate of coastal retreat, both at the quarry site and for a considerable distance down-drift. However, transport cells are generally small along the mainland coast of the Beaufort Sea, and there are many small depositional spits and points that represent sediment sinks. These could be quarried without substantial permanent environmental effects. The volumes of gravel available in these local spits and beach-ridge complexes generally amount to less than 0.1 million m^3. Gravel mining on mainland beaches should be restricted to these small accumulations.

The offshore islands of the Beaufort Sea contain larger and more tempting supplies of gravel. Volumes of several million m^3 are present in many places. However, the offshore islands are mostly relict features, representing the coarse residue from erosion of land masses that have long since disappeared (Hopkins and Hartz, 1978). If the islands were removed, they would never be reconstructed by natural processes. Thus, mining of the offshore islands would cause irreversible environmental changes.

Extensive gravel-mining on the islands would reduce their perimeter and thus impact or even eliminate feeding and resting habitats for several bird populations during the late summer migration or molt (Connors, 1976, 1977, 1978; Johnson, 1978; Schamel, 1976, 1978). Cross and Howe Islands are critical nesting habitats for certain bird populations and have been nominated as ecological reserves. Duck, Niakuk, and western Cooper Islands are also heavily used by nesting birds and should not be quarried (Divoky, 1978).

Because the mainland and island shorelines are important migratory corridors for anadromous fish as they travel east and west along the Beaufort Sea coast, consideration should be given to the possible effects of turbidity resulting from gravel mining on the beach. The effects seem likely to be insignificant, however, because nearshore waters are often turbid due to storms.

Physical oceanographic consequences of extensive gravel mining of the offshore islands would include a reduction in shelter and an increase in wave energy in the adjoining lagoons. Coastal erosion would be accelerated. In many areas, gravel mining would open new passes between lagoons and the open sea, resulting in substantial and unpredictable changes in lagoon circulation, extent of winter shorefast ice, and summer ice movement. Although a few islands are wide enough so that small amounts of gravel could be removed without immediate or drastic environmental consequences, large-scale removal of gravel from offshore islands should be prohibited.

3. Consequences of gravel mining - boulder patches and gravel on and beneath the sea bottom:

The only known source of boulders possibly suitable for riprap is the large boulder patch that lies northeast of the mouth of the Sagavanirktok River between Point Brower and Narwhal Island. Whether boulders there are abundant and large enough for mining to be practicable has not been determined, but if mining were undertaken, the biological effects might be drastic. Ice gouging and other natural disturbances are evidently minimal, because the boulder patch is unique among Beaufort Sea areas studied thus far, in supporting kelp beds and a large and varied epifauna. Its significance as a food resource for fish, higher sea mammals, and birds has not yet been determined, but may be considerable. Studies of the possible biological significance of the boulder patch will be undertaken on this newly discovered substrate, and must be available before quarrying of boulders is permitted there.

Other patches of gravel on the sea bottom provide substrate for attached epifauna which may, in turn, be a significant food resource for animals higher in the food chain. However, ice-gouging and plowing tends to keep most bottom areas unstable and limits the density of attached epifauna on gravel. Dredging of these gravel patches would probably create disturbances comparable in intensity to natural ice-gouging and plowing. Patches of gravel on the sea bottom other than the boulder patch northeast of the Sagavanirktok River could probably be mined with minimal long-term environmental effect, but they are generally too small to constitute a significant gravel resource.

The widespread sheet of Pleistocene gravel that lies 3 to 10 m beneath the sea floor constitutes the largest, most widely distributed, and most conveniently located gravel resource within the 1979 Beaufort Sea lease area. If this deposit were quarried by dredging, temporary depressions would be created in the sea floor. The depressions would be wide and shallow with gently sloping sides. They probably would be filled by natural processes within a few decades. Suction dredging would create a mild local turbidity plume, which would be more severe with clam-shelling. Turbidity plumes at the construction site evidently would be minimal for barge-dumping, but intense if fill were placed by clam-shell. The turbidity plume would be comparable in intensity to turbidity caused by storm waves, ice gouging, strudel scour (bottom scour at points where overflowing river water drains through the ice during spring floods), and direct influx of muddy river water. The Colville River, for example, contributed 7.5×10^9 m^3 of water containing 4.2×10^6 metric tons of sediment during the unexceptional spring flood of 1962 (Arnborg et al., 1966, 1967).

Dredging presumably must be undertaken during the summer open water season, which is also the most biologically active season. The actual excavation would have only local and negligible biological effects. However, dredging in lagoon areas might release some hydrogen sulphide into the water column. Problems caused by the high turbidity might include clogging of the gills of larvae of certain benthic crustaceans and burial of weakly mobile infauna and epifauna such as some species of clams. Clams are a significant diet item for oldsquaws at certain seasons, but otherwise are not heavily utilized by birds, mammals, and fish in the Beaufort Sea. Dredging would be most damaging in relatively enclosed and highly productive lagoons such as Simpson Lagoon. Gravel dredging should be avoided in Simpson Lagoon, and probably in other narrow productive lagoons, but seems likely to have few adverse consequences in the broader embayments or on the open shelf.

4. Consequences of gravel mining - onshore gravel sources:

Borrow pits in the Prudhoe Bay area are presently concentrated along river channels, although some pits are so deep that they reach the Pleistocene gravel sheet that extends laterally throughout the coastal plain and the continental shelf. The Pleistocene gravel is also available beneath lakes or, indeed, beneath almost any part of the coastal plain from the Colville River eastward. Thus, mainland gravel pits could be developed in almost any environmentally acceptable site.

Mining of gravel in river channels is undesirable, because it disrupts stream flow and affects the habitat and life cycle of anadromous fish. Wetlands and marshes are also undesirable sites for gravel-pit development, because they provide nesting and feeding habitat for many species of migratory birds (see section on BIRDS). Tidal marshes are especially important for migrant geese in autumn (Derksen et al., 1977). Historic and prehistoric native villages, campsites, and cemeteries are concentrated along the Beaufort Sea coast. Gravel pits should be sited a kilometer or more inland in order to avoid damage to coastal marshes and wetlands, and to both known and unrecognized cultural sites along the coast.

It appears that large thaw lakes, deeper than 2 m and located a kilometer or more inland, are the most desirable and least ecologically harmful sites for development of mainland gravel pits. Gravel in these sites is likely to be naturally thawed; biological impact will be minimal; and after cessation of gravel quarrying, the pits can be filled with water for use as a year-round reservoir.

5. Conclusions:

The widespread sheet of buried Pleistocene gravel is a major resource that can furnish gravel almost anywhere it may be needed on the coastal plain, and in many places on the continental shelf eastward from the Colville River and Harrison Bay. Onshore pits quarrying the Pleistocene gravel should be sited away from the immediate coast, river channels, and wetlands and marshes. Basins of large, deep thaw lakes are probably the lease environmentally damaging and best sites for on-land gravel mining. The Pleistocene gravel can also be dredged throughout much of the submerged continental shelf with little or no long-term adverse environmental effects, but Simpson Lagoon and possibly some other narrow lagoons should be avoided.

Mining of large quantities of gravel from the offshore islands will cause damaging and irreversible environmental changes and should be forbidden. Duck, Howe, Niakuk, Cross, and western Cooper Islands are important nesting habitats for bird populations and should not be quarried. Mainland beaches must also generally be avoided, but small quantities of gravel can be removed from some spits and points without serious long-term adverse consequences.

A large quantity of boulders possibly usable as riprap are scattered in an extensive boulder patch between Point Brower and Narwhal Island, but possible exploitation should be deferred for several years, so that the productivity and ecological significance of this unique habitat can be evaluated.

The cumulative effects of industrial development tend to be ecologically much more serious than the effects of single, isolated operations. While the ecological effects of a single gravel-mining operation on- or off-shore may be trivial, the effects of mining gravel in a great many separate sites could prove to be disastrous. For this reason, gravel-mining should be concentrated in the smallest possible number of sites.

Use of Natural and Artificial Islands and Causeways

1. Effects of use of natural islands:

Flaxman, Gull, and Niakuk Islands, and some of the islands in the Sagavanirktok River delta, have been used as exploratory drill sites; use of other islands no doubt will be proposed. Exploratory drilling on Flaxman Island resulted in destruction of vegetation through burial beneath a drill pad and an airstrip. The size and shape of Gull Island was retained, but freeboard was raised by adding gravel confined within sheet piling, so that the island was transformed into a small mesa standing above the surrounding shallow water. Niakuk Island appears to have been altered little, and a colony of glaucous gulls has continued to nest on the island during summer, apparently unaffected by the winter drilling.

Those parts of the Beaufort Sea islands that are composed of relict Pleistocene sediments (Flaxman, Tigvariak, Cottle, Bertoncini, Pingok, and the Eskimo Islands) support tundra vegetation and bird fauna similar to those of the mainland; the islands are unique only in that some are inaccessible to mammalian predators during summer. However, historic and prehistoric sites tend to be concentrated on these islands. Cultural and archaeological resources should be inventoried and protected before any of the "tundra islands" are allowed to be used for petroleum exploration or production.

The low-lying constructional sand and gravel islands are biologically significant in offering shelter and protection to vulnerable ducks and shore birds, especially oldsquaws and phalaropes, during the late summer (Vermeer and Anweiler, 1975; Johnson, 1978). A few islands are also significant as nesting habitat: western Cooper Island has a large colony of Black Guillemots and Arctic Terns; Cross Island has many nesting Common Eiders; Niakuk Island has Glaucous Gulls; Duck Island has Black Brant, Glaucous Gulls and Common Eiders; and Howe Island has a large population of Snow Geese (Divoky, 1978). Cross Island also has an old cabin of recognized cultural-historical significance. These islands should not become sites of production wells, and all except Niakuk Island should also be closed to winter exploratory drilling.

The principal effects from use of the natural islands as year-round drilling and production sites would be from industry's almost certain protection of the rapidly eroding shores of the relict Pleistocene islands, and stabilization of the rapid migration of the constructional islands; increased noise and activity; and a potential for large blow-outs during the exploratory and development phases, as well as chronic small fuel spills from support operations during the production phase. Stabilization, per se, would not have adverse environmental or ecological effects, but the form of the stabilizing wall or embankment might. Steep or vertical retaining walls (e.g. sheet piling) at the shoreline would prevent molting birds from walking up the beach and thus decrease the value of the islands as shelter for resting birds. Ecologically, the ideal perimeter for a stabilized island would consist of a hardened slope not steeper than 30% rising from a sand and gravel beach. Phalaropes and Oldsquaw ducks are fairly tolerant of noise and human movement (Johnson, 1978), and so the activity surrounding a well rig would have little direct effect upon the principal bird populations feeding and resting near the islands during late summer. However, the flightless Oldsquaws concentrated there would be especially vulnerable to oil spills, and even minor fuel spills by support vessels and vehicles could have serious effects during late summer. The hazard is so serious that biologists are opposed to drilling of any sort during August and September on islands near Simpson Lagoon.

2. Effects of construction of artificial islands:

Artificial gravel islands would perturb the environment in ways that are analogous to the effects of the smaller and more isolated natural islands such as Reindeer, Cross, and Thetis. Small offshore islands can refract and focus waves in a way that may accelerate erosion on nearby island or mainland shores 2 km or so away, with subsequent deposition of eroded material elsewhere (e.g. in interbarrier inlets). More knowledge is needed concerning height, direction, and energy of waves in various parts of the Beaufort Sea before we can predict these effects. Artificial islands will also tend to anchor shorefast ice. On the outer shelf, their presence might extend the zone of winter shorefast ice seaward.

Ice-bearing permafrost will form quickly in artificial gravel islands, but during the first two or three decades, the interstitial fluids will consist of a two-phase mixture of ice and brine, and the frozen gravel will not be strongly bonded (see Section 3). Thus, development of permafrost probably will not add significantly to the strength and stability of artificial gravel islands during the period of their useful life as petroleum production platforms.

Artificial islands, if constructed with gently sloping perimeters, will affect the biota in pretty much the same way that natural offshore gravel islands do. They will provide shelter, protection against land-mammal predators, and additional shoreline which may attract molting birds and other habitues of the nearshore zone, depending upon location. However, the organisms attracted to the island will be especially vulnerable to damage should blow-outs or fuel spills occur.

3. Effects of causeways:

Construction of causeways will perturb the environment in ways analogous to the effects of natural spits. For example, a causeway from Oliktok Point to Pingok or Leavitt Island would make open-ended Simpson Lagoon more like Elson Lagoon, which is closed on the west by Point Barrow Spit. A long, poorly designed causeway could cause alterations in the circulation within a lagoon or between lagoon and open shelf. Causeways will tend to anchor winter shorefast ice and reduce its freedom of movement during spring breakup. The presence of a causeway cuts down wave fetch, so a long causeway could have a substantial effect upon the wave regime. By implication, the longshore current pattern in a lagoon or an embayment. Smaller waves are less capable of resuspending bottom sediments and consequently changes in thickness and character of bottom sediments can result from causeway construction. Changes in circulation, ice cover, and wave regime may alter the annual temperature, salinity, and nutrient regime in the lagoon. An uninterrupted causeway can disrupt or block the shore-parallel movement of sea mammals, flightless birds, anadromous fish and invertebrates, and the long-shore transport of food detritus. Causeways will disrupt beach drift, and unless corrective measures are taken, will cause pile-up of sediment on the updrift side and beach starvation and accelerated erosion downdrift.

Corrective measures are available to mitigate most of these effects. Littoral drift can be maintained, for example, by pumping sand and gravel across the causeway to maintain normal transport. Properly designed openings will allow circulation to be maintained so that disruption of temperature, salinity, and nutrient regimes, and movement of the biota, will be minimal.

Causeways should have gaps in the form of culverts or, preferably, bridges. The spacing and size of the gaps depends upon local conditions, but should be designed to maintain normal circulation. It may be necessary to accumulate observations on natural circulation for about 2 years before designing causeways. In any case, causeways should have large openings nearshore and next to offshore islands, in order to facilitate movement of flightless molting birds and anadromous fish. Openings need to be large enough to permit self-clearing of ice during spring breakup. Bridges are preferable to culverts because culverts have fixed cross-sections. Beneath bridges, the reduced channel width resulting from causeway construction can be compensated by deepening as accelerated currents scour the bottom.

Like artificial islands, causeways lengthen the shoreline and increase the area of sheltered waters available to molting or resting birds. However, causeways connecting islands to mainland will give foxes and caribou better access to islands. Foxes occasionally come ashore from winter ice onto the islands anyhow, but causeways could greatly increase their access during summer which could have serious effects upon nesting populations.

The presence of causeways could prove extremely useful in the event of a major oil spill. Floating oil would be much easier to confine and recover if its dispersal were blocked or channeled by a causeway.

4. Abandonment of artificial islands and causeways:

Decisions and planning prior to the development of an oil field involve economic considerations, whether the responsibility lies in the hands of a private corporation or an agency of a national government. If cost items are not predictable, economic decisions must be extremely conservative. Consequently, there is pressure to make long-term cost decisions at the earliest possible moment. Because removal of artificial islands and causeways after abandonment can involve costs at least equal to those involved in the initial construction, consideration must be given at an early moment as to whether and to what degree removal will be required.

Abandoned artificial islands and causeways can be hazards to navigation, and it may be necessary to completely remove some of them in the interest of safety. However, complete removal of artificial islands may have as much adverse environmental impact as did the original construction. Populations of birds and marine animals that have become dependent upon the artificial structures may be displaced. Dismantling of shore protection and excavation of fill will create local turbidity and bottom disturbance, and serious disturbance will also take place at the disposal site. Dredging, barging, or truck hauling will create new opportunities for fuel spills and other environmental contamination. Consequently, serious consideration should be given to the desirability of either leaving artificial islands and causeways intact, or removing their shore protection and allowing them to assume the form of the rapidly migrating natural sand and gravel islands.

If islands and causeways are not removed, bridges and culverts should be dismantled, so that the artificial structures are severed from land and access by mammalian predators is minimized. Some long-term monitoring may be necessary to ensure that openings are not closed by longshore transport. Consideration should be given to encouraging revegetation by halophytes to create a sparse plant cover similar to that on the older natural sand and gravel islands. Placement of suitable litter would provide shelter and nesting materials for birds.

We recommend that lease stipulations state that artificial causeways and islands may generally be left intact except for removal of bridges and culverts. However, the regulatory agency should reserve the right to require the developer to assume responsibility for providing appropriate mitigating measures, in the event that an artificial structure or altered natural feature proves to be environmentally undesirable, or dangerous to shipping.

5. <u>Conclusions</u>:

With proper design and scheduling, many of the natural islands of the Beaufort Sea could be used for exploratory and developmental drilling and as production sites with low negative environmental consequences. Certain islands (western Cooper, Cross, Duck, and Howe Islands) which are important nesting habitats, should, however, be kept untouched; for the same reason, Niakuk Island should be used only for exploratory drilling and only during winter. Historical and archaeological sites should be inventoried and protected before use of the tundra-covered Pleistocene islands is permitted. If islands are to be stabilized, a gently sloping beach should be retained, at least on the south-facing side, so that resting birds can haul out. Post-breeding and resting bird aggregations in Simpson Lagoon and probably other narrow lagoons are extremely vulnerable to oil spills; biologists are opposed to permitting drilling in these areas during August and September.

Causeways may cause more serious perturbations of the environment. A long causeway can alter circulation, wave regime, ice cover, temperature, salinity, and nutrient balance in a lagoon, seriously disrupt beach-drift of sediment and longshore movement of anadromous fish and molting birds, and provide access by land predators to nesting or molting bird populations on offshore islands. Properly designed openings can minimize some, but not all, of these perturbations. In spite of their disadvantages, a causeway could prove extremely useful in limiting the dispersal of oil during a major spill event.

Dismantling and removal of artificial islands and causeways may create as much environmental disturbance and involve at least as much cost as the original construction. Biota may have become dependent on the causeways and artificial islands and serious consideration should be given to leaving in place those structures that do not pose serious hazards to navigation, with or without their slope protection. If the structures are allowed to remain, they should be severed from land, and consideration should be given to enhancing their usefulness by encouraging slight revegetation and leaving suitable litter for shelter and nesting materials.

We note again that such effects are cumulative, and that the impacts of a great many operations may be ecologically disastrous, even through construction of a single artificial feature may have little effect. A few artificial islands and causeways can be constructed in appropriate places without severe adverse consequences, but the lacing of the 1979 lease area with multiple artificial islands, stabilized natural islands, and interconnecting causeways could have disastrous cumulative effects upon the biota of this arctic region.

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12. ENVIRONMENTAL HAZARDS TO OFFSHORE OPERATIONS

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Introduction

In this section we attempt to address the major environmental obstacles to offshore development along the coast of the Beaufort Sea. It evolved through an open panel discussion among those participants in the Arctic OCS Environmental Assessment Program with backgrounds in a variety of different disciplines, interested members of the Barrow community, and representatives of the petroleum industry.

As a basis for discussion, we utilized a document recently prepared by a Committee of the Alaska Oil and Gas Association (AOGA). This document, included here in part as Appendix I, gives industry's appraisal of environmental hazards to development. We found the document to be very helpful, particularly regarding industry activities that would occur in developing proposed lease tracts along the Beaufort Sea coast. The following section on offshore operations uses portions of the AOGA document nearly verbatim. There was general agreement on the nature of the principal environmental hazards to be surmounted in the safe development of the Beaufort Sea coast. There was, however, considerable variation in opinion as to the level of knowledge necessary for safe offshore petroleum development.

The Beaufort Sea coast of the Arctic Ocean is one of the least inviting coastlines in the world. The land is quite flat, dotted with innumerable lakes, and rises very gradually to the south towards the Brooks Range. Patterned ground features indicative of permafrost are present everywhere except in the immediate vicinity of stream channels. The general trend of the coast is east/west and there are a number of rather large embayments. Along the coast there are several series of offshore barrier islands. The outermost of these islands (Cross Island) is located 21 km north of the coast, but most of the islands are within 10 km of the coast. Many of the islands are largely void of vegetation, are composed of sand and gravel, rise only a few meters above sea level, and are vulnerable to rapid erosion and changes in shape during severe summer storms. Between the islands and the mainland the water is quite shallow (< 8 m), and in a number of nearshore areas the thickness of first-year ice is sufficient to cause freezing to the sea floor. North of the barrier islands the sea gradually deepens, reaching depths of 20 m at approximately 10 km offshore from the islands. (At some locations this depth of water is found quite close to the islands, e.g., 4 km north of Flaxman Island.)

Because of its arctic location, the Beaufort Sea beyond the continental shelf is essentially ice-covered year-round. However, in the waters over the continental shelf, there is usually an ice-free season which may last up to 2-3 months. There may be essentially no ice-free season during summers when the winds are unfavorable, i.e., when they keep the drift ice against the coast. The maximum thickness of first-year ice that can form during a winter is just over 2 m. Within the barrier islands, the ice cover is fast (relatively motionless) most of the winter, although appreciable movement can occur in both the fall and spring (freeze up and breakup) periods. Seaward of the islands the fast ice extends some distance further offshore. The extent varies from year to year and with the time of year. A representative example of late winter ice zonation in the waters over the Alaska Beaufort Sea Shelf is shown in Figure 12.1. In late winter, the fast ice frequently extends out to the 25-30 m isobath.

Seaward of the fast ice, the pack ice moves in a sporadic, sometimes oscillating or jerking motion, with the general drift being from east to west. During the winter the net movement along the coast is quite small. However, movements in excess of 20 km per day are not rare during the summer when the fast ice has melted or moved away from the coast and the pack ice has broken up into individual pans. Although most of the ice in the pack ice zone is first-year ice, "intrusions" of thicker multi-year ice into near-coastal waters are not unusual. Extensive pressure ridge formations are also quite common. In some locations large accumulations of intensely deformed ice survive the summer, and gradually metamorphose into very large, thick masses of low salinity, high strength ice. Also, ice islands (tabular icebergs from the Ellesmere Island ice shelves) are known to drift along the coast of the Beaufort Sea. When large pressure ridges, floebergs, or ice islands ground, they can be gradually pushed along by the surrounding ice pack, causing grooves to be gouged in the sea floor.

It is within this environment that proposed offshore oil and gas activities will occur. It is an environment that is strikingly different from that encountered during typical offshore operations in more temperate climates. At first thought, it might appear that the environmental hazards along the Beaufort Sea coast are so severe that safe operations are impossible. This is not the case. For instance, there are tested operational techniques, such as the construction of artificial gravel islands, that can clearly be used safely inside the barrier islands and probably also in the shallower waters seaward of the islands. In water deeper than 13 m (40 ft) environmental hazards increase rapidly. Even here, safe operational schemes can be developed if the hazards that must be surmounted are clearly delineated. The cost of safe operations may, however, make the development of certain high risk tracts of land uneconomic. There is little doubt that in water exceeding 20 m, operations along the edge of the Beaufort Sea can be considered "frontier" in every sense of the word, with ice as the foremost developmental problem, followed by high storm surges and waves carrying massive ice fragments.

Nature of Offshore Operations

To assess the effect of the environment on offshore operations, it is first necessary to know what sort of activities are envisioned. The AOGA document identifies the following:

I. Pre-lease (and Post-lease) Transport

Marine Transport

Seismic boats, supply barges and other support vessels will be required to operate in open water. Although these vessels may be ice-strengthened, they will have little if any ice-breaking ability.

Ice Surface Transport

The movement of surface vehicles across the fast ice will be required for seismic exploration, construction (e.g., gravel transport), rig movements, supply operations, and personnel transfer. Vehicles may be wheeled, tracked or sled-mounted and some of the vehicles will be quite heavy.

II. Exploration Drilling

Grounded Barges

The drilling platforms would consist of one or more barges ballasted so that they sit on the ocean bottom. Such systems would be limited to shallow water (< 5 m). Barges could also be surrounded by a gravel berm.

Artificial Ice Islands

These ice drilling platforms would be formed *in situ* by the artificial thickening of a part of the natural ice sheet. Such schemes would be limited to shallow water (< 5 m) in order to provide sufficient time during a single winter for both platform construction and drilling.

Gravel Islands

Artificial gravel islands are a proven concept for offshore arctic operations. They can be made large enough to withstand expected ice loads, even considering extensive ice motion. They can be built either in the winter (by trucking gravel over the ice) or in the summer (by barging or dredging in open water). Their limitations arise mainly from the large gravel volume and construction time required for deeper water. Construction of such islands would probably be limited to areas of fast ice cover in winter.

Barrier Islands

Natural islands offer relatively stable drilling platforms that would require only minor modifications to be used for drilling.

Cone-shaped Gravity Structures

This type of offshore platform, in which the cone shape of the bottom-founded leg(s) causes the ice to fail in bending (weak failure mode) as opposed to compression (strong failure mode), may be used for exploratory drilling in deeper water where they are more economical than gravel islands. During the summer period such structures could be refloated and towed to new locations.

Floating Platforms

Floating drilling vessels (barges or ships) may possibly be used during the ice-free season in water over 13 m deep. Such operations are currently used only during the summer open water period and generally in water over 20 m deep. Stringent requirements to maintain the position of the drill ship directly over the borehole limit their use in shallow water.

III. Development and Production

One major requirement for structures utilized in the development and production of an oil or gas field is a lifetime for the structure in excess of the expected life of the field. Another requirement is the identification of an acceptable method for transport of the oil or gas from the offshore well to onshore pumping stations.

Gravel Islands

Gravel islands (including grounded barges with a gravel berm) are well suited for development and production platforms in shallow arctic waters. The island freeboard and beach protection would be designed against the extreme storm conditions expected at the site. It is presumed that the islands would naturally develop a permafrost core which would increase their lateral stability against ice pressure. Defensive measures would also undoubtedly be utilized to attempt to prevent ice from overriding an island.

Barrier Islands

Natural barrier islands could readily be transformed into production islands. If an island were low or very small the freeboard might have to be raised above the level of the maximum storm tides and measures taken such as the construction of the ice fences to prevent ice from overriding the island.

Cone-Shaped Gravity Structures

These structures, which would presumably be similar to the "cones" used for exploratory drilling, would primarily be used in deeper water where gravel islands are not feasible.

Subsea Completions

In some cases subsea completions without surface piercing structures may be possible for either primary development or satellite wells. The wells would be drilled by use of either movable "cones" or floating platforms, and would be completed below mudline to provide protection against bottom gouging by ice. Routine well servicing would be performed by the use of "Through-Flow-Line" techniques.

Causeways

Industry would like, where possible, to provide access to production islands located in shallow water via gravel causeways. In addition to providing year-round logistic entry, causeways would serve as pipeline corridors between the wellhead and the mainland, using conventional elevated or buried construction modes.

Buried Pipelines

In the absence of a causeway, buried offshore pipelines will be required to transport oil and gas between the wellhead and the mainland. The depth of burial will be specified so that the pipeline will always be below the expected depth of current ice gouging.

Elevated Pipelines

At some locations, pipelines may have to be elevated above water (e.g., to prevent nearshore permafrost degradation).

Tunnels

The use of tunnels for logistics and transportation corridors between the mainland and offshore is appealing, inasmuch as the approach avoids all ice-related problems. Industry, however, doubts that this approach is viable because of the high cost of tunneling.

Hazards

A hazard assessment can only be completed when one combines an understanding of the strengths and weaknesses of a proposed system with knowledge of the environmental constraints that are expected at a specific operational site where the system is to be deployed. We will first briefly discuss the ice hazards related to the different activities we have described, inasmuch as ice is clearly the distinguishing feature along the Beaufort Sea coast. Then we will discuss other possible hazards. We will concentrate on major hazards that might cause a complete disruption of operations or be the limiting factor in the design or utilization of a specific system.

Ice

There are four major sea ice zones, as well as an open water season, that impact.

1. Open Water. Conventional marine transport, as well as the use of floating drilling vessels, are activities that are essentially restricted to times when sea ice is absent. If the offshore summer pack ice moves into an area, conventional ships may be unable to operate, could sustain hull damage, and might be pushed aground by the ice pack. The operation of floating drilling vessels may therefore be severely curtailed, in that ice motion can force the ship off its station above the drill hole. In any such operation both the wellhead and the BOP (blowout preventer) stack would have

to be located below mudline in excavated craters or jetted-in caissons. Also the vessel would have to be prepared to rapidly disconnect from the drill string and move off-site if concentrated pack ice moved into the area. Therefore, good all-weather ice reconnaissance and ice forecasting are essential to the efficient and safe operation of such systems.

2. Bottom-Fast Ice. This zone occurs just offshore of the main coast and is restricted to water depths under 2 m (i.e., locations where the undeformed sea ice is thick enough to freeze to the bottom). When bottom-fast ice is discussed it is usually assumed to be in an area where ice motion during the winter is negligible. In such areas, grounded barges or artificial ice islands would be very cost-effective platforms for exploratory drilling. However, both these systems are unable to tolerate lateral ice motions in excess of a few meters. To reduce the effect of ice movement a "moat" has been kept open around one artificial ice island during the winter. In general, the thicker the fast ice, the more stable it becomes because more of it is grounded. The main hazards would undoubtedly occur either in the fall when very large motions (in excess of 1 km) are known to occur even within the barrier islands, or in the spring when significant motions of thick, albeit deteriorated sea ice have been encountered at some sites along the coast. Utilization of systems sensitive to ice motion presupposes the availability of a reasonable amount of data on fast ice motions in the vicinity of the proposed drill site. Also, if the wellhead and BOP stack are located below mudline, ice motion presents more of a problem to the operator than to the environment as ice effects would be unlikely to cause a blowout. It is conceivable that the best strategy at some sites would be to curtail operations during the short periods in the fall and spring when the ice cover is most likely to shift. Other options would be to utilize the more stable and more costly methods of either surrounding the grounded barges with gravel berms or constructing artificial gravel islands.

3. Floating Fast Ice. This zone occurs just offshore from the bottom-fast ice and extends seaward for varying distances depending upon the time of the year. Ice conditions within the fast ice zone can change dramatically from year to year, depending upon the forces and movements to which the weak fall ice is subjected. As the fall ice continues to thicken and strengthen, it becomes more resistant to deformation. Therefore, the potential for extensive deformation within the fast ice zone gradually decreases as the winter progresses. There is some debate as to where the outer fast ice boundary is most likely to be located. Many times it is taken to be at the 20-m isobath since at many locations this water depth coincides roughly with the location of the edge of the fast ice during early winter. However, the OCSEAP studies (see section on Sea Ice) have shown that the fast ice edge may lie well seaward of the 20-m isobath in late winter. For offshore resource development purposes, it is much safer and therefore more appropriate to select the 15-m isobath as the outer edge of the "stable" floating fast ice because this boundary tends to separate regions where the fast ice is relatively undeformed from regions where encounters with

very large moving ice masses can definitely be expected during early winter freeze-up. Perhaps when more years of observation are available it will prove safe to consider this boundary to be further seaward, especially on a site-specific basis.

Anywhere within the floating fast ice zone large (< 100 m) movements of cold, thick sea ice must be presumed to be possible. Available information suggests that such movements are quite likely seaward of the barrier islands, becoming much rarer between the islands and the coast. However, unless site-specific information is available to the contrary, drilling activities proposed for the floating fast ice zone must be prepared to contend with such movements. Because of their sensitivity to ice movement, artificial ice islands and simple grounded barges appear as possibilities only in areas where ice movement would be negligible. The stability of grounded barges could be enhanced by surrounding them with gravel berms or by utilizing artificial gravel islands, an approach that has proven to be very effective in the fast ice zone of MacKenzie Bay. In both these cases, it would also appear desirable to utilize additional defensive measures to prevent ice from overriding the site. Also, precautions would have to be made to prevent a blowout from occurring even if the site were to be destroyed by rapid ice movements. Another possible system that could be utilized in such areas is a cone-shaped gravity structure which would be designed to resist the forces which occur during ice movement and piling.

Gravel causeways also would be susceptible to lateral ice movements although their presence would undoubtedly tend to stabilize the nearby ice cover. Particularly sensitive systems would be elevated pipelines running along a causeway or an elevated pipeline connection coming from a buried offshore line onto the land. (Such connections might have to be used in areas where there are permafrost problems and causeways are not permitted for a sea-land transition.) As mentioned earlier, in nearshore areas ice movements are most probable during the fall or the spring when (fortunately) the ice is not at its thickest or strongest. Further offshore, movement appears to be possible even during mid-winter or very early spring, based on experience gained north of the Mackenzie Delta. The more information concerning fast ice motion available prior to construction, the better engineers will be able to anticipate potential problems in their designs. One consideration that is undoubtedly of importance is the observation that south of the barrier islands large multi-year floes are rarely found, while north of the barrier islands multi-year floes of appreciable size (up to several hundred meters in diameter) are commonly found within the fast ice.

Ice surface transport would also be utilized within the floating fast ice zone because the surface of this ice is smooth enough to permit travel without too many detours. The ice thicknesses required for safe operation of different heavy vehicles are known. If care is taken in scouting potential routes to determine variations in ice thickness, there should be little difficulty in carrying out safe and efficient operations. One hazard that must be considered is the result of ice movements that would open small leads (3-5 m in width) within the fast ice. If thin ice forms across such leads and the ice is then covered by drifting snow, the frozen leads become traps for surface vehicles. Unfortunately, at present there is no method for predicting when such leads are likely to form. When frozen leads close, the thin ice in the lead is deformed into a pressure ridge. These ridges are also dangerous to cross with heavy vehicles, but easy to see.

Finally, it should be mentioned that adequate data required on the observed depths* of gouging of the bottom sediments by ice are necessary so that feeder pipelines and wellheads can be buried deep enough to be safe from such problems.

4. Pack Ice. This zone extends seaward of the fast ice zone. For this discussion, the southern limit of the pack ice zone will be based on early winter (October-November) ice conditions. Thus, the ice in the grounded ice zone and the floating extension of the fast ice shown in Fig. 12.1 are considered here to be parts of the pack ice zone. This is based upon the fact that during early winter the ice forms the grounded ice zone at about the 15-m depth contour and ice seaward of this depth is part of the pack. Indeed, the grounded ice zone forms during this period when the pack moves toward the coast, crushing and piling up the thin, newly-formed seasonal ice. The potential for significant lateral ice movements well in excess of a kilometer exists at all times of the year but is particularly high in the early winter. However, as the ice thickens and becomes stronger, the compactness and inertia of the pack ice increase and its susceptibility to deformation decreases.

Any structure contemplated for this ice zone would have to be designed to withstand the forces exerted by moving masses of cold, thick first-year ice and by large multi-year floes with embedded pressure ridges. Consideration would also have to be given to the potential forces produced by impacts with thick, massive floebergs and ice islands, as well as the expected recurrence intervals of such impacts. It would appear improbable that an offshore structure could be built that would survive the impact of a large ice island. Nevertheless, the construction of structures that would be displaced or destroyed as a result of such an impact might still be economically viable if the probability of such an occurrence is sufficiently low and a spill could be avoided. However, there is no escaping the fact that in this zone ice/structure interaction problems are severe. Most likely, artificial gravel islands would be utilized out to water depths of 20 m, the economically limiting depth for such structures. They would undoubtedly have to be armored by some means to prevent major erosion by the moving ice and to prevent the ice from completely overriding the island. For deeper waters, cone-shaped gravity structures are currently believed to be the most likely approach. The possibility of ice-induced erosion around the bases of such structures is a problem that

Editor's Note: OCSEAP is seeking to understand gouging phenomena sufficiently well to be able to predict extreme gouge depths for design purposes.

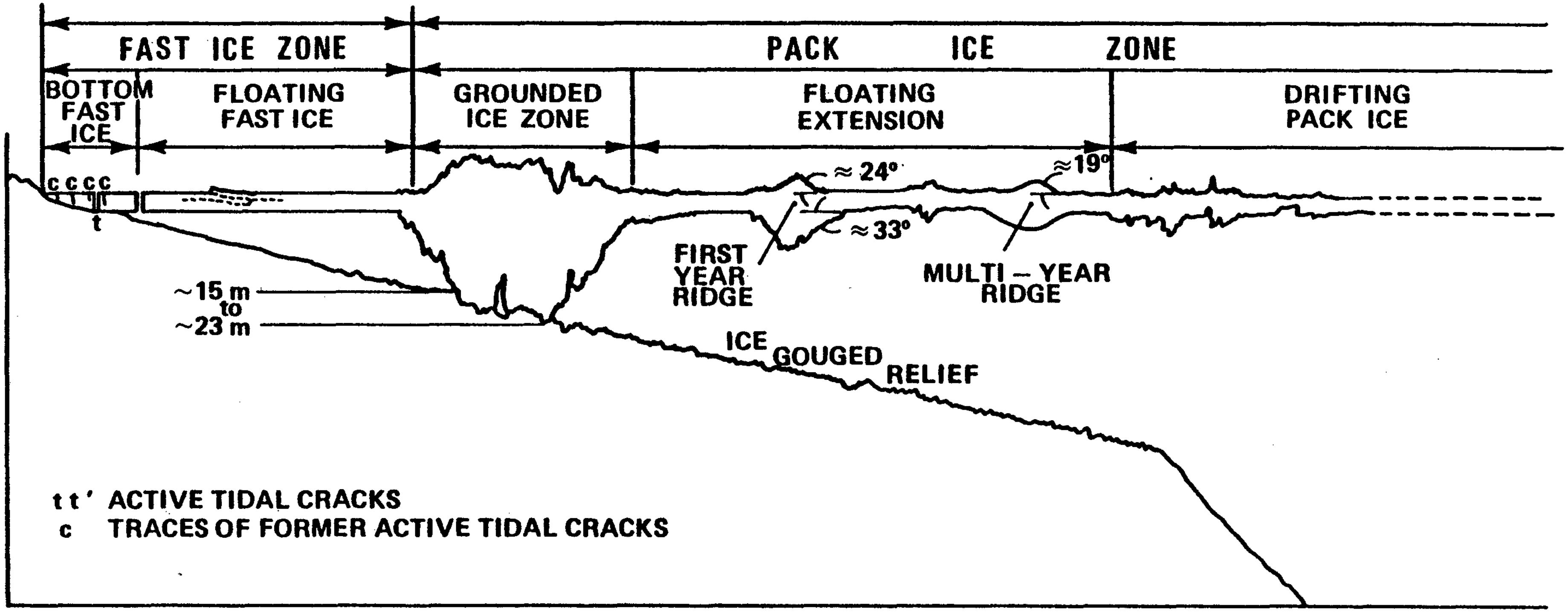

Fig. 12.1 Late winter ice zonation of the Beaufort Sea Coast, indicating terminology used in this report

clearly must be considered. Also, the deck structure of the platform must be high enough above the ice that ice pile-ups are not a problem. Estimates of this height would probably be based on conceptual models of the pressure ridging process coupled with observational data on the heights of grounded first-year ridges.

Finally, any pipelines to the mainland would have to be buried in the seafloor sediments below the depth of present day ice gouging. Establishing this depth requires good observational data on the depth of existing ice gouges. In the grounded ice zone (Fig. 12.1), gouging is both deep (several meters) and frequent.

Other Environmental Hazards

Waves: Wave data are required to determine the freeboard needed for various offshore structures. This is particularly true of structures in shallow water near the coast. Also, wave-induced erosion of both natural and artificial gravel islands could be a problem if suitable precautions are not taken. However, these problems should not be difficult to handle, and on gravel islands the wave protection system could probably be combined with a system for minimizing problems of ice override.

Surges: Major storm surges are generated by westerly blows and generally occur near the end of the open water season when the fetch between the land and the semi-continuous pack ice is at its maximum. The worst storm surge on record for the Alaskan Beaufort Coast occurred in September 1970. The height of the surge was 3 m and wave heights were also estimated at 3 m. Evidence suggests that similar events may be expected to have a recurrence interval of 25 to 100 years.

Because the land is low, extensive coastal areas are inundated by such surges, posing a significant threat to installations. Bluff retreat of up to 60 m or more can occur in a single storm and large amounts of sediment are transported to the east. All but the highest barrier islands are entirely awash and undergo considerable erosion, and some smaller islands may completely disappear. Clearly, offshore platforms, artificial gravel islands, causeways, and elevated pipelines on causeways could sustain significant damage. As the westerly winds during such storms bring the pack ice up against the coast, ice fragments of several hundred tons could override the islands.

In addition, winter surges have been recorded up to 1.4 m in height. These surges are not always clearly related to a local storm. Although not as spectacular as summer surges, winter surges could cause significant problems for artificial ice islands or grounded barges that are sensitive to significant ice motions. Clearly the existence and likelihood of both winter and summer surges must be taken into account in the development of safe operations for the Beaufort Coast.

Currents: Information on currents will be required to estimate coastal erosion rates and scour around the foundations of bottom-founded offshore structures. Inasmuch as available information indicates that the currents along the Beaufort Coast are not large, this is not believed to be a major problem.

River Flooding: When the spring runoff from the large coastal rivers such as the Colville and the Sagavanirktok enters the Arctic Ocean, the water initially flows over the bottom-fast ice out onto the floating fast ice where it ultimately passes beneath the ice through drainage holes and cracks. The estimated depth of this flood water would have to be considered by engineers designing nearshore grounded barges for drilling platforms or utilizing artificial gravel islands for the same purpose. Such flooding may also trigger lateral shifts in the fast ice.

Thermal Erosion of the Coastline: Because the coastal bluffs contain a large amount of ice, wave action along the coast may cause the rapid recession of exposed portions of the coast. As was mentioned earlier, bluff retreats of over 60 m have been noted in a single storm. Protection of selected stretches of beach from such erosion should not be too difficult although it clearly would be expensive. Such protection would undoubtedly have to be provided at sites where pipelines that are buried offshore cross onto the land via elevated connections.

Wind: Wind data are required to calculate wind loads on offshore structures. Existing wind records for coastal stations along the North Slope should provide reasonable design estimates. Of particular interest are combined sets of atmospheric pressure, fetch, wind, wave and surge measurements. Such observations can be useful in "calibrating" operational models used to forecast waves and storm surges.

Air Temperature: Air temperature data can be useful to designers in anticipating problems such as "low-temperature brittleness" that may occur in certain construction materials. Existing temperature records should be adequate for this purpose.

Superstructure Icing: Because ice conditions in the Beaufort Sea limit sea spray to times when the sea is ice-free, superstructure icing would only be expected to be a problem during fall. General estimates of the magnitude of the problem can be obtained from existing weather records, estimates of the effective fetch during fall storms, and icing information from other locations such as the North Sea and the Sea of Okhotsk. We would not expect superstructure icing to be a severe problem along the Beaufort Sea coast unless barge or ship drilling occurs in winter and an open water moat is maintained around the barge or ship to limit the effects of sudden ice movement. Should such drilling systems be used, superstructure icing resulting from water vapor escaping from the moat surface may pose a problem.

Seismicity: Seismicity in the proposed lease area is very low, but there is a seismically active area, with a linear trend NW-SE, in the vicinity of Kaktovik (Barter Island). During the last 2 years approximately 200 earthquakes, with magnitudes between 1 and 4, were recorded in this area. Previous records indicate that magnitudes of 5-6 can be expected. The earthquake for the Beaufort coast would probably have a magnitude of approximately 6. The area of active seismicity is close enough to the present sale area that structures within the latter very likely would be affected by ground accelerations from moderate earthquakes close by. This hazard cannot be adequately evaluated.

Permafrost: At the present time no catastrophic problems are anticipated from offshore permafrost. At locations in the floating fast ice zone as well as further offshore, the top of the bonded permafrost is below, but not always far enough below the sea floor so that pipelines and the foundations of offshore structures would not be entirely within the thawed near-surface layer. Generally, our knowledge of the distribution of subsea permafrost in this zone is very limited. In the bottom-fast ice zone the permafrost can extend right to the sea floor and the presence of permafrost would definitely have to be considered in foundations and buried pipeline design. Potential difficulties with buried offshore feeder pipelines in this ice zone are one of the reasons that industry strongly favors the use of gravel causeways as pipeline conduits.

When hot oil starts to flow from the offshore wells, the attendant heat will probably cause melting of the subsea permafrost and produce differential subsidence. This is a problem that must be accounted for in the well-bore design. If the subsidence process were to continue unabated, it could result in system failures and serious production delays. Similar problems occur in the colder land-based permafrost, and techniques which have been designed to combat those problems will also prove useful offshore.

Clathrates and Gas-Charged Sediments: Clathrates, also called "frozen gas hydrates," are known to occur at the lower boundary of the ice-bonded sediment section and can result in high pressures when they are penetrated during drilling. Evidence that clathrates exist offshore can be found in high resolution seismic reflection records from many regions of the inner shelf. These records show intermittent patches of acoustic energy loss, which in other regions have been found to be positively correlated with the presence of gas-charged sediments. Drilling should proceed cautiously in areas where the presence of clathrates is suspected.

Data Needs

Additional information on ice movement as a function of ice thickness and time of the year would be very useful both in itself and as data to develop a model to forecast fast ice movement. Such information is critical to the safe design of systems that require defensive measures to minimize ice loads, i.e., grounded barges and artificial ice islands. The information is also important when considering the possible overriding of artificial and natural gravel islands by ice, planning defensive measures against this, calculating safe freeboards, and predicting the size of ice pile-ups around different types of structures.

Retrospective studies should be made of summer invasions of heavy pack ice into nearshore areas. Particular attention should be paid to the reliability with which these invasions can be predicted by numerical modeling techniques. Such invasions have a significant impact on the economics and possibly even the safety of open-water operations such as marine transport and drilling from floating platforms. Improved data on the rates of ice movement, ice concentration variations, ice thickness distributions and the distribution of floe sizes could be utilized in developing statistical models for structural design. More observations of the nature of the ridging process around large grounded ice features would help in developing improved mechanical models of ice sheet/structure interactions. Of particular interest are expanded observations on the nature of large ridges embedded within multi-year ice floes and on the development and characteristics of floebergs. Such data are essential for the optimum design of cone structures and of gravel islands that are sited in deep water. At the present time a gravel island is being designed for construction in 29 m of water north of the Mackenzie Delta and conical structures are being discussed for siting in up to 75 m of water.

Statistical information is needed on the number, distribution, size, and thickness of ice islands currently adrift in the Arctic Ocean. Also useful would be estimates of the likelihood of future ice island calving from the Ellesmere Island ice shelves. These data, when combined with existing knowledge of the drift of the ice pack in the Arctic Ocean, can be utilized to produce risk estimates for the collision between an ice island and an offshore structure located off the coast of the Beaufort Sea. Statistical information is also needed on the depth and frequency of ice gouging of the sea floor along the Beaufort Sea coast. Particularly desirable would be studies of variations in parameters such as sediment type, geographic location, and bottom slope on the nature of gouging. Such information is particularly needed for the pack ice zone where the economic feasibility of buried pipelines may depend upon the required depth of burial.

One final point relating to sea ice. The OCSEA Program has largely been devoted to collecting improved information on the types of ice entities that can be found along the Beaufort Coast and how these entities behave. There has been little consideration given to bridging the gap between the nature of the ice and the effective estimation of the ice-induced loads that a structure will encounter. This is not an easy gap to fill, in that ice loads on structures depend on the strength of the ice, which is in turn a function of parameters including ice salinity, temperature, crystal structure, strain rate, the geometry of the structure, the size of the stressed regions, and the failure mechanism. A proper development of this subject will require a combination of theory, experiment, and field work. In addition, improved instrumentation and experimental procedures will undoubtedly be required.

Other important needs include the development and testing of an adequate model for predicting both ocean and ice surges. Input to such a model would require improved and expanded information on atmospheric pressure variations. A related need is the development of a storm wave model, its verification through hindcasting, and the utilization of such calculations to estimate coastal erosion and nearshore sediment transport.

Conclusion

We have attempted to discuss a number of areas in which the environment can have a significant impact on offshore operations along the Beaufort Sea coast. If the nature of the environmental hazard is understood and incorporated into the initial design and subsequent operation of a system, safe and efficient operation can certainly be achieved although at times the price will be high. The Beaufort Sea coast is truly a frontier area in the sense that many of the environmental problems encountered there, in particular those associated with the presence of ice, are different from the problems that are usually encountered in petroleum development of an ice-free coast. There is, however, operational experience that has been gained in other areas where ice is common, such as the Canadian Arctic and Cook Inlet, and it is directly applicable to the Beaufort Sea coast.

Considering the geography of the coming lease sale as well as this experience, one can divide the lease area into three sub-areas. The first of these includes the barrier islands and the shallow, protected water between the barrier islands and the coast. The development of this acreage is clearly within the capability of existing tested systems, although there will be considerable flexibility in design and decisions as to the most effective approach for each specific site. The second sub-area extends from the barrier islands offshore to a water depth of 15 m. This is clearly a region of more danger from the environment, as the expected ice motions are larger. However, encounters with very thick ice masses are not likely. Although more difficult, operations here can be achieved by reasonable extensions of existing systems. The third sub-area, which is located offshore of the 15 m water depth, is a true frontier area for operational systems and procedures. To survive here one must be able to cope with all the hazards the Arctic Ocean can offer, including encounters with formidable ice masses. Good design for this challenging region will definitely require a thorough knowledge of environmental hazards and sea ice mechanics coupled with solid inventive engineering.

Appendix I

The following tables, produced by the Alaska Oil and Gas Association (AOGA) list industry's concerns with ice and other potential environmental problems. The table should not be viewed as a complete listing of possible activities and hazards; only the more promising and generally applicable systems and the principal environmental factors have been included.

LEGEND

First Character refers to severity of the environmental hazard

0 No Concern
1 Some Concern
2 Considerable Concern
3 Major Concern

Second Character refers to availability of technology to deal with the environmental hazards

A Technology presently available
S Technology expected to be available short term (<5 years)
L Technology expected to be available long term (5-10 years)

Third Character refers to data needs

0 No additional data needed for design or operation
1 Additional data needed to optimize design or operation
2 Additional data needed to establish economic feasibility of design or operation

N/A - Not Applicable

Application

V very likely
L likely
P possible

ICE ENVIRONMENTAL CONCERNS
1. BOTTOM FAST ZONE

Activities	Application	Freeze up Movement	Winter Sheet Ice Movement	Breakup Movement, Override	Summer Pack Ice Invasions	FY Ridges	Multiyear Ice
I. Transport (Pre and Post Lease)							
Marine Transport		N/A	N/A	N/A	1A0	N/A	N/A
Ice Surface Transport		N/A	0A0	N/A	N/A	0A0	0A0
II. Exploration Drilling							
Drilling Structure							
Grd. Barges	V	2A0	1A1	2A1	2A1	0A0	0A0
Ice Islands	L	N/A	1A1	2A1	N/A	0A0	0A0
Gravel Islands	V	0A0	1A0	1A1	1A1	0A0	0A0
Barrier Islands	V	0A0	0A0	1A1	1A1	0A0	0A0
III. Development							
Drilling Structure							
Grd. Barges with Gravel Berm	V	0A0	1A1	1A1	1A1	0A0	0A0
Gravel Islands	V	0A0	1A1	1A1	1A1	0A0	0A0
Barrier Islands	V	0A0	0A0	1A1	1A1	0A0	0A0
Buried Pipelines	V	0A0	0A0	0A0	0A0	0A0	0A0
Elevated Pipelines	P	1S1	1S2	1S2	1S2	0A0	0A0
Causeways	V	0A0	1A0	1A0	1A1	0A0	0A0

ICE ENVIRONMENTAL CONCERNS
2. FLOATING FAST ZONE

Activities	Application	Freeze up Movement	Winter Movement	Breakup Movement Override	Summer Pack Ice Invasions	FY Ridges	MY Ice	Gouging
I. Transport (Pre and Post Lease)								
Marine Transport		N/A	N/A	N/A	1A1	N/A	N/A	N/A
Ice Surface Transport		N/A	2A0	N/A	N/A	1A0	0A0	N/
II. Exploration Drilling								
Drilling Structure								
Float. Platform	L	2S0	N/A	N/A	3A1	N/A	N/A	2A1
Grd. Barges	L	2A0	2A2	2A2	2A1	1A0	1A0	2A1
Ice Islands	L	N/A	2A2	2A2	N/A	1A0	1A0	2A1
Gravel Islands	V	0A0	1A1	1A1	2A1	1A0	1A0	N/A
Cones	L	0A0	1A0	2S2	2S2	1A0	2S2	2A1
Barrier Islands	V	0A0	1A1	1A1	2A1	0A0	0A0	N/A
III. Development								
Drilling Structure								
Gravel Islands	V	0A0	1A1	1A1	2A1	1A0	1A1	N/A
Cones	L	0A0	1A0	2S2	2S2	1A0	2S2	N/A
Subsea	P	2S0	2A2	N/A	3A1	N/A	N/A	1A1
Barrier Islands	V	0A0	1A1	1A1	2A1	0A0	0A0	N/A
Buried Pipelines	V	0A0	0A0	0A0	0A0	0A0	0A0	1A1
Causeways	P	0A0	1A1	1A1	2A1	1A0	1A0	N/A

BEAUFORT SEA
ICE ENVIRONMENTAL CONCERNS
3. PACK ICE AND STAMUKHI ZONES

Activities	Application	Winter Ice Movement	Summer Pack Ice Invasions	MY Floes	Stamukhi	Floebergs	Ice Islands	Gouging
I. Transport (Pre and Post Lease)								
Marine Transport		N/A	2A1	N/A	N/A	N/A	N/A	N/A
Ice Surface Transport		3L0	N/A	0A0	3L0	0A0	0A0	N/A
II. Exploration Drilling								
Drilling Structure								
Float. Platform	L	N/A	3A1	N/A	N/A	N/A	N/A	3A1
Cones	V	1A0	3L2	3L2	2L1	3L2	2A0	3A1
III. Development								
Drilling Structure								
Gravel Islands	P	1A1	3S2	3S2	2S1	3S2	3S2	N/A
Cones	V	1A1	3L2	3L2	2L1	3L2	3L2	N/A
Tunnels	P	N/A	N/A	N/A	N/A	N/A	N/A	1A0
Subsea	P	2A2	3A1	N/A	N/A	N/A	N/A	3S2
Buried Pipelines	V	N/A	2A1	N/A	N/A	N/A	N/A	2S2

OTHER ENVIRONMENTAL FACTORS

Activities	Air Temperature	Super-Structure Icing	Corrosion	Seismicity	Permafrost	Adfreeze
I. Pre-Lease						
Marine Transport	0A0	1A0	1A0	N/A	N/A	N/A
Ice Surface Transport	0A0	N/A	0A0	0A0	N/A	N/A
II. Post-Lease						
Drilling Struct.						
Float. Platform	1A0	1A0	1A0	0A0	1A0	N/A
Grd. Barges	0A0	1A0	1A0	0A0	1A0	1A0
Ice Islands	1A0	N/A	N/A	0A0	1A0	N/A
Gravel Islands	0A0	N/A	N/A	1A0	1A0	N/A
Cones	1A0	1A0	1A0	1A0	1A0	2S1
Barrier Islands	0A0	N/A	N/A	0A0	1A0	N/A
III. Development						
Drilling Struct.						
Grd. Barges	0A0	0A0	1A0	1A0	1A1	1A0
Gravel Islands	0A0	N/A	N/A	1A0	1A1	N/A
Cones	1A0	1A0	1A0	1A0	1A1	2S1
Tunnels	N/A	N/A	N/A	1A0	2A1	N/A
Barrier Islands	0A0	N/A	N/A	1A0	1A1	N/A
Subsea	N/A	N/A	0A0	1A0	1A0	N/A
Pipelines						
Buried Pipelines	0A0	N/A	1A0	1A0	1A1	N/A
Elevated Pipelines	1A0	1A1	1A0	1A0	1A1	N/A
Tunnels	N/A	N/A	N/A	1A0	2A1	N/A
Causeways	0A0	0A0	N/A	1A0	1A1	N/A

OTHER ENVIRONMENTAL FACTORS

Activities	Waves	Surges	Currents	River Flooding	Seashore Thermal Erosion	Wind
I. **Pre-Lease**						
Marine Transport	1A0	0A0	0A0	N/A	N/A	1A0
Ice Surface Transport	N/A	N/A	N/A	1A0	N/A	1A0
II. **Post-Lease**						
Drilling Struct.						
Float. Platform	1A1	1A1	1A1	N/A	N/A	1A0
Grd. Barges	1A1	1A1	0A0	1A0	N/A	0A0
Ice Islands	1A1	N/A	1A0	1A0	N/A	1A0
Gravel Islands	2A1	2A1	1A0	1A0	N/A	0A0
Cones	1A1	1A1	1A0	N/A	N/A	1A0
Barrier Islands	2A1	2A1	0A0	0A0	1A0	0A0
III. **Development**						
Drilling Struct.						
Grd. Barges	2A1	2A1	1A1	1A0	N/A	0A0
Gravel Islands	2A1	2A1	1A1	1A0	1A0	0A0
Cones	1A1	1A1	1A1	N/A	N/A	1A0
Tunnels	N/A	N/A	N/A	N/A	N/A	N/A
Barrier Islands	2A1	2A1	2A1	0A0	1A0	0A0
Subsea	N/A	N/A	N/A	N/A	N/A	N/A
Pipelines						
Buried Pipelines	1A1	0A0	1A1	1A1	1A1	N/A
Elevated Pipelines	2A1	2A1	0A0	1A0	1A0	1A1
Tunnels	N/A	N/A	N/A	N/A	N/A	N/A
Causeways	2A1	2A1	1A1	1A0	1A0	0A0

Appendix II

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Synthesis Meeting, Barrow, Alaska

24-27 January 1978

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