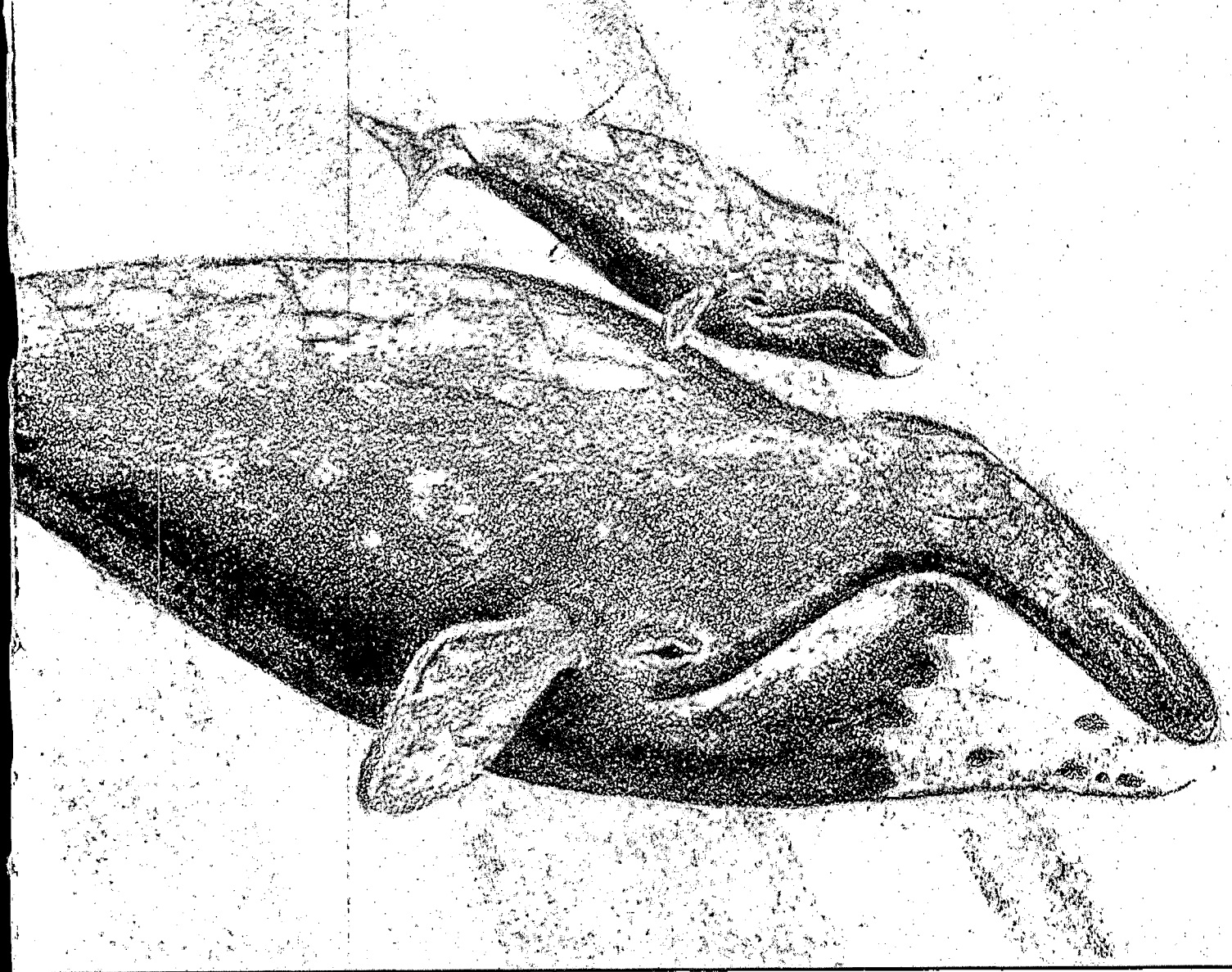
Dale

Outer Continental Shelf Environmental Assessment Program

Proceedings of a Synthesis Meeting:

The Diapir Field Environment and Possible Consequences of Planned Offshore Oil and Gas Development

Chena Hot Springs, Alaska, 25-28 January 1983



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Notices

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Preface

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) was established by a basic agreement between the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of the Interior, Bureau of Land Management (BLM) to conduct environmental studies on Alaskan continental areas identified by BLM for potential oil and gas development. In 1982, the Minerals Management Service (MMS) was formed within the U.S. Department of Interior and assumed responsibility for federal offshore leasing and administration of the related environmental studies program. Recently, through reorganization within NOAA, OCSEAP is now administered through the Ocean Assessment Division of the National Ocean Service in Anchorage, Alaska.

As a major portion of the Alaskan OCS studies program, OCSEAP's activities have included review of existing data, planning and management of original studies of all aspects of marine science, and transfer of information to MMS and other users. One method by which this information transfer takes place is through interdisciplinary synthesis meetings.

OCSEAP synthesis meetings address environmental issues and resource use conflicts which may arise in proposed oil and gas lease areas. OCSEAP investigators, other scientists, OCSEAP management, MMS personnel, and representatives from state government, the petroleum industry, local residents, and other interest groups attend these meetings.

The Beaufort Sea area has a relatively long history of OCSEAP-sponsored synthesis meetings and synthesis reports. The first meeting was held in Barrow, Alaska, in February 1976. The resulting report was published in 1977. This was followed by synthesis meetings held in January 1977 (at Barrow) and April 1981 (at Chena Hot Springs).

This report is a result of the fourth Beaufort Sea synthesis meeting, which was organized through the efforts of Drs. William M. Sackinger and Steven T. Zimmerman, and was held at Chena Hot Springs, Alaska, January 25-28, 1983. The first two days of the meeting consisted of disciplinary workshops on the following subjects:

1. *Pollution Transport.* This involved trajectory analysis using scenarios of expected oil- and gas-related developments.
2. *Biological Resources.* These included primary production and invertebrates, fish, birds, and marine mammals, and the characterizations of ecological zones on a seasonal basis.
3. *Physical Hazards.* Items included sea ice, permafrost, and other hazards.
4. *Oil Spill Cleanup.* Discussions were oriented toward technology available for the cleanup of spilled oil in broken ice environments.

These sessions were followed the third and fourth days by interdisciplinary discussions and analyses of the following issues: biologically sensitive areas and times, subsistence, noise effects, causeways and gravel sources, subsea pipelines and landfalls, and cumulative effects.

This report is largely the end product of the synthesis meeting. However, it also includes a significant amount of information that postdates the meeting or is appropriate to make the report more comprehensive. The depth and breadth of the subject matter vary considerably among chapters. This reflects the quality and quantity of available information plus editorial discretion in an attempt to accurately portray the results of the workshops, particularly those involving analyses of issues.

P.R. Becker
Editor

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This report was prepared with contributions and assistance from scientists and managers from the Outer Continental Shelf Environmental Assessment Program, the Minerals Management Service and several other Federal agencies, the State of Alaska, the petroleum industry, universities, and the public at large. Special thanks are due the workshop chairpersons and meeting participants who submitted text and graphic material for the report.

Cover illustration by Paula Wolfe

Part I

Characteristics of the Diapir Field Area

Chapter 1
Introduction

by Paul R. Becker

1.1 DESCRIPTION OF THE SALE AREA

The Diapir Field Outer Continental Shelf (OCS) Planning Area consists of the continental shelf of the Alaska Beaufort Sea plus the northeast portion of the Chukchi Sea shelf (Fig. 1.1). This area covers approximately 72,800 km^2 (Grantz *et al.* 1981). It extends from the Canadian border near Demarcation Point (141° W) westward to 162° W. The continental shelf in this area is relatively narrow (60-120 km in width), with the widest part in the Chukchi Sea portion of the sale area. The extreme western boundary also extends the farthest north—up to 73° N.

The onshore region bordering the lease offering area is sparsely settled; the great majority of permanent residents are native Inupiats. This region lies completely within the North Slope Borough, which has a resident population of 4,305 (North Slope Borough 1979). The largest village, Barrow, has a population of 2,715. The rest of the population is divided among seven other villages.

Although political, social, and economic changes have accelerated during the past couple of decades, primarily due to increased development associated with the oil and gas industry, traditional land uses continue to dominate the lifestyle of the resident population. (The only real industrial development site is at Prudhoe Bay.) Although the amount of land and resource use varies from village to village, subsistence hunting and fishing continue as important functions in supplying food and other products for most individuals. A discussion of subsistence resources is presented in Chapter 18.

The coastline of the Diapir Field lease offering area is indented with shallow bays and lagoons and has extensive development of spits and low, offshore (barrier) islands. This coastline is the northern boundary of the Arctic Coastal Plain, a physiographic province characterized by low-lying, wetland tundra. The Arctic Coastal Plain is progressively wider from east to west. At its maximum, south of Point Barrow, it is over 160 km wide. The tundra consists of grasses, sedges, lichens, mosses, and low-growing to prostrate woody shrubs growing in a thick, spongy mat of accumulated organic peat. Summer thaw and poor drainage result in a wet substrate over most of the plain.

The most characteristic morphologic features of the Arctic Coastal Plain are ice-wedge polygons and shallow thaw lakes and thaw ponds. Ice-wedge polygons are formed when temperature-induced contraction cracks fill with water and freeze. A continual thawing-freezing process results in the formation of innumerable depressions bounded by ridges (ice-wedge polygons). Where ponded water collects in these depressions, ground temperatures increase, causing permafrost degradation and the eventual formation of thaw ponds. As the process continues, thaw ponds enlarge, coalesce, and form shallow lake basins. Most of the small ponds are less than 1 m in depth, while lakes are generally 1.5-3 m in depth and are about 2 km in length. The grasses and sedges associated with these wetlands provide prime habitat for the support of large numbers of breeding and postbreeding loons, waterfowl, gulls, terns, and shorebirds. The interspersed upland tundra is used by passerines, ptarmigan, and raptors. Bird use of coastal and marine habitats is described in Chapter 10.

The tundra is underlain with layers of permanently frozen soil (permafrost). Without the presence of this permafrost, the wetland habitat of the Alaska Coastal Plain would probably not be as extensive. The annual precipitation is very low

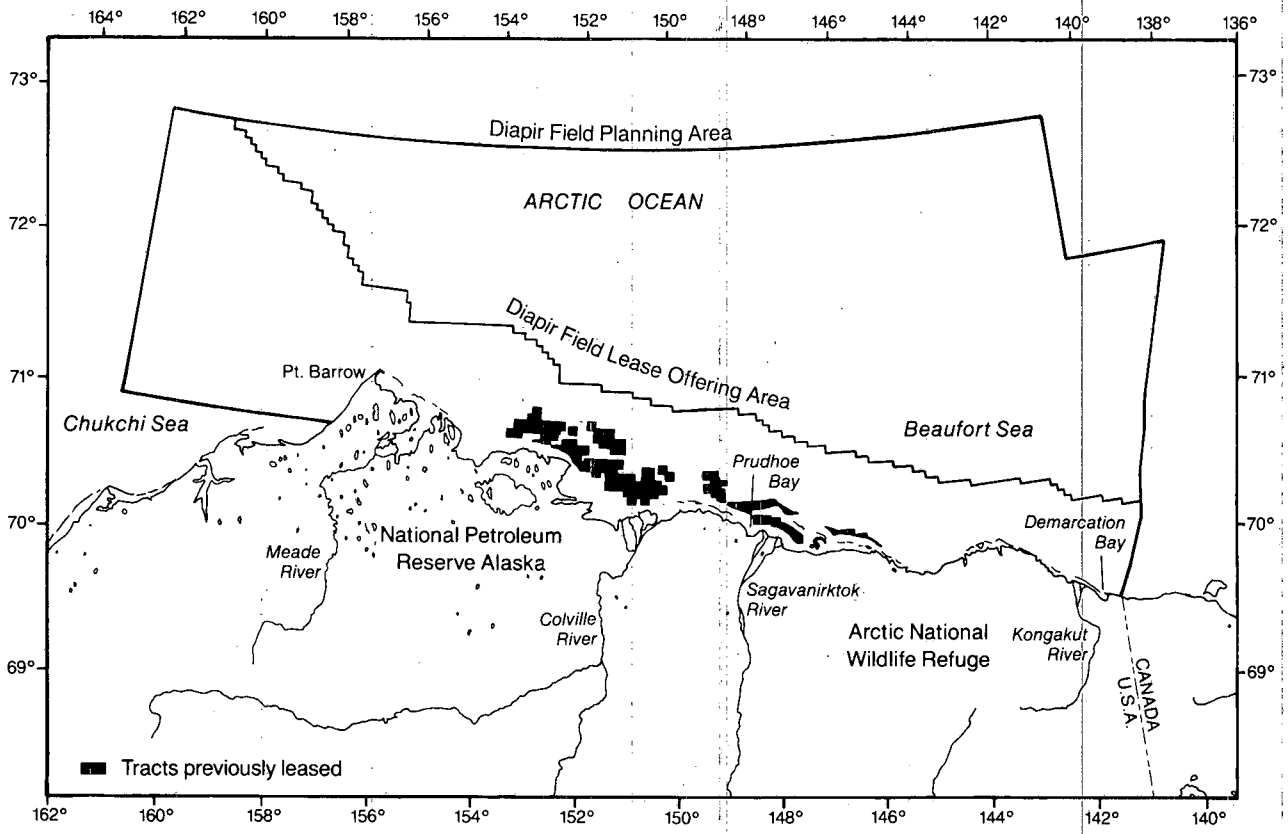

Figure 1.1—Diapir Field, Sale 87 lease offering area.

(10-20 cm), most of it in the form of rainfall during the months of July and August (Searby and Hunter 1971). During most of the year the Arctic is covered by a shallow layer of stable cold air which is effectively isolated from the atmosphere above. Thus, the air temperature is largely determined by the temperature of the earth's surface, which remains relatively cold. July and August have average temperatures of 4°C and 3°C, respectively. The summer months are characterized by cool maritime winds, cloudiness, fog, and frequent drizzle, all conducive to very low rates of evaporation. The little moisture that falls as rain does not percolate through the soil and is not lost to underground aquifers because of the impermeable permafrost. Therefore, the low evaporation rate and the presence of permafrost tend to keep the tundra more or less water saturated.

Most of the water resources remain frozen for 7 to 9 months of the year. Winter temperatures average −26°C to −32°C, with wind chill factors much lower (Searby and Hunter 1971). Although breakup usually begins in September, both freeze-up and breakup are quite variable. Freeze-up may begin anytime between the first of September through mid-December, and breakup, from late May through late August. However, snow accumulation during the winter provides sufficient water to produce peak spring runoff in the river systems, replenish lakes and ponds, and contribute surface water to the wet, tundra soils.

The Alaskan Beaufort Sea derives the majority of its sediments from rivers that flow only during the short summer; in fact, most of this riverine sediment discharge occurs during breakup. These streams are characteristically shallow, with low gradients. They flow in braided and complex meandering channels among the shallow lakes of the coastal plain. The Colville River is the largest (>640 km long; 61,440km^2 drainage area) of these rivers; its drainage area is 30% of the Arctic slope (AINA 1974). The Colville River also has the most diverse assemblage of anadromous fishes in the Alaskan Beaufort Sea; spawning populations of char, ciscoes, whitefishes, smelt, chum salmon, and pink salmon occur here (see Chapter 9).

The rivers west of the Colville River have different geomorphic and hydrologic characteristics and are dominated by a different fish fauna than those streams to the east (see Chapter 9). Rivers west of

the Colville River do not originate in the Brooks Range but drain tundra-covered slopes of the Arctic Foothills and Coastal Plain provinces. They are usually shallow, have poorly integrated drainage, and flow in meandering channels through the numerous lakes once they reach the coastal plain. They flow in fluvial, unconsolidated deposits and continually shift courses, creating oxbow lakes, point bars, ridges, and swales (Walker 1973). These streams provide habitat that supports whitefishes, ciscoes, and some salmon.

The large streams east of the Colville River originate in the Brooks Range. They have braided patterns, which frequently persist to the Beaufort Sea. These streams are characterized by innumerable gravel and sand bars separated by a maze of shifting channels (Walker 1973). The presence of perennial springs in these systems is associated with spawning grounds of Arctic char, the only anadromous fish to be found in the streams between the Colville and the Mackenzie rivers.

Most of the Arctic Slope rivers have built conspicuous deltas, which protrude directly into the Beaufort Sea (for example, the Sagavanirktok River). Other systems consist of estuaries filled by several rivers. Dease Inlet is an example; into it flow the Meade, Inaru, and Oumalik rivers and part of the Ikpikpuk River. The deltas of the larger rivers are thought to provide overwintering habitat for ciscoes, whitefishes, and char.

In addition to fluvial sediment discharge, sediments are also contributed to the Beaufort Sea by coastal erosion, causing shoreline retreat. Beaches experience wave and current action during the short summer season. This is increased by the relatively large waves generated by summer storms. The barrier islands themselves, and the mainland coast, where unprotected by these islands, are subject to considerable erosion by wave action.

The shoreline is characteristically a low bluff about a meter high, composed of peat, frozen silts, and ice wedges. The peat, bound together toward the surface by vegetation, overhangs the ice and frozen silt to the water's edge. The exposed frozen materials melt when exposed to the sun and warm air. After thawing, the shoreline is undercut by ocean waves. Geomorphic change is rapid, and the shores are highly unstable, a condition accelerated by a rising sea level in recent centuries.

The Beaufort Sea coastline is characterized by extensive development of sand and gravel barrier islands and shallow lagoonal systems. The barrier islands provide summer nesting habitats for eiders, gulls, and terns, and many of the lagoons contain excellent feeding areas for anadromous fishes and shorebirds. Besides true barrier islands, other islands created during shoreline retreat are also present. These lie farther offshore, with deeper waters between them and the mainland (e.g., Narwhal Island and Stefansson Sound). Most of this nearshore coastal area is underlain by permafrost that extends in irregular patterns tens of kilometers offshore. The subsea permafrost of the sale area is described in Chapter 3.

The offshore islands determine the nature of much of the nearshore physical and biological environment along the Beaufort Sea coast. These islands can effectively moderate the influence of the inshore movement of the polar pack ice and, in the few weeks of summer, partially separate the cold, saline waters of the open Beaufort Sea from the warmer, brackish waters that generally flow from east to west in a narrow band along the mainland coast.

The lagoons of the central and western Beaufort Sea coast generally have large openings in their barrier island systems, which provide little restriction to water exchange between the lagoons and the Beaufort Sea ("open" lagoons). In contrast, the lagoons of the eastern Beaufort Sea tend to have small openings in their barrier island systems and exhibit limited exchange (see Chapter 5).

The oceanographic processes in the Diapir Field area are influenced by the clockwise circulation of the Beaufort Gyre, the intrusion of Bering Sea water from the west, freshwater discharge from coastal rivers, and prevailing wind conditions. There appear to be two different circulation regimes. The inner shelf (landward of the 40-m isobath) is primarily wind driven, particularly in summer (Aagaard 1981). Wind may also significantly influence under-ice circulation on the inner shelf during the winter.

Seaward of the 40-m isobath, the flow is relatively slow throughout the year and locally aligned with the isobaths. This current has a mean eastward flow.

During the open-water season, a band of turbid, brackish, relatively warm water is a characteristic feature of the nearshore regime. This water is the product of ice-melt and river discharge; the pattern of its development depends on temperature and the resulting degree of ice-melt and river discharge, nearshore currents, prevailing winds, and the locations of barrier islands. The barrier islands tend to restrict exchange between the brackish waters and

offshore marine waters. In the absence of the barrier islands the plume may extend 20-25 km offshore. Westerly winds tend to push marine water inshore and restrict the offshore movement of the plume, while easterly winds tend to push the plumes farther offshore. This brackish water has an effect on the distribution of anadromous fishes along the coast since they tend to congregate in these turbid areas.

Wind has a major effect on the physical and biological environment of the Alaskan Beaufort, influencing times of sea ice breakup or freeze-up, creating nearshore currents, and moving ice floes.

Surface winds are relatively constant. The yearly average for the coastal zone is 15-20 mph at exposed locations. Calm conditions exist only 1.3% of the time at Barrow (AINA 1974). Discussions of circulation in the sale area are presented in Chapters 4 and 5.

The presence of sea ice has a large influence on the physical conditions and the movement of biota into and out of the Diapir Field area. The Beaufort Sea is ice covered 9-10 months of the year and can freeze up to 2.4 m in thickness in one season. The thickness of multiyear ice averages 4 m; ice island and ice ridges occur with keels as much as 50 m in thickness (see Chapter 2).

Sea ice formation usually begins in September (freeze-up) and continues through the winter and into the early spring. By early spring well-defined zones of sea ice have developed along the coast. These three zones are the landfast ice (both bottomfast and floating fast ice), the pack ice, and the stamukhi zone. The landfast ice varies in its extent of development. By the end of the winter it may extend less than 1 km or as much as 50 km offshore. During the formation of these three zones, the floating pack ice is transported westward by the prevailing currents, shearing against the landfast ice and forming pressure ridges that ground along the nearshore edge (stamukhi zone). These pressure ridges may exceed 10 m in height and have keels tens of meters in depth. Within this stamukhi zone the gouging of the sea floor by ice keels is most frequent, but not necessarily restricted to this zone. These gouges can be up to 4 m in depth. Under the influence of prevailing currents and extreme winter onshore winds, the movement of pack ice onshore can also result in ice masses overriding the coastline.

The extent of formation and the location of sea ice is probably the single most important factor affecting the movement and behavior of fishes, birds, and mammals. Many species congregate in open water near the edge of the pack ice and move with the ice. The leads which form in the ice during the spring and early summer provide pathways for migrating birds and mammals. Various phenomena associated with sea ice are discussed in Chapters 2, 3, and 12.

When compared with more temperate regions, the number of species that occur in the Diapir Field area is relatively low. The food webs are generally simple and direct. The short summer periods are characterized by dramatic increases in biological activity, as biota that are absent during the winter months migrate into the region to reproduce and feed. These migratory species include shorebirds and waterfowl, anadromous fishes, and marine mammals such as bowhead and belukha whales, walrus, and bearded and spotted seals. The food webs that support these biota have been described for the lagoonal systems and offshore open-water areas, as well as those associated with the pack-ice (refer to Chapters 7-11 and 13).

During freeze-up, only a very few animals remain to overwinter. These include ringed seals, polar bears, and Arctic fox. A key fish species during this period is the Arctic cod, which is very abundant and provides an important source of food for overwintering ringed seals.

1.2 PROPOSED ACTION

Sale 87 is the third Federal OCS oil and gas lease sale to be conducted for the Beaufort Sea Diapir Field. Sale 87, like the first two sales, will result in leases issued for 10-year terms.

The first Federal OCS oil and gas lease sale in the Beaufort Sea (Joint Federal/State Beaufort Sea Sale) was held in December 1979. Twenty-four of the 46 Federally-offered tracts and 62 of the 71 State-offered tracts were leased. The second Beaufort Sea sale (Sale 71) was held in October 1982 and resulted in the lease of 121 of the 338 tracts offered. In addition to these, the state of Alaska held eight other oil and gas lease sales in the North Slope and adjacent nearshore areas of the Beaufort Sea. The description of activities expected to be the result of Sale 87 is given below and is primarily based on MMS (1983).

Oil resource estimates for the Sale 87 area range from 0.55 to 12.36 billion barrels (Table 1.1). Mean case estimates are 3 billion barrels of oil and 7.75 trillion cubic feet of gas.

The timing of events and levels of activities used in the scenario at the Diapir Field Synthesis Meeting is based on the assumption that the amount of economically recoverable oil is approximated by the mean case resource estimates. Based on the mean case estimates, exploration resulting from the sale will begin in 1986 and continue through 1993. Assuming that the first discovery occurs in 1988, delineation wells will be drilled during the period 1989-94. Thirty exploration wells, nine oil delineation wells, and three gas delineation wells are projected in the mean case (Table 1.1).

Half of all exploration wells might be drilled year-round from artificial gravel-islands, caisson-type structures, or semisubmersible (caisson) drilling units. With icebreaker support, ice-strengthened drillships and conical drilling units (CDU's) could operate during the period of late breakup through early freeze-up. Both of these platforms have the capability of working in relatively deep water. Drillships are designed to work in waters of 15-300 m depth, while the CDU's can work in depths of 40-60 m. In contrast, the gravel-islands will be built in waters shallower than 20 m. Caisson structures and semisubmersibles have been built on submerged berms in waters that range from 13 to 31 m deep and could also be constructed in shallower or deeper waters.

Table 1.1—Resource estimates and activity levels for three alternative estimates of recoverable resources.

	Low	Mean	High
Oil Estimate (billion barrels)	0.55	3.0	12.36
Gas Estimate (trillion cubic feet)	0	7.75	26.00
Exploration Wells	7	30	44
Delineation Wells (oil)	3	9	13
Delineation Wells (gas)	0	3	5
Production Platforms (oil)	1	5	13
Production Platforms (gas)	0	3	5
Production and Service Wells (oil)	30	155	625
Production and Service Wells (gas)	0	34	112
Shore Bases	1	3.5*	3.5*
Trunk Pipeline Miles (oil)	200	400†	400†
Trunk Pipeline Miles (gas)	0	200	400

* 0.5 shore terminal at 50/50 share with Canada for environmental controls.

† This does not include 250 miles of pipeline assumed needed onshore to support the area west of Point Barrow if it were developed.

Source: MMS (1983)

The exploration drilling will probably start on those leased tracts nearshore, using gravel-islands or caisson-retained islands as platforms. Gradually the activities will proceed farther offshore, employing semisubmersibles, ice-reinforced drillships, and/or CDU's. It is estimated that 39,000 tons of drilling mud and 72,150 tons of cuttings will be disposed on site under conditions prescribed by EPA's pollutant discharge permit. These figures are based on the assumptions that 39 wells will be drilled for exploration and delineation, that 1,000 tons of mud solids per well will be used, and that 1,850 tons of cuttings will be produced per well.

Although existing gravel islands might provide some source material for artificial island construction, additional gravel sources will probably be required. Trucks would be used to transport fill material from onshore borrow sources, and barges and dredges would be used to move offshore fill material. While offshore dredging and island construction would occur in the open-water season, transport of materials by truck would occur over ice roads during the winter.

Deadhorse-Prudhoe Bay would be the most likely primary forward support base for exploration, development, and production phases. Although the support operations for exploration, development, and production would be very similar, the level of activities would be the greatest during the development phase. In addition to Deadhorse-Prudhoe Bay, some temporary support bases would probably be located in proximity to the offshore operations. Support facilities would include airstrips, housing quarters, warehouse space, and overwintering moorage to accommodate barges and dredges. Possible locations for support facilities include the deactivated Distant Early Warning (DEW) Line sites, such as Camp Lonely or Oliktok Point to the west of Prudhoe Bay and Bullen Point to the east. In addition, barges may be used as support bases and could contain drilling supplies and emergency facilities, as was done in the continental offshore stratigraphic test (COST) well in Norton Sound. These barges could either be used independently or in conjunction with onshore facilities.

Development activities would involve platform development, drilling production wells and service wells, and laying pipelines. Along with adding to

existing facilities, three new and/or improved shore bases would be needed to service offshore field production.

Several types of production platforms could be used in the Diapir Field. The scenario employing the mean case resource estimate assumes that production wells would be located on five platforms with 25 production and 6 service wells per platform. Each platform would have two drilling rigs. Approximately half of these platforms would be gravel or caisson-retained islands and the technology would be an extension of that used for exploration. However, the production islands would have to be bigger and able to withstand ice and storm forces over longer periods of time. Production fields close to shore may require causeway construction connecting the drilling platforms with shore-based operations. Causeways could also provide protection for and access to offshore pipelines.

Other production platform types for the deeper waters of the Beaufort Sea include steel or concrete cone-shaped structures considered to be the best design to withstand ice forces in waters of 60-foot or deeper depths. Production fields that are located significant distances from the shore may require satellite support bases at the production sites.

It is assumed that drilling platforms would be on site in 1994 and that development drilling would begin in 1995, 7 years after the initial discovery. It is estimated that the average oil production well would require 500 tons of mud solids and produce 1,250 tons of cuttings, and that the average gas production well would require 450 tons of mud solids and 1,225 tons of cuttings. Thus, it is estimated that it would be necessary to dispose of 193,750 tons of cuttings from oil production wells and 41,650 tons of cuttings from gas production wells. Most of the drilling mud solids would be recycled to other production wells.

Pipeline construction would begin in 1994 and continue for 6 years. Two offshore trunk lines would probably be connected to the Trans-Alaska Pipeline System (TAPS). One line would extend east from Prudhoe Bay, with possible landfall sites at Bullen Point, where there could be onshore support facilities, or at the landfall site used for the Endicott production pipeline. One line would extend from Prudhoe Bay to Point Barrow, with possible landfall sites to the east of Harrison Bay and the Colville River. Booster stations would probably be required on the two pipelines on each side of Prudhoe Bay. The landfall area for the latter offshore line might also be located at the hypothetical support base near Camp Lonely and connect with the Kuparuk pipeline. An onshore pipeline might extend west from Point Barrow. It would cross the North Slope between Point Belcher and TAPS Pump Station No. 3, south of the 500-foot contour line and north of the Colville River.

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Chapter 2
Sea Ice Hazards

by William F. Weeks

In the interim synthesis report (Weller *et al.* 1978) and the synthesis for Sale 71 (Norton and Sackinger 1981) the gradually expanding body of knowledge concerning the characteristics and behavior of the Beaufort Sea shelf ice has been described. These reports include discussions of ice properties, drift, pressure ridges, ice override and pileup, ice gouging, and other factors, which should be consulted in addition to the information given herein. This chapter focuses on information obtained specifically for the Sale 87 area.

The area covered by Sale 87 is very large, extending from the eastern Chukchi Sea to the Canadian border, and roughly 150 km north of the coastline. It encompasses extensive regions along the coast, some of which are not protected by barrier islands, and includes the Chukchi coast from Barrow to Peard Bay, a region where the formation of flaw leads is common throughout the winter. Of most importance, it also includes large areas of heavy polar pack ice which is not only extremely deformed and thick, but highly mobile.

Because of operational and logistics problems, and since previous lease sales have been confined to the Beaufort Sea nearshore areas, very little ice research related to OCS leasing has been done in the Chukchi Sea or in the heavy polar ice of either the Chukchi or Beaufort seas.

2.1 SHORE ICE RIDEUP AND PILEUP

Sea ice rideup and pileup along Arctic coasts are frequent and unpredictable events that have destroyed boats and piers and on occasion crushed houses and their occupants (Kovacs and Sodhi 1980; Dekin 1982). Documentation of such events is of great importance to engineers confronted with the problem of designing nearshore facilities along the coast of the Beaufort Sea.

Field studies by Kovacs (1983) allow an extension of the data base developed by Kovacs and Sodhi (1980) and Kovacs *et al.* (1982). The recent work is based on observations made during the period 1979-82. Both summer and winter observations are included. It was found that although onshore ice movements of up to 20 m are relatively common, movements of over 100 m are very rare. Extensive photodocumentation of such events is given. Figure 2.1 shows a cross section of a pileup observed in 1982 on Spy Island.

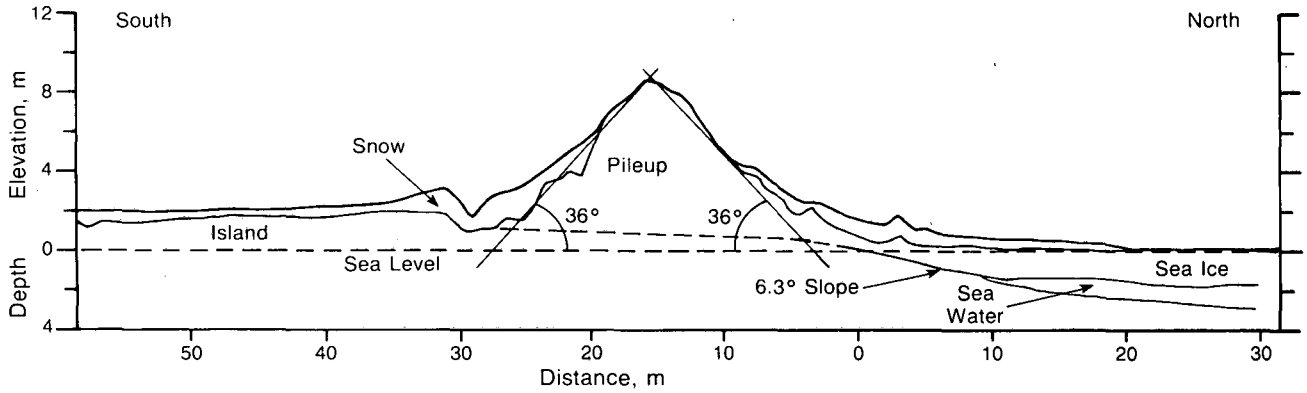

Figure 2.1—Cross section of 1982 Spy Island sea ice pileup. (Adapted from Kovacs 1983.)

Even considering these additional data, the observational data base is still insufficient to make confident predictions of either the frequency or the severity of these events, although such analyses have been attempted (Harper and Owens 1981). It does appear, based on data acquired to date, that fall (when the ice is less than 0.5 m thick) and spring (when the sea ice melts away from the shore) are the times when rideup and pileup are most likely to occur. Winter events, although known, are rare.

2.2 FLOE SIZES IN THE EASTERN BEAUFORT SEA

One item of interest to designers is the size of the ice floes that drift along the coast of the North Slope. Surprisingly, little information is available on the subject (Wadhams 1983). Early work was reported by Weeks *et al.* (1980) based on SLAR imagery obtained in the early fall of 1975. It was observed that the diameters of multiyear floes located off Barrow and Cape Simpson could be fit by a negative exponential. The largest floe had a diameter of 3.6 km. Considering that these floes achieved their rounded shapes and sizes by rotation and abrasion during drift, the form of the size distribution was explained by simply assuming that the size of floes changes proportionally to their diameter (D) and the distance (dl) through which they have traveled. Therefore, $dD = -DdL$, which when integrated gives $D = b \exp[-dL]$.

These observations have been extended by Stringer *et al.* (1982a) using Landsat imagery as a data base. Four different time periods were studied: June 2, July 7, July 12, and August 5. A log-log plot was used to linearize the data. Average floe sizes (S) for each time period were 1, 1.3, 1, and 0.08 km², respectively, and the largest floes were 32, 53, 13, and 4.6 km², respectively. Figure 2.2 shows a representative plot. Taking !S as an estimate of floe diameter, we obtain 7.3 km as the largest observed diameter in the sample. Such observations are largely missing during the winter due to a lack of suitable imagery, as well as the difficulty of identifying individual floes during that period.

2.3 SUMMER ICE CONCENTRATIONS

Summer ice concentrations are of interest in that many types of nearshore operations are limited by the presence of appreciable amounts of drift ice. Therefore the ice conditions set the operational window. Stringer *et al.* (1981) have examined all

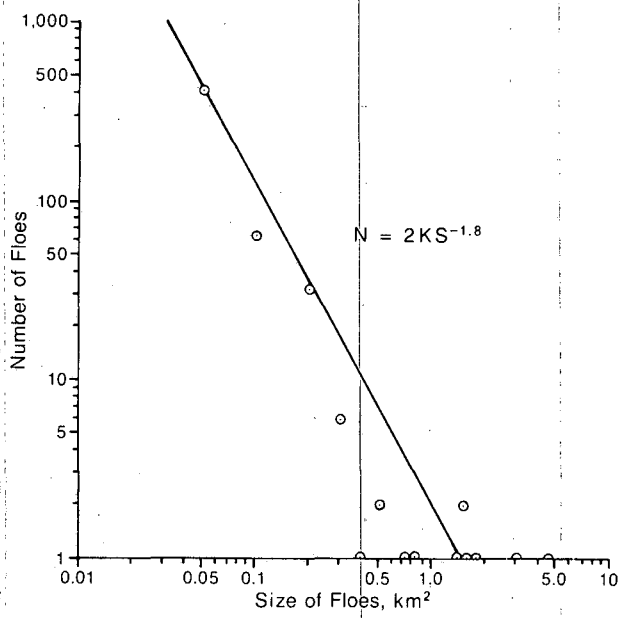

Figure 2.2—Log-log plot and best visual fit of floe size versus number for a 400 km² area. (Adapted from Stringer *et al.* 1982a).

available Landsat imagery for the six 15-day periods from 15 June to 15 September (1972 through 1980). Each period is described by two maps, the first showing the average ice concentration for the time period and the second indicating regions characterized by a particular concentration category 50% or more of the time. Figure 2.3 shows a representative map (July 1-15) of ice concentration. When these data are combined with similar information collected from a variety of sources (including Landsat) for the time period 1953 to 1975 (Cox and Dehn 1981), an extremely valuable picture of the behavior of the nearshore ice in the vicinity of Prudhoe Bay in the summer might begin to emerge. It would be useful to undertake similar studies for the complete Beaufort and Chukchi coast, inasmuch as the data are available.

2.4 WIDTH AND PERSISTENCE OF THE CHUKCHI POLYNYA

It has long been known that along the Chukchi coast between Barrow and Point Hope, there is often a wide lead just offshore of the fast ice. Even during the dead of winter this lead may be several kilometers wide during periods of strong easterly (offshore) winds. Similar features are commonly found in the Bering Sea on the south side of the Seward Peninsula, on the north side of Kotzebue Sound, in the lee of St. Lawrence Island, and at

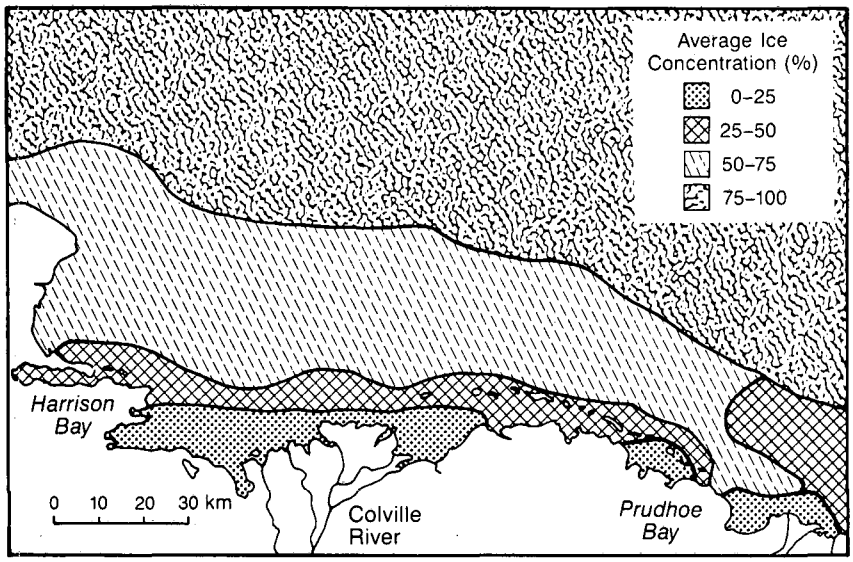

Figure 2.3—Average summertime ice concentrations in the Prudhoe Bay-Harrison Bay region (1-15 July). (Adapted from Stringer *et al.* 1981.)

the east end of Norton Sound. The Chukchi polynya is of interest for several reasons. During the summer it is an important migratory pathway for marine mammals and waterfowl, and shipping lane. It also offers an avenue for the rapid movement of spilled oil along the coast (Reimer *et al.* 1981). During times when new ice is forming it could facilitate the movement of oil off the coast by incorporating it within newly formed ice.

Stringer *et al.* (1982b) have studied the width of this polynya at six locations for 9 months out of the year (November through January excluded because of viewing problems). Table 2.1 shows these observations for Point Belcher, just west of the western edge of the Sale 87 area. The imagery used spanned the time period 1974-81. The table is self-explanatory with the exception of the next to last row, whose title could be more clearly stated as the percentage of occasions when the lead was more than 300 km wide. Note the systematic increase from February to September in both the extreme maximum width and the average maximum width. This study clearly demonstrates the highly variable nature of this important ice feature.

A significant study of Chukchi sea ice motion was made by Reimer *et al.* (1981), who found that sea ice can be rapidly transported from Point Barrow to Cape Lisburne and beyond. It would be very useful to attempt to develop improved forecast models for the ice behavior along this coast and to monitor sea ice drift using data buoys.

Table 2.1—Chukchi polynya width summary statistics, Point Belcher.

	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Polynya width (km):									
Average width	0.2	0.4	0.8	9	10	25	64	195	100
Average standard dev.	0.5	0.8	1.4	10	14	20	59	141	96
Extreme maximum width	8	14	17	63	64	120	296	560	550
Average maximum width	1	2	4	26	31	48	95	283	241
Extreme minimum width	0	0	0	0	0	0	0	10	0
Average minimum width	0	0	0	1	0.6	9	40	112	8
Occurrence (%):									
Days min. of zero width	100	100	100	81	90	57	20	0	81
Occasions of zero width	72	80	70	25	38	24	13	0	32
Occasions of >300 km	0	0	0	0	0	0	0	32	14
Days measured	60	80	84	78	59	42	18	26	54

Source: Stringer *et al.* 1982b.

2.5 ICE DEFORMATION AND PRESSURE RIDGES

The phenomenon of ridging and deformation has received considerable attention because ridges are believed to be a major offshore hazard. In fact, it is the opinion of some investigators that multiyear ridges may provide the force estimates that would set the design for certain classes of offshore structures.

One item of investigation has been determination of the southern boundary location of the "shear zone" along the eastern Beaufort Sea (Stringer *et al.* 1982c). The boundary is, at a given time, designated by a series of active leads and/or shear ridges separating the largely immobile fast ice from the moving pack. In Figure 2.4, the location of this boundary is given for three different times of the year. In general the boundary is located near the 20-m isobath during the period 1 February to 15 June, although it tends to be located inshore of the 20-m isobath in exposed regions and also generally bridges embayments in the isobath. Although 20 m is a good median location, extreme shear zone boundaries have been observed as far inshore as the 10-m isobath (Kovacs 1976). The reason for specific interest in the locations of this boundary is that it defines the seaward limit of stable fast ice where under-ice pooling of spilled oil may occur and where fast-ice conditions apply to the design and operation of offshore facilities (Kovacs *et al.* 1981). It is also the extreme landward boundary of possible spring migration routes of whales.

Stringer *et al.* (1982d) have also expanded their observations of large shear ridges in the eastern Beaufort Sea from 5 years to 9 years based on the use of Landsat imagery. In general, the minimum detectable ridge sizes are roughly 200 m in width and tens of kilometers in length. In Figure 2.5, a composite is given of all the massive ridges observed in the eastern Beaufort Sea during the time period 1973-81. Clearly, such large ridge systems are an integral part of the environment and must be considered in offshore design. Figure 2.5 is also useful in considering the concept of a shear zone because there is an obvious 20- to 60-km band north of the coast in which the ice is more highly deformed than farther to the north in the main pack. In fact, all of the ice (except for the fast ice areas) in Figure 2.5 is believed to show more deformation than the pack ice to the north of the map area. One reason for this is that the zone near the coast is composed largely of thinner, more deformable first-year ice as compared to the thicker multiyear ice located farther north.

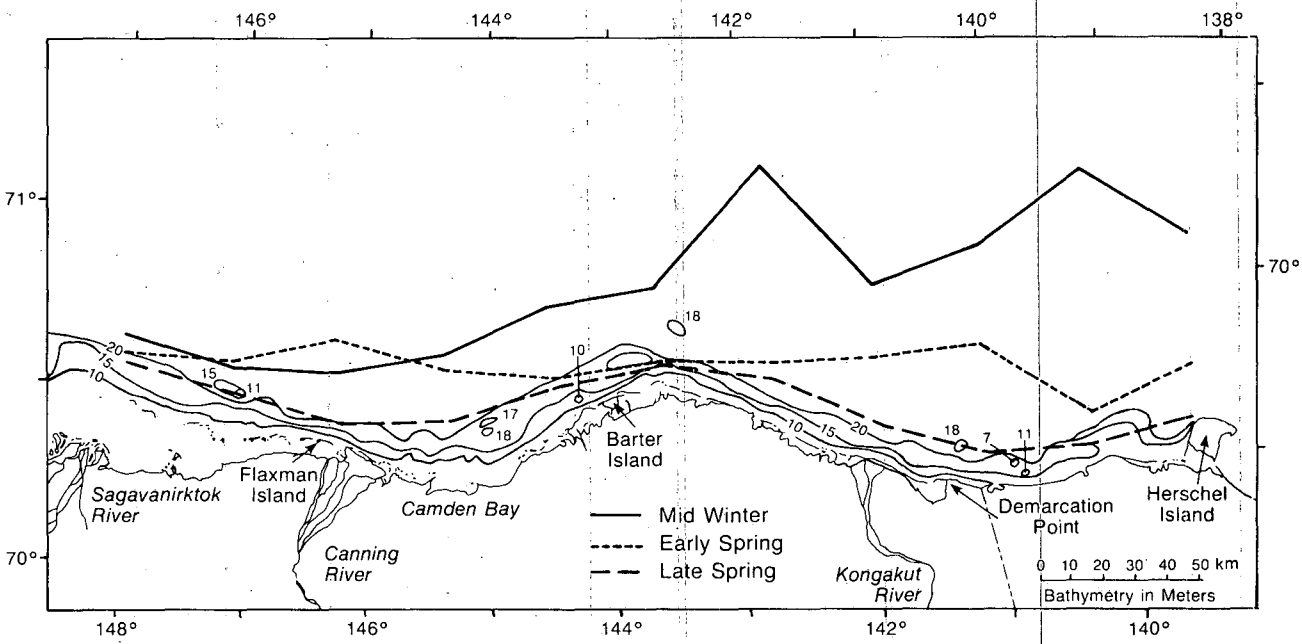

Figure 2.4—Comparison of the seasonal median shoreward edges of the shear zone. (Adapted from Stringer *et al.* 1982c.) This figure shows the median shoreward edges of the shear zone for the three seasonal analysis periods. East of central Camden Bay these data behave in a systematic fashion, being farthest offshore in midwinter and progressing toward shore as the season advances. To the west of central Camden Bay, this systematic behavior breaks down offshore from the Canning River, then returns to predicted order at the western edge of the study area.

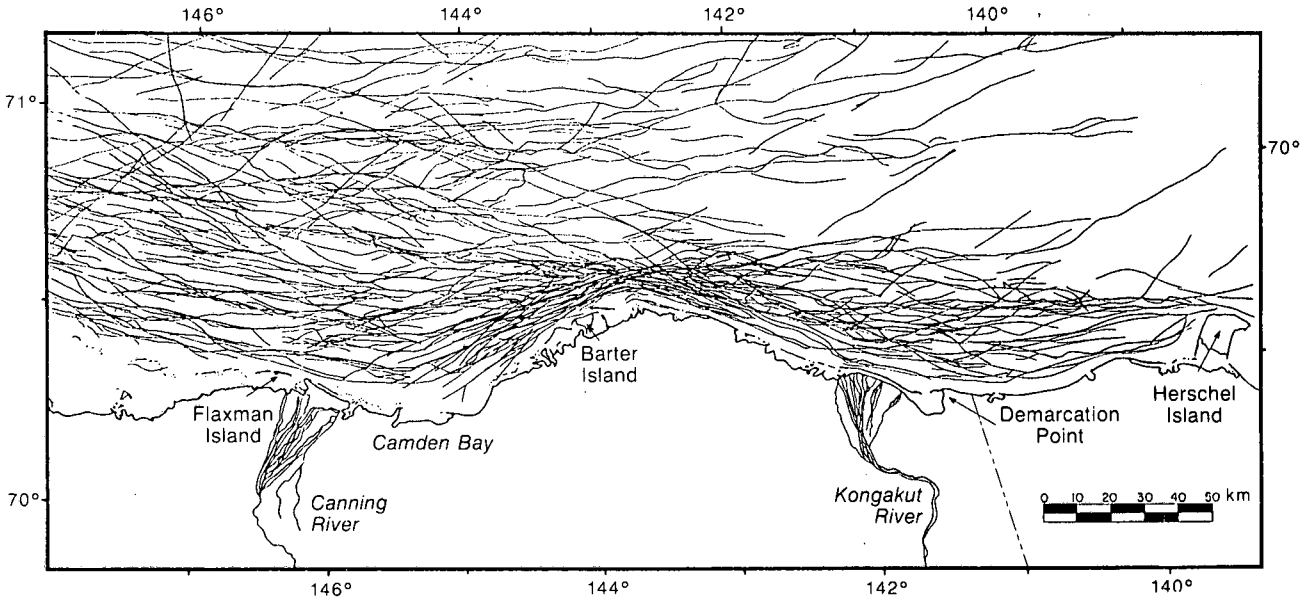

Figure 2.5—Composite map of all massive ridges observed in the eastern Beaufort Sea study area during the period 1973-81. (Adapted from Stringer *et al.* 1982d.)

Quantitative information on ridging still comes largely from laser profiling of ridge sails (Tucker *et al.* 1979; Weeks *et al.* 1980), although a small amount of submarine sonar profiling of ridge keels is available for the northernmost portion of the Sale 87 lease area (Wadhams and Horne 1980). The number of ridges per 20-km interval (μ) is shown as a function of distance from shore in Figure 2.6 for six locations along the Beaufort and Chukchi coasts. All sites except Point Lay are in or near the Sale 87 area. The maximum number of ridges occurs between 20 and 80 km of the coast and there is a general decrease in the values at sites farther to the north. This is in general agreement with the observations of Stringer *et al.* (1982d), discussed earlier, and the observations of Wadhams and Horne (1980), who noted an increase in the intensity of the ridging on the coastward portions of the submarine tracks. The difference in the ridging characteristics of the nearshore ice and the ice offshore in the main pack is clearly shown in Figure 2.7, which gives a plot of the laser data linearized as a plot of log probability density versus height. The data obtained well offshore at the AIDJEX sites show consistently lower ridge heights than either the Kaktovik (Barter Island) or Cross Island observations. These data can also be used to calculate the probabilities of a given ridge exceeding a specified value. The values (Pc(h)) are given in Figure 2.8. If it is assumed that the ice at Barter Island and AIDJEX drifts at the same mean velocity (2.5 km/day), one would (at a fixed location) expect to encounter 8,600 and 2,400 ridges per year, with likely maximum heights of 7.6 and 5.7 m, respectively. Clearly, sites nearer the coast appear to be more hazardous if only the heights of the expected ridges are considered. This brings one to the topic of the properties of different types of pressure ridges.

2.6 PRESSURE RIDGE CHARACTERISTICS

The structure of first-year pressure ridges has recently been investigated by Tucker and Govoni (1981) and Tucker *et al.* (1984). Measurements include sail height, width, and slope for 84 ridges. A clear relationship between ridge height and ice block thickness (Fig. 2.9) may be described well by assuming the height to be a function of the square root of ice thickness. This relationship can be derived from an energetics argument based on a buckling failure. Based on a limited sample, there does not appear to be a distinguishable year-to-year variation in the internal morphology of first-year ridges. Figure 2.10 shows the ratio of sail height to block thickness versus block thickness. At least for thin ice, ridge heights can clearly form that are many times higher than the ice thickness, in agreement with the predictions of Parmerter and Coon (1973). The regular interrelations between ridge geometry and its internal structure are encouraging, suggesting that it may prove possible to completely formulate ridge-structure interactions within an internally consistent analytical framework.

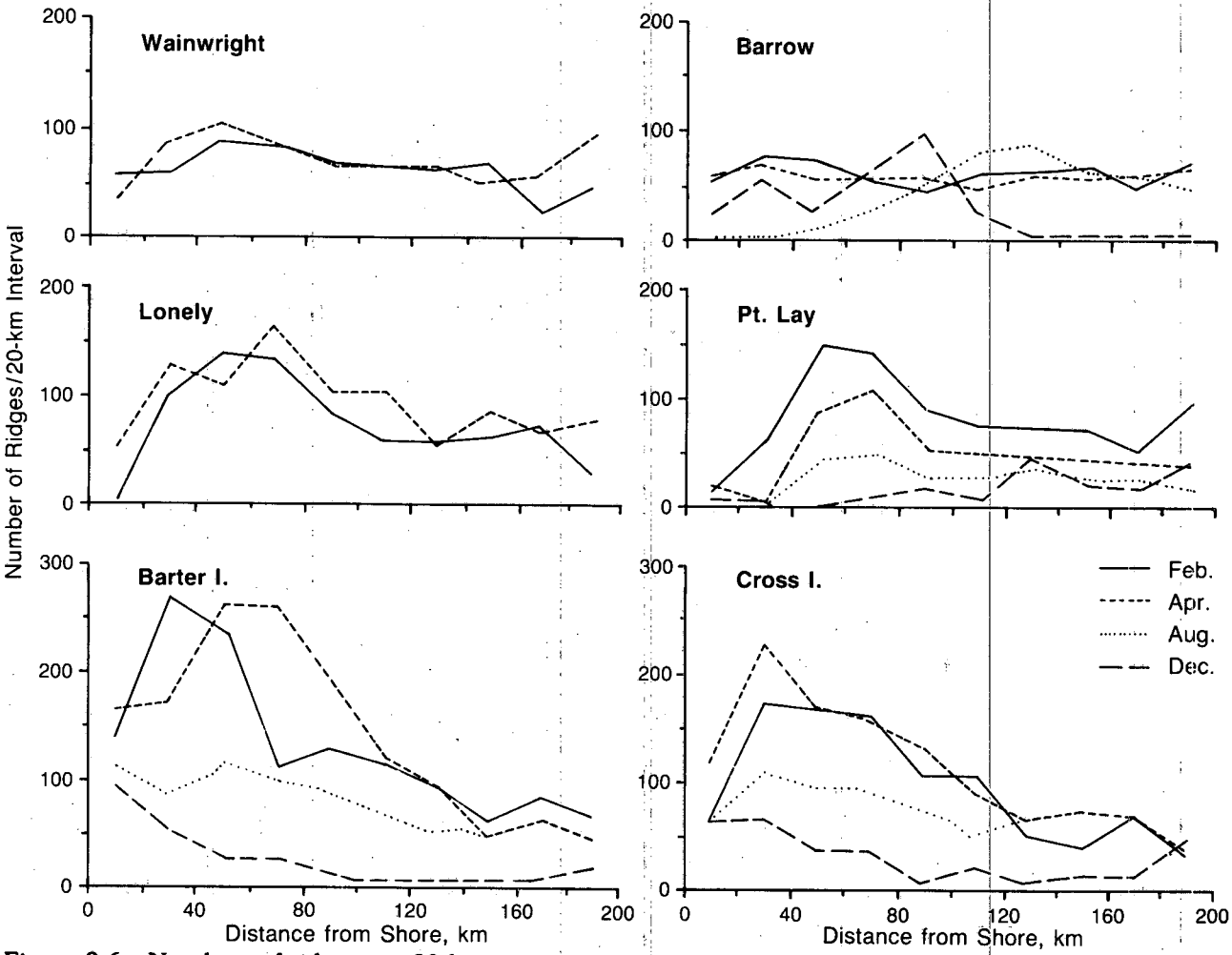

Figure 2.6—Numbers of ridges per 20-km interval (μ) as a function of distance from shore for all locations and sampling times in 1976. Values are plotted at the center of the sampling interval. (Adapted from Tucker *et al.* 1979.)

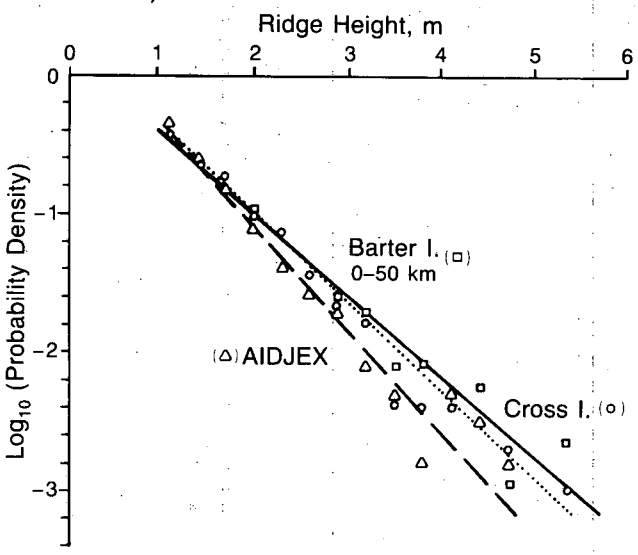

Figure 2.7—Log-linear plot of the probability density per foot vs. ridge height for the first 50 km of the Barter Island traverse, the complete Cross Island traverse, and the traverse between the AIDJEX stations, Blue Fox and Snowbird. (Source: Wadhams and Horne 1980.)

Even less is known about multiyear ridges than first-year ridges. Multiyear ridges and thick, hummocked floes probably represent the most severe ice features that offshore structures in the Beaufort and Chukchi seas will have to routinely resist. Kovacs (1983) examined 11 multiyear ridges near Prudhoe Bay and found that such ridges typically are voidless, containing ice with a mean brine-free density between 0.84 and 0.86 Mg/m^3 (Fig. 2.11). New observations continue to support the earlier suggestion of Kovacs that multiyear ridges have relatively constant sail height to keel depth ratios of about 1 to 3.3 in contrast to a ratio of about 1 to 5 for first-year ridges (Fig. 2.12).

To calculate forces associated with structure and multiyear-ridge interactions, information is needed both on the geometry of such ridges and the properties of ice in them. Work on the ice properties was undertaken by the Minerals Management Service and a consortium of oil companies headed by Shell Petroleum (Cox *et al.* 1983). The program consisted of a field sampling program to obtain ice

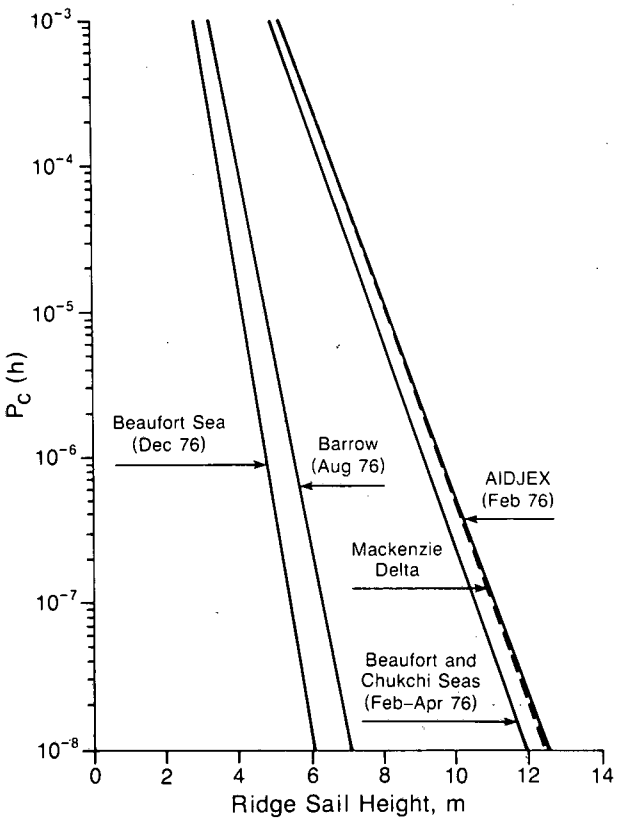

Figure 2.8—Semilog of Pc(h), the probability that a ridge encountered at random will have a height of at least h meters, versus ridge sail height. (Source: Tucker *et al.* 1979.)

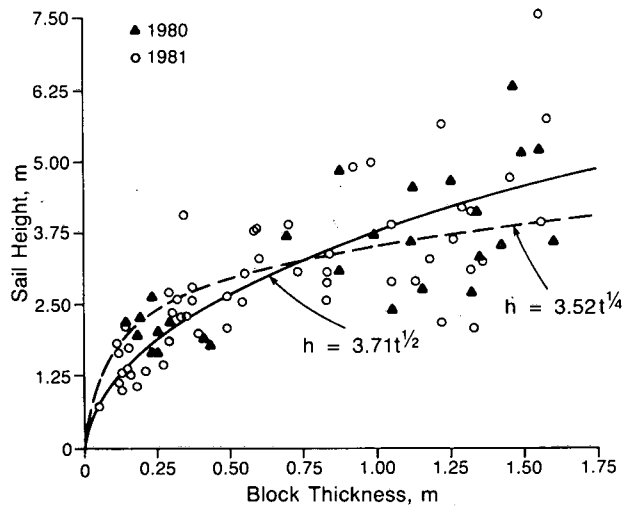

Figure 2.9—Sail height as a function of block thickness. Best fit curves as a function of $t^{1/4}$ (flexure failure) and $t^{1/2}$ (buckling failure) are also shown. (Source: Tucker and Govoni 1981.)

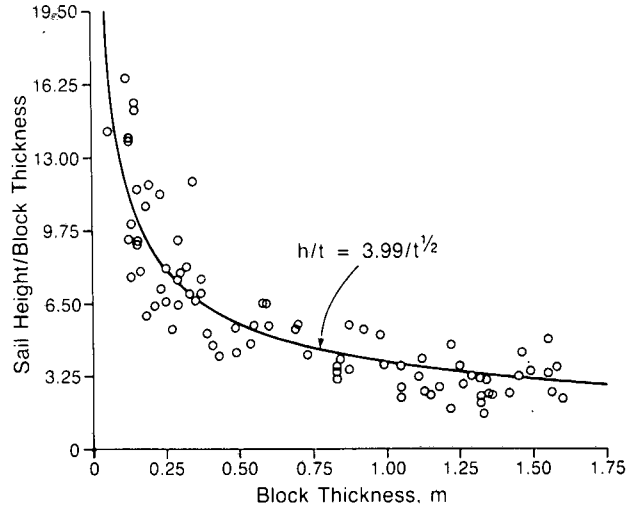

Figure 2.10—Ratio of sail height to block thickness as a function of block thickness. Best fit square root curve is also shown. (Source: Tucker and Govoni 1981.)

from multiyear ridges north of Prudhoe Bay and a laboratory testing program at CRREL. Tests performed to date include uniaxial compression, tension, and triaxial measurements at two strain rates (10^{-3} and 10^{-5}/s) and temperatures (−5 and −20°C). New test procedures were developed and great care was taken in general test procedures. Structural analysis has shown that the ice in multiyear ridges is highly variable and is composed of columnar ice, granular ice, mixed granular and columnar ice, and brecciated ice. The columnar ice can be found in any orientation. Ice from ridge sails had an average salinity of 0.7% while ridge keels showed an average value of 1.5%. Their respective bulk densities were 0.876 and 0.899 Mg/m³. Summaries of the strength and initial tangent modulus for the unconfined compressive tests are given in Tables 2.2 and 2.3. Both strength and initial tangent modulus data increase with increasing strain rate and decreasing temperature. The strength and initial tangent modulus were also found to decrease with increasing porosity. The effect of porosity on strength was most pronounced in the 10^{-3}/s tests where flaws and cavities play a more important role in brittle behavior. Only a limited analysis of the effect of ice structure on strength has been completed. Columnar ice with strong c-axis alignments consistently gave the highest strength values. Granular ice consistently gave lower strength values as compared to columnar ice. Statistical studies (Weeks *In press*) of the variation of strength within and be-

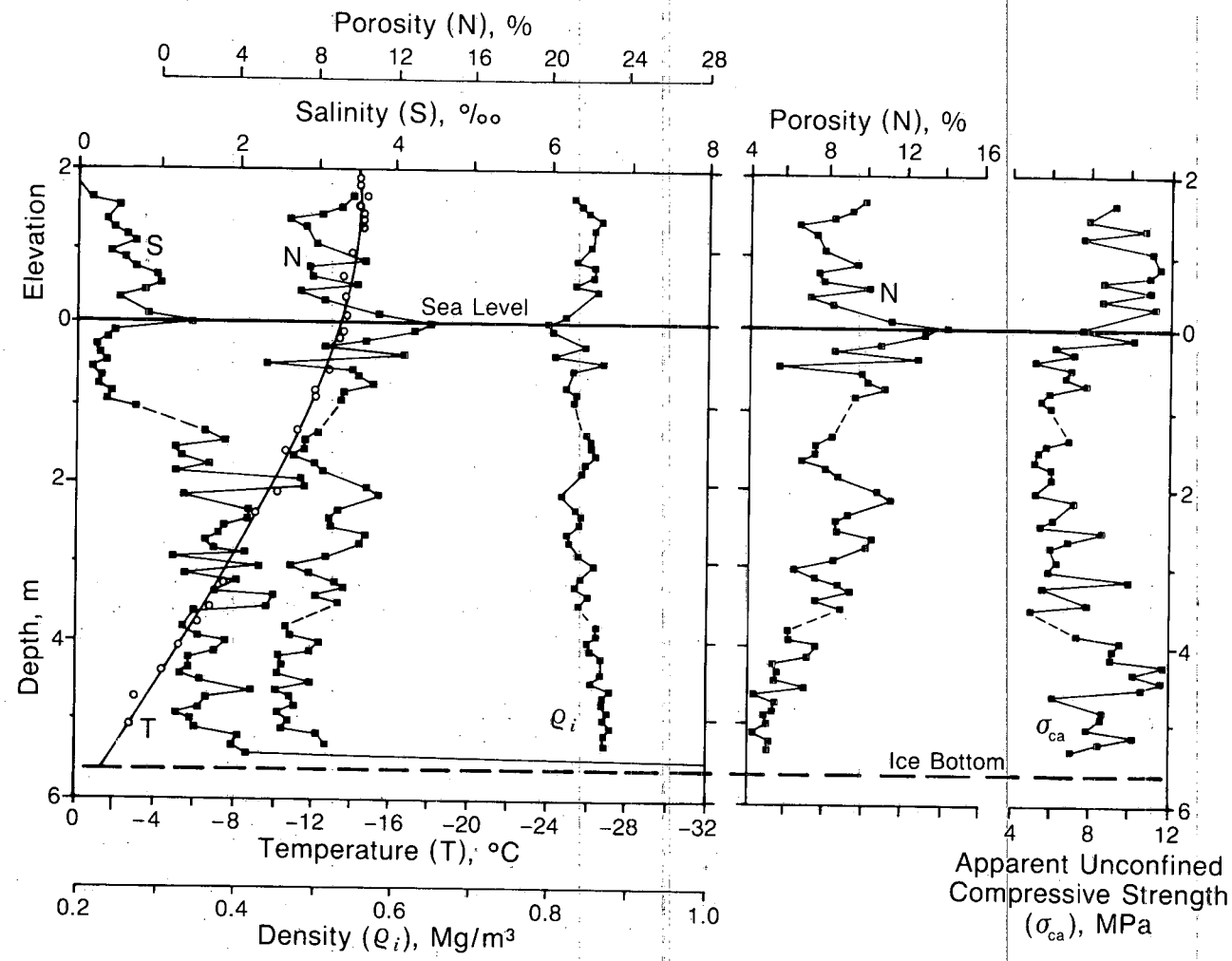

Figure 2.11—Salinity, porosity, temperature, and brine-free density of the ice versus depth in multiyear ice ridge 9, and the apparent unconfined compressive strength and porosity of the ice at -10°C. (Source: Kovacs 1983.)

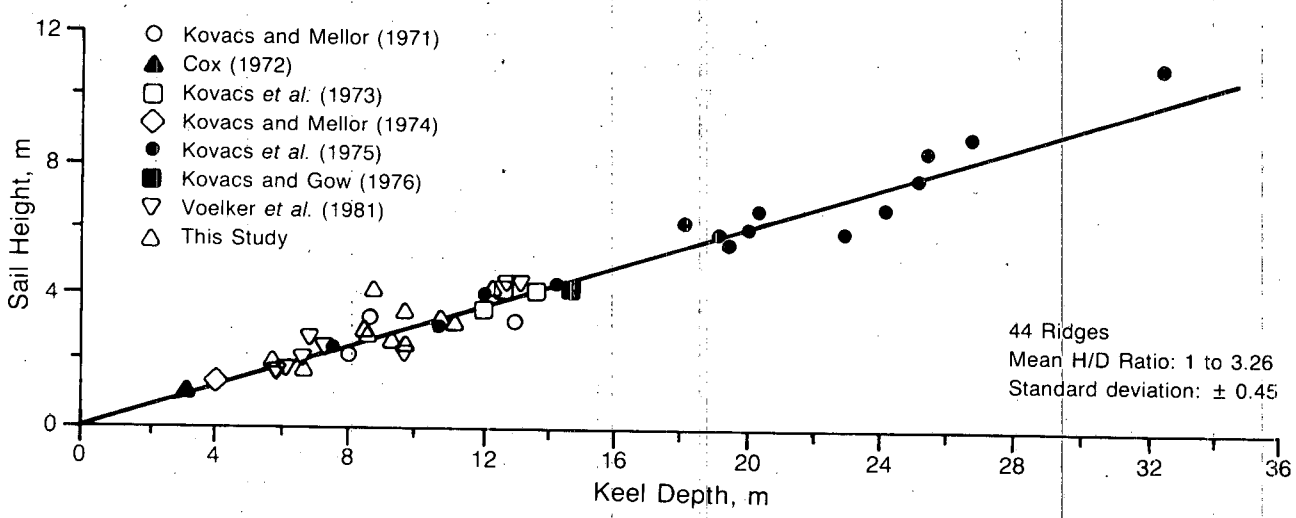

Figure 2.12—Sail height versus keel depth in multiyear ice ridges. (Source: Kovacs 1983.)

Table 2.2—Summary of compressive strength data for multiyear pressure ridge ice samples.

	Uniaxial Compressive Strength						
	Maximum		Minimum		Mean		
	(MPa)	(lbf/in^2)	(MPa)	(lbf/in^2)	(MPa)	(lbf/in^2)	Samples
−5°C (23°F):							
10^{-5}/s	7.52	1,090	0.47	68	2.34 ± 1.08	340 ± 157	71
10^{-3}/s	10.90	1,580	2.39	346	6.06 ± 1.63	879 ± 237	69
−20°C (−4°F):							
10^{-5}/s	4.26	6.7	1.17	170	2.79 ± 0.69	404 ± 100	41
10^{-3}/s	12.68	1,838	7.03	1,020	9.63 ± 1.39	1,396 ± 202	41

Source: Cox *et al.* 1983.

Table 2.3—Summary of initial tangent modulus data for multiyear pressure ridge ice samples.

	Initial Tangent Modulus						
	Maximum		Minimum		Mean		
	(GPa)	(lbf/in^2 × 10^6)	(GPa)	(lbf/in^2 × 10^6)	(GPa)	(lbf/in^2 × 10^6)	Samples
−5°C (23°F):							
10^{-5}/s	11.45	1.660	2.41	0.350	5.11 ± 1.74	0.741 ± 0.252	71
10^{-3}/s	14.00	2.030	4.95	0.718	7.07 ± 1.38	1.025 ± 0.200	71
−20°C (−4°F):							
10^{-5}/s	13.79	2.000	3.45	0.500	6.14 ± 1.68	0.890 ± 0.244	41
10^{-3}/s	10.83	1.570	4.89	0.709	7.62 ± 1.19	1.105 ± 0.173	40

Source: Cox *et al.* 1983.

Table 2.4.—Estimated burial depths assuming one contact between a pressure ridge keel and the pipeline in 100 years.

				Line Normal to Gouges		Line at 20° to Gouges	
Location	$\bar{g}$ (gouges km^{-1} yr^{-1})	λ or (λ−1) (m^{-1})	Length of Line (km)	Gouges Crossing Line During 100-yr Lifetime	Burial Depth (m)	Gouges Crossing Line During 100-yr Lifetime	Burial Depth (m)
Lagoons	5	7.7	20	10,000	1.40	3,420	1.26
		7.7	100	50,000	1.61	17,101	1.61
		6.7	20	10,000	1.57	3,420	1.41
		6.7	100	50,000	1.81	17,101	1.81
Seaward of	5	7.3	20	10,000	1.46	3,420	1.31
barrier islands		7.3	100	50,000	1.68	17,101	1.54
(water depth =		6.3	20	10,000	1.66	3,420	1.49
5 to 10 m)		6.3	100	50,000	1.92	17,101	1.75
Seaward of	5	3.2	20	10,000	3.08	3,420	2.74
barrier islands		3.2	100	50,000	3.58	17,101	3.25
(water depth =		2.2	20	10,000	4.39	3,420	3.90
25 to 30 m)		2.2	100	50,000	5.12	17,101	4.63

Source: Weeks *et al.* 1984.

tween multiyear pressure ridges consistently show that the largest contributor to such variations is the large variance within a given core. Relative to this contribution, no significant difference was found between cores within ridges or between ridges.

Table 2.5.—Comparisons between burial depths to the top of a 76-km pipeline for 1,000-, 100-, and 10-year return periods.

Lifetime (yr)	Water Depth (m)	$\bar{g}$	λ or $(\lambda-1)$ (m^{-1})	Burial Depth (m)	Source
1,000	15	5	5.5	2.54	1
		5	4.5	3.06	
		10	5.5	2.66	
		10	4.5	3.21	
	15			6.24	2
	25	5	3.7	3.67	1
		5	2.7	4.96	
		10	3.7	3.86	
		10	2.7	5.22	
	25			8.10	2
100	15	5	5.5	2.12	1
		5	4.5	2.54	
		10	5.5	2.24	
		10	4.5	2.70	
	15			4.4	3
	15			5.50	2
	25	5	3.7	3.05	1
		5	2.7	4.11	
		10	3.7	3.24	
		10	2.7	4.36	
	25			4.7	3
	25			7.02	2
10	15	5	5.5	1.70	1
		5	4.5	2.03	
		10	5.5	1.82	
		10	4.5	2.19	
	15			4.76	2
	25	5	3.7	2.43	1
		5	2.7	3.25	
		10	3.7	2.62	
		10	2.7	3.51	
	25			5.94	2

Sources: (1) Weeks *et al.* 1984, (2) Wadhams 1983, (3) Pilkington and Marcellus 1981.

2.7 ICE GOUGING OF THE SEA FLOOR

Recent work on the U.S. Geological Survey data set on ice-induced gouges in the sea floor (Weeks *et al.* 1984) has significantly improved the earlier analysis discussed in the Sale 71 synthesis report. These results are quite interesting when compared with the results of studies by Pilkington and Marcellus (1981) and Wadhams (1983). Their estimates of return periods for gouges of different depths are based on characteristics of the assumed ice cover drifting over the area of interest. There are appreciable differences in the results of the different estimates, the Weeks *et al.* (1984) estimates consistently being the lowest (Tables 2.4 and 2.5). Considering that even the lowest estimates are near the maximum existing capabilities of subsea pipeline trenching systems, it is important that these estimates be improved. One important parameter that is very poorly known is the frequency of gouging at the present time. It is essential to obtain improved estimates of this parameter by repeated mapping of the sea floor in areas of interest. Such data are almost nonexistent for the Chukchi Sea.

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Chapter 3
Environmental Hazards At and Beneath the Sea Floor

by Peter W. Barnes, J. Craig, R. Lawrence Phillips, and P. V. Sellmann

With contributions from D. M. Hopkins, J. L. Morack, T. E. Osterkamp, P. Smith, W. J. Stringer, and W. F. Weeks.

Our group concentrated on knowledge gained since the Sale 71 synthesis report. The basic philosophy was to define major hazards that would be encountered during exploration drilling activities, and the broader range of hazards that might be encountered during development activities, including seafloor pipelines, shoreline crossings, and shore facilities. We considered meteorological extremes to have been adequately treated in earlier syntheses and do not discuss the associated hazards.

The area considered for Sale 87 is expanded from earlier sales, to include the outer continental shelf and slope. The data base is concentrated on the inner shelf, where most of the initial exploration will probably occur. Farther seaward the data base is insufficient.

3.1 SUB-SEAFLOOR HAZARDS

The polar ice pack, active tectonism, seafloor instability, shallow gas concentrations, overpressured shale diapirs, natural gas hydrates, subsea permafrost, and other potential hazards to petroleum development occur in the Beaufort and northeastern Chukchi seas. Although ice occurrence and movement probably present the greatest obstacle to offshore development, other geologic conditions will hamper platform siting and drilling operations even when ice does not.

The following material is extensively paraphrased from Grantz *et al.* (1982).

3.1.1 Active Tectonism

Most of the area of OCS Lease Sale 87 has historically been aseismic with the exception of a zone of concentrated seismic activity in the vicinity of Barter Island. Biswas and Gedney (1978) conclude that this active seismic zone is a northeastern extension of the central Alaska seismic zone. The magnitude of measured earthquakes near Barter Island ranges from less than 1.0 to a maximum of 5.3. Consequently, structures designed for use in oil and gas exploration and development in the southeastern portion of the lease sale area should be able to withstand ground vibrations from shallow earthquakes of this magnitude.

High-angle tectonic faults, which affect Tertiary and occasionally Holocene deposits, are abundant from Camden Bay eastward on the Beaufort shelf. The age and local abundance of these faults are coincident with the zone of Holocene uplift, diapirism, and modern earthquakes. In addition to these active tectonic faults, north-dipping, down-to-the-basin gravity faults underlie much of the central and western Beaufort shelf. These faults displace the sedimentary prism of the shelf toward the continental slope. The gravity faults formed in a passive tectonic environment and, although they occasionally displace Holocene sediments, they have not generated earthquakes of sufficient magnitude to be detected by the seismograph networks. In addition to the potential hazard of continued movement of faults on the Beaufort shelf, a more serious hazard is created by the upward migration of hydrocarbons (mainly gas) along these faults. Various types of traps at shallow depths create the possibility of blowouts during exploratory and development drilling.

3.1.2 Mass Sediment Movement and Seafloor Instability

Most of the Beaufort outer shelf and upper slope seaward of the 50- to 65-m isobaths is disrupted by active bedding-plane slides and massive slumps developed in poorly consolidated Holocene and Pleistocene sediments. These slide zones involve

large tabular blocks that have moved seaward, which are separated by deep, open crevasses, rotational slump terranes, and hummocky rubble piles. The evidence for repeated and continuing failure of broad, thick masses of unconsolidated sediment in much of the Sale 87 area seaward of the shelf break indicates a potential hazard to petroleum development structures.

3.1.3 Shallow Gas

Shallow free gas has accumulated in several geologic environments beneath the shelf and slope of the western Beaufort and northeastern Chukchi seas. In some areas acoustic anomalies indicate the presence of natural gas deposits migrating upward along faults from underlying strata (thermogenic origin). In other cases, the gas originates in surficial sediment as a product of bacterial metabolism of organic material (biogenic origin). Wherever it occurs, shallow free gas must be considered a potential hazard. Free gas can cause abnormally low strengths in shallow sediments, which must be accounted for in structural designs, and creates the possibility of blowouts during drilling in deeper strata.

3.1.4 Overpressured Shale

Numerous diapirs disrupt the sediments and, in places, the sea floor on the continental shelf slope and rise east of 146° W. These diapirs are interpreted to be shale-cored and constitute a westward extension of the shale-diapir province of the western Canadian Beaufort shelf. Shale diapirism is an indication of overpressuring within the geologic section and therefore may pose a drilling hazard.

3.1.5 Natural Gas Hydrates

Gas hydrates (solids composed of light gases caged in the interstices of an expanded ice crystal lattice) are evident on seismic data as a prominent reflecting horizon 300–700 m beneath the sea floor on the outer Beaufort shelf and continental slope. Gas hydrates are stable under the low temperatures and relatively high pressures prevailing in water depths exceeding 300 m as well as in nearshore areas containing subsea permafrost. Seismic reflection data also suggest that free gas accumulates beneath the impermeable gas hydrate zone. Gas hydrate decomposition may release large quantities of methane and perhaps other hydrocarbon gases during drilling and creates a potential hazard to exploratory drilling.

3.2 SUBSEA PERMAFROST

Although the thickness of subsea permafrost may be as great as that of permafrost found on adjacent land areas, its properties can be very different. Differences in properties can be related to higher temperatures and higher salt contents offshore. Mean annual surface temperatures on land may be approximately −10°C, in contrast to mean annual seabed temperatures of approximately −1.5°C in parts of this lease area. The seafloor temperatures are more comparable to those expected much further south, on land, in central Alaska's discontinuous permafrost zone. Segregated ice masses and layers will exist offshore; however, massive ice features will be most common along the coast where thaw of ice-bonded material has not progressed many meters below the seabed.

The engineering consequences of the higher subsea permafrost temperatures and high salt contents are that subsea ice-bonded materials have lower strengths than comparable materials found on land and there is opportunity for more rapid thaw given comparable thermal disturbance. The overall properties and distribution of subsea permafrost will be more variable than those of permafrost on adjacent land areas because of the high subsea temperatures, variations in material type, and variable coastal erosion and inundation rates.

The subsea permafrost zone is a very large and unique geological setting. The rate and nature of changes that take place in this environment are extremely dynamic. In addition to the relatively rapid degradation of relic permafrost originally formed on land, ice-bonded permafrost can also form in this environment. Our knowledge of subsea permafrost distribution and properties is still limited by the fact that there have been very few direct observations from drilling. New information continues to confirm the complexity of this setting.

The size and quality of the available subsea permafrost data base on the Beaufort Sea decreases rapidly with distance from shore. Most OCSEAP- and industry-sponsored investigations have been in less than 20 m of water. All direct information from drilling observations is also from this depth zone. Out to the shelf break 90-m water depth and beyond, observations are based on seismic data.

Seismic data for industry studies generally terminate at water depths around 90 m; however, some widely spaced lines acquired by the USGS in the Beaufort and Chukchi seas (Grantz and Dinter 1980) extend beyond this depth. No offshore wells

or boreholes exist beyond the coastal zone. Since identification of ice-bonded permafrost by seismic techniques becomes more difficult as the permafrost section warms, information from this region is mostly conjectural.

Recent geological and paleontological studies on the Arctic Coastal Plain by L. D. Carter, J. K. Brigham, and D. M. Hopkins provided some insight into paleoclimatic conditions during periods when sea level was low and the continental shelf was exposed to permafrost formation. These intervals were characterized by periods of very dry, very cold temperatures. This description is based in part on the occurrence of stabilized sand dunes that were active 35,000 to 13,000 years ago, which suggest a dry, windy climate and lack of vegetation. This also suggests that the large near-surface ice wedges found on the Arctic Coastal Plain formed during the last 13,000 years. Prior to this time, it appears that there was little snow cover, and blowing sand may have filled winter frost cracks. Consequently, permafrost formed in coarse-grained sediment would have relatively low ice content.

Amino-acid racemization studies of molluscs collected in mud and beach gravel of the last interglacial age along the Chukchi and Beaufort coasts provide a basis for estimating ground temperatures during the last 125,000 years. The racemization of amino acids is both time and temperature dependent.

Racemization ratios in shells from the 125,000-year-old Pelukin (last interglacial) deposits were found to be remarkably low. Because the age of these deposits, with their distinctive faunas, is not in doubt, a series of models indicating the thermal history necessary to explain the ratios was prepared.

The calculations indicate that mean diagenetic temperature (mean ground temperatures affecting the mollusk shells) averaged −16°C during the interval from 120,000 until 15,000 years B.P. If parts of this long period had a milder climate—a good possibility—then the most severe intervals must have been even colder. For comparison, present mean annual temperatures at Prudhoe Bay and Barrow are, respectively, −9° and −12°C. We can conclude that mean temperatures at the air/ground interface were 4° to 7°C lower at times when sea level was low and the present relict permafrost formed on the Beaufort Sea shelf.

3.2.1 Beaufort Sea Coastal Zone

Extensive distribution of ice-bonded permafrost in the Beaufort Sea coastal zone (0-20 m water depth) has been confirmed by drilling (Osterkamp and Harrison 1976, 1980; Sellmann and Chamberlain 1979; Miller and Bruggers 1980; Harrison and Osterkamp 1981; Osterkamp and Payne 1981). Interpretation of seismic records has helped to determine distribution patterns in the coastal subsea permafrost (Rogers and Morack 1980, 1981; Sellmann *et al.* 1980; Neave and Sellmann 1982). The greatest amount of control and seismic data is from the Harrison and Prudhoe bay regions. Seismic data analysis along the coast has helped to tie these areas together and extend our knowledge to both the east and the west.

Permafrost distribution in the Beaufort Sea from Flaxman Island to Lonely is extremely variable. At least two large areas exist that have ice-bonded material at shallow depths near the seabed: one near Prudhoe Bay and the other in Harrison Bay (Fig. 3.1). The occurrence of shallow, ice-bearing permafrost near Harrison Bay and to the west was supported by water jet drilling and bore hole studies near Lonely, northwest of Cape Halkett, northwest of Atigaru Point, and north of Thetis Island (Harrison and Osterkamp 1981; Osterkamp and Harrison 1982). The shallow ice-bonded materials near Prudhoe Bay were confirmed by OCSEAP drilling and the USGS Conservation Division Program (Miller and Bruggers 1980). Seismic data helped to extend the limits of this zone, which has been observed to extend as much as 35 km from shore off Prudhoe Bay (Neave and Sellmann *In press*). This shallow ice-bonded material can be within 10 to 30 m of the seabed. As shown in Figure 3.1, the shallow zone near Prudhoe Bay extends north of the Sagavanirktok River delta, northwest of Reindeer Island, and possibly to the east offshore from the barrier islands as far as Flaxman Island.

Velocity data from OCSEAP studies (Rogers and Morack 1981; Neave and Sellmann 1982) also suggest that shallow ice-bonded material occurs in at least the eastern part of Harrison Bay, with extensive shallow material in the remainder of the bay likely, based on Osterkamp and Harrison's (1982) observations off Thetis Island and Atigaru Point.

Along segments of the coast where shallow, high-velocity material is absent, seismic data analyses suggest much deeper ice-bonded material with high-velocity zones at depths of up to 230 m. Some of these zones, based on varying depths to the high-velocity horizons, are shown in Figure 3.1. In some cases there is good evidence for the high-velocity material being ice-bonded permafrost, since it can be traced with decreasing depth back to shallow

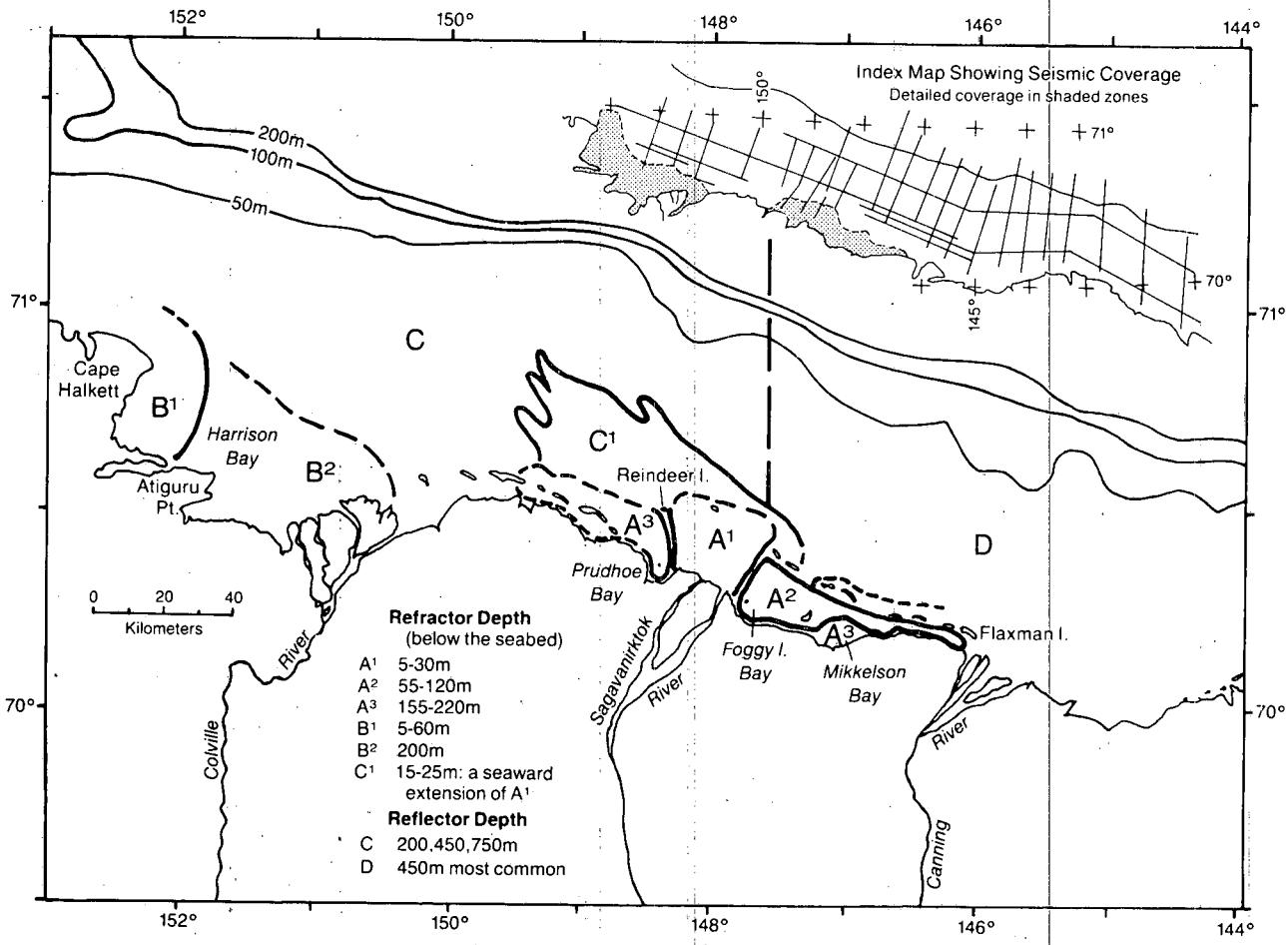

Figure 3.1—Zones with similar velocity structure and distribution which may be related to permafrost distribution. (Adapted from Neave and Sellmann *In press*.)

high-velocity material at the coastline.

In Prudhoe and Mikkelsen bays, high-velocity refractors occur between 150 m and 220 m below the seabed. The position of the refractor in Prudhoe Bay is supported by logs from an offshore well where the refractor position corresponds with the top of ice-bonded permafrost (Osterkamp and Payne 1981). The structure appears to continue seaward in some parts of this study area as a reflector (Neave and Sellmann *In press*).

3.2.2 Chukchi Sea Coastal Zone

Ice-bearing or ice-bonded permafrost has not yet been observed in the Chukchi Sea. Our very sparse knowledge of surficial deposits on the Chukchi shelf also suggests that it will not be found except within a few hundred meters of the most rapidly retreating segments of the mainland coast and rapidly migrating barrier bars. Rogers and Morack (1981) observed high-velocity material along the immediate coastline near Icy Cape. However, no drilling was done to determine whether it was ice-bonded material or rock. We cannot exclude the possibility that ice-bearing permafrost will ultimately be found on the northernmost part of the shelf, at or near the latitude of Point Barrow. Present data in the Chukchi Sea are insufficient to allow us to assess the occurrence, distribution, and properties of ice-bonded permafrost as a hazard to OCS development (Osterkamp and Harrison 1982).

Lack of ice-bonded sediment beneath the Chukchi shelf is suggested by: (1) the relatively high temperatures of the overlying waters, (2) the extremely thin layer of Quaternary sediments, in most areas within a few tens of kilometers of the present shore (Osterkamp and Harrison 1982), and (3) the low rates of coastal retreat of mainland bluffs and offshore barrier bars.

Rock at or near the seabed could pose problems for offshore development. It cannot be assumed

that the rock will provide an ideal foundation for structures, since it may contain segregated ice. Excavation in the rock may be extremely difficult for pipeline projects, etc. The thin layer of sediments over the rock suggests that offshore sources of gravel for construction may be limited (Osterkamp and Harrison 1982).

It is envisioned that since the entire shelf was exposed to cold subaerial temperatures during sea-level minima, presumably subfreezing temperatures penetrated to depths of several hundred meters. The materials involved were mostly low-moisture-content, very compact shale and weakly cemented sandstone of Cretaceous age. It is unlikely that the rock will contain any large quantities of segregated ice. The relatively warm water of the Alaska Current has likely since warmed the bottom and probably destroyed relict permafrost in all except the most northern parts of the shelf. Coastal retreat and barrier bar migration are also relatively slow because much of the coast is defended by compact, lithified Cretaceous rocks. In addition, dominant winds are not normal to the shore and wave attack is at an oblique angle, reducing wave energy available to erode the coast. The result may be that thawing of relict permafrost by relatively warm, saline sea water proceeds almost at the same rate as coastal retreat.

3.2.3 Outer Shelf

The sea level during the late Wisconsin glacial maximum, approximately 18,000 years B.P., was about 100 m lower than at present, suggesting that most of the shelf out to the shelf break was exposed during this period and therefore could contain relict permafrost. Analysis of seismic data provides the only clue to the distribution of ice-bonded permafrost on the outer shelf (water depth 20-90 m) since no drilling has been done.

A problem with the use of seismic analysis for study of relict ice-bonded permafrost far from shore is related to the long time available for warming of the permafrost section. Warming of the permafrost to temperatures just below 0°C can reduce seismic velocities to a point where they are similar to those of the adjacent thawed material, making detection difficult.

The only features that may be permafrost-related appear as a result of reflection analysis. Reflection data for the lines west of Foggy Island Bay in area C (Fig. 3.1) define three distinct horizons, at 200, 450, and 750 m. The 200-m reflections may be correlated with nearshore refractors in areas A3 and B2. A tie seems likely between the 200-m reflector and the nearshore 200-m refractor that can be connected with onshore permafrost. This correlation, as well as that of the 450-m reflector with the bottom of ice-bonded permafrost, may be possible. The reflection data from the lines east of Foggy Island Bay are not of the same quality as the western lines, and the 450-m reflector is most common to this region. However, there are zones within this area that have shallower and deeper reflectors. It therefore appears that these deep horizontal reflectors are common to the shelf from Harrison Bay to the Canadian border, in some cases extending out to the shelf edge.

The likelihood of the deep structures on the shelf being related to permafrost may be supported by similar observations in the Canadian Beaufort Sea, where deep layers thought to be ice-bonded permafrost are present more than 100 km from shore (Hunter *et al.* 1976). Additional weak evidence that permafrost may exist out to the shelf edge is suggested by a noticeable improvement in the quality of seismic records beyond the shelf margin, indicating a considerable change in material properties.

No significant accumulation of ice-bonded materials appears likely beyond the shelf break. However, gas hydrates could be encountered near the seabed beyond the shelf break. Gas hydrates have been inferred from seismic work; the low temperatures and relatively high pressures encountered at these depths are ideal for their formation (Grantz and Dinter 1980).

3.3 HAZARDS AT THE SEABED FROM SEA ICE

3.3.1 Ice Gouging—Beaufort Sea

The pattern of dominant ice gouge alignment parallel to regional isobaths as mapped west of the Canning River (Barnes *et al.* 1981) continues eastward to the Canadian border (Fig. 3.2). The Barter Island region, forming a major promontory jutting out into the pack-ice drift of the clockwise-rotating Beaufort Gyre, separates two regions with distinctly different isobath trends and ice gouge trends. The mean gouge orientation of 103°T in the study area is heavily weighted by trend determinations corresponding to the northwest-trending isobaths east of Barter Island. By comparison, the mean gouge orientation west of the Canning River is 90°T.

Ice gouge density values (adjusted gouge counts per kilometer of trackline) east of Barter Island

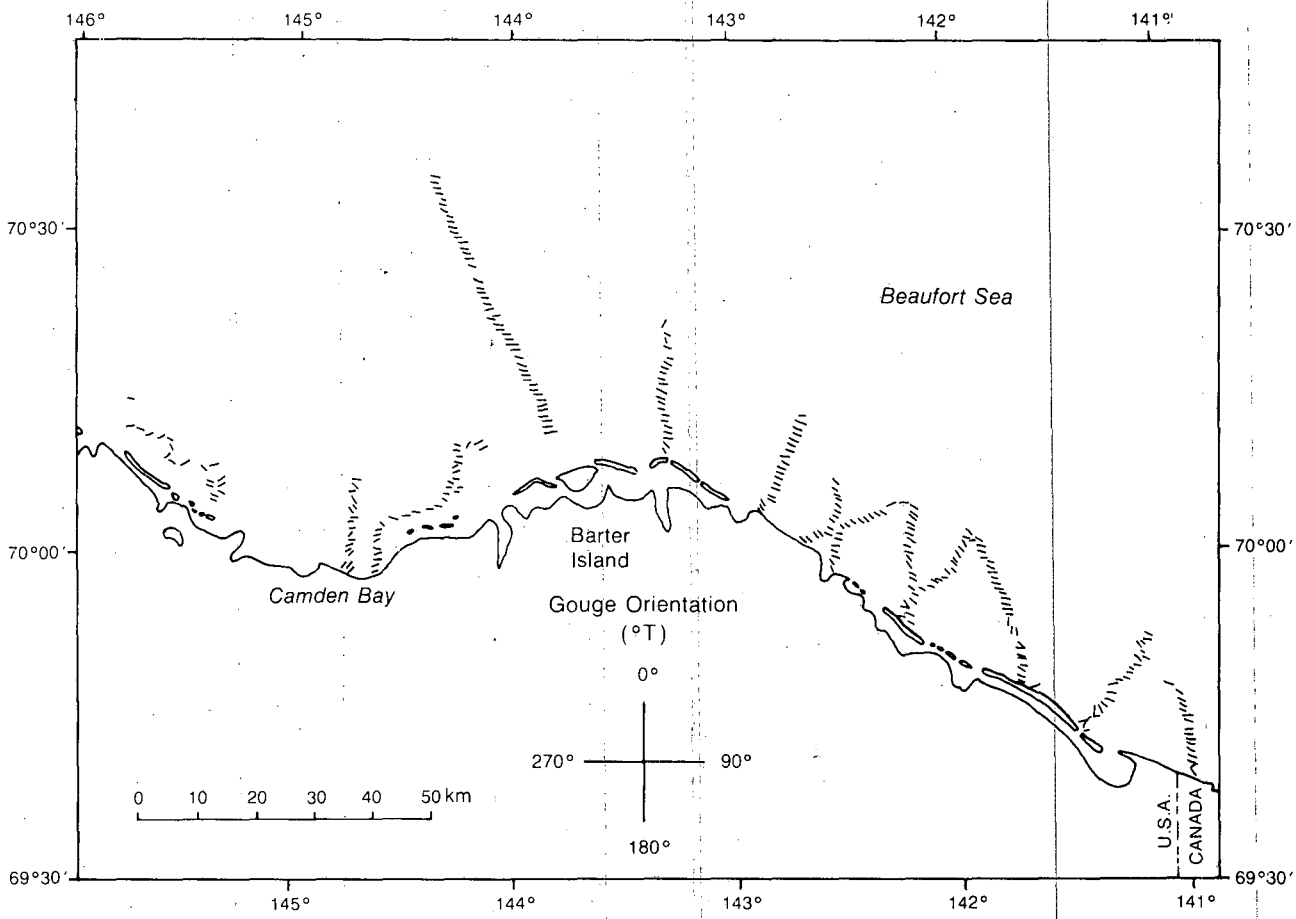

Figure 3.2—Gouge orientations in the Barter Island area. Each line represents the dominant gouge orientation measured over 1 km of trackline.

show a well-defined zone with over 150 gouges/km of trackline in water 18-36 m deep (Fig. 3.3). This zone has been defined by Reimnitz *et al.* (1978) as the stamukhi zone. There is a clear trend of increasing gouge densities from the shore to the stamukhi zone, and decreasing gouge densities from there to 589 m of water depth. The greatest water depth at which a gouge was seen was 58 m. The mean gouge density in the survey area is 108, compared to a value of 63 for the region west of the Canning River. We believe that these higher gouge counts are explained largely by the fact that mean water depth for the areas surveyed here is 25 m, whereas west of the Canning River the mean depth is 17 m (Barnes *et al.* 1981).

The maximum gouge incision depths have been contoured in Figure 3.4. Again the 18-m isobath is a dividing line between maximum incision depths of less than 1 m inshore and greater than 1 m offshore. The maximum incision depths and the maximum gouge widths continue to increase seaward and do not begin to decrease until the very outer ice gouge limit observed. The mean for all maximum incision depths in the study area is 0.8 m, compared to 0.5 m for the western region. The mean of the maximum incision widths is 10 m, versus 8 m for the western region. Again the larger gouge size can be explained in part by the greater average water depth in the present study area.

Ridges are highest between the 25- and 45-m isobaths, and decrease from there seaward. This is contrary to the continuous increase in gouge depth and width measurements with increasing water depth. Total ice gouge relief (incision depth plus ridge height) shows an increase offshore with a slight drop near the outer limit of ice gouging. Barnes *et al.* (1980), based on the highest ridges and greatest incision depths seen in the western area, speculated that total relief could reach 8 m in a single gouge. In the present study the greatest value for total relief seen in a single gouge was 8 m and found in water 38 m deep.

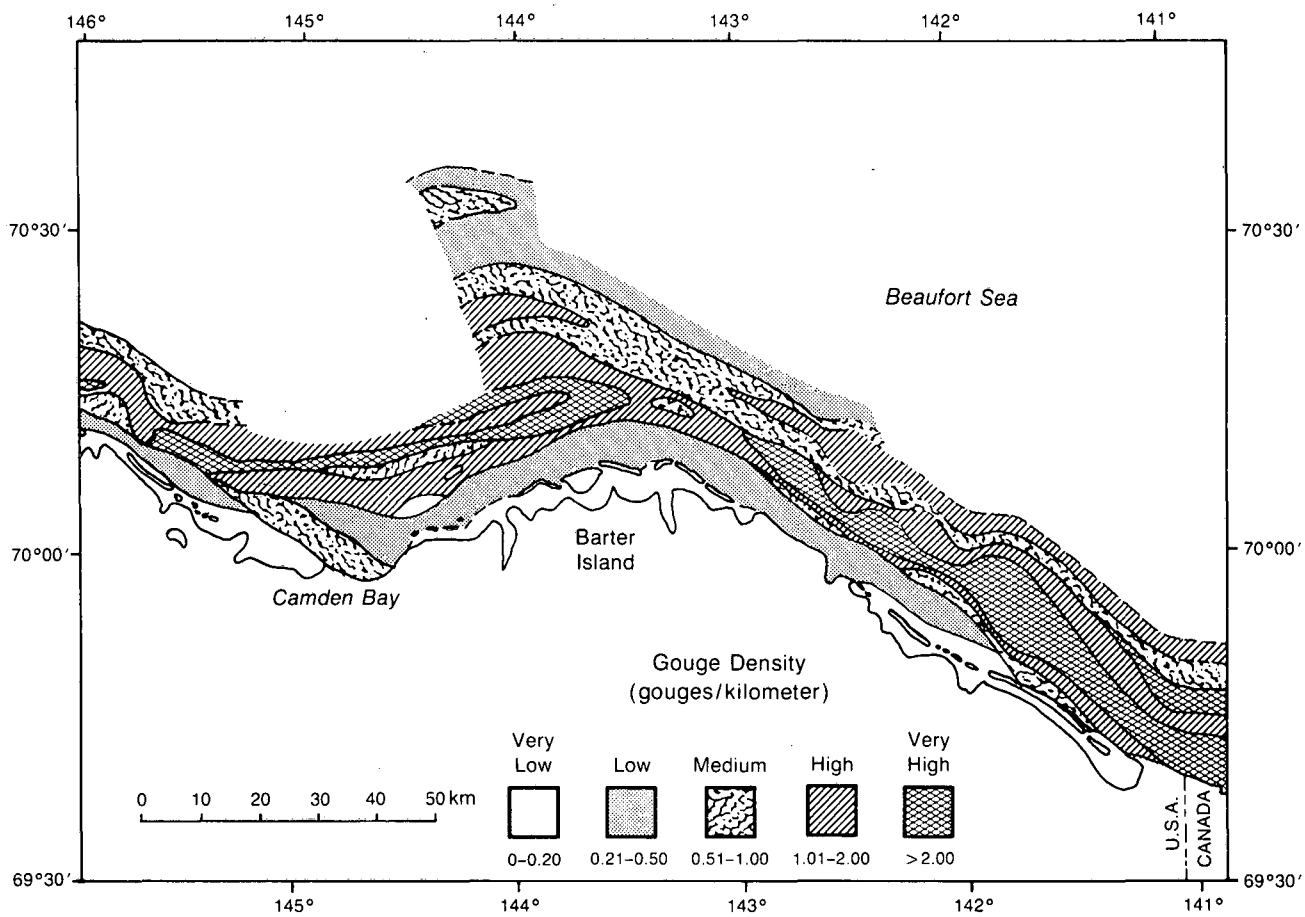

Figure 3.3—Ice gouge density values for the area from Camden Bay to the Canadian border.

The mean values calculated for ice gouge parameters in the area east of the Canning River are greater than those of the area to the west (Barnes *et al.* 1982). This can be explained by the exclusion of surveys in lagoons and bays from our present data analysis. Aside from this difference, the overall patterns are found to extend all the way to the Canadian border and probably beyond. Along the entire Alaskan shelf, the 18-m isobath separates inshore low density and size values. The stamukhi zone, lying between 18 and 36 m of water depth, in all areas stands out by having the highest values on most parameters measured, but east of the Canning River the values do not decrease offshore with the same consistency as to the west of the Canning shelf. In the present study area, the pattern of highest gouge densities corresponds rather well with a 5-year composite of ice ridges prepared by Stringer (1978) and shown in Figure 3.5. The significance of the 13-m isobath as a boundary between areas of mild and severe ice hazards (Kovacs 1980) has not shown up in our data analysis for the length of the shelf.

The trends of water depth contours in the present study area are more northerly on the average than those west of the Canning River, and a comparison of ice gouge trends in the two regions supports previous conclusions that the plowing action aligns with the isobaths. In this study we were again able to demonstrate the tendency for ice gouges to align more consistently isobath-parallel on the up-drift (eastern) side of major promontories, and more variably on the down-drift side (Barnes *et al.* 1982).

The lack of gouges on the crests of shoals in the stamukhi zone, along with the presence of hydraulic bedforms in coarse granular materials, again supports our contention that active hydraulic processes reshape, and perhaps help to rebuild, features that should soon be eliminated by ice scouring. Even in the consistent presence of stamukhi (grounded floes) on the shoals during surveys we rarely detect gouges, while the surrounding low and more protected terrain with cohesive surface sediments is highly gouged.

The total vertical relief possible for a single gouge was previously estimated (Barnes *et al.* 1982) by

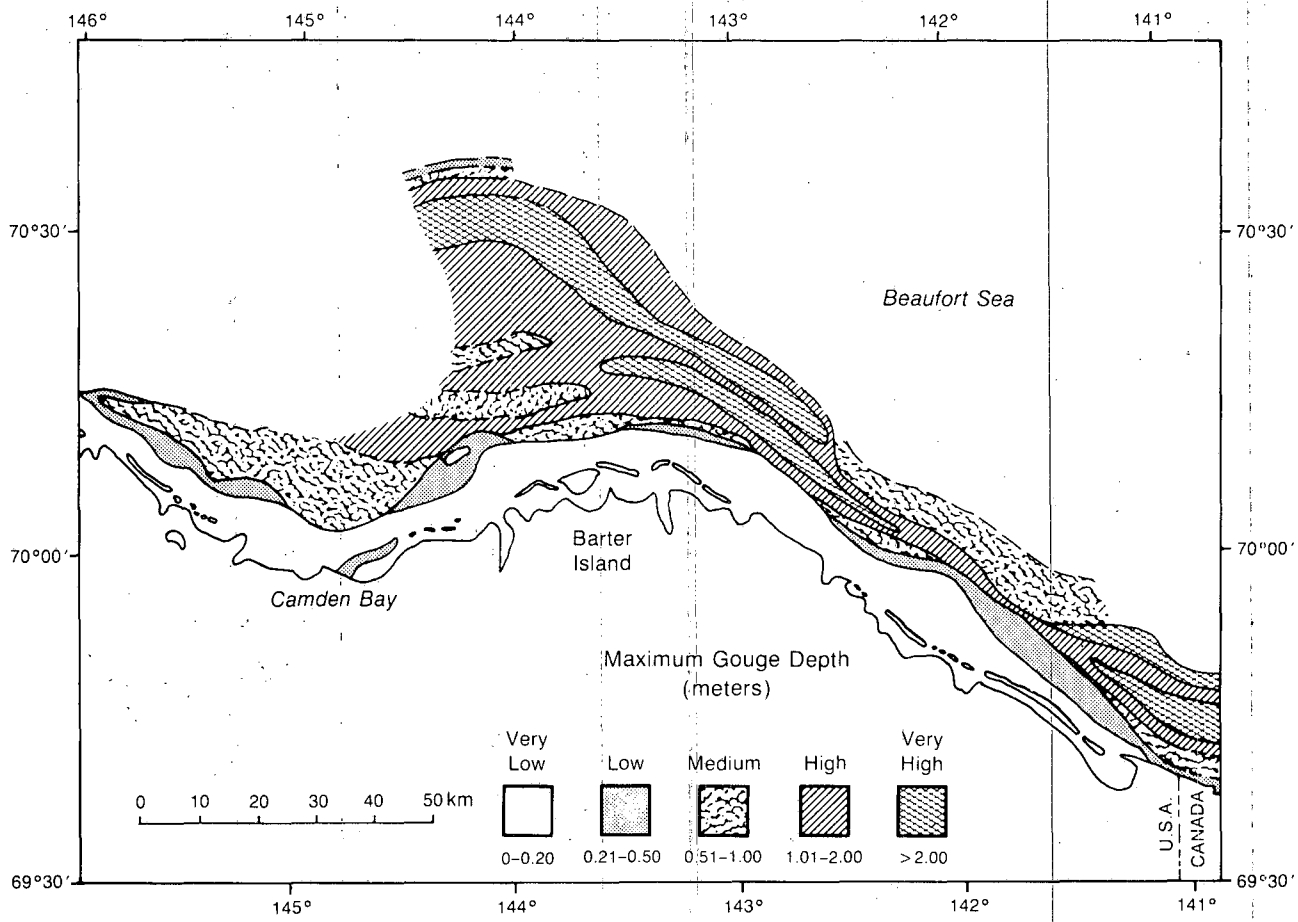

Figure 3.4—Contour map of ice gouge maximum depth for the area from Camden Bay to the Canadian border.

adding the highest ridge from one gouge to the deepest trough of another. In the recent surveys we found 8 m of total relief across a single gouge, leading us to believe that accurate estimates of ice gouge extremes can now be made from our large volume of data.

Drifting ice scraping the sea floor appears to be an efficient planation agent, producing erosional unconformities and truncating thick sets of dipping strata. We believe that hydraulic processes alone acting on the same surface would have sculptured it in accordance with the resistance to erosion offered by the different geologic units. Relatively well-indurated beds would form scarps. The ice pack acting on an extensive, non-homogeneous surface, however, seems to take the different lithologic units down to the same level by focusing mainly on the high points. Viewed in this light, the existence of major, well-defined shoals, is more perplexing.

So far we have been unable to relate the intensity of ice gouging to the underlying geology. Thus, one could also argue that all geologic strata exposed to the action of ice in the study area are weak compared to the forces of the moving ice keels.

3.3.2 Evidence for Greater-than-Expected Ice Depth

Favorable ice conditions in 1981 and a relatively narrow shelf east of the Canning River enabled the R/V *Karluk* to survey ice gouges in generally greater water depth than has been possible in the western sector. One particular line was extended to the very shelf edge. In general, the relationship between ice gouging and water depth in the study area is similar to that determined for areas west of the Canning River, with lowest values for certain gouge parameters inshore and offshore of the stamukhi zone. In the present study, ice gouges were traced to a maximum water depth of 58 m. Beyond that we saw only very broad, subdued relief features unrelated to ice keel interaction. Among the bedforms seaward of gouges we found slope-parallel, rhythmic lineations of 3 m wave length but less than 20 cm of relief, which we interpret

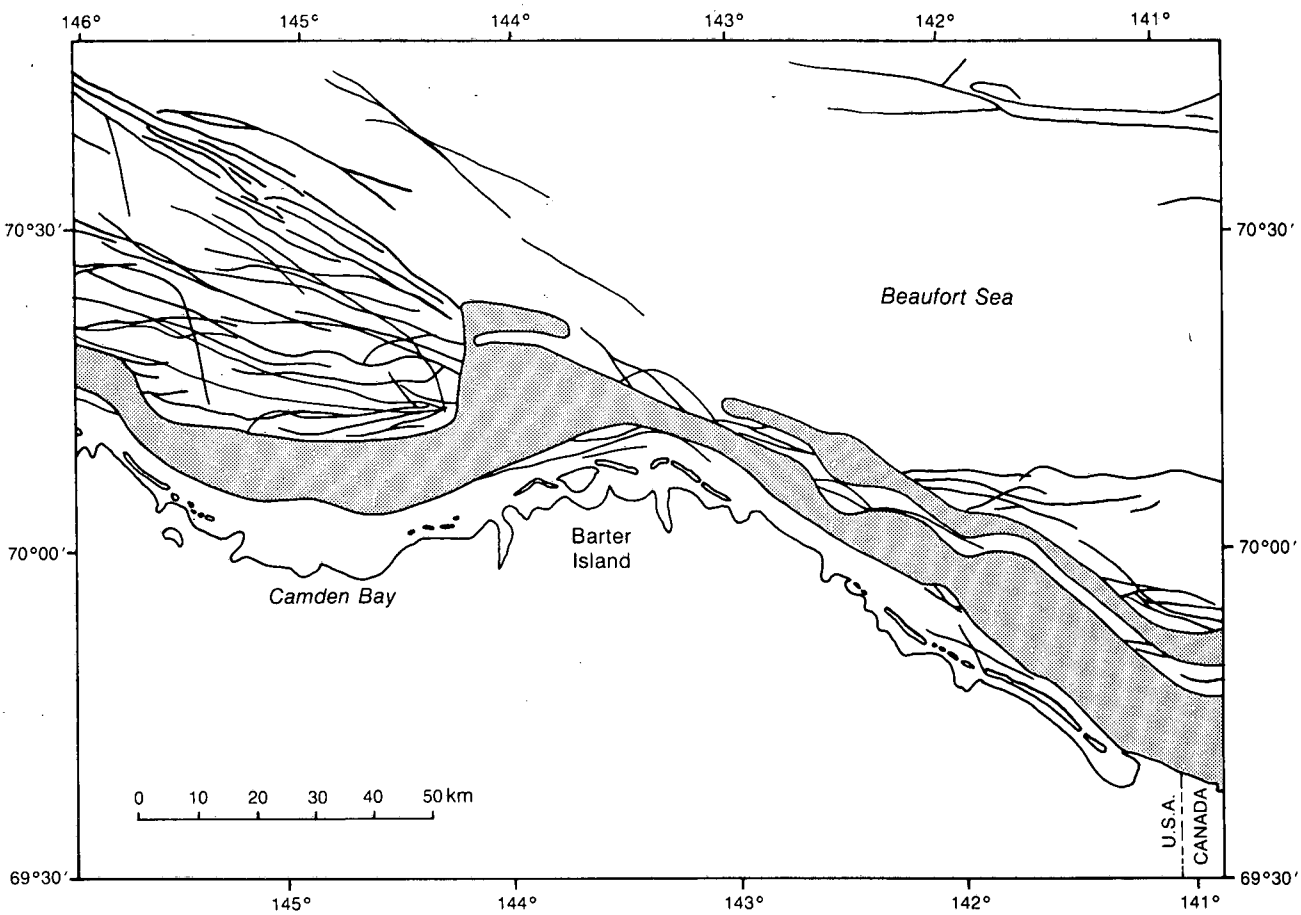

Figure 3.5—Composite of ice ridges in the Barter Island area from 1973 to 1977, from Stringer *et al.* (1978). Shaded area indicates zones of high density gouging (>100 gouges/km) that were contoured from data of the present study.

as probable hydraulic bedforms. These indicators, along with the presence of surface gravels rather than fine materials, the subdued nature of gouge relief forms, the seaward decrease in ridge height relative to trough depth and width, and especially the recorded current pulses of up to 50 cm/s along the shelf edge (Aagaard 1977) all suggest that active currents rework the deepwater gouges. Judging from these considerations, the gouges found at 58 m of water depth are modern rather than relict (produced during lower stands of sea level). Surficial hyperbolic reflections on Uniboom crossings of the shelf edge between Barrow and the Canadian border, and the accompanying surface roughness, are fairly certain indicators for the presence of ice gouges. These indicators can be traced in 28 representative traverses to maximum water depths of 60-64 m (Dave Dinter, U.S. Geological Survey, pers. comm., 1982).

Our previous contention that ice gouges seen on the Beaufort Sea shelf at depths greater than 47 m (the deepest keel actually observed) are modern has recently found additional support. Marine geologic studies by Canadian workers in the southern Beaufort Sea no longer call for lower sea levels to account for the deepest gouges observed. Also, statistical treatment of ice keel distributions in Arctic deep water allow for 60-m-deep keels to occur at a rate of one every few hundred years (Peter Wadhams, pers. comm., 1982). These findings are of little consequence at the present state of petroleum development in the Alaskan Beaufort Sea, but may in the future assume considerable importance.

3.3.3 Ice Gouging—Chukchi Sea

Ice movement and subsequent ice grounding and gouging of the seabed within the Chukchi Sea are controlled in part by the bathymetry. The northeast-trending and deepening Barrow Sea Valley provides a conduit for the southward movement of pack ice and allows deep-draft ice to intrude into the Chukchi Sea south of Barrow. To the west of

the Barrow Sea Valley, Hanna Shoal rises to 25 m of water depth and is pervasively gouged (Grantz *et al.* 1982). The shoal and the ice field often grounded there apparently serve as an important bifurcation obstruction to pack ice drifting westward and southward onto the Chukchi shelf. To the north and southeast of the shoal there are dense gouge concentrations, whereas to the southwest, gouges are sparse and very shallow. On the north flank of Hanna Shoal in a roughly east-trending zone between about the 40- and 52-m isobaths, there are random, dense concentrations of gouges. Out to approximately the 48-m isobath, gouges are seldom incised deeper than 2 m. Beyond this, out to about the 52-m isobath, gouges as deep as 3 to 4 m in depth are common. Gouges are extremely sparse and shallow beyond the 54-m isobath. Shallow solitary gouges in water as deep as 64.5 m occur to the east of Hanna Shoal (Grantz *et al.* 1982).

East of Hanna Shoal the Barrow Sea Valley provides a conduit for southward movement of pack ice. At the north flank of the valley a northeast-trending dense concentration of gouges less than 2 m deep occurs between depths of 40 and 47 m. Dense concentrations of gouges as deep as 5 m occur in water 48 to 55 m deep, and shallower, sparse gouges occur in deeper water (Grantz *et al.* 1982). Gouge incisions to 4.5 m deep are also reported at depths ranging from 36 to 40 m within the Chukchi Sea (Toimil 1978).

Intense ice gouging of the sea floor along the east flank of the Barrow Sea Valley occurs on the steep slopes and within the stamukhi zone. Directly north of Point Barrow ice gouging varies from 20 to 30 cm deep out to 8 m of water depth; to the west at approximate depths of 10 m the slope rapidly increases, and multi-gouge incisions extend to approximately 40 m depth. Within this intensely gouged zone between depths of 30 to 35 m the maximum gouge depth is 1.5 m. Rex (1955) also reports that ice gouging, to 3 m depth, is developed between the 6- and 30-m isobath on the inner shelf off Point Barrow. The Quaternary sediment cover in this region ranges from 1 to 2 m in thickness within the maximum ice gouge zone, which suggests that the underlying Cretaceous(?) bedrock prevents deeper gouge incision. Directly off Barrow within the east flank of the Barrow Sea Valley, ice gouging, to 1 m depth, is observed to 57 m depth on linear, northeast-trending sediment banks.

South toward Peard Bay along the east side of the Barrow Sea Valley, the intense ice gouging is restricted to the sloping seabed between depths of 8 to 30 m and extends offshore to the south as the seabed gradient decreases. North and east of Peard Bay, the stamukhi zone starts at depths of 20 to 22 m and is defined by an intensely gouged ridge 2 m in height (Phillips *et al.* 1982). Most of the gouges are oriented parallel or sub-parallel to the isobaths. Off Point Franklin, the stamukhi zone and steep seabed slopes coincide. Within the stamukhi zone, the highest density of gouging occurs at depths ranging from 14 to 24 m where the gouges parallel the isobaths. The gouges vary from 20 to 70 cm deep within this zone. To the west and north, migrating ripples and sand waves have filled in the gouges. The deepest ice gouge observed west of Point Franklin was 1.6 m deep at 8 m of water depth. South of the Peard Bay region, the ice gouge intensity abruptly decreases in the vicinity of Point Belcher. Northward-migrating sandwave fields apparently have filled in the gouges in this region (Phillips *et al.* 1982).

The recurrence interval of ice gouging of the sea floor on the Chukchi Sea is unknown at the present time. Where the steep slopes exist along the east flank of the Barrow Sea Valley, a higher recurrence interval of ice gouging could be expected due to access of variable-draft ice keels to this region.

3.3.4 Strudel Scouring Near Rivers

Strudel scour craters as great as 20 m wide and 4 m deep are excavated by vertical drainage flow during the yearly spring flooding of vast reaches of fast ice surrounding arctic deltas; they form at a rate of about 2.4 km^2/yr. Monitoring two such craters in the Beaufort Sea, we found that in relatively unprotected sites they fill in by deposition from bedload in 2–3 years. Net westward sediment transport results in sand layers dipping at the angle of repose westward into the strudel-scour crater, whereas the west wall of the crater remains steep to vertical. Initially, the crater traps almost all bedload, including sand, pebbles, and organic detritus. As infilling progresses, the materials are increasingly winnowed, and by-passing must occur. Over a 20-m-wide sector, an exposed strudel scour trapped 360 m^3/yr. This rate should be applicable to a 4.5-km-wide zone with equal exposure and similar or shallower depth. Within this zone, the transport rate is 40,000 m^3/yr, similar to estimated longshore transport rates on local barrier beaches. On the basis of the established rate of cut and fill, all the delta-front deposits should consist of strudel-scour fill. Vibracores typically show dipping, interbedded sand and lenses of organic material draped

over very steep erosional contacts, and an absence of horizontal continuity of strata—criteria that should uniquely identify high-latitude deltaic deposits. Given a 2- to 3-year life-span, most strudel scours seen in surveys must be old. The same holds true for ice gouges and other depressions not adjusted to summer waves and currents, although these features record events of only the past few years. In view of such high rates of bottom reworking of the shallow shelf, any human activities creating turbidity, such as dredging, would have little effect on the environment. However, huge amounts of transitory material trapped by long causeways planned for offshore development would result in major changes in the environment.

3.3.5 Ice Wallow

Broad, undulating, nonlinear relief forms of the arctic nearshore environment composed of closed depressions and isolated knolls undergo major changes in relief over a period of 3 years. The bedforms are produced by current and wave erosion and deposition around grounded ice during high-energy events in the nearshore zone. The area is characterized by an irregular and complex pattern of closed depressions and isolated knolls with relief of 2 to 3.5 m.

The large potholes in the nearshore region seem to be large counterparts to sea-ice kettles seen on beaches. These are on a small scale compared to the pattern of isobaths, where larger ice blocks interact with wave and current regime.

The ice wallow depression may also be partially the result of vertical movement of bergy bits in a seaway. This movement produces pulsating flows that transport sand away from the point of ice impact. Processes of cut and fill will have to be considered in the construction of pipelines through the littoral zone.

3.4 HAZARDS FROM STORM CURRENTS AND WAVES

Tidal currents, wave- and wind-generated currents, and the offshore, shore-parallel Alaska Coastal Current modify the sea floor along the eastern Chukchi Sea by erosion and transportation of sediment as migrating bedforms. While nearshore currents are generated by winds, the offshore region is dominated by northeast-directed storm currents and the northeast-flowing Alaska Coastal Current.

The tides are small in the Chukchi Sea, and the tidal range along the eastern coast is generally less than 30 cm. The tides are of the semidiurnal type (Creager 1963; Wiseman *et al.* 1973). The tidal wave moves from north to south in the Chukchi Sea (Coachman and Aagaard 1974). Tide-generated currents can be expected to be of limited velocity along the open coast. Within lagoons and embayments, however, tide-generated currents are reported up to 204 cm/s within the tidal passes east of Barrow (Rex 1955).

Storms during the summer months usually result in winds from the southwest which move across the Chukchi Sea. The maximum fetch then develops across the open water (Wiseman and Rouse 1980). Waves can be much more severe in the Chukchi than in the Beaufort, such as those encountered during the 1975 sealift. The resulting storm waves and storm-generated currents may erode and scour the sea floor as well as result in intense sediment transport on the shelf and on the shoals.

Wind-generated currents are extremely variable both in velocity and in direction of movement for the nearshore region (Wiseman and Rouse 1980). The predominant summer winds are from the northeast, generating nearshore current velocities of 4–20 cm/s (Hufford 1977). The wind-generated currents generally follow the bottom contours (Wiseman and others 1974). Daily variations in current direction are reported for the nearshore regions (Wiseman and Rouse 1980).

The Alaska Coastal Current represents a northeast-flowing "warm" water mass derived from the Bering Sea (Paquette and Bourke 1972). The current approaches the coast off Point Franklin and Barrow. Surface velocities of up to 200 cm/s are reported southwest of Point Franklin (Hufford 1977). A returning southward-flowing, clockwise gyre develops off the Alaska Coastal Current north of Point Franklin, off Skull Cliff. To the west of Point Franklin on the west side of the Barrow Sea Valley, another returning southwest-directed current is reported with surface velocities of 80 cm/s. The southwest-flowing currents are poorly defined in space and time. Large, clockwise-rotating, spiral currents are reported west of Barrow and may represent interaction between the Alaska Coastal Current and the westward-flowing current of the Beaufort Gyre (Solomon and Ahlnäs 1980). The effects of these poorly defined currents are to erode sediment and expose bedrock on the sea floor, and to transport sediment as migrating sandwave fields.

3.4.1 Sand Waves

Data on sea floor modification, erosion, and rates of sediment transport are lacking for this region. The seabed records the effects of the active northeast-flowing Alaska Coastal Current. Linear, northeast-trending, gravel-sand ribbons occur to the northwest of Point Franklin. An extensive northeast-migrating sandwave field is located to the north of Point Franklin which apparently forms a series of discontinuous sandbanks parallel to the coast to near Barrow. Directly off Barrow, bedrock is exposed on the steep slopes of the Barrow Sea Valley; at depths of 50-60 m, two shore-parallel linear sand(?) banks are located at the break in slope of the east flank of the Barrow Sea Valley.

On the west side of the Barrow Sea Valley northwest of Point Barrow, an extensive field of bedforms is identified at depths of 100-300 m (Eittreim *et al.* 1982). The bedforms have amplitudes up to 5 m and wave lengths of 100 m and are interpreted as mud waves.

The bedforms within the Barrow Sea Valley record evidence of active currents eroding the substrate and transporting sediment. The rates of sediment transport and stability of the bedforms and sandbanks are unknown for this area.

3.4.2 Artificial Islands

Artificial islands and causeways of sand, gravel, and mud undergo changes which affect their impact on the natural physical and biological environment. One of these islands, Niakuk III, was built in about 4 m of water, with sandy gravels. Without erosional protection, this artificial island was expected to change in a manner similar to the natural islands, often amounting to several meters per year.

The initial rectangular shape of the island changed significantly within 1 year of the island's construction (Fig. 3.6). The northeastern segment of the island was displaced and the shoreline eroded about 80 m. Recurved subaerial spits developed to the west and south and extended 70-80 m beyond the original shores of the island. Only the southwest corner of the island appeared in 1980 as it did when built the previous year.

The predominant factor affecting the artificial island has been erosion and redeposition of sediment from the northeast quadrant. About one-third of the island's volume had been displaced from its original emplacement site during the first year. It is estimated that 30,000 m^3 of sand and gravel were reworked, transported, and redeposited during one open-water season. This is a very high rate compared to natural coastal sediment transport to be expected for 1 year for arctic sand and gravel beaches (Nummedal 1979). The high rate is believed to be related to fall storms or the lack of a substantial permafrost core. The unnaturally steep slopes of the artificial island may act to increase the rate of sediment transport and reworking.

Artificial islands will migrate to the southwest as the materials from the original island are used as a sediment source for the elongation of spits similar to natural islands. The resulting southwesterly migration will probably leave a pavement of lag gravel on the sea floor, remnant from the passage of the island mass.

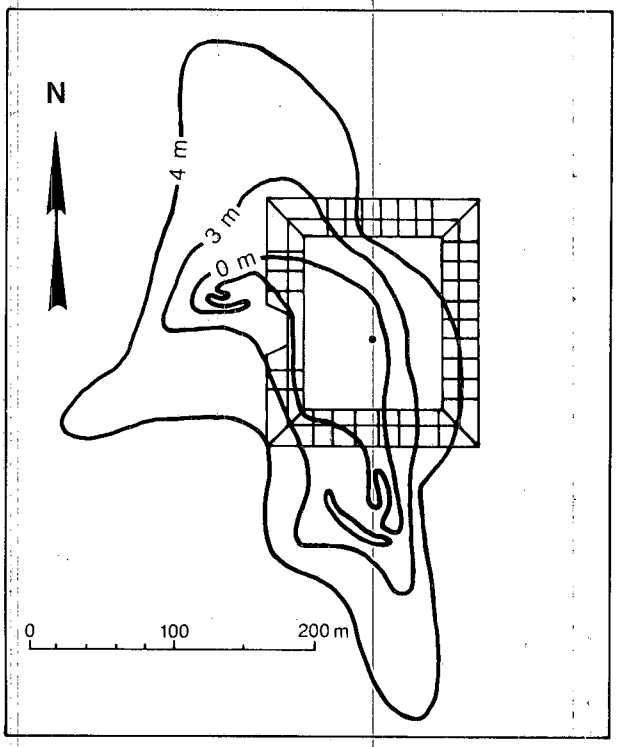

Figure 3.6—Niakuk III as originally built, superimposed on its shape as determined from 1980 survey data.

3.4.3 Causeways

Repetitive bathymetric surveys and subjective observations indicate that sediment deposition is occurring in the vicinity of the artificial-fill causeway at Prudhoe Bay (Fig. 3.7). Previously, the area had been one of seabed erosion. The change in environment is related to the change in wave and current regime brought about by the causeway construction.

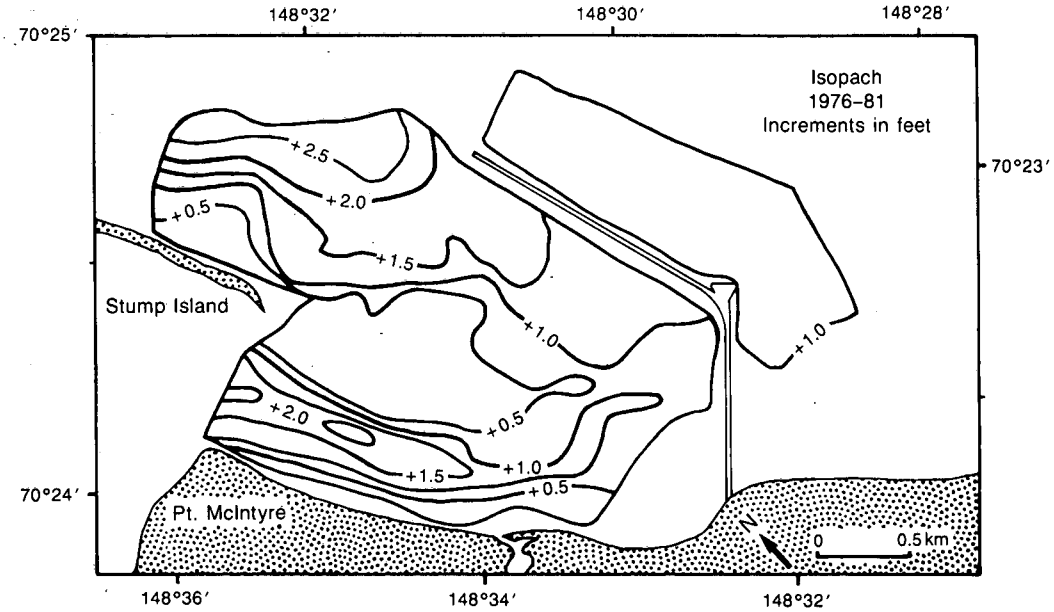

Figure 3.7—Extended isopach map (in feet) showing bathymetric changes overlapping data sets obtained from 1976 to 1981.

The combination of obstruction to shore-parallel transport and the deflection of low offshore results in sedimentation in the vicinity of the causeway; the dominant winds from the northeast favor fine-grain sedimentation in the lee. Thus, the causeway acts as a groin to decrease currents and to allow sediment to be deposited. Extension of the causeway from the waterflood project will extend the area of quiet waters and deflected currents and will extend the area of sedimentation seaward. Providing openings similar to those in the existing barrier island chains might maintain the present sediment transport regime.

3.4.4 Anchor and Frazil Ice Formation

During the fall, anchor and frazil ice formation increases nearshore sediment transport and erosional processes, which influences coastal and artificial island stability. Observations in the fall of 1982 suggest three significant, yet poorly understood, processes:

1) *Freezing of the seabed.* During freeze-up, the coastal seabed freezes to depths of several centimeters and stabilizes the sediments against normal erosional processes. In some cases, frozen slabs of sediment are broken from the bottom and may be deposited on the beach or incorporated within the ice canopy if ice content is high enough to float the ice-sediment mixture. The seabed freezing is also a potential mechanism for over-consolidation of seafloor sediments.

2) *Anchor ice formation on the seabed.* Mounds of sediment-laden ice crystals form on the seabed in water depths to at least 4 or 5 m. These are ice growths on the sea floor, in contrast to freezing of the sea floor above. These features do not last into winter and are believed to be associated with the freeze-up processes in some manner; however, their modes of origin and ultimate fates are uncertain.

3) *Frazil ice formation in nearshore waters.* The formation of frazil ice at freeze-up is now basically understood. The frazil ice, in some poorly understood manner, increases the sediment content of nearshore waters and results in the entrainment of sediments in the forming ice canopy. Frazil ice also increases erosion in areas influenced by this type of ice during storms at this time of year.

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Chapter 4
The Beaufort Current

by Knut Aagaard

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The southern Beaufort Sea is generally portrayed as a region of mean westward water and ice motion corresponding to the southern edge of the anticyclonic gyre of the Canada Basin. However, except over the inner continental shelf, the average subsurface motion is actually in the opposite direction: over the slope and shelf seaward of about the 50-m isobath there is a strong mean eastward motion. This eastward flow is by far the most conspicuous feature of the regional circulation, and I will refer to it as the *Beaufort Current.*

4.1 HYDROGRAPHY

It has been clear for some years that an eastward flow exists on the shelf at least occasionally, since in summer the most prominent hydrographic feature on the shelf is a subsurface temperature maximum, generally found seaward of about 40-50 m depth. This temperature maximum is associated with the eastward flow of water originating in the Bering Sea. The influx was first described by Johnson (1956), and has since been discussed by Hufford (1973), Mountain (1974), Paquette and Bourke (1974), and others.

The warm water that enters the Beaufort Sea has come through the eastern Bering Strait and followed the Alaska coast around Point Barrow. This intrusion is in fact composed of two water masses, called Alaskan coastal water and Bering Sea water by Mountain (1974). Summer temperatures of the Alaskan coastal water west of Barrow can be as high as 5-10°C, but the salinities are low, at less than 31.5‰. The Bering Sea water is more saline and is contained in the density range 25.5 to slightly over 26.0 in σ_t, as has been demonstrated in the detailed analyses of Mountain (1974) and Coachman *et al.* (1975). Figures 4.1 and 4.2 show the temperature on density surfaces associated with the two intruding water masses. The restriction of the warm eastward flow to the outer continental shelf and the slope is clear, as is the difference in extent of influence of the two water masses. The Alaskan coastal water mixes rapidly with the ambient surface water as it moves eastward and is not clearly identifiable east of about 147-148° W. On the other hand, the Bering Sea water, with its deeper temperature maximum (in the σ_t range 25.5-26.0), can be traced at least as far as Barter Island at 143° W.

The temperature maximum over the shelf (as contrasted to offshore over the deep basin) is primarily a summer phenomenon. Figure 4.3 shows the temperature-salinity correlation at two stations on the shelf near 153° W. Station W25-19 was taken in early November 1976 and W27-1, at the same location, the following March. The temperature maximum of about −0.9°C at 43 m depth at station 19 occurred at $\sigma_t = 25.8$ and represents Bering Sea water having rounded Point Barrow earlier in the year at a higher temperature. Sometime later in the winter, the Bering Sea temperature signal is effectively erased on the shelf, as shown by the temperature-salinity correlation in the upper 50 m at station W27-1; down to about 40 m, where the density is 26.5 in σ_t, the water is at the freezing point. Such low temperatures extending into or past the density range of the core of Bering Sea water are typical on the shelf in winter, and in fact these conditions can readily be found already in November. Therefore one probably cannot generally use temperature to trace the Bering Sea water on the Beaufort shelf much past freeze-up in the fall. Moreover, after that time the new water entering the Beaufort Sea from the Chukchi is itself near the freezing point after being cooled in its fall and winter transit northward. Delineation of the east-

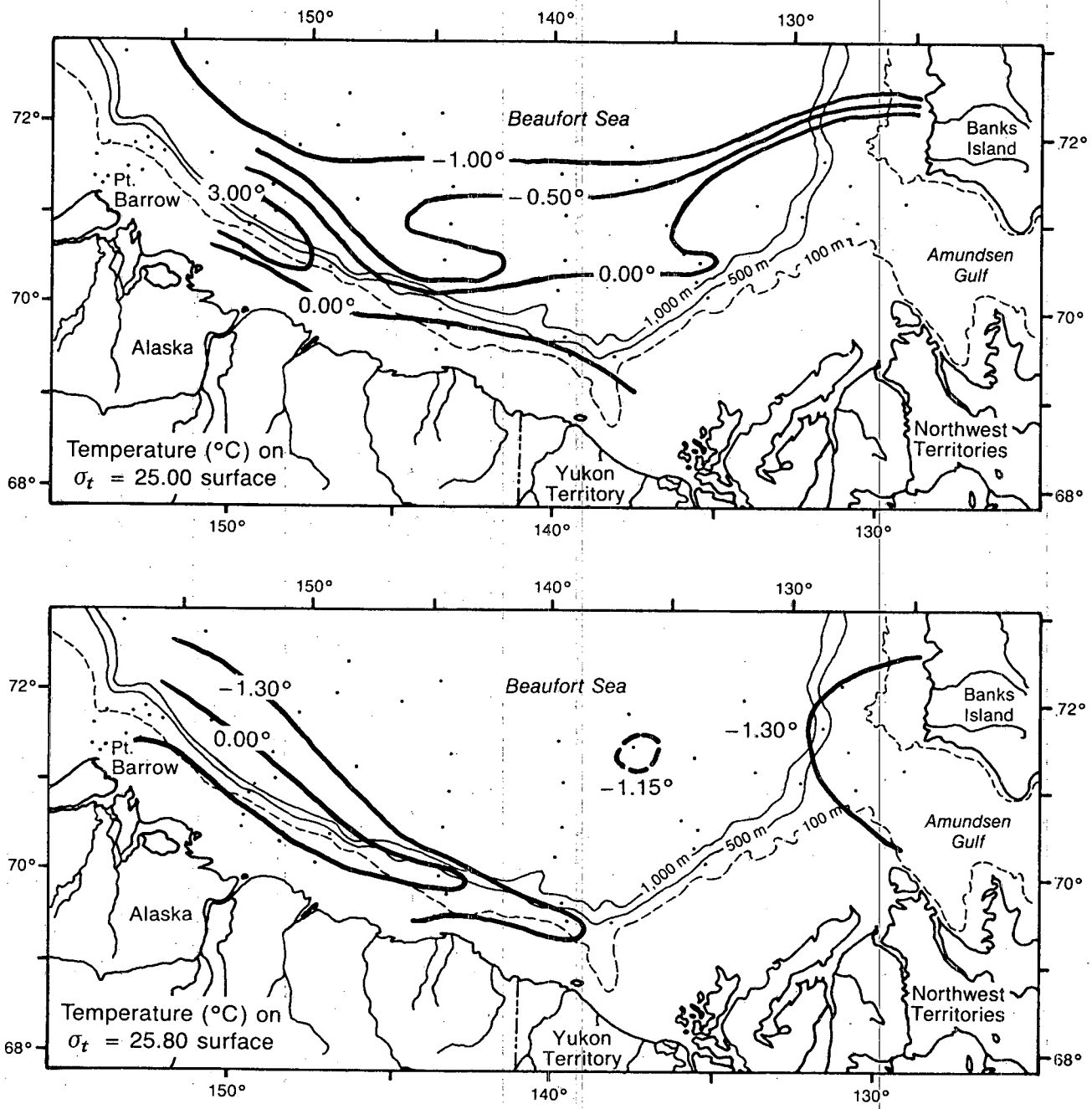

Figure 4.1—Temperature on density surfaces corresponding to Alaskan coastal water (σ_t = 25.00) and Bering Sea water (σ_t = 25.80), August-September 1971. Dots represent station positions. (Adapted from Mountain 1974.)

ward flow under these conditions depends on hydrographic parameters other than temperature, or on direct current measurements.

The patchiness of the temperature distribution in Figure 4.2 is particularly interesting. Mountain (1974) attributed such features to interruptions in the influx of warm water onto the Beaufort shelf, and, in fact, the appropriate variability has been observed upstream in the Barrow Canyon (Mountain *et al.* 1976). On the other hand, similar temperature structures commonly seen in frontal regions elsewhere in the ocean are frequently attributed to flow instabilities (see Wadhams and Squire 1983 for a recent example from an ice-covered area). However, except perhaps during density upwelling events (Hufford 1974) and near the major

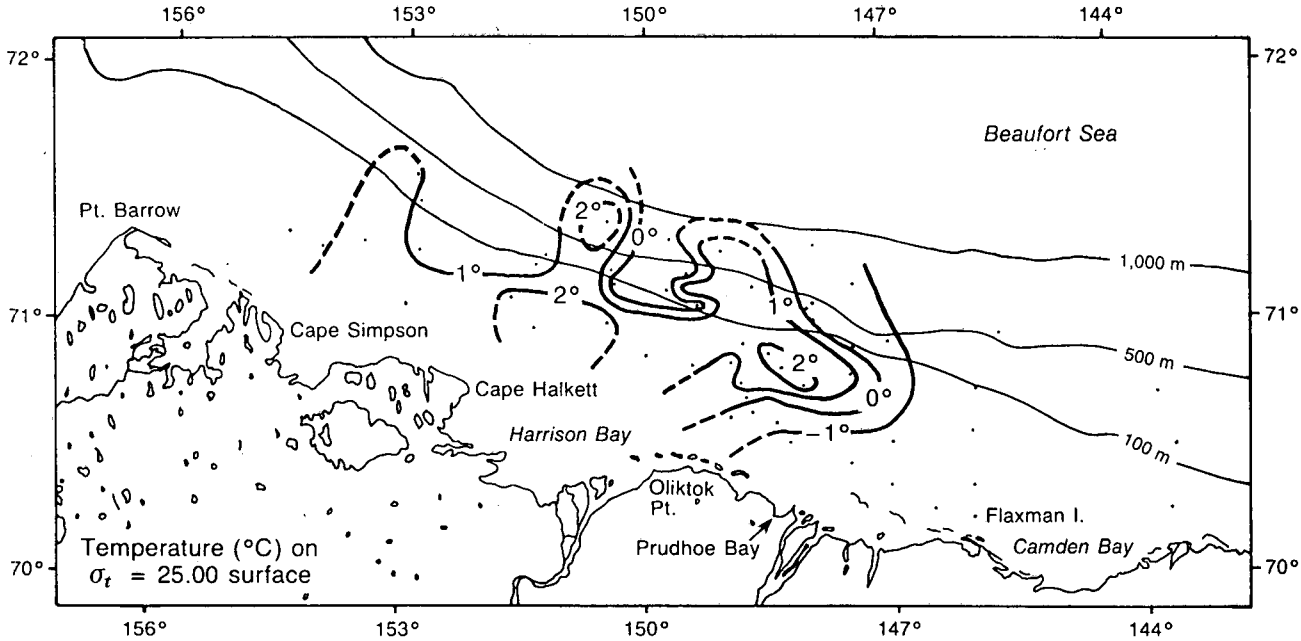

Figure 4.2—Summer temperature on density surface σ_t = 25.00. Dots represent station positions. (Adapted from Mountain 1974.)

rivers during peak discharge, marked density fronts do not appear to be present over the Beaufort shelf. Although in summer sizable temperature gradients are associated with the warm waters carried by the Beaufort Current, normally a strong summer density front does not exist (Fig. 4.4). During winter the temperature maximum disappears and persistent strong fronts of any kind appear to be absent over the shelf (Fig. 4.5). While it is therefore doubtful whether frontal dynamics are of major importance in the shelf regime, temporary or weak fronts exist. Hunkins (1979), in fact, calculated an e-folding time of 28 days for baroclinically unstable

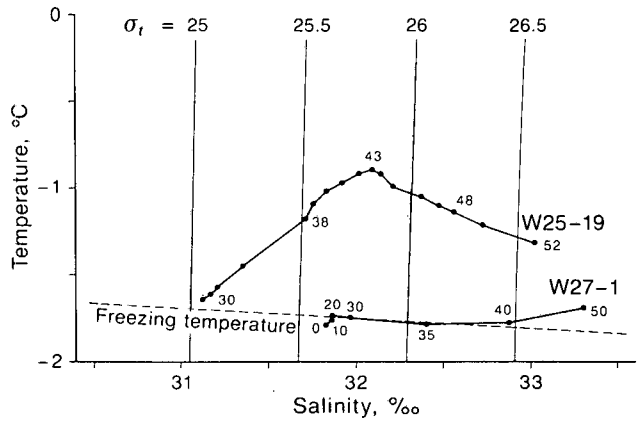

Figure 4.3—Temperature-salinity correlations at a fall (W25-19) and a winter (W27-1) station near 153° W.

current perturbations north of Point Barrow. This is a very slow growth rate and points toward the inefficacy of baroclinic instabilities in producing mesoscale features over the Beaufort shelf.

Although the strong Bering Sea hydrographic signal is predominant, the eastward flow probably also involves water masses other than those from the Bering Sea. This would be particularly true seaward of the shelf break.

4.2 CURRENT MEASUREMENTS

Over a 4-year period beginning in March 1976 we obtained a total of 2,335 record days of moored current measurements on the Beaufort Sea shelf between 146° and 152° W (Table 4.1). The mooring techniques that were developed for these ice-covered waters have been described by Aagaard *et al.* (1978).

The measurements are summarized in Figure 4.6 in the form of current roses. At each indicated mooring site, the current rose for a particular instrument (instrument depth given adjacent to the rose) represents both the mean speed and the direction, the latter in terms of the frequency of occurrence of the current in each 20° sector. For example, at mooring LO-5 on the outer shelf, which recorded from 13 March to 7 October 1978 (Table 4.1), the current was predominantly toward 100 ± 10°. It registered in this sector 43% of the time, and the

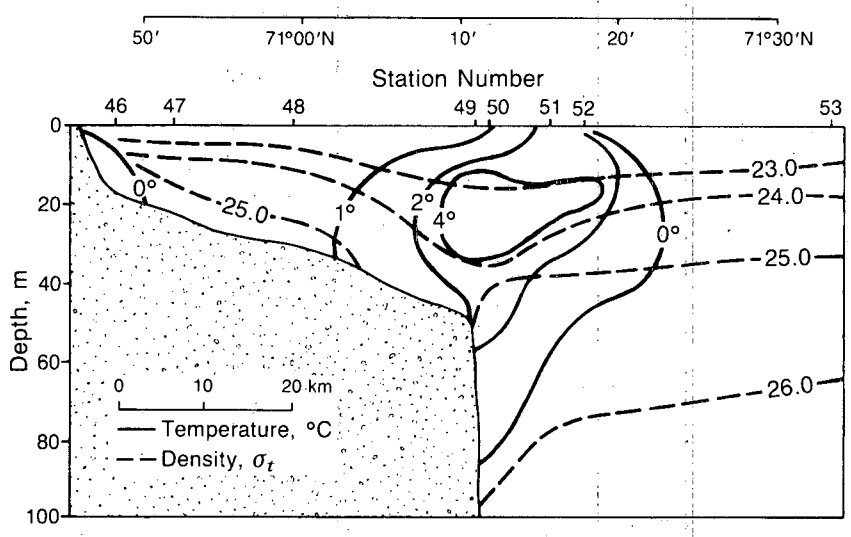

Figure 4.4—Summer temperature and density section across the shelf and upper slope at 150° W. (Adapted from Mountain 1974.)

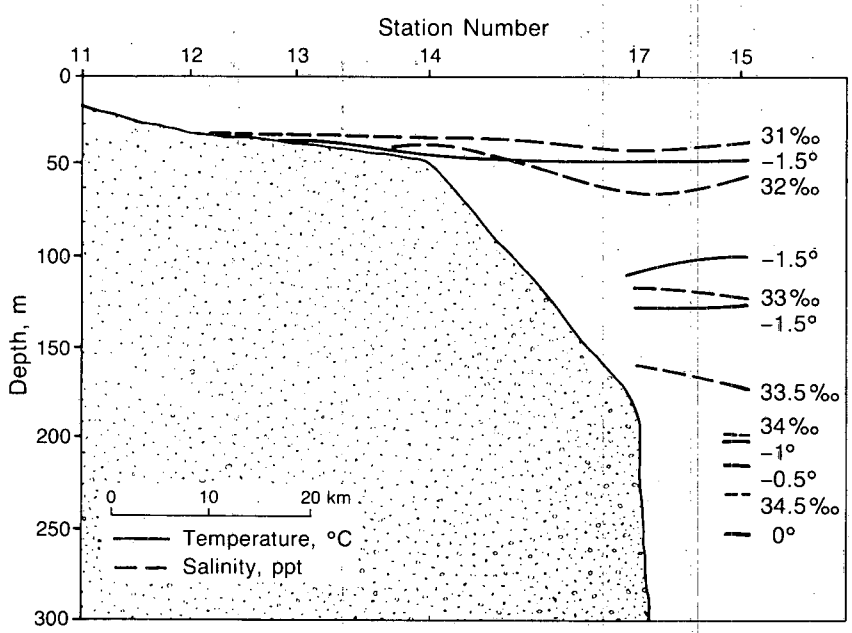

Figure 4.5—Winter temperature and salinity section across the shelf and upper slope near 147° W.

mean speed over the nearly 7 months was about 15 cm/s. At the same location the next most commonly observed current was in the reciprocal direction, and in the mean it was about 2 cm/s slower.

Figure 4.6 by itself provides no information on observational time spans, and must therefore be examined together with Table 4.1. For example, at site LO-1 the rather round current rose at 78 m represents just over a week of measurements, whereas the elongated elliptical rose at 152 m represents nearly 7 months and is therefore, in a probabilistic sense, far more representative of the current conditions.

4.3 THE INSHORE REGIME

It is useful to consider the Beaufort Current against the contrasting background of the circulation on the inner shelf. Several investigators have found evidence for wind-driven circulation there in the summer (Barnes and Reimnitz 1974; Hufford and Bowman 1974; Hufford *et al.* 1974, 1977; Wiseman *et al.* 1974; Barnes *et al.* 1977; Drake 1977). In general, there appears to be a westward water motion driven by the prevailing easterly winds, but the circulation responds rapidly to changing wind conditions, such that under westerly

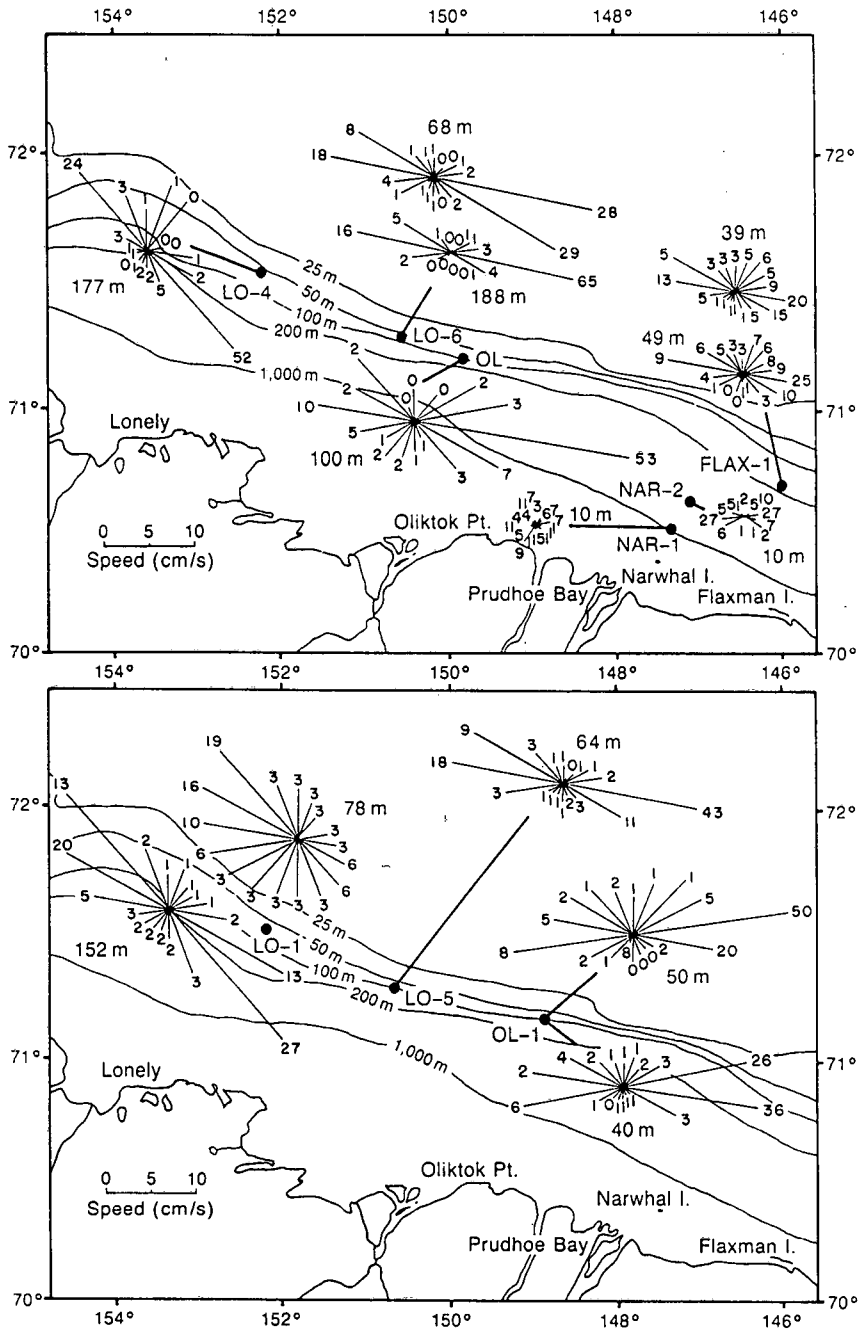

Figure 4.6—Current roses at Beaufort Sea mooring sites. Each vector represents the mean current in a 20° sector, the vector length being proportional to the speed (see scale). The number at the end of each vector is the frequency of occurrence of a current within that 20° sector. Depth of measurement is shown adjacent to each rose. Heavy dots show mooring locations.

winds (which is the secondary wind mode) the motion is eastward. More recently, Matthews (1981a) and Barnes and Reimnitz (1982) concluded, mainly from drifter data, that significant flow on the inner shelf is primarily a summer phenomenon, when the winds drive near-surface currents about 3% of the wind speed. Bottom currents were deemed considerably slower.

Little work has been done on the winter circulation. However, during March and April 1976 we obtained two 3-week winter current records from the inner shelf: NAR-1 and NAR-2, from water 27 and 38 m deep, respectively (Fig. 4.6). Both instruments were under fast (or grounded) ice, NAR-2 near the outer edge and NAR-1 14 km farther inshore. The flow was relatively slow and there was little net motion (Fig. 4.6). Examination of the individual records shows that the currents never exceeded 10 cm/s and were generally less than 5 cm/s. The mean flow during the 3 weeks was essentially negligible: 0.1 cm/s at NAR-2 and 0.3 cm/s at NAR-1.

Table 4.1—Beaufort Sea current records.

Mooring	Latitude (N)	Longitude (W)	Water Depth (m)	Instrument Depth (m)	Valid Record Begins (GMT)	Valid Record Ends (GMT)
NAR-1	70°32.2′	147°20.0′	27	10	28/3/76	22/4/76
NAR-2	70°38.7′	147°09.0′	38	10	28/3/76	19/4/76
OL	71°12.6′	149°53.0′	225	100	27/5/77	1/9/76
LO-1	71°31.1′	152°11.3′	192	78	29/3/77	6/4/77
				152	29/3/77	20/10/77
LO-4	71°31.8′	152°15.3′	192	177	13/11/77	30/10/78
LO-5	71°17.0′	150°44.1′	99	64	13/3/78	7/9/78
LO-6	71°17.7′	150°37.9′	203	68	11/3/78	4/9/78
				188	11/3/78	14/9/78
FLAX-1	70°43.6′	146°00′	59	39	22/2/79	22/7/79
				49	22/2/79	22/7/79
OL-1	71°10.0′	148°52.7′	60	40	21/2/79	6/3/80
				50	21/2/79	6/3/80

The low-frequency variability at the two sites was quite similar. Moreover, comparison with the simultaneous wind record from nearby Narwhal Island suggests that much of the variability was wind-driven. The progressive vector diagrams (Fig. 4.7) show that the initial motion was northeastward at both sites; this was near the end of a period of southwest winds of 5-7 m/s. The current then set southwest from 1 to 6 April, during which time the wind blew from the northeast at 5-6 m/s before weakening in the last 2 days. The wanderings of the current vectors during the following week (with a net north or northeast displacement) were under variable winds. From 13 to 15 April the wind was west-southwesterly at 5-8 m/s and the current followed within one-half day, setting eastward. Finally, from late on 15 April the winds blew from the northeast, with episodes to 8 m/s, during which time the current vectors were directed westward. Generally these displacements were much smaller (perhaps one-half as great) at NAR-1 than at NAR-2, consistent with greater frictional damping at the latter site, which was in shallower water farther inshore under the fast ice. The NAR-1 record does not significantly lag NAR-2 in phase, as would be expected if the current inshore of the fast-ice edge were generated by lateral entrainment. It is therefore probable that the wind-induced currents were responses to coastal wind set-up (or, conceivably, directly to atmospheric pressure gradients). The pertinent offshore length scale over which the effects of set-up should be observable (the barotropic deformation radius) is 125 km for a water depth of 20 m. (This can be contrasted with the baroclinic radius of 2.5 km, calculated from a STD section done the previous month.)

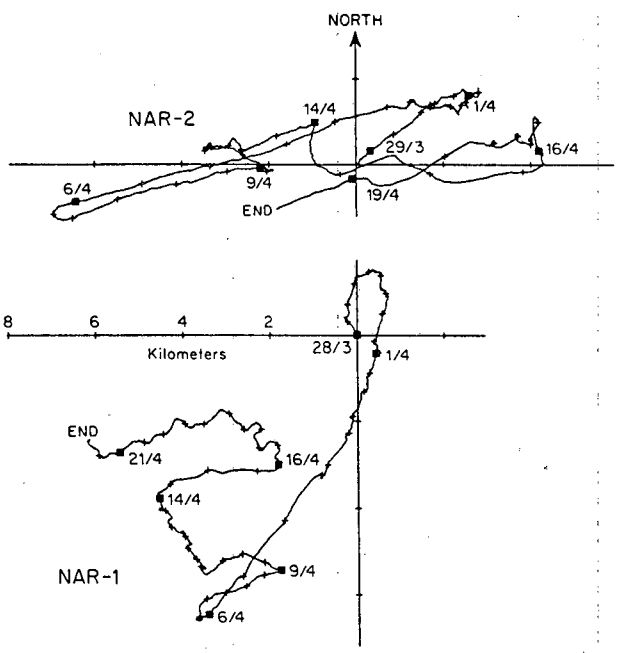

Figure 4.7—Progressive vector diagrams for the current at 10 m depth during March-April 1976 at moorings NAR-1 (27 m water depth) and NAR-2 (38 m water depth). The moorings were separated by 13.9 km. The time ticks are 12 h apart.

The clear suggestion of these winter flow measurements on the inner shelf is that even though the

Table 4.2—Outer shelf mean and maximum currents.

Mooring	Instrument Depth (m)	Record Length (days)	Mean Velocity Speed (cm/s)	Mean Velocity Direction (°T)	Maximum Speed (cm/s)
OL	100	95	12.8	99°	56
LO-1	78	9	Record too short		
	152	205	2.3	154°	61
LO-4	177	352	4.8	142°	66
LO-5	64	208	3.8	100°	66
LO-6	68	172	6.4	112°	60
	188	188	6.9	102°	57
FLAX-1	39	149	1.0	67°	34
	49	149	1.3	73°	33
OL-1	40	380	7.0	89°	73
	50	380	9.2	82°	70

kinetic energy levels are suppressed in winter (at least under the fast ice), a wind-driven circulation component exists throughout the year. How far inshore under the fast ice the wind effects persist is not known, but there is evidence for at least a 15-km extension shoreward of the fast or grounded ice edge. Indeed, if the response to the winds is through coastal set-up, wind effects would be expected to extend essentially to the coast (or to the barrier islands).

There is undoubtedly also a thermohaline circulation on the inner shelf, although the present data cannot address this issue. Most notably, we should expect a nearshore buoyancy-driven flow during the summer runoff and a density-driven circulation associated with brine drainage during the winter. The latter has been discussed by Matthews (1981b), but the evidence for it is inconclusive (contrast Barnes and Reimnitz 1982).

Finally there is the question of possible effects of the fast-ice edge itself. The role of an ice edge in promoting characteristic horizontal and vertical circulations is a topic of increasing interest (see Røed and O'Brien 1981 and Niebauer 1982 for physically different recent examples). However, it is doubtful that the fast ice edge is of much consequence in this regard in the Beaufort Sea. Normally there is essentially no open water seaward of the edge, nor is there strong and prolonged shear at the edge. Instead, the close ice pack seaward of the fast ice moves rather slowly, so that at the edge the ocean probably does not have strong lateral discontinuities at its upper surface.

4.4 THE BEAUFORT CURRENT

Seaward of about the 50-m isobath, the flow is substantially different, being characterized by relatively strong flow throughout the year which is locally aligned with the isobaths (Fig. 4.6). The consistent orientation of the velocity vectors parallel with the isobaths resembles the situation on narrow shelves elsewhere (Hickey 1979). Although the bathymetry portrayed in Figure 4.6 suggests the local isobath trend at LO-4 to be about 120°, more detailed bathymetric constructions for the area indicate a southwestward indentation in the topography in this area. The local isobath orientation may therefore well be more southeast-northwest, as the current measurements at both LO-1 and LO-4 suggest. Because of the regional variation in isobath trend, the actual orientation of the prevailing current varies by about 45° over the entire mooring area, but for simplicity we consider the octant east to southeast as easterly and west to northwest as westerly. The statistically prevailing current direction at each site is easterly, and this sector contains the strongest currents (except at FLAX-1) (Fig. 4.6). Thus the net motion everywhere is toward the east (see also Table 4.2).

4.4.1 Extent and Dynamics of the Mean Flow

The records from FLAX-1, moored in 60 m of water, show a flow regime that is less constrained directionally and has a slower mean eastward motion than at the other offshore moorings. This suggests that although the Beaufort Current was

still observed at that location, the instruments were near the inshore edge of the current. Consequently, as a rule of thumb we can estimate the Beaufort Current lies seaward of about the 50-m isobath.

The northern edge of the current is far less clearly defined, but the eastward flow probably extends seaward a considerable distance. The deepest moorings, OL and LO-6, were at depths of 225 and 203 m, respectively. Mooring OL recorded the fastest mean flow of any site and LO-6 the third fastest. Furthermore, the current at the upper instrument at LO-6 was about 40% stronger than at LO-5, which was moored inshore at the same time in water only 99 m deep. These measurements show no diminution of the current seaward, but rather a strengthening.

The hydrography also points to a considerable seaward extent of the Beaufort Current. For example, Figures 4.1 and 4.2 suggest eastward flow seaward of the 1,000-m isobath. Likewise, although there is only a hint of it in Figure 4.5, the vast majority of the STD sections across the shelf and over the slope clearly show a sinking of the isopycnals seaward. A good example is given in Figure 4.8. This density distribution corresponds to a geostrophic shear in which the eastward current increases with depth. The effect extends at least to the end of the sections, which were generally in water deeper than 600 m. Such a shear is in agreement with that observed at all three moorings where currents were recorded at two different depths; at LO-6, FLAX-1, and OL-1 the mean current in each case increased downward (Table 4.2). Therefore, not only does the Beaufort Current extend seaward a considerable distance and increase downward, but at least over the slope it also transports water masses in addition to those from the Bering and Chukchi seas. A deep flow of Atlantic water eastward along the slope was in fact suggested some years ago by Newton and Coachman (1974), based on core layer analysis and on finding a trough in the deep dynamic topography over about the 2,500-m isobath.

These various lines of evidence imply that the Beaufort Current typically extends from near the surface to the bottom between about the 50- and 2,500-m isobaths, a horizontal distance of 60-70 km. If this view proves to be correct, then the eastward flow over the shelf is the inshore manifestation of a major boundary current which is part of the large-scale circulation of the Canada Basin. The driving force for such a large-scale boundary current is unknown, but Sverdrup-type calculations using the curl of the wind stress show only westward flow in the southern Beaufort Sea (Newton 1973).

If the flow over the shelf is part of the large-scale circulation, then it is not surprising that attempts to understand the dynamics of the shelf flow in more local terms have been only partly successful. For example, the mean winds over the southern Beaufort Sea are easterly, so local wind-driving is not a viable mechanism for the mean eastward flow. Mountain (1974) argued that a mean eastward motion might be driven by the momentum flux of the upstream flow; *i.e.*, the flow through the Bering Strait, which continues northward along the Chukchi coast of Alaska. A similar opinion was advanced by Hufford (1975). In this view the outer shelf flow in the Beaufort Sea would be strongly inertial, and the local momentum balance might be maintained by the advective influx of momentum, the retarding effect of bottom friction, and the augmenting or retarding effect of winds, depending on whether they were westerly or easterly. Mountain (1974) showed through a scale analysis that in the absence of favorable (westerly) winds, such an inertial current likely would be restricted by the bottom friction to lie west of about 143-145° W, which represents a propagation of 500 km or less. Since the prevailing winds in fact are easterly and the wind effects are very important to the momentum balance, we should expect an inertially driven flow to diminish significantly toward the east and disappear in the Canadian Beaufort Sea, even if Mountain's scaling greatly overestimated the effects of bottom friction.

Neither expectation is borne out by observations. For example, comparison of the mean eastward current strength at mooring sites with records longer than 3 months shows that with the exception of the FLAX-1 measurements at 146° W, which appear to have been very near the inshore edge of the Beaufort Current and are therefore anomalous in this connection, there is no diminution of current speed toward the east. On the contrary, the flow appears to increase toward the east, although since the mean speed variation at any given meridian is nearly as large as the trend, such a conclusion is highly tenuous.

There is also very clear evidence for an extension of the mean eastward flow along the Canadian Beaufort Sea shelf. In particular, moored current measurements made on the outer shelf between 129° and 137° W by Huggett *et al.* (1975) showed mean flow toward the northeast of up to 8 cm/s

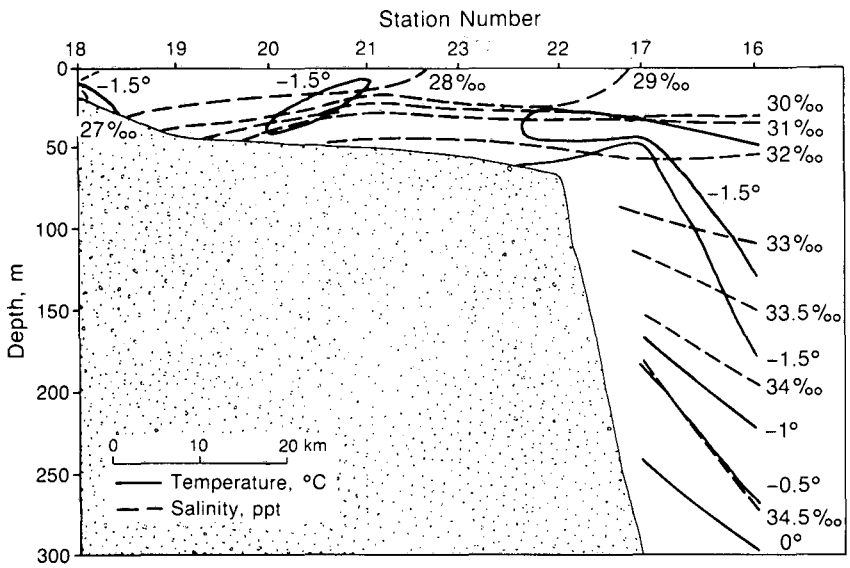

Figure 4.8—Fall temperature and salinity section across the shelf and upper slope near 142° W.

over 3½ months during 1975.

The conclusion must therefore be that the Beaufort Current extends along the entire Beaufort Sea shelf and slope, and that an inertial explanation of the mean eastward flow is contrary to observation. On the other hand, there is evidence (discussed below) of inertial effects contributing to the low-frequency variability of the flow over the western part of the Beaufort shelf.

The discussion so far has been restricted to the subsurface flow. We do not have current measurements on the outer shelf above about 40 m depth, so cannot be sure of the motion near the surface. It is possible that the mean surface motion is westward rather than eastward. Not only are the prevailing easterly winds appropriate to such driving, but the baroclinic structure on the outer shelf is also appropriate. For example, in about 80% of the 17 CTD sections we took across the shelf during 1975-77, the dynamic topography over the outer shelf was such as to sustain a geostrophic shear in which the motion at the surface was westward relative to that at 40 m. The mean geostrophic velocity difference between these levels (excluding the 20% of cases with reversed shear) was about 7 cm/s. Examination of Table 4.2 shows that this roughly corresponds to the mean easterly flows calculated from the current records, suggesting little or no mean geostrophic motion at the surface. At the shallowest of the paired measurements made in the strong eastward flow, at OL-1, the observed long-term mean shear (2 cm/s over 10 m) is just about what we calculated as the mean baroclinic effect (7 cm/s over 40 m). The geostrophically balanced baroclinicity in the upper layer may therefore by itself be sufficient to offset the deeper mean eastward flow. Furthermore, this baroclinic structure results from an upper-layer salinity that, except during summer, decreases seaward. Such a salinity distribution might result from salinization of the shelf water during freezing or from upwelling of saline water onto the shelf. The interesting possibility thus arises that if there is a mean westward motion in the upper layer, it may be due as much to the presence of dense water on the shelf as to direct wind effects. Appropriate models would in that case have to be both thermohaline and wind-driven.

4.4.2 Low-Frequency Variability

While both the mean and the strongest motions are eastward on the outer shelf, at least below the surface layer, Figure 4.6 shows the secondary mode to be westerly and to contain the next-fastest flow. Figure 4.9, showing the daily mean current over a year at LO-4, illustrates the characteristics of the motion and can be taken as representative of the low-frequency longshore flow on the outer shelf. The flow alternates sharply between about 140° (the primary mode) and 320° (the secondary mode). The nominally easterly flow (actually southeast) is both the fastest and the most persistent of the two principal flow directions, so that we see a mean easterly motion upon which is superimposed a strong reciprocating low-frequency signal with a typical period of 3-10 days.

Figure 4.10 shows the spectral characteristics for the first 6 months of the LO-4 record. The refer-

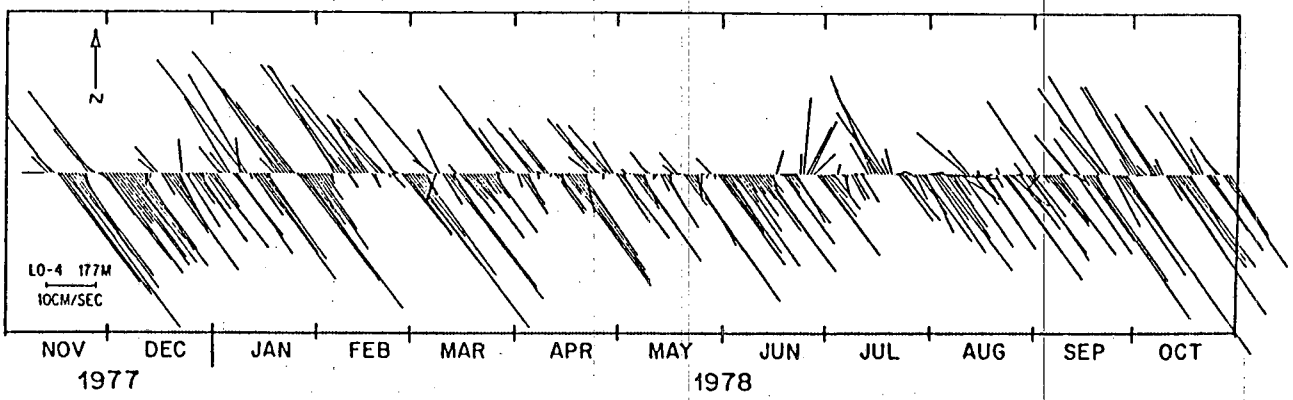

Figure 4.9—Daily mean current at 177 m at mooring LO-4. Water depth is 192 m. The speed scale is indicated by the bar.

ence coordinates for the current have been rotated 50° clockwise, so that the U-component is oriented toward 140°, parallel with the principal current axis (and presumably also parallel with the isobaths). The energy is seen to be almost entirely contained in the longshore mode (U-component), principally at the lowest frequencies. In contrast, the already low energy level in the cross-shelf (V) component drops off even further at frequencies less than about 0.5 cycle per day (cpd). Moreover, obvious tidal peaks are absent. The relatively low tidal energy level is typical for the Beaufort shelf. For example,

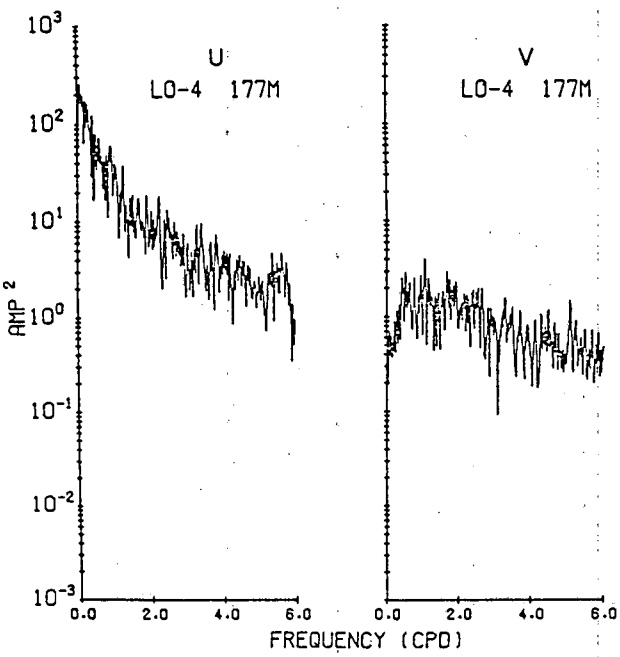

Figure 4.10—Energy-conserving spectra for first 6 months of LO-4 current record. U-component is longshore (140°) and V-component offshore (50°).

semidiurnal amplitudes range from less than 1 cm/s to perhaps 3 cm/s, depending upon location.

A more detailed examination of the frequency band between about 0.1 and 0.4 cpd reveals considerable spectral structure, and comparison with the second 6 months of the LO-4 record shows notable differences between the two portions of the record. The low-frequency statistics are thus nonstationary. In effect, this current regime appears to have a rather broad low-frequency forcing and admittance, such as, for example, would be expected for a wind-driven regime.

While a locally wind-driven regime would force current events that are essentially synoptic over a large portion of the Beaufort shelf, there is also evidence that current fluctuations can propagate over such distances at rates comparable to the mean flow speed. These events point toward the importance of inertial effects in contributing to the low-frequency variability over the western part of the Beaufort shelf. From 25 August 1976 to 10 August 1977, a current meter was moored west of Cape Lisburne in the Chukchi Sea at 68°55′ N, 167°21′ W. Designated NC-7 (Coachman and Aagaard 1981), it was located in the core of the northerly flow along the Chukchi coast. It overlaps in time the LO-1 record during the period 29 March-10 August 1977. Comparison of these two records initially suggested no relationship. However, if the time scale is shifted about 106 days, so that 14 December 1976 in the NC-7 record coincides with 29 March 1977 in the record from LO-1 (Fig. 4.11), then there is a remarkable similarity. Specifically, at the beginning of the LO-1 record, there were two long periods of nearly uninterrupted westward flow, 24 and 28 days in duration, separated by 6 days of eastward flow. Each major period

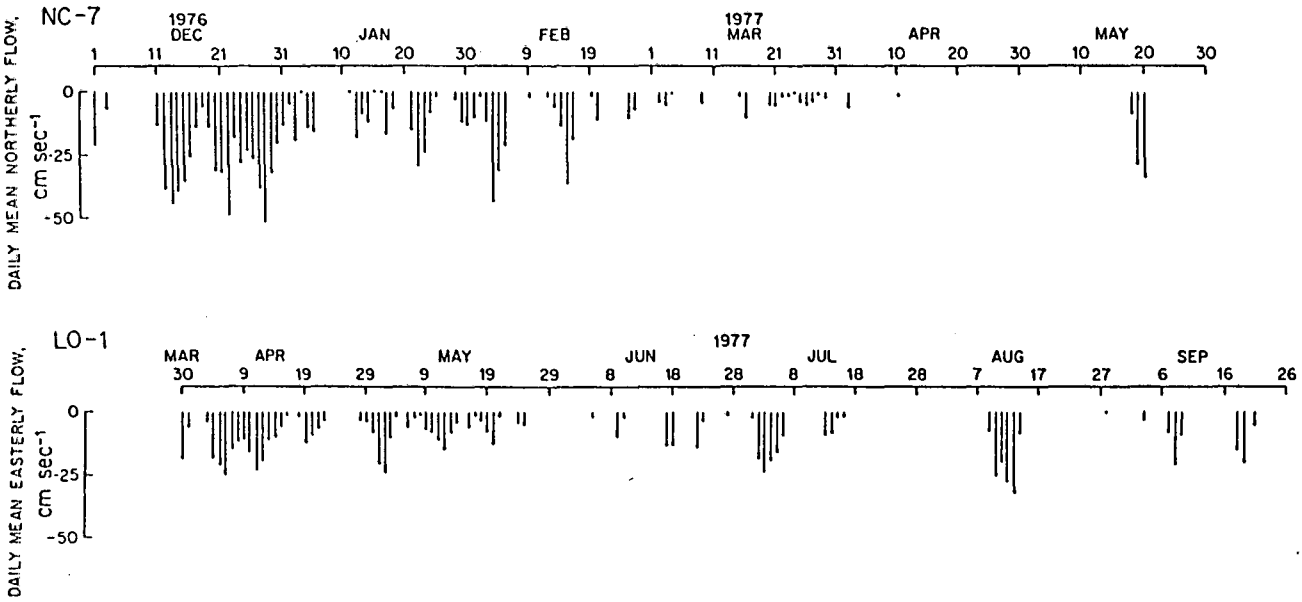

Figure 4.11—Southerly flow events at NC-7 near Cape Lisburne in the Chukchi Sea during December 1976-May 1977, and westerly flow events at LO-1 during March-September 1977. Where no daily mean flow is shown, the current was in the normal northerly (NC-7) or easterly (LO-1) direction.

of reversed (westward) flow had four or five subordinate oscillations within it. These major reversals are unique in our Beaufort Sea records. Similarly, beginning 11 December 1976 there were two 26-day periods of southward flow at NC-7, again interrupted by 6 days of normal flow. Each major reversal (southward) had four or five embedded subordinate oscillations. There were no other reversals of comparable duration at any time during the year-long record, nor anywhere else at a large number of mooring sites farther west in the Chukchi Sea, Bering Strait, and northern Bering Sea, other than at the mooring immediately west of NC-7 (NC-6), which was also in the core of the mean northward flow along the Chukchi coast.

The NC-7 and LO-1 record portions which contain the reversals in longshore flow are well correlated (0.58 with a lag of 106 days, which is significant at the 95% level), while the remaining portions are uncorrelated. Furthermore, there is nothing in the Barrow wind records to suggest local wind forcing as the cause of the prolonged LO-1 current reversals. Winds during 30 March-25 May 1977 were from the easterly sector about 75% of the time but were very light, reaching 5 m/s on only one day, and were usually in the range 1-3 m/s. The similarity between the two current records with respect to these unusual events therefore suggests that the absence of eastward momentum advection by the mean flow was dynamically important in at least these distances. That is, the long periods of reversed flow at LO-1, located on the western Beaufort shelf near 152° W, may in large degree reflect the absence of momentum input during a period that was determined by upstream events in the Chukchi Sea. Moorings NC-7 and LO-1 were separated by about 650 km, suggesting a signal propagation rate of 7 cm/s, roughly comparable to the long-term mean flow in the area. However, a propagation distance of 650 km exceeds that predicted by Mountain's (1974) scale analysis by as much as a factor of 2, even in the absence of opposing easterly winds. Alternatively we might therefore more appropriately consider major upstream flow events to be forced synoptically along the entire Chukchi coast, as Mountain *et al.* (1976) did. In order to explain the prolonged reversals, this only requires the flow to persist inertially from Point Barrow eastward to the LO-1 site, a distance less than 200 km, which is easily supportable by scaling arguments. It is not known how much farther eastward on the shelf momentum advection from the Chukchi Sea might contribute to the flow, since LO-1 was the only mooring deployed at the time.

In general, the Beaufort Sea current records prove to be correlated both vertically and over intermediate horizontal distances. For example,

Figure 4.12 shows the coherence and phase for the U-component at the two LO-6 instruments. The low-frequency band is seen to be both coherent and nearly in phase vertically over a depth of 120 m. Furthermore, examination of both the daily means and the energy spectra for the two instruments shows that while there are minor differences, the low-frequency energy levels are not substantially different overall (Table 4.2). Thus the suggestion is that the entire water column between these levels responds nearly as a single unit. Since the largest density stratification occurs above the level of the upper instrument, this is dynamically reasonable.

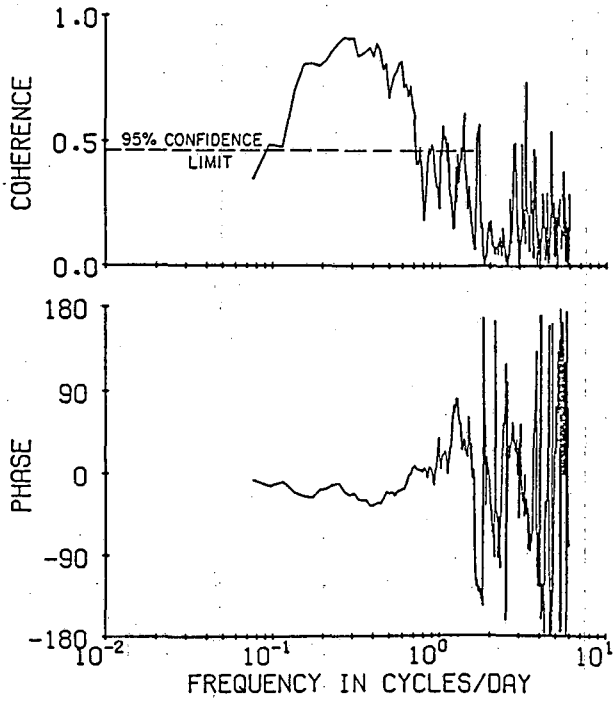

Figure 4.12—Coherence and phase relations for the upper (68 m) and lower (188 m) LO-6 current records, U-component (longshore).

The mooring records are fairly well correlated at intermediate separations on the shelf. For example, Figure 4.13 shows the daily mean longshore component at the LO-4 and deep LO-6 instruments, separated by 63 km. It is clear that many of the low-frequency events are both coherent and nearly in phase. The 35-h filtered data from the two instruments yield a correlation of 0.64 with a lag of only 6 h. For the given station separation this implies a phase propagation of nearly 300 cm/s. Although we cannot definitively preclude these events as representing the propagation of wave-like disturbances (an internal Kelvin wave has a phase velocity of about 65 cm/s under typical winter shelf conditions), comparison of the current records with the wind field suggests that wind forcing is a principal cause of the low-frequency variability.

4.4.3 Wind Forcing

Wind records suitable for comparison with the current measurements are available in the form of geostrophic winds, calculated by T. Kozo, at 72° N, 150° W during 18 February-31 July 1979, a nominal point about 100 km from OL-1 and 200 km from FLAX-1. Surface winds and pressures are also available from Barter Island, over 100 km to the east of FLAX-1, for 23 February-4 May and 30 May-22 July 1979. I refer to these latter two periods as parts 1 and 2 of the surface wind records.

Statistically, the wind and current records are correlated at low frequencies. For example, Figure

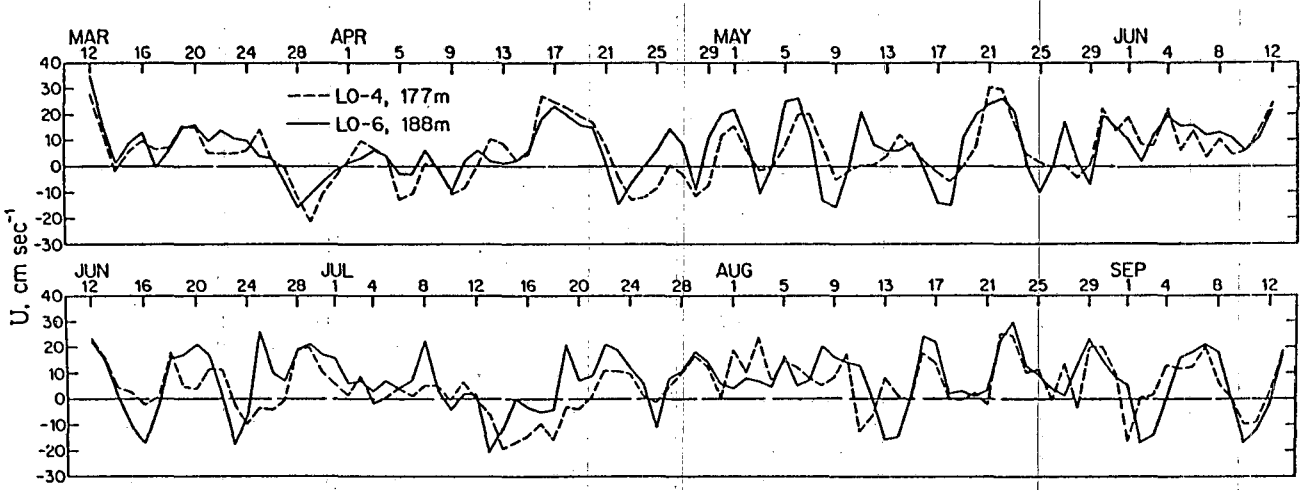

Figure 4.13—Daily mean U-component of velocity (longshore) at the LO-4 and lower LO-6 instruments. The moorings were 63.4 km apart.

4.14 shows the coherence and phase spectra between the U-components of current at the upper FLAX-1 instrument and of the surface wind at Barter Island during part 1. Likewise, Figure 4.15 shows the coherence between the U-component at the upper OL-1 instrument and the geostrophic wind. The records from the lower instruments at each mooring are very similar to those from the upper instruments. While the correlation with the geostrophic wind is somewhat poorer than the correlation with the surface wind, the overall suggestion of the two figures is of a current reasonably coherent with the wind at time scales longer than about 2-3 days. Figure 4.14 shows no statistically significant phase difference, while Figure 4.15 suggests a changing phase relation, with the current lagging the wind at the lowest frequencies but leading at frequencies of 0.2-0.4 cpd. Except close to the coherence and

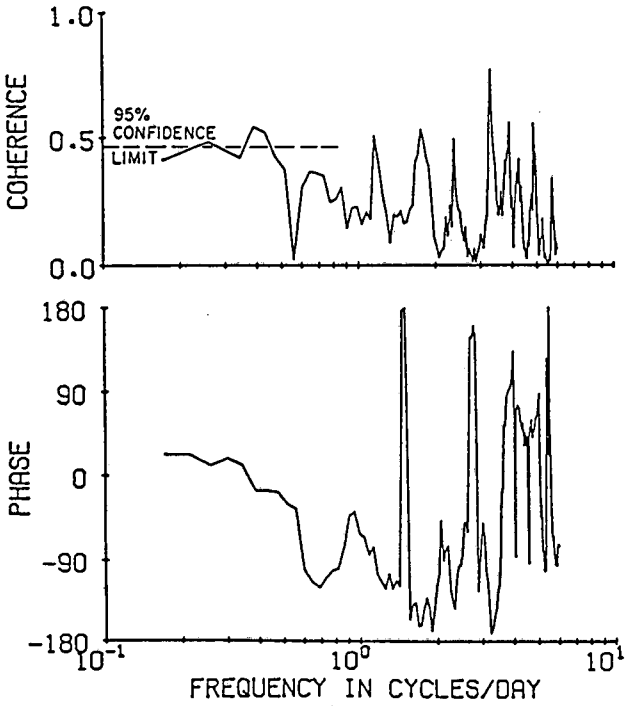

Figure 4.14—Coherence and phase relations for the upper FLAX-1 (39 m) current record and the Barter Island surface winds, 23 February-4 May 1979, U-component (longshore).

phase peaks near 0.3 cpd, however, the positive phase difference is not statistically significant. (The 95% confidence limit is about ±39°.) There was no significant positive phase difference between the current and the surface wind during part 2 of the Barter Island wind record.

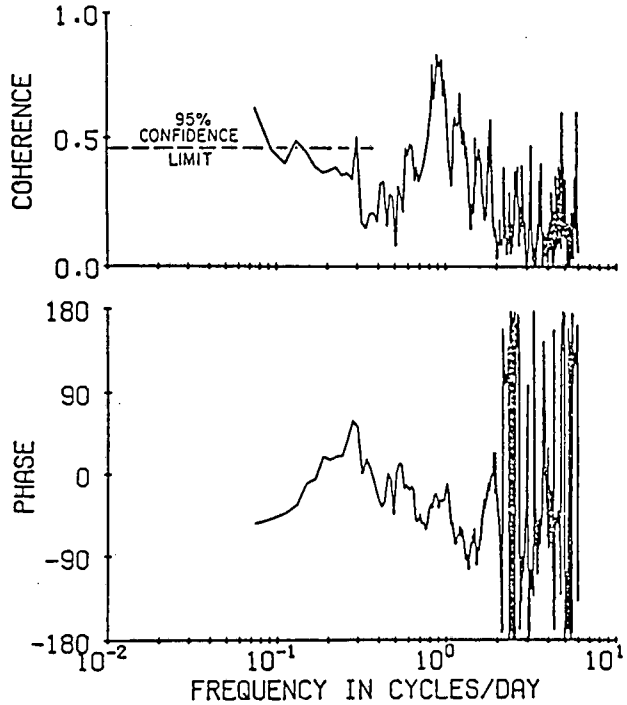

Figure 4.15—Coherence and phase relations for the upper OL-1 (40 m) current record and the geostrophic wind at 72° N, 150° W, 18 February-31 July 1979, U-component (longshore).

Except for a significant but slightly smaller correlation between the east component of current and the north component of wind (zero phase difference), no other wind and current combinations prove coherent. The implication of these calculations is therefore that a significant portion of the low-frequency variability in the longshore current is wind-driven, primarily by the longshore wind component, with which it is nearly in phase. The governing mechanism is probably a coastal (or fast-ice edge) Ekman layer divergence, giving rise to a geostrophic longshore flow; *i.e.*, the low-frequency wind driving is local and acts through coastal set-up. Seaward of the baroclinic deformation radius (2-3 km) the response would be barotropic, thus uniform with depth (Fig. 4.12). Wind-driven events would essentially be in phase with the wind (the response time scale is the inverse of the Coriolis parameter, which is less than 2 hours) and coherent in the longshore direction over the coherence scale of the wind itself (Fig. 4.13). These expectations are in agreement both with our observations and with the general results of wind-driven coastal circulation models (Allen 1973; Hamilton and Rattray 1978).

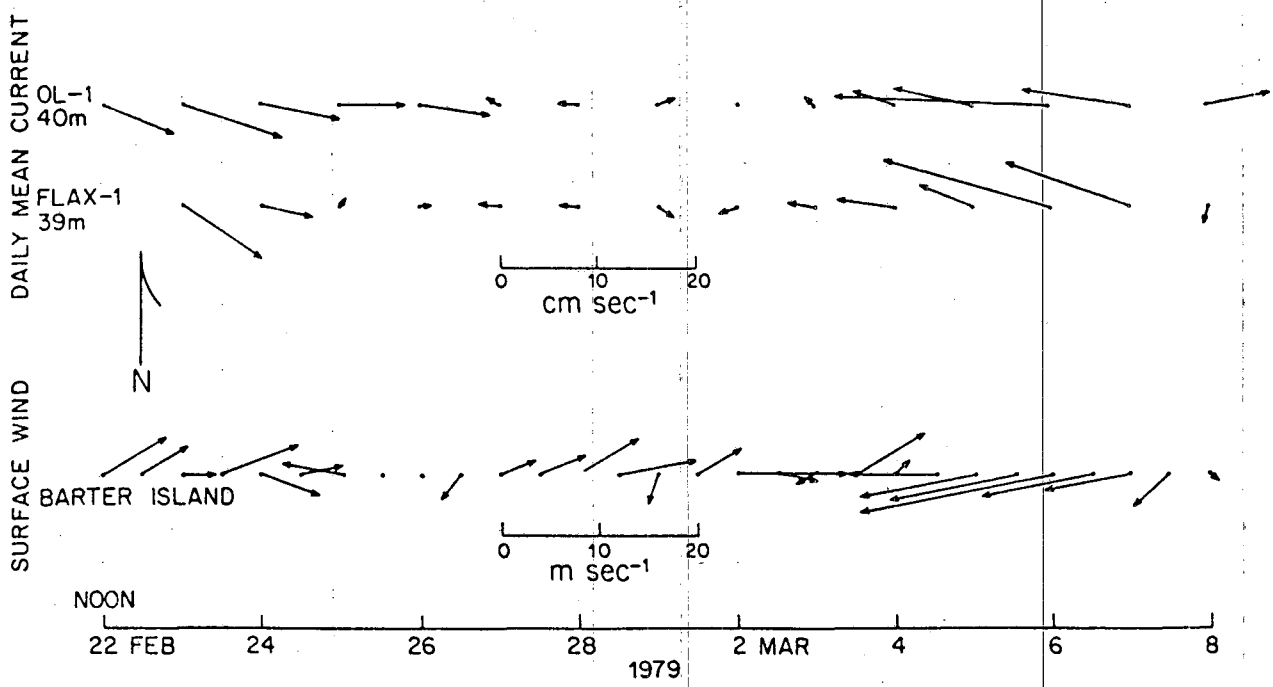

Figure 4.16—Daily mean current at the upper OL-1 and FLAX-1 instruments, together with surface wind at Barter Island, 22 February-8 March 1979.

Examination of individual events in the current records also suggests wind forcing as contributing to the low-frequency variability. For example, comparison of the Barter Island winds with the OL-1 and FLAX-1 current records shows that under strong easterly winds the current normally reverses. This appears to hold in about 75-80% of the instances when the easterly winds exceed 8-10 m/s. On the other hand, current reversals also occur that are not obviously related to the wind. Figure 4.16 shows an example of both kinds of events, depicting surface winds and OL-1 and FLAX-1 currents during 22 February-8 March 1979. Initially, winds and currents were in the same direction (eastward), but during the period centered around 28 February, the currents were weak and variable (and included some westward motion), while the winds continued moderately strong toward the east. About 4 March the currents entered an increasingly pronounced reversed mode which peaked on 6 March. The winds at Barter Island, meanwhile, had begun blowing toward the west at midnight on 4 March; they reached their maximum strength on 6 March, coincident with the current peak.

The conclusion from these considerations is that the longshore wind plays an important, but not always prevailing, role in the low-frequency variability of the subsurface longshore flow. The wind appears to be particularly important in flow reversals. Specifically, when the winds are easterly at 8-10 m/s or more, the currents over this part of the shelf will normally reverse and set westward. Ascertaining the dynamics of the wind-driven flow with some certainty and detail will require special experiments, the most difficult part of which may be to obtain good measurements of the offshore wind field. Probably much of the noise in the present wind and current coherence calculations is due to an inadequate definition of the wind stress.

4.4.4 Long-term Variability

Two moorings, LO-4 and OL-1, were deployed for a year and the records are therefore long enough to provide an indication of variability on at least the seasonal time scale. Examination of the 3-week mean longshore currents at these moorings shows no seasonal signal, however, and both the strongest eastward (OL-1) and westward (LO-4) 3-week mean currents occurred in late January and early February. A distribution-free runs-test indicates that the 3-week means constitute random sequences. There is, however, some tendency toward the lower significance limit on the number of runs; *i.e.*, there is some indication of a persistence of currents weaker or stronger than the mean, on time scales several multiples of the 3-week time base.

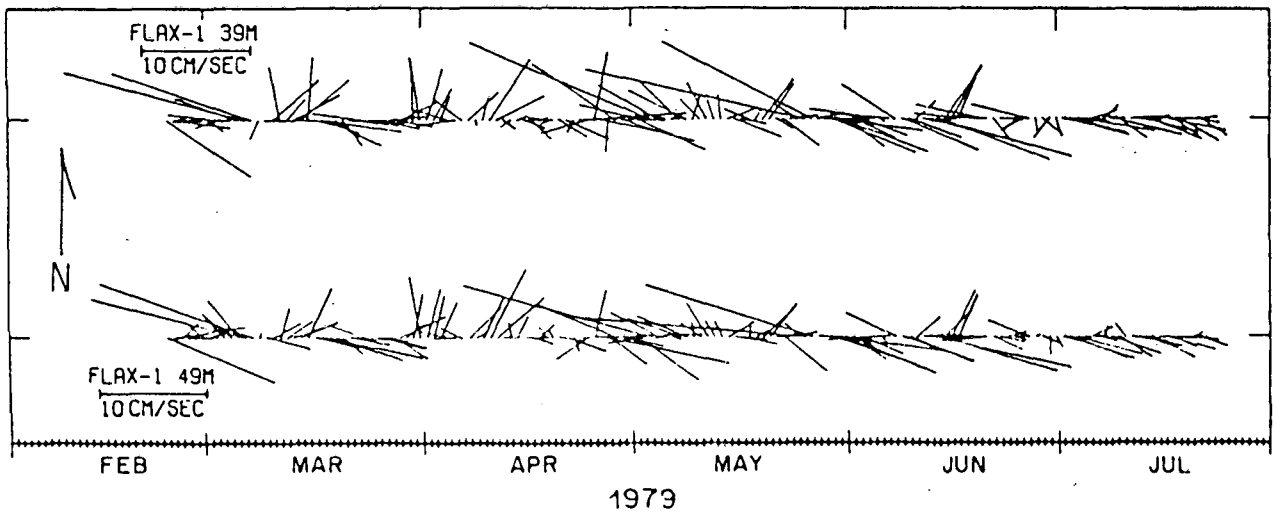

Figure 4.17—Daily mean current at mooring FLAX-1. Water depth is 59 m. The speed scale is indicated by the bar.

The annual mean flow at the lower OL-1 instrument in 1979-80 was nearly twice that at LO-4 in 1977-78. Although this suggests that there may be large interannual variations in current strength, the difference in means could conceivably be due largely to differences in location of the moorings. However, OL-1 was a shallow mooring, probably located close to the inner edge of the Beaufort Current, where the NAR-1, NAR-2, and FLAX-1 records all suggest reduced flow, whereas LO-4 was close to the shelf break. Interannual variability is therefore a very plausible explanation for the difference between the OL-1 and LO-4 records.

Overall, the impression is of a long-term mean easterly flow which, although variable on extremely long time scales, does not exhibit regular seasonal variations. Rather, there are random fluctuations on a time scale of 1-2 months or more, probably including significant interannual variations.

4.5 CONCLUSIONS

Substantially different circulation regimes prevail on the inner and outer shelf. The demarcation zone between the regimes lies near the 50-m isobath. The inner shelf is strongly wind-driven in summer, but it undergoes large seasonal changes and is far less energetic in winter, although wind effects probably persist even under the fast ice close to shore.

In contrast, the outer shelf circulation is energetic at subtidal frequencies throughout the year. Its dominant feature is the Beaufort Current, a bathymetrically steered mean eastward flow extending seaward from the 40-50-m isobaths at least to the base of the continental slope. The flow apparently increases with depth. This relatively strong (about 10 cm/s), deep-reaching boundary current is probably part of the large-scale circulation of the Canada Basin, and is thus not locally driven. However, the portion of the Beaufort Current overlying the shelf can be modified by local forcing, most importantly by the wind. In the western part of the shelf, momentum flux from the Chukchi Sea through Barrow Canyon also appears to be dynamically important.

Much of the significance of the energetic outer shelf circulation, and of the Beaufort Current in particular, is that it provides an efficient dispersal and transport mechanism. This means not only that events on the Alaskan shelf can propagate long distances into the Canadian Beaufort Sea, but also that events in other places affect the north Alaskan shelf. For example, water from the Bering Sea has a major impact on the Beaufort shelf hydrography and undoubtedly also on the biota.

Furthermore, near the inshore edge of the Beaufort Current there are in fact frequent cross-shelf motions which are capable of transporting materials between the inner and outer shelf regimes. For example, Figure 4.17 shows the daily mean current at FLAX-1. Flow events directed seaward were more common than landward ones (compare also the current roses in Fig. 4.6); cross-shelf flow was relatively strong (daily means frequently exceeded 5 cm/s); and such events typically had a duration of 3 days or more. (A particle being moved off-

shore at 5 cm/s for 3 days will undergo a total excursion of 13 km.) Offshore flow occurred most frequently during the first 3 months, although there is no obvious reason why this should be so. There appears to be no significant correlation between the cross-shelf flow and either wind component, though this may conceivably be due to an inadequate representation of the local wind field. The important point for present purposes is that cross-shelf flow is frequent and links the Beaufort Current with the nearshore environment.

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Chapter 5
Arctic Nearshore and Lagoon Circulation

by Lon E. Hachmeister

The physical setting of the Beaufort Sea is such that the Beaufort shelf is virtually completely covered by ice for all but two to three months of the year. The ice cover insulates the underlying waters from both the atmospheric temperature and wind fields and provides a source of dense brine in the winter and fresh meltwater in the spring and summer. Spring melting of the sea ice coincides with a massive influx of freshwater runoff from the land, both of which stabilize the upper surface water, retain solar heat, and further enhance melting of the sea ice. Depending on the wind field for a particular year, the open-water lead along the coastline may be as wide as 100-200 km and extend the entire length of the Beaufort Sea. The wind field in the western Beaufort is typically dominated the year around by easterly or northeasterly winds, whereas the eastern Beaufort exhibits dominant easterly and northerly winds in the summer and westerly or southwesterly winds in the winter. This wind pattern in the eastern Beaufort moves surface waters and ice offshore in the summer and onshore in the winter.

The shelf in the central and western Beaufort Sea is relatively narrow, with the shelf break typically occurring 80-90 km offshore. Lagoon systems characterizing this region of the Beaufort coastline have been termed "open" lagoons—open to the wind-driven longshore transport and to onshore-offshore transport due to numerous large openings in their offshore barrier island systems.

In the eastern Beaufort Sea the shelf is slightly narrower (approximately 40-60 km). The barrier island systems tend to be closer to the coastline, more extensive, and closed to direct flowthrough by the longshore current, thus limiting the exchange of water between the longshore currents and the lagoons to a small number of openings in the barrier island system (limited exchange lagoons). In many limited exchange lagoons, the exchange of water is restricted to one or two major entrances. These lagoons, which typically have very narrow entrances, exhibit highly localized current jets at the entrances in response to periodic tidal forcing and have been termed "pulsing" lagoons.

Patterns of water movement on the shelf exhibit strong continuity in the longshelf direction (paralleling isobaths) and large zonal variability in the cross-shelf sense (crossing isobaths). Following Aagaard and Anderson (1981), the region of the shelf landward of the 40-m isobath, which exhibits one set of characteristics, is referred to here as the inner shelf. The area of the inner shelf landward of the 20-m isobath with activity marked by ice and/or surface waves, and which exhibits higher summer temperatures and lower salinities than the water between 20 and 40 m, is referred to as the nearshore, following Truett (1981).

The Beaufort coast in general experiences relatively small changes in sea level due to astronomical tides (approximately 0.1-0.3 m); however, meteorologically induced variations may range from as much as +3.0 to −0.9 m (Schaeffer 1966; Matthews unpubl. data). The largest setup typically occurs in the fall when long stretches of open water are common and the winds are predominantly westerly, driving water onto the shelf.

5.1 INNER SHELF

Although current measurements on the inner shelf are extremely sparse due to the difficulty of maintaining moorings in the presence of sea ice, drifter data reported by Matthews (1981) and current meter measurements made by Aagaard and Anderson (1981) give some indication of both

open-water and ice-covered water movements. It has been generally agreed that water movement on the Beaufort inner shelf is wind-driven. This hypothesis is further supported by Matthews' drifter data which suggest that the motion of all recovered drifters resulted from prevailing wind-driven currents, both for open-water and under-ice releases. Drifter travel times and computed current speeds were consistent with values of approximately 3-4% of the wind transport for the same periods, with under-ice motion being significantly less. Aagaard and Anderson (1981), in direct measurements of winter currents on the inner shelf near Narwhal Island, also reported that the under-ice water movement was quite slow but that the observed (0.1-0.3 cm/s) net movement was directed toward the west consistent with the mean wind direction. Daily current speeds and directions, however, were as high as 5-10 cm/s and closely followed the variability of local wind patterns.

If these conditions can be extrapolated to the eastern Beaufort Sea, then current patterns on the eastern inner shelf would be expected to show a more even distribution of both easterly and westerly currents. Prevailing winds along the central and western Beaufort are from the east-northeast during all seasons. However, in the eastern Beaufort the distribution of winds is more bimodal. At Barter Island, for example, 35% of the time the average winds are from the east-northeast to east and for 25% of the time from the west-southwest to west (Searby and Hunter 1971), with winds predominantly from the west during the winter and from the east during the open-water season (Brower *et al.* 1977). If the inner waters in the eastern Beaufort Sea follow the local wind patterns, one could expect to observe mean current patterns to the east in the winter and to the west in the summer, following local wind patterns.

5.2 NEARSHORE AND LAGOONS

Considerable research has been accomplished in the Beaufort nearshore and lagoon regions. Results of two such programs have been summarized by Matthews (1979) and Hachmeister and Vinelli (1983). Results of these field measurement programs in the central Beaufort Sea between Flaxman Island and Oliktok Point, and the eastern Beaufort between Barter Island and Demarcation Bay, are consistent with present understanding of lagoon and nearshore flow. Winter conditions find dense brine (more than 40‰) collected in Simpson Lagoon (an open type of lagoon) in waters deeper than 2 m with temperatures near −2°C, moving slowly in response to tidal forcing. Complete flushing of the lagoon occurs during river overflow in early June. Following this, saline water appears again in the lagoon and solar radiation heats nearshore and lagoon waters to as high as 10-12°C. Matthews (1979) noted that the month of August is marked by the appearance of cold and saline frontal systems rapidly moving through Simpson Lagoon and alternating with warmer brackish water. Although storms vertically mix the shallow nearshore and lagoon waters, the frontal systems continually reestablish themselves throughout the summer months. Hachmeister and Vinelli (1983), on the other hand, found that currents within Angun Lagoon and Pokok Bay in the eastern Beaufort (pulsing lagoons) are quite sluggish except near the lagoon entrances where high (>77 cm/s [1.5 kt]) currents pulse in and out of the lagoons in response to tidal forcing. Dense brine collection has not been documented in these and other pulsing lagoons, possibly due to deep channels located at the lagoon entrances.

Observed currents in the lagoons and nearshore regions are predominantly wind-driven. Superimposed on the mean wind-driven currents are short-term effects of storm passages, and tidal effects dominated by diurnal M_2 forcing. Current speeds are such that flushing rates in open lagoons similar to Simpson Lagoon may be about 3-4 days with mean easterly winds, but water exchange in pulsing lagoons similar to Angun Lagoon may be considerably less.

5.3 CROSS-SHELF AND LONGSHORE EXCHANGE

On the inner shelf, currents have been demonstrated to be primarily wind-driven. In the western Beaufort Sea beyond Barter Island this would indicate year-round mean currents to the west along the coastline, as shown by drifter studies by Matthews (1981) and Barnes and Toimil (1979). However, in the eastern Beaufort Sea, winds are more bimodal and currents will exhibit a bimodal distribution with a mean eastward flow in the winter and a mean westward flow in the summer (Brower *et al.* 1977); this is typical of 8 out of 10 summers according to Kozo (1983).

During open-water periods wind conditions will tend to induce a cross-shelf movement of Beaufort nearshore and surface waters toward the offshore, to be replaced by subsurface inner shelf waters and, under some conditions, to induce upwelling on the

outer shelf as observed by Hufford (1974) and others. Upwelled waters on both the eastern and western outer shelf may then be further transported landward to the inner shelf and nearshore regions by estuarine flow or, under average wind conditions for the Beaufort Sea, by offshore movement of wind-driven nearshore and surface waters, as described above.

Longshore transport of water has also been demonstrated to be primarily wind driven (Fig. 5.1). This implies mean longshore transport to the west during the open-water season with easterly reversals occurring as mean wind conditions are modified by the passage of localized weather systems.

The inner shelf long- and cross-shelf circulation is therefore characterized as driven primarily by the local wind fields, with longshore current speeds about 3-4% of the wind speed. In the western Beaufort Sea this implies net westward water movement; in the eastern Beaufort it implies a bimodal distribution of currents with eastward

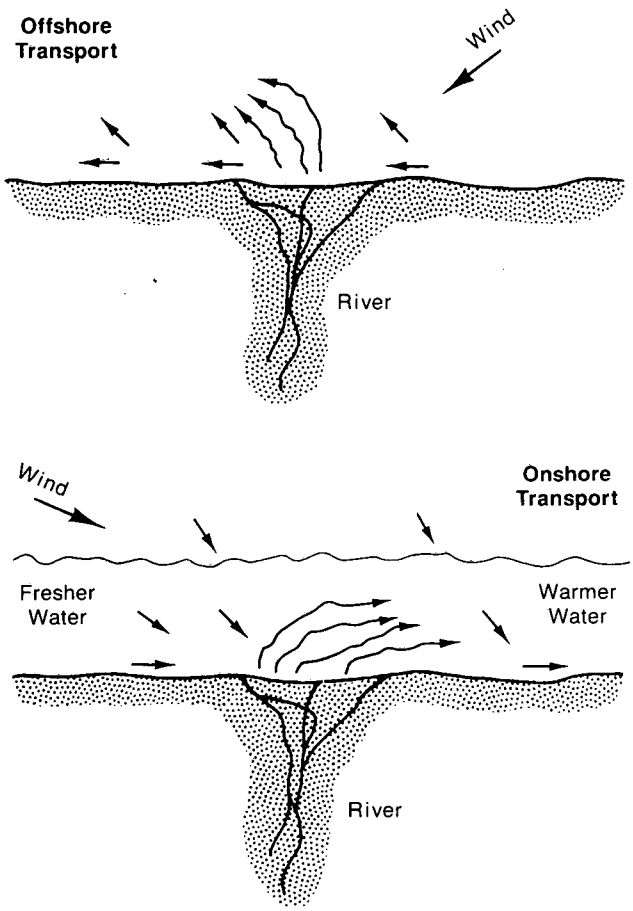

Figure 5.1—Nearshore lagoon circulation, showing general wind effects on onshore and offshore transport. (Adapted from Hachmeister and Vinelli 1983.)

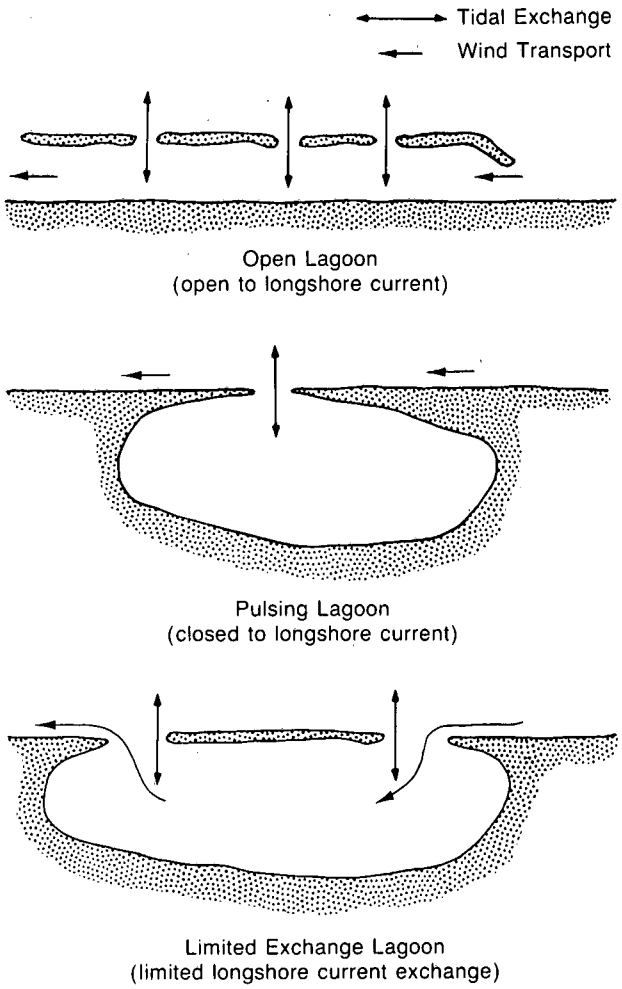

Figure 5.2—Basic lagoon types: open, pulsing, and limited exchange. (Adapted from Hachmeister and Vinelli 1983.)

currents dominating in the fall and winter and westward currents dominating in the summer. Mean year-round wind speeds cluster about 5 m/s in the Barter Island area, although Kozo (1983) indicates some reduction in winds eastward toward Demarcation Bay. These average wind speeds imply mean wind-driven transport at characteristic speeds of 15-20 cm/s in the open-water period. Aagaard and Anderson (1981) and Matthews (1981) indicate that under-ice speeds would be greatly reduced at these wind speeds.

5.4 LAGOON-BARRIER ISLAND CHARACTERIZATION

The three basic lagoon types appearing on the Beaufort Sea coastline are illustrated in Figure 5.2. Open lagoons are open to both longshore currents and cross-shelf exchange through multiple large

openings among the barrier islands. Pulsing lagoons have one major entrance through the coastline and are closed to longshore currents; exchange with the nearshore waters occurs primarily via tidal pumping of water through the major entrance. Limited exchange lagoons have limited longshore current throughput via multiple openings along the coastline. One or more small rivers or streams typically empty into pulsing and limited exchange lagoons, providing a source of fresh water, particularly in early spring.

5.4.1 Open Lagoons

The most extensively studied example of an open lagoon system is Simpson Lagoon. Considerable data have been collected on both the biological and physical environments in multiyear, OCSEAP-sponsored field studies of Simpson Lagoon and the nearshore region. This discussion, however, addresses only results pertaining to a description of the physical environment of the lagoon. Figure 5.3 illustrates the effects of the mean summer wind conditions on Simpson Lagoon circulation patterns. In general, nearshore water enters the lagoon in the eastern and central portion and is advected through the lagoon in a manner similar to the wind-driven longshore transport seaward of the barrier island chain. Multiple large openings in the lagoon system and the open end allow considerable flow-through of the nearshore waters. Exchange is therefore largely due to advection of new water masses through the lagoon rather than input/local mixing/output, as typifies a limited exchange lagoon.

Tidal effects (Fig. 5.4) are superimposed upon the wind-driven component of the circulation and periodically modulate that component's effect. Depending on the strength of the wind-driven currents in a particular break in the barrier islands, the tide may only modulate the mean flow in the entrance or it may actually reverse the flow during the opposing cycle of the tidal current.

Matthews (1979) estimated that the flowthrough in Simpson Lagoon occurs at 3-4% of the mean wind speed, which would indicate lagoon water

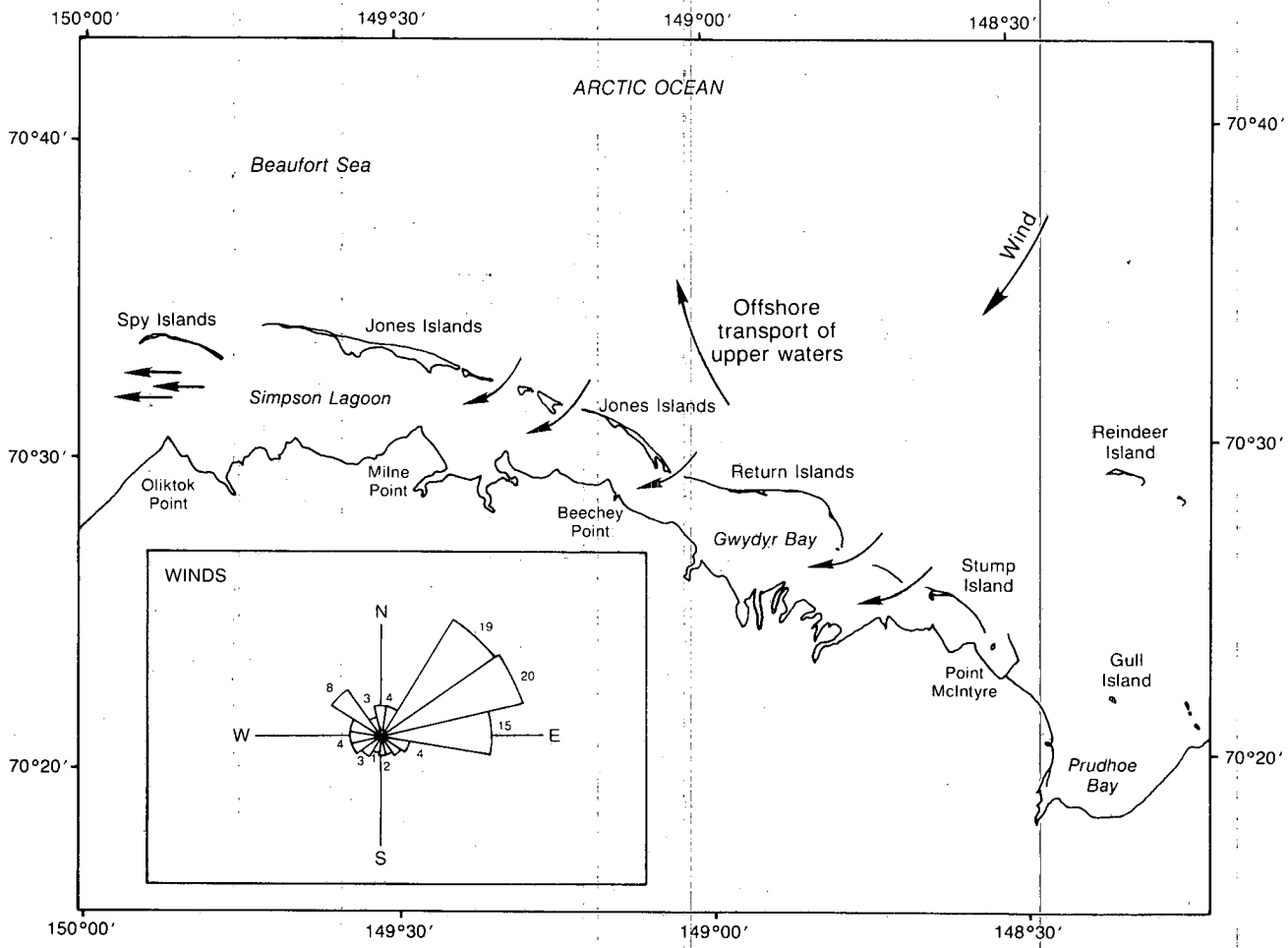

Figure 5.3—Effects of mean summer wind conditions on circulation patterns in an open lagoon. (Adapted from Hachmeister and Vinelli 1983.)

turnover of about 3-4 days when mean wind speed is 18.5 km/h (10 kt). The net wind-driven transport of waters east to west through the lagoon is accompanied by some offshore transport of the warm, fresh, surface nearshore waters and replacement by cooler, saltier, offshore waters. Tidal currents selectively introduce this nearshore water to the lagoon interior at each entrance on successive flood tides. On ebb tides, the net westward flow is reduced and lagoon waters collect near the eastern entrances of the lagoon to form pools of warmer, fresher water. On successive flood and ebb tides, these pools of alternating cooler, saltier, nearshore water and warmer, fresher, lagoon water (formed by mixing of nearshore water from previous cycles and fresh water from river runoff) experience a net westward transport through the lagoon interior. A more detailed analysis of these data was presented by Hachmeister and Vinelli (1983).

When an abrupt change is observed in the mean northeasterly wind pattern during east-to-west lagoon flow, causing a reverse in the direction of the mean flow through the lagoon, a corresponding abrupt change is observed in the characteristics of the lagoon waters. The shift from northeasterly to northwesterly winds retains the warm, fresher, lagoon waters in the nearshore region, where exchange with the lagoons continues, and nearshore and lagoon waters become almost identical. This in turn is accompanied by the disappearance of the alternating nearshore and lagoon water masses through the lagoon (as nearshore and lagoon waters become identical) and observance of uniform, warm, intermediate-salinity water. An accumulation of nearshore water along the coastline would also lead to the observed sea level increase of 50-100 cm. The reestablishment of the mean easterly wind field would reestablish the differential between lagoon and nearshore waters. Matthews (1979) reported more detailed data which substantiate this description of circulation in a lagoon such as Simpson Lagoon.

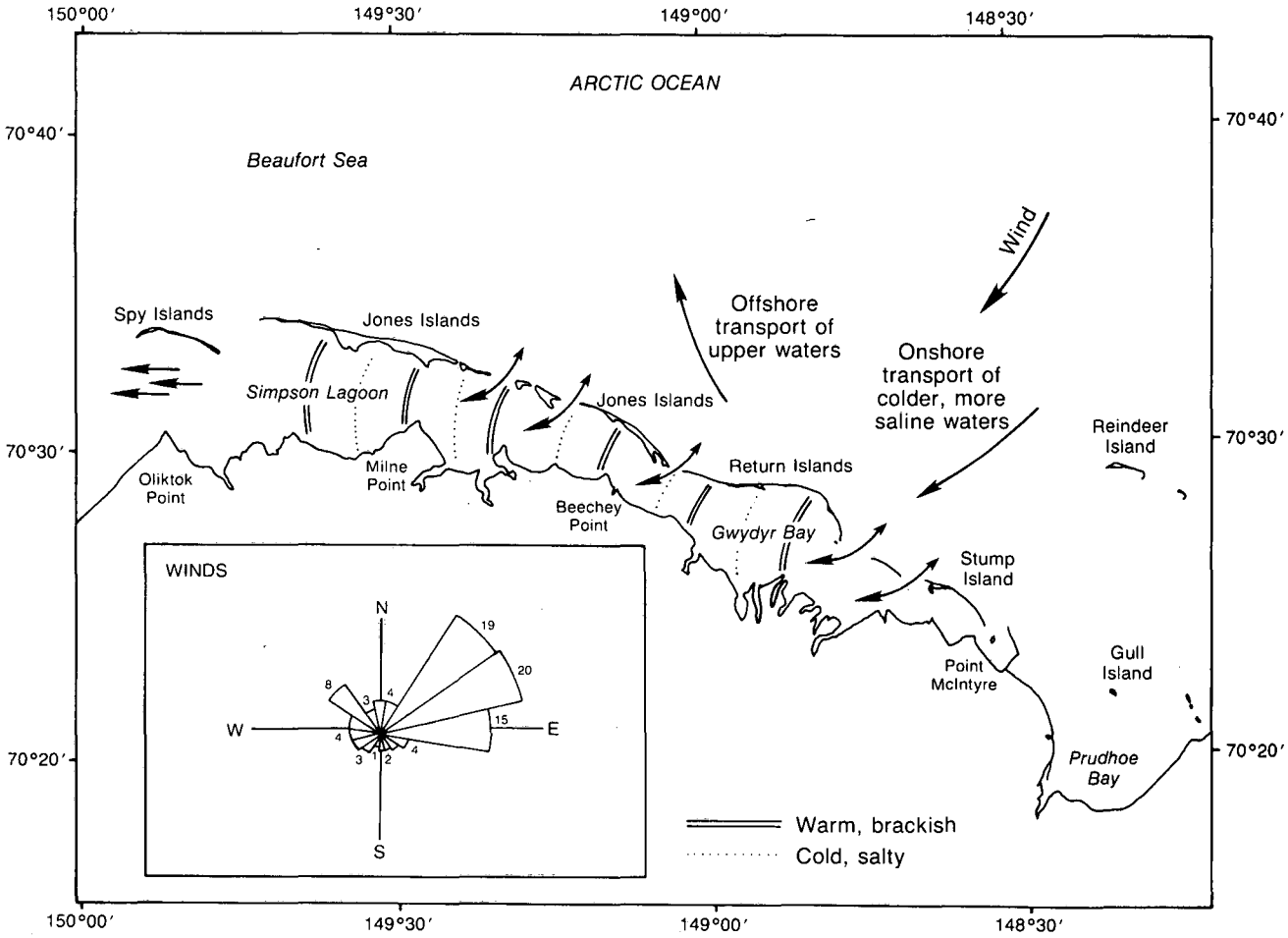

Figure 5.4—Combined wind and tide effects on circulation in an open lagoon. (Adapted from Hachmeister and Vinelli 1983.)

5.4.2 Pulsing Lagoons

The pulsing lagoon type was the focus of study in a more recent field program (Hachmeister and Vinelli 1983). Figure 5.5 illustrates the combined wind and tidal effects of available exchange in this type of lagoon using Angun Lagoon and Pokok Bay from the eastern Beaufort coastline as examples. Illustrated in this figure are mean summer conditions with winds predominantly from the east. In a manner similar to the open lagoon case, easterly winds result in somewhat higher nearshore salinities and lower nearshore temperatures for tidal exchange with the lagoon. In addition, circulation in the lagoon itself may depend on the lagoon geometry, with greater mixing observed for a lagoon with the geometry of Pokok Bay than for a lagoon with the shape of Angun Lagoon.

Figure 5.6 illustrates the circulation patterns anticipated for westerly winds. As in the open lagoon case, the fresher, warmer, nearshore water is maintained on the coast and advected eastward in the longshore current. As observed in the Simpson Lagoon data, during westerly winds the nearshore water is warmed to temperatures equal to lagoon water and the nearshore and lagoon entrance waters become almost identical. However, when easterly winds are reestablished the nearshore waters cool as warm water is driven offshore and the pulsing effect of cool-water-in/mixing/warm-water-out is observed. Because there is no net flowthrough of the waters entering the pulsing lagoons, sensors placed in the interior of Angun Lagoon and Pokok Bay do not experience the alternating patterns of nearshore and lagoon water observed in Simpson Lagoon (Hachmeister and Vinelli 1983).

Physical models developed to study circulation and flushing in lagoons and small embayments provide useful information for interpreting measurements made in the present study. Nece *et al.* (1979) studied the effects of geometry and the size and placement of lagoon entrances on flushing effi-

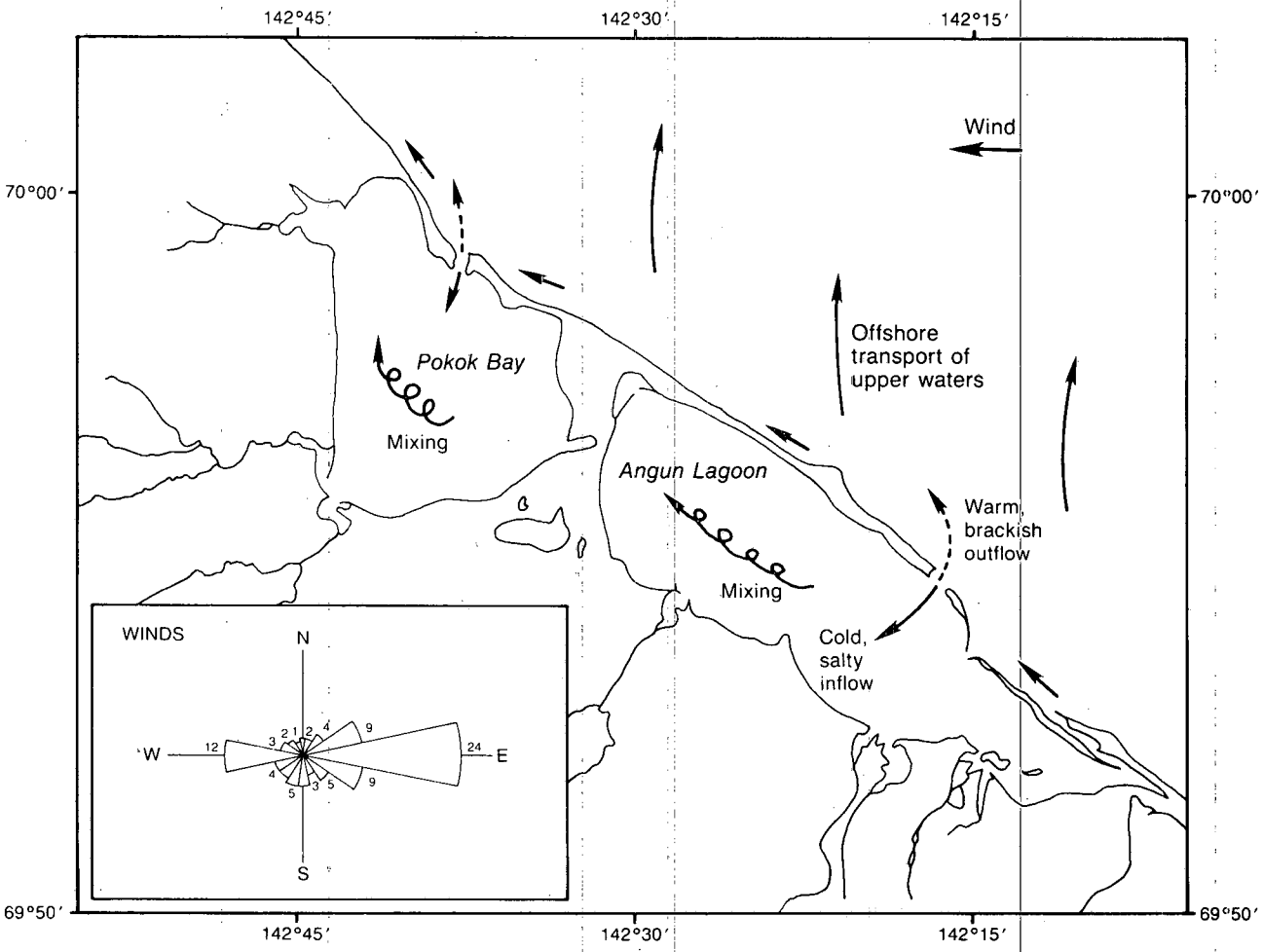

Figure 5.5—Combined wind and tide effects in pulsing lagoons during easterly winds. (Adapted from Hachmeister and Vinelli 1983.)

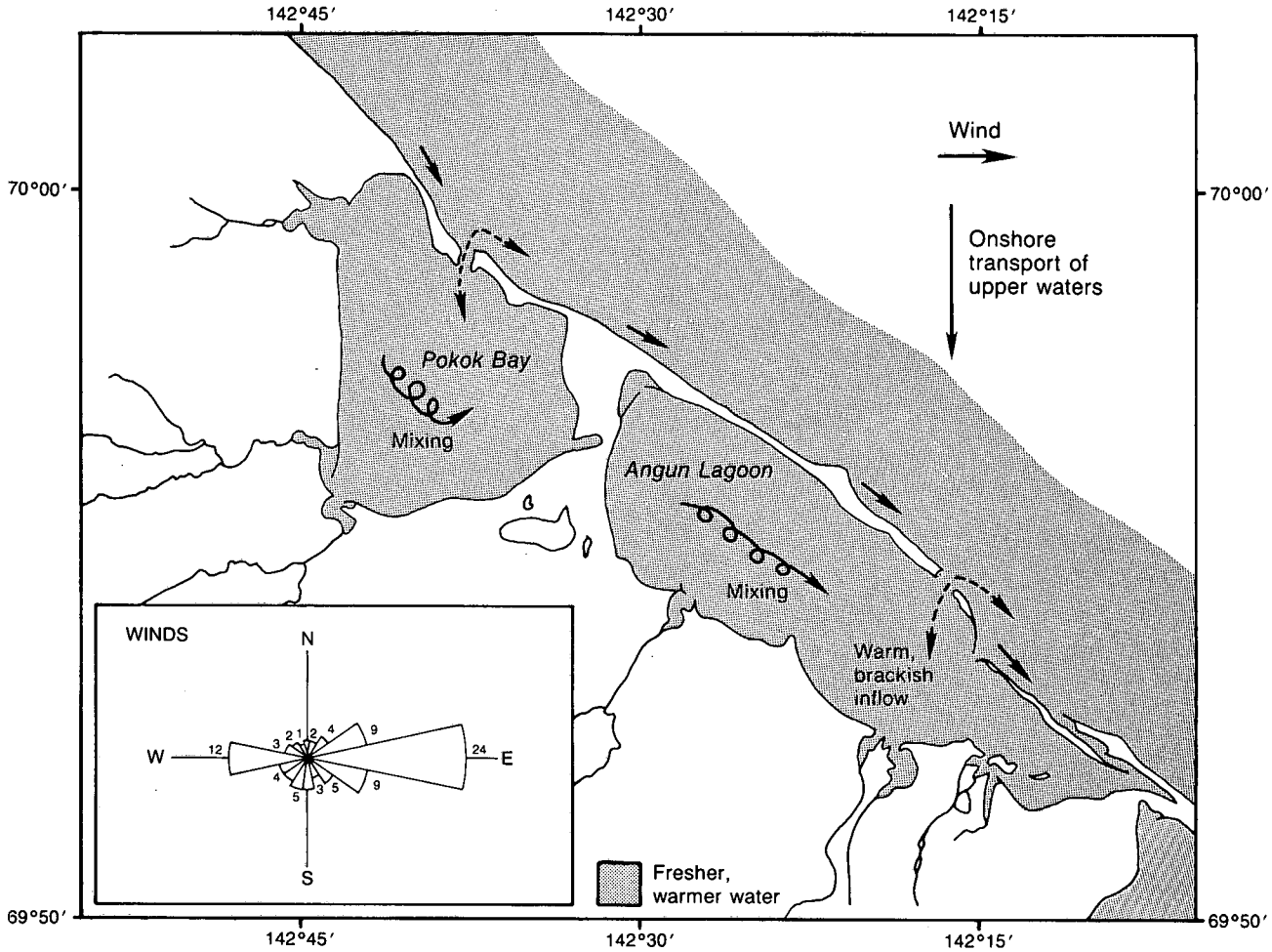

Figure 5.6—Combined wind and tide effects in pulsing lagoons during westerly winds. (Adapted from Hachmeister and Vinelli 1983.)

ciencies of small embayments. Figure 5.7 shows an example of the distribution of exchange coefficient (percent water exchange per tidal cycle) in an embayment similar in geometry to Pokok Bay. In this case the distribution of the flushing properties is uniform. The average flushing efficiency for a lagoon with this shape, according to this study, ranges from 90 to 100%. In comparison, flushing efficiency for Pokok Bay was crudely estimated at 15 to 20% near the lagoon center. However, the tidal ranges utilized by Nece were a factor of 10 greater than those observed in the Beaufort Lagoon system. Flushing efficiencies might therefore be expected to be greater in the model studies than in the actual lagoons. Regardless, the results for Simpson Lagoon are considerably different, giving estimated exchanges of about 3-4 days (8-10 days for ideal tidal flushing), which yields over a 200% efficiency compared to tidal flushing alone.

If a model geometry similar to that of Angun Lagoon is used, an interesting phenomenon arises. Nece *et al.* (1979) found that multiple circulation cells develop in the lagoon when lagoon length-to-width ratios are greater than 3; as a result, cells farthest from the entrance do not participate fully in the exchange processes and exhibit reduced flushing efficiencies. In a lagoon with a geometry similar to that of Angun Lagoon (length-to-width ratio = 5), three circulation cells are observed. Figure 5.8 illustrates the results of a model study with an embayment having approximately the same geometry as the western portion of Angun Lagoon. The results indicate that near the lagoon entrance exchange coefficients may be as high as those for the Pokok model (23-27%). However, exchange as low as 1-2% is observed at the far end of the lagoon away from the entrance. Therefore, the overall flushing efficiency due to tidal effects alone therefore would be about 48%, which is less than half of the efficiency predicted for a pulsing lagoon such as Pokok Bay. The region of the lagoon farthest from the entrance is, however,

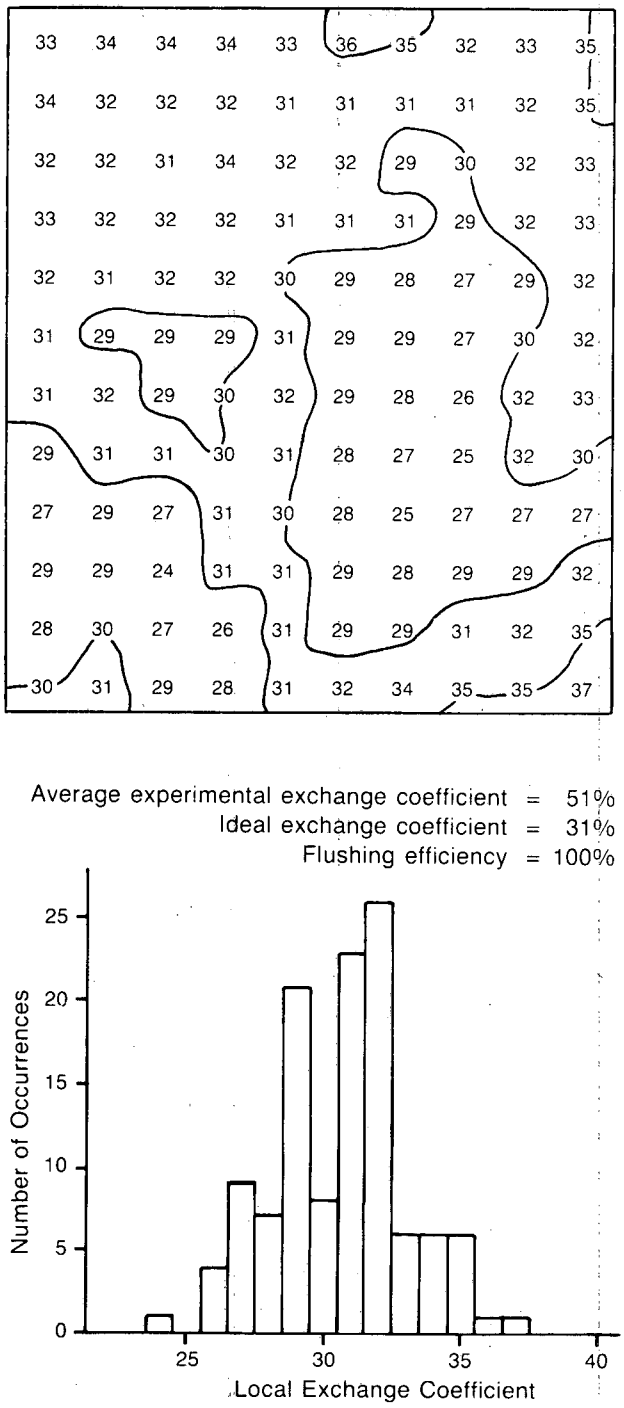

Figure 5.7—Model of exchange coefficient distribution in a pulsing lagoon similar in geometry to Pokok Bay. (Adapted from Nece *et al.* 1979.)

virtually isolated from the exchange processes and shows efficiencies as low as 8-10%. As in the case of the Pokok model, however, modeled tides are a factor of 10 greater than those observed in Angun Lagoon and actual flushing efficiencies are expected to be considerably less than those modeled.

Current measurements in the far western end of Angun Lagoon show persistent north-northeast current direction (Hachmeister and Vinelli 1983), indicating a mean clockwise circulation in this portion of the lagoon. Following Nece *et al.* (1979), if three circulation cells exist in the lagoon west of the main entrance then the central cell should exhibit net counterclockwise circulation and the cell immediately adjacent to the entrance should exhibit clockwise circulation. That this is so is substantiated by visual observations of inflowing currents and surface drifter motions near the lagoon entrance.

These results are for tidal flushing only; considerable wind mixing may occur in addition to the exchange which is enhanced by the input of fresh water into the surface waters at the isolated end of Angun Lagoon. However, in the absence of large quantities of fresh water, as might be expected in the late summer and fall under mean easterly winds, flushing of pulsing lagoons such as Angun Lagoon might be considerably slower than indicated by typical ideal flushing estimates based on volume exchange alone.

Approximately 15% of the Beaufort Sea coastline east of Barter Island possesses such pulsing lagoons. Further detailed study of the flushing characteristics of these lagoons would be helpful. In contrast, the lagoons in the western Beaufort from Barter Island to Point Barrow are almost all of the open type, similar to Simpson Lagoon.

5.4.3 Limited Exchange Lagoons

In the Chukchi Sea region of the Sale 87 area, the nearshore is composed almost exclusively of limited exchange lagoons with extensive barrier island systems and multiple small entrances. A recent study of Peard Bay, a two-entrance, limited exchange lagoon on the northeast Chukchi coast, shows enhanced flushing over pulsing lagoons, including net transport through the lagoon entrances which presumably is wind driven. Figure 5.9 shows the results of a model study of a small embayment with two small entrances (one entrance is twice the size of the other), similar to Peard Bay; the predicted flushing efficiency for a lagoon with this geometry is 84%, compared to 48% for a single-entrance lagoon with the geometry of Angun Lagoon. In addition, given two entrances and the relationship of the Peard Bay geometry to the local wind field, enhanced flushing due to flowthrough of nearshore waters during strong easterly or westerly winds (as has been observed) is highly probable.

Limited exchange lagoons, of which pulsing lagoons are a subset, are defined by a capacity for throughput of nearshore waters which is limited by

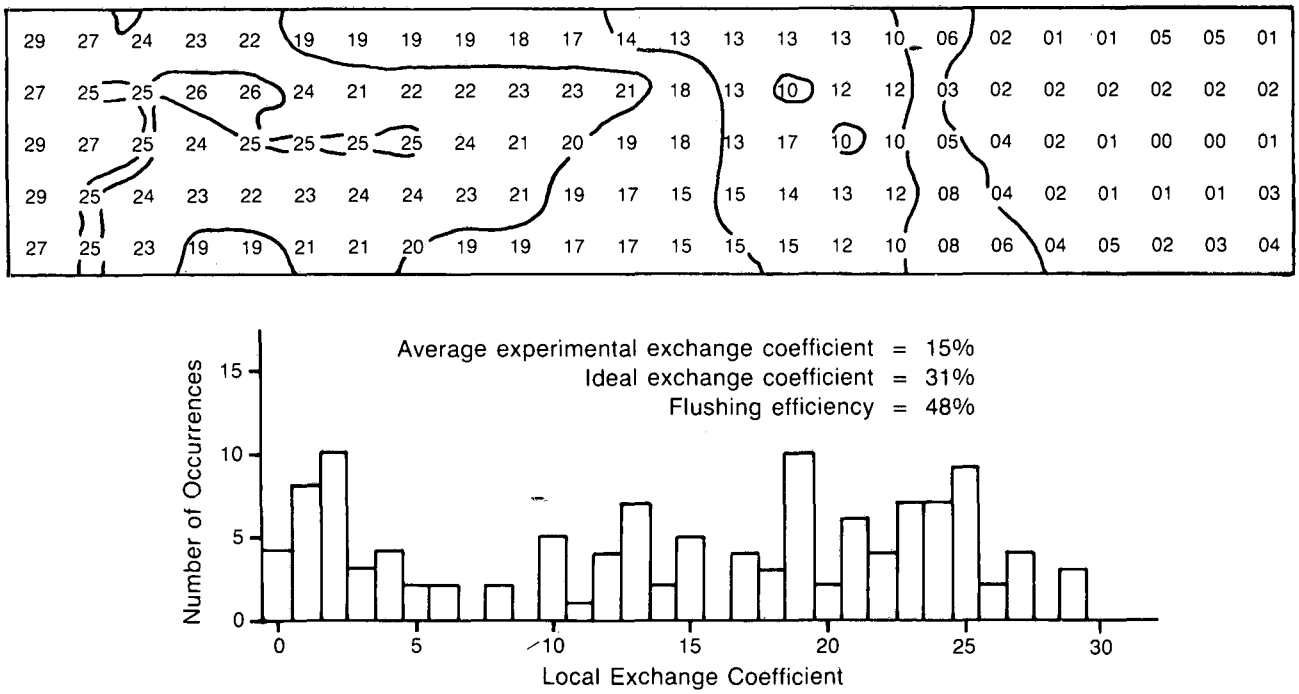

Figure 5.8—Model of exchange coefficient distribution in a pulsing lagoon similar in geometry to Angun Lagoon. (Adapted from Nece *et al.* 1979.)

nearshore barrier island systems. Beaufort Lagoon is actually composed of several small, interconnected, narrow lagoons with an extensive barrier island system. The barrier island system there (commonly designated as Icy Reef) has a relatively small number of openings distributed along its extent. Several of the openings are quite large, allowing the possibility of net wind-driven flowthrough of the waters from the longshore current. At the far western end of Beaufort Lagoon is Nuvagapak Lagoon, followed by (moving eastward) Egaksrak Lagoon, Siku Lagoon, Pingokraluk Lagoon, and Demarcation Bay. Major entrances include Nuvagapak Entrance to the west (which actually consists of two openings: one narrow and quite deep, the other wider but relatively shallow), Egaksrak Entrance, Siku Entrance, and the main entrance to Demarcation Bay.

Flowthrough—*i.e.*, purely advective exchange, as was discussed for open lagoons—is expected to be considerably less than observed for Simpson Lagoon. However, considerably more advective exchange than for the pulsing lagoons is indicated. The observed range of flushing efficiency calculated for open and pulsing lagoons has been estimated at 200% and 15-20%, respectively, for Simpson and Pokok lagoons. If model results for Pokok Bay and Angun Lagoon geometries scale the same (100% flushing efficiency for Pokok Bay and 48% average efficiency for Angun Lagoon), then actual average efficiencies for Angun Lagoon may be as low as 7-10% given a 15-20% estimate for Pokok Bay. Therefore, a considerable gain in flushing efficiency might be expected for the limited exchange lagoons, depending on the degree of wind-driven advection through the lagoons. For example, if advection in Nuvagapak Lagoon is only 0.5% of a 3-m/s easterly wind (1.5 cm/s) as compared to 3-4% observed in Simpson Lagoon, then flushing efficiency could be increased to 75%, with water exchange occurring in as little as 12 days.

Numerous limited exchange lagoons exist in the eastern Beaufort Sea, including the lagoons typically considered as forming Beaufort Lagoon and the lagoon systems inside Icy Reef to Demarcation Bay. To the west, Oruktalik, Tapkaurak, and Jago lagoons are similarly configured. Those limited exchange lagoons, whose entrances may or may not exhibit some phenomenon characteristic of pulsing lagoons, depending on the degree of wind-driven advection through the particular lagoon, occur over 75% of the coastline of the Beaufort nearshore east of Barter Island.

5.5 CONCLUSIONS

Lagoon-barrier island geometries vary between the eastern and western Beaufort Sea shelf: open

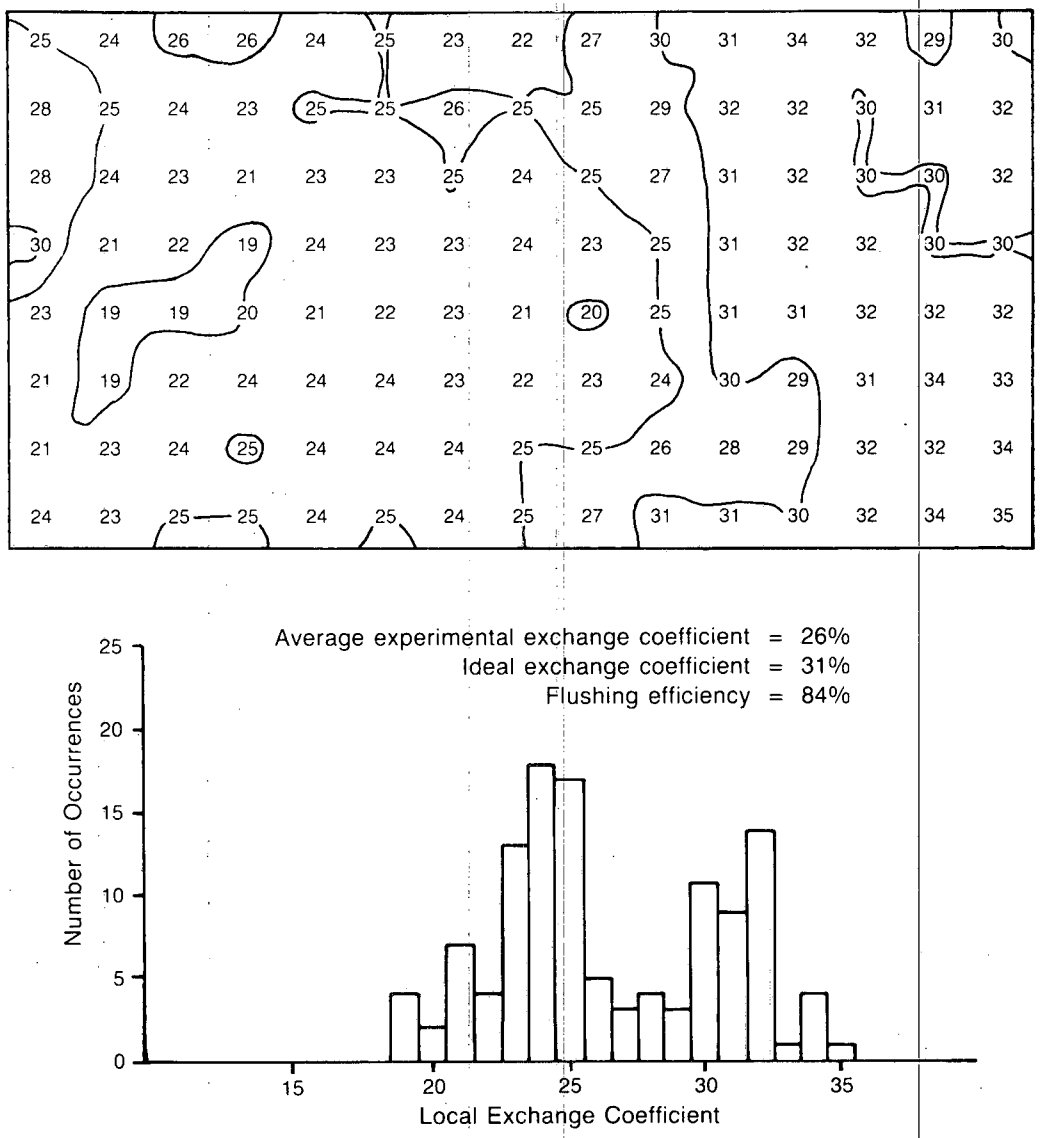

Figure 5.9—Model of exchange coefficient distribution in a limited exchange lagoon with two entrances similar in geometry to Peard Bay. (Adapted from Nece *et al.* 1979.)

lagoons are the dominant form along the western Beaufort coast from Barter Island to Point Barrow, and pulsing and limited exchange lagoons are dominant along the eastern Beaufort and northeast Chukchi coasts. The greatest flushing efficiencies for the three lagoon types occur in the open lagoons, such as Simpson Lagoon. These lagoons are open to flowthrough by the coastal longshore currents and may exhibit flushing efficiencies equal to 200% of tide-induced exchange alone.

Flushing efficiencies for pulsing or limited exchange lagoons are, however, expected to be considerably less. For example, the flushing efficiency of Pokok Bay (a pulsing lagoon that should exhibit good flushing characteristics with a centrally located entrance and a length-to-width ratio of approximately 1) may be as low as 15-20% in the absence of enhanced baroclinic flow. On the other hand, Angun Lagoon (a pulsing lagoon with a length-to-width ratio of 5 and an off-center entrance, thus predicted poor flushing characteristics) may show average overall flushing efficiencies which are half of those observed for Pokok Bay. In addition, Angun Lagoon contains some isolated regions away from the entrance which may have tidal flushing efficiencies only 10% of those calculated for Pokok Bay.

However, under the influence of wind forcing, and particularly under the influence of westerly winds which force water onto the nearshore region and into the lagoons, vertical mixing and increased horizontal exchange occur which may temporarily

increase the exchange efficiencies of these types of lagoons to equal that observed for Pokok Bay. The critical wind speed required to vertically mix the lagoon waters appears to be about 18.5 km/h (10 kt) for early spring stratifications and is anticipated to be considerably less for late summer conditions when vertical stratification is reduced. In either case, however, flushing efficiency for these eastern Beaufort lagoon types is considerably less than that observed for the open western lagoons and seems to be only a fraction (15-20%) of that which would be estimated from volume-exchange calculations alone. These reduced flushing rates make the eastern Beaufort and northeast Chukchi lagoon systems more vulnerable to impact by oil and gas exploration activity, if such activities cause disruptions in the exchange processes which renew the lagoon properties. These exchange processes also must be considered as major natural processes for removing any direct contamination by oil or drilling by-products.

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Chapter 6
Sand and Gravel Sources*

by David M. Hopkins

The broad expanse of the Sale 87 area extends far beyond the limits of shorefast ice, and thus includes large areas not accessible over winter shorefast ice. Furthermore, much of the area cannot be explored from offshore islands.

The nature and distribution of fill resources differ from one part of the Sale 87 area to another, and exploration and development there may require movement of considerable quantities of sand and gravel fill for long distances. Consequently, as exploration extends beyond the fast-ice limit, requirements for fill will probably result in a great deal more water traffic during the open season, and the use of icebreakers to extend the navigation season.

6.1 ANTICIPATED REQUIREMENTS

The importance of stable structures utilizing sand and gravel fill during offshore exploration and development was discussed by Weller *et al.* (1978). Some sand and gravel fill used in exploration islands will probably be recycled for use in production islands. Platforms in water less than 5 to 6 m deep are likely to consist of artificial islands defended by sandbags or other coarse armoring material but otherwise unconstrained. Farther seaward, but at depths less than 30 m, artificial islands confined by concrete caissons are likely. As exploration progresses, we anticipate that movable monocones as described by Jahns (1979) will be used in water deeper than 10 to 15 m. Ultimate sand and gravel requirements for offshore structures will number tens of millions of cubic meters.

Future developments are likely to require new logistic bases on the shore. A currently proposed causeway that would extend the natural spit at Oliktok Point might serve the Sale 87 area as well as the nearby onshore production areas for which the pier is intended. Bullen Point, Cape Halkett, Lonely, and the Barrow area are other possible sites for causeways. The proposed causeway at Oliktok Point might also be used as a pipeline landfall as production begins in the Sale 87 area. Other likely sites for new logistic bases are promontories near deep water such as Kaktovik and Lonely. New logistic bases will create continuing and great needs for gravel for storage pads as well as for maintenance of landing docks. The total fill requirements for a single logistic base would be about 1×10^6 m^3.

6.2 SOURCES OF SAND AND GRAVEL

6.2.1 Onshore Sources

Upland sources of gravel are abundant and widespread east of the Colville River, and sand underlies vast mainland areas west of the Colville River and south of the Kogru River; but most of the region north of the Kogru Peninsula and Teshekpuk Lake is devoid of useful concentrations of sand and gravel. Gravel and sand *are* available from upland sites between Barrow and Peard Bay.

With respect to possible restrictions on borrow removal the region east of the Colville River is similar to the region around Prudhoe Bay, in that frozen gravel is present nearly everywhere at depths no greater than 5 m. The overburden consists mostly of peat, silt, and fine sand, and the same constraints apply to its removal as those applying to quarrying of onshore gravel deposits adjoining the 1979 Joint Federal-State Lease Sale area. West of the Colville River, virtually unlimited quantities of frozen dune sand stabilized by turf or a thin cover of peat underlie the mainland south of the Kogru

*This chapter is basically a revision of chapter 7, Beaufort Sea Sale 71 synthesis report (Hopkins 1981).

River and Teshekpuk Lake.

Immediately north of the belt of stabilized dune sand is a belt of marine silty fine sand which is 25-35 km wide and extends westward from the Kogru River through Teshekpuk Lake.

Small amounts of coarse fill can be obtained from small bodies of sandy gravel and pebbly sand (about 1×10^5 m^3 each) that occur as low hillocks and mounds scattered in a linear belt extending from the Eskimo Islands westward through the southern part of the Kogru peninsula and thence westward along the north shore of Teshekpuk Lake. The sandy gravel is frozen and is overlain by peat, silt, and fine sand generally less than 1 m thick.

Northward from this strip of gravelly hillocks, the Arctic Coastal Plain is underlain by ice-rich peat and silty, peaty, thaw-lake deposits several meters thick. Beneath these lie frozen overconsolidated clay and silt, locally containing concentrations of boulders. Local concentrations of boulders might be sufficiently abundant to furnish riprap to armor piers and artificial islands against surf erosion. No other sources of material useful in construction of piers and offshore islands are known to occur in this 30-km-wide belt of the Arctic Coastal Plain north of Teshekpuk Lake, west of Harrison Bay, and east of Point Barrow.

The beaches along the coast of the Beaufort Sea are narrow and thin and contain only small quantities of sand and gravel. Those adjoining the coast between the Colville River and Point Barrow are especially narrow and thin; in most places, they contain negligible quantities of coarse material. The Distant Early Warning Line station at Lonely has already fully utilized the fairly large but still limited amount of sand and gravel from the beaches there, and lack of a nearby source of additional coarse fill limits expansion of the site.

Large supplies of sand are present in coastal bluffs along most of the Chukchi Sea coast between Barrow and Peard Bay. A large gravel deposit containing a minimum of several hundred thousand cubic meters is exposed in the coastal bluffs about 10 km north of Peard Bay.

6.2.2 Shelf Paleovalleys

Several paleovalleys are believed to extend across the Beaufort Sea shelf (Hopkins 1977). Only the Sagavanirktok paleovalley has been well delineated by offshore drilling (Smith *et al.* 1980). It begins in Prudhoe Bay, turns northwest to pass between the West Dock and Reindeer Island, and has been traced farther northwestward to a point about 10 km north of the mouth of the Kuparuk River. Gravel in the Sagavanirktok paleovalley is unfrozen and lies beneath soft, unconsolidated marine clay, silt, and fine sand up to 10 m thick. This paleovalley is a dependable source of coarse, gravelly fill.

Geological reasoning suggests that a paleovalley should also be present off the mouth of the Colville River in eastern Harrison Bay, but the geophysical techniques employed thus far are not capable of delineating a buried valley filled with gravel, and drilling has been inadequate to verify its presence. Both proprietary drilling and permafrost drilling by OCSEAP investigators T. Osterkamp and W. Harrison (pers. comm.), however, suggest that a line from Oliktok Point to Thetis Island crosses a submerged and buried geologic boundary between silt and clay to the west and unfrozen gravel to the east. This boundary probably marks the western margin of the Colville paleovalley.

Offshore drilling in 1976, 1977, and 1979 by OCSEAP scientists and the U.S. Geological Survey between Gwydyr Bay and Brownlow Point encountered gravel overlain by 10 m or less of fine marine sediments in all boreholes between the coast and the Midway, McClure, Stockton, and Maguire islands. Gravel may be present at similar depths throughout the entire shallow shelf area shoreward of the barrier islands in the localized area.

Paleovalleys are probably also present on the Beaufort Sea shelf between Cape Bullen and Demarcation Point. The several large streams draining from the Romanzof Mountains across the Arctic National Wildlife Refuge to the Beaufort Sea coast must once have extended across the now-submerged continental shelf. In all likelihood, they carved valleys during low sea-level episodes which then became filled with gravel when the sea level rose again. Like the Sagavanirktok paleovalley, ancient submerged gravel-filled valleys of such streams as the Canning, Sadlerochit, and Okpilak rivers probably lie concealed beneath a few meters of marine mud of Holocene age. However, the very sparse geophysical data are insufficient to permit delineation of paleodrainage on the continental shelf off the Arctic National Wildlife Refuge.

6.2.3 Inner Shelf Surficial Sources

In Harrison Bay, there are several potential sites for mining sand and gravel on the surface of the sea bed, including Pacific and Finger shoals. Most of these bodies are present because hydraulic forces are focused at these locations.

Pacific Shoal is a broad body consisting mainly of sand standing no more than 1.5 m above the surrounding bottom (Barnes *et al.* 1980). Finger Shoal is a field of linear, parallel sand waves oriented north-south that are 1.5 m high and 200 m wide, sitting on a surface of stiff, silty clay. A shoal similar to Pacific Shoal lies to the south (Reimnitz and Minkler 1981). These areas each contain about 100,000 m^3 of clean gravel.

Active sand ridges, 1 to 2 m thick and 100 m or more wide, lie within the 10-m isobath in a belt extending from Pingok Island westward past Spy and Thetis islands. Studies by Barnes and Reimnitz (1979) and Reimnitz *et al.* (1980) indicate these are active hydraulic bedforms. Off Pingok Island, these sand bodies are longshore and transverse bars that are products of and affect littoral processes, including erosion rates on Pingok Island; mining would accelerate erosion of the island. However, mining of the western part of the zone would probably have few or no adverse environmental effects and could yield about 100,000 m^3 of sandy fill.

The outer fringes of the 2-m bench off the Colville River delta consist of fine sand interbedded with mud layers rich in organic matter (Barnes *et al.* 1979). If suitable for construction material, about 1.5×10^6 m^3 of muddy sand could be removed.

6.2.4 Chukchi Sea Sediment

Near shore within the Chukchi Sea from Point Barrow south to Peard Bay, the Quaternary sediment cover over Cretaceous bedrock varies from very thin deposits associated with bedrock exposures at Skull Cliff to deposits up to 20 m thick off Barrow. These deposits thin rapidly in the offshore direction and are less than 2 m thick at depths of about 30-35 m off Barrow and less than 1 m thick at depths of 8-19 m off Skull Cliff to the south. North of Peard Bay and directly off Point Franklin, nearshore sediment cover attains a maximum thickness of 16 m; but directly to the west, the Quaternary-Holocene sediment cover thins to 1-2 m at a depth of 30 m. The most significant possible source of fill is a northward-migrating sand-wave field that lies north of Point Franklin. This extensive sand accumulation is at least 11 m thick and lies at a depth of 20 m.

6.2.5 Shoals in the Stamukhi Zone

Several shoals with at least a surficial cover of sand are found beneath the stamukhi zone on the middle or outer part of the Beaufort shelf. Best delineated are those in the outer part of the Sale 87 area. Stamukhi Shoal, 20 km north of Pingok Island (Reimnitz and Maurer 1978; Barnes *et al.* 1980), and Weller Bank, more than 40 km north of the Colville River delta (Barnes and Reiss 1981), are bodies of sand and gravel of unknown origin that project 5-10 m above the sea floor. Stamukhi Shoal is adjoined on the west by a sand apron that curves southwestward and consists of hydraulic bedforms up to 2 m thick (Reimnitz and Kempema 1983). These shoals, including the subtle bottom elevations southwest of Stamukhi Shoal, in some way determine the position of major ice bastions in the stamukhi zone (Reimnitz *et al.* 1977, 1978; Rearic and Barnes 1980; Reimnitz and Kempema 1983). Weller Bank, the largest and most equidimensional body of sand and gravel, also forms a boundary between fast ice and moving ice, controlling the position of the stamukhi zone.

Other shoals, about which even less is known, are found in waters 12 to 40 m deep on the eastern Beaufort shelf between the Canning River and Demarcation Point. Although some of these shoals are known to be mantled with sand and gravel, the nature of the material forming the cores remains unknown.

The dynamics of the interaction between shoals and grounded sea ice are uncertain, and the possible effects upon position of the stamukhi zone that might result from quarrying them has not been established. Our ignorance of the history, dynamics, and composition of these shoals is a serious data gap that should be corrected, to determine whether or not they can be safely quarried or otherwise modified in order to fill part of the need for fill materials on the Beaufort Sea shelf.

6.3 CONSEQUENCES OF SAND AND GRAVEL MINING

6.3.1 Onshore and Beach Areas

The consequences of, and constraints upon, mining sand and gravel from onshore and beach areas adjoining the Sale 87 area are similar to those outlined for the 1979 Joint Federal-State Lease Sale area (Weller *et al.* 1978). Stream beds should be avoided because of potential damage to overwintering fish populations; wetlands and, especially, tidal marshes should be avoided because of their relatively high organic productivity and value as nesting habitat. The immediate coastal area should be avoided because of the possibility of historic and prehistoric occupation and burial sites there.

Quarrying of sand and gravel from beaches can accelerate the already rapid rates of coastal erosion present along part of the Sale 87 area. Quarrying of sand and development of roads to sand quarries in the large area of stabilized dunes in the eastern area of the National Petroleum Reserve will result in local reactivation of blowing sand. Disturbances can be minimized by developing quarries as closed depressions and allowing them to fill with water after abandonment, by limiting quarrying to the winter months, and by using ice roads for haulage.

6.3.2 Offshore Dredging

Earlier discussion of the consequences of dredging in the 1979 Joint Federal-State Lease Sale area focused on the disturbance of the bottom, potential burial of benthic organisms by siltation, and increases in turbidity with possible attendant clogging of the gills of filter feeders. All of these disturbances seem comparable in intensity to effects upon the biota produced by natural disturbances, including ice gouging, resuspension of sediments during storm surges, and excavation by strudel scour during spring breakup flooding of the shorefast ice (Weller *et al.* 1978).

Removal of fill from the bottom in certain areas can significantly affect the stability and permanence of offshore islands. As noted in section 20.2.3, removal of sand waves off Pingok Island could result in accelerated erosion and rapid destruction of the island. Most of the other offshore islands are migrating landward by about 10 m per year. Development of a submerged borrow pit in the lee of one of these islands could result in the disappearance of the island.

Thetis Island seems especially vulnerable, and because of the increasing intensity of use of the island and surrounding waters, conflicts may arise. Because it is the only barrier island in Harrison Bay, Thetis Island is regularly used as shelter for ship and barge traffic. However, from mid-June to mid-August the island supports one of the largest breeding concentrations of Common Eiders in the Alaskan Beaufort Sea, as well as small breeding populations of geese (Brant), gulls, and terns. Like other islands in the Jones Islands, as many as 10,000 flightless Oldsquaws may concentrate behind Thetis Island during the mid-July to mid-August molting period.

As noted in section 6.2.5, the shoals on the outer shelf control the position of the stamukhi zone. Removal of these shoals in the outer part of the lease area would result in a shoreward shift, probably a drastic one, in the position of the stamukhi zone. Likewise, emplacement of an artificial island or firmly anchored steel production cone outside of the shoals could be expected to displace the stamukhi zone in a seaward direction.

Probably the most significant consequence of construction of artificial islands will be increased water traffic. Fill cannot be trucked over the ice beyond the limits of shorefast ice, and fill will almost certainly have to be carried to more remote artificial island sites by barge, either from stockpiles on the beach or from submerged dredge pits. The problem is intensified by the limited number of borrow sites throughout much of the sale area. An increase in vessel traffic in the area should be expected. A lengthening of the barging season through the use of icebreakers during early summer and late autumn will increase the ice hazards to such water traffic. Some interaction between whale migrations and dredging, barging, and dumping of fill should also be anticipated.

Large suction dredges that may be used to provide fill for artificial islands would need a deep and sheltered winter anchorage protected from moving ice. If such dredges are sheltered in man-made harbors in the lee of barrier islands, care must be taken to avoid creating sea-bottom depressions that can lead to depletion of the islands.

6.4 DOCKS AND CAUSEWAYS

Considerable new knowledge has been generated concerning mesoscale circulation and nutrient sources in some of the lagoons along the Beaufort coast. Because the lagoons are among the most productive areas in the Beaufort Sea, disruption of circulation and interruption of nutrient supplies by causeways is a serious concern. It is clear that the openings between barrier islands are vital to the maintenance of circulation and must not be filled and closed. It has also been determined experimentally that the existing West Dock causeway at Prudhoe Bay modifies local circulation. It is possible that proliferation of causeways to planned and possible future production islands will have cumulative effects upon circulation and nutrient supply pathways.

From east to west the possible sites of artificial causeways include Bullen Point, the Sagavanirktok River delta, Oliktok Point, Cape Halkett or near Lonely, and a site in the vicinity of Point Barrow. A causeway, West Dock, already exists west of Prudhoe Bay. In addition, lease sales in Harrison

Bay, near Prudhoe Bay, and in Camden Bay may result in causeways similar to those proposed for the Sagavanirktok delta/Duck Island project during development of these areas. A major concern is the cumulative effects multiple causeways may have on the anadromous fish populations in the summer nearshore band of warm brackish water.

It has been postulated that disruption by causeways of the temperature-salinity regimes along these areas may result in certain physiological stresses and/or modifications of behavior in anadromous fishes which may lead to long-term declines in their abundance. Such effects may subsequently lead to declines in subsistence and commercial fisheries of the Beaufort region.

These hypotheses are based on recent studies by Fechhelm and Gallaway (1982) and Neill *et al.* (1982) which have shown that an important anadromous species, the Arctic cisco, exhibits a definite temperature preference which relates to its distribution along the coastline. By modeling movements and distribution of Arctic cisco relative to changes in temperature and salinity around the Waterflood Causeway, Neill *et al.* (1982) concluded that an estimated 7% reduction in fish density would occur in an area of less optimal conditions in the lee of the causeway.

Although such reductions are only theoretically displayed, they point to the need for further investigation, especially in the light of the additional causeways that may be proposed and constructed. In addition, such changes may pose barriers to migration or movement of anadromous species that require fresher, less saline conditions, such as broad and humpback whitefishes. The implication is that reducing the nearshore habitat used primarily for feeding may stress such populations.

Causeways have an important and not entirely negative impact on shorebird populations. Phalaropes and terns are attracted to barrier islands, spits, and artificial causeways for foraging. The construction of causeways, then, provides additional sheltered feeding areas, but also concentrates birds in areas subject to oil spills and other hazards. Causeways bridging barrier islands may affect the accumulation or distribution of zooplankton in lagoons, and in turn affect birds and other biota.

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Chapter 7
Regional Primary Productivity

By Donald M. Schell

The Beaufort and Chukchi seas present a paradox in that they are characterized by areas of high productivity in close proximity to areas of extremely low primary production. The coastal zone of the Beaufort Sea and the southern Chukchi Sea is inhabited by large numbers of fishes, birds, and marine mammals whereas the perennial ice zone a few hundred miles to the north is a biological desert with a very sparse fauna sustained by the lowest primary production of the world oceans.

This synthesis considers the factors governing primary production in the Beaufort Sea, and through the extrapolation of uptake rate measurements (corrected for ice cover and nutrient availability) made in the coastal waters, a map of annual production has been assembled. In addition, a hypothesis describing the physico-chemical processes governing nutrient supply to nearshore phytoplankton is presented with supporting data and theoretical considerations. The resulting model of nutrient dynamics and phytoplankton productivity may account for observed distribution of consumers in the coastal waters.

7.1 NUTRIENTS

The large input of terrestrial organic matter to the Beaufort Sea has been described in considerable detail (Schell *et al.* 1982). Over 50% of the carbon input to the coastal zone (inside the 10-m contour) is derived from terrestrial sources and consists primarily of peat particles eroded from the coastline or transported by the major rivers. The direct role of this carbon in trophic energetics of marine fauna is very limited. Carbon isotope studies on marine fauna have shown that very little of the peat carbon is transferred up the trophic levels (Schell 1983). The fate of the carbon is apparently oxidation by microflora with mineralization of the associated organic nitrogen. The ammonia produced is recycled by phytoplankton in the summer and is used as an energy source by nitrifying bacteria in the winter. Figures 7.1 and 7.2 show nitrate concentrations and salinities along a transect north of Stefansson Sound in May. Hypersaline water forming in Stefansson Sound as the ice freezes drains downslope at a rate sufficient to turn over the water volume of the sound in about 40 days. (For a detailed consideration see Schell *et al.* 1982.) In contrast, the nitrate concentrations increase very rapidly, indicating active nitrifying populations with a consequent increase of nitrate-N equivalent to about 0.1 mg-atoms N/liter-day. This nutrient-rich water apparently moves downslope to a depth below that sampled on the transect.

The fate of this nitrate may be deduced from the work of Aagaard *et al.* (1981) and Melling and Lewis (1982) which addresses the formation of hypersaline under-ice water in the eastern Beaufort Sea. They describe a downslope drainage in winter with the cold, dense water then spreading horizontally outward on deeper water of higher density. This shelf water "interleaves" in a layer out to an estimated 100 km in the situation which they described. If the water acquires a high nitrate concentration from the nutrient regeneration in the nearshore zone, this mechanism may serve as a major means of offshore transport of nitrogen and loss to the system. This sequence is shown schematically in Figure 7.3.

A possible mechanism by which a portion of this nitrate may be reintroduced to the euphotic zone is coastal upwelling due to wind stress during the open-water months. Increase in the speed of the Beaufort gyre and Coriolis effects may result in the offshore transport of low density surface water

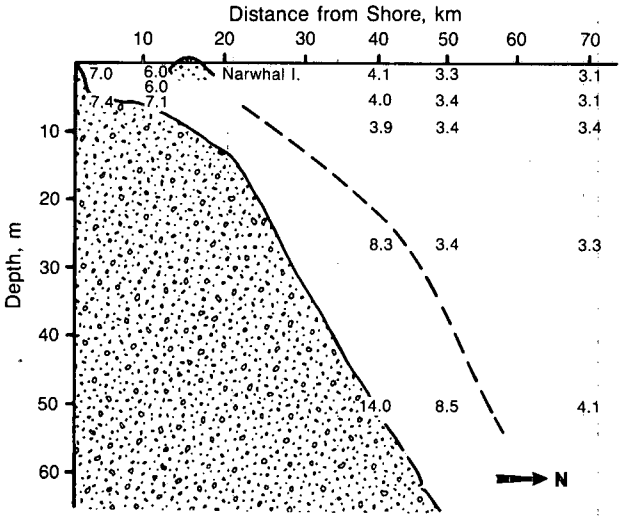

Figure 7.1—Nitrate concentrations (μg-atoms N /liter) along a transect north of Stefansson Sound, May 1982.

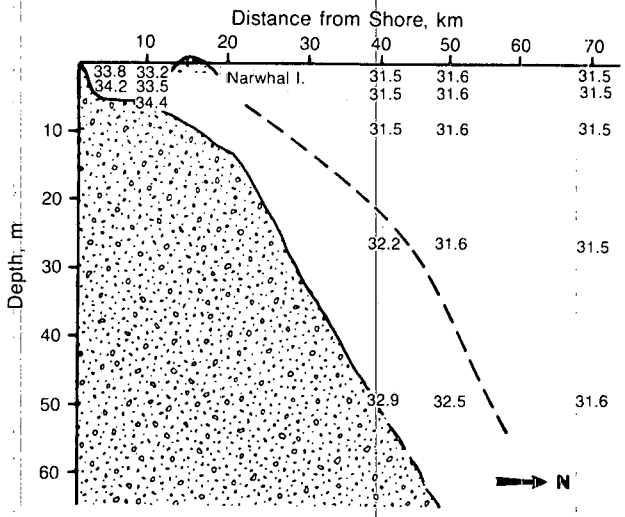

Figure 7.2—Salinities (ppt) along a transect north of Stefansson Sound, May 1982.

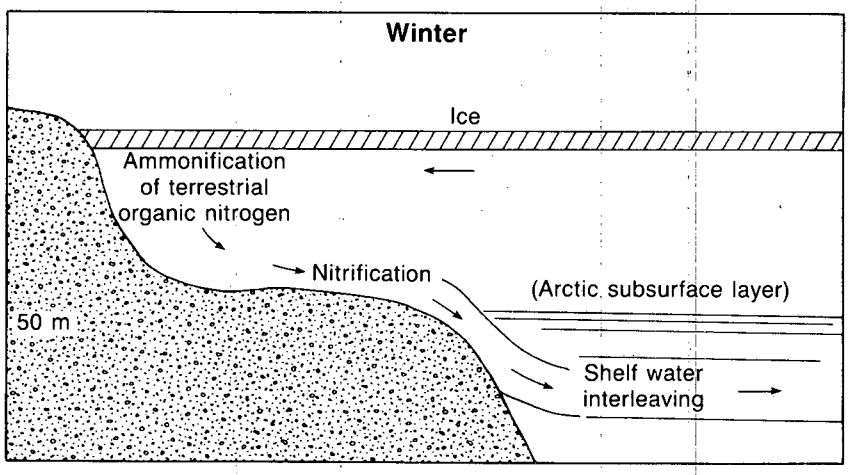

Figure 7.3—Winter processes controlling nutrient concentrations in Beaufort Sea waters inferred from late winter salinities and nitrate concentrations.

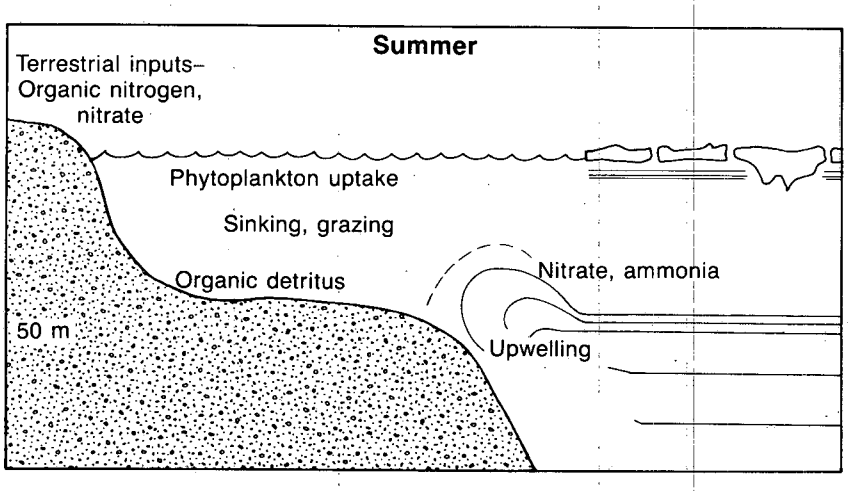

Figure 7.4—Summer processes supplying nutrients to shelf phytoplankton populations. Offshore perennial ice and summer meltwater stratification effectively prevent mixing of deep water into the upper 75-100 m.

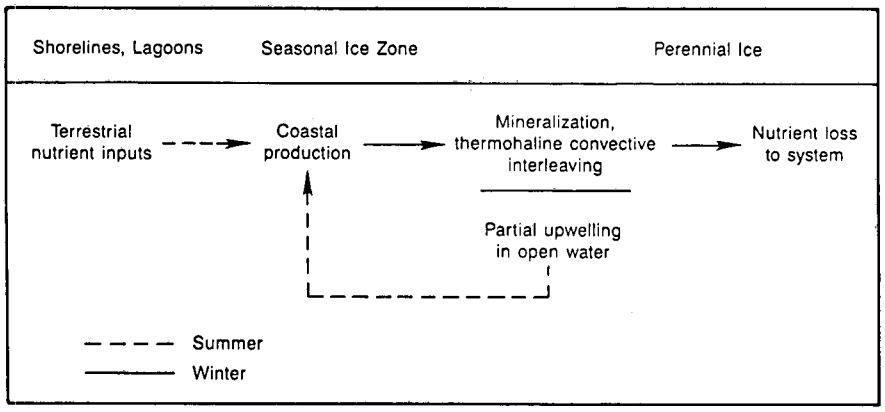

Figure 7.5—Word model of nutrient dynamic processes in shelf waters of the Beaufort Sea. Loss of nutrients results from winter convection to depths below the euphotic zone at distances offshore where perennial ice prevents advection upward.

and upwelling of deep water onto the shelf. Continued transport shoreward coupled with higher light intensities would result in phytoplankton blooms in this nutrient-rich water. Figure 7.4 schematically depicts this mechanism. Since this represents a recycling of part of the original inputs of organic nitrogen derived from terrigenous sources, the feedback effect may support a region of higher primary production in the zone of open water along the Beaufort Sea coastline. Integration of these processes in a word model is presented in Figure 7.5. Although the processes described are supported by experimental data (Schell 1974) and oceanographic measurements (Matthews 1981; Hufford 1974), there are no quantitative data which would enable the assessment of the importance of these processes to annual productivity of the nearshore region. As additional data are acquired, the role of the physical processes in dominating the biological productivity may become clearer.

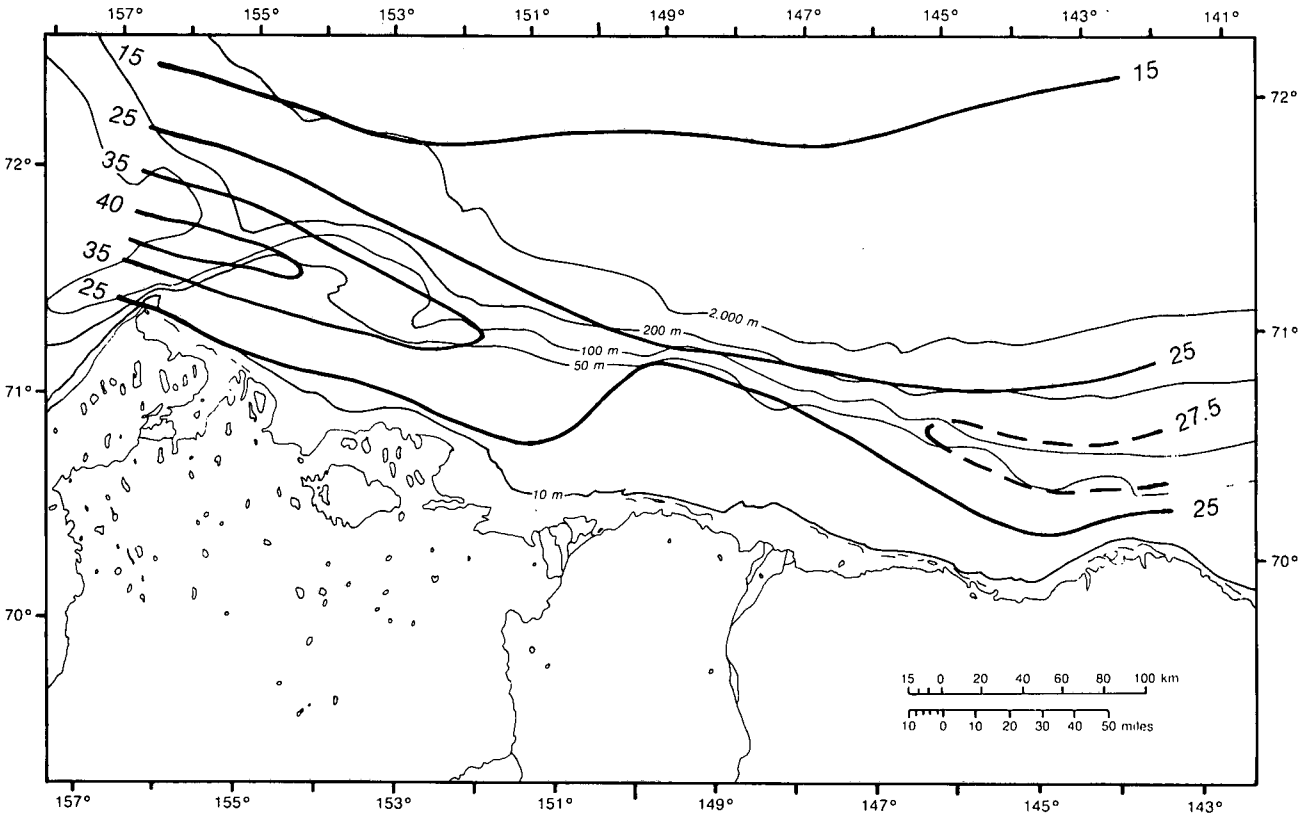

Figure 7.6—Annual primary production (g C/m²) projected from ice retreat data, euphotic zone depths, and 14C-uptake rate measurements. (Redrawn from Schell *et al.* 1982.)

7.2 PRIMARY PRODUCTION

The primary productivity and nutrient data collected during the past few years by OCSEAP investigators, as well as information in the literature, have been used by Schell *et al.* (1982) to construct contoured primary productivity maps of the Beaufort Sea. Figure 7.6 shows the average annual productivities during the years 1978-80. The details of constructing this map are described in the report listed and serve to point out the sharp gradients in primary productivity along an offshore transect. It is probably not coincidental that a superimposition of observed high densities of marine mammals and birds on this map falls upon the zones of highest primary production. The authors point out that the areas of high productivity probably vary greatly from year to year in response to meteorological and ice conditions and therefore the quantitative values of the contours serve only as indicators of the magnitude of expected production. I would emphasize that the contoured values of primary productivity represent *minimum* seasonal production based upon primary productivity rate measurements above the Arctic surface layer pycnocline (50-75 m). Evidence is mounting that upwelling events (Aagaard *et al.* 1981; Hufford 1974) and deep production (William G. Harrison, pers. comm.) may be the dominant processes governing summer production in the Arctic and are as yet very poorly described.

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Chapter 8
Invertebrates

by Lyman K. Thorsteinson

Biologically, the Alaskan Arctic Ocean often seems sparsely populated and of diminished productivity when compared to other portions of the Alaskan continental shelf. Coastal and pelagic ecosystems appear simplistic in light of their invertebrate food base and the relatively small number of species that fulfill the nutritional requirements of most vertebrate consumers each year. Yet food does not appear to be a limiting factor affecting vertebrate abundance. The Arctic is characterized by extreme environmental conditions; however, the life histories of the invertebrates in a variety of habitats offer many fascinating clues as to their adaptation to this environment. More than 300 invertebrate species have been identified in the Beaufort Sea, and additional species seem likely, particularly among the taxonomically complex amphipod group. Invertebrates occupy a suite of unusual arctic habitats from the fast ice zone in the very nearshore to the under-surface layer beneath sea ice, and may play an important role in arctic ecology.

The Diapir Field planning area contains an expanse of invertebrate habitats in the southwestern Beaufort and northeastern Chukchi seas. The area covers approximately 72,000 km^2 and extends from 5 to 527 km offshore in depths from 2 m to greater than 200 m (DOI 1983). In the Alaskan Beaufort Sea, the Diapir Field is largely contained shoreward of the 100-m isobath, a region characterized by a shallow and narrow continental shelf (approximately 50,000 km^2), with the shelf break usually between the 50- and 70-m contours at 55 to 100 km from the coast (Figure 8.1). As such, the lease area and adjacent waters encompass benthic communities and species associations from the very nearshore to the upper continental slope in the Alaskan Beaufort Sea, and to greater depths to the west in the Chukchi Sea.

The initial invertebrate studies sponsored by OCSEAP in the Beaufort Sea in 1975 were primarily reviews and syntheses of existing information. Since 1976 OCSEAP studies have focused on nearshore and coastal dynamics because the technological capability to exploit petroleum resources was concentrated in shallow depths; exploitation of petroleum resources in deeper waters and offshore areas with severe ice stresses is far in the future (Norton and Weller 1984). Invertebrate research thus has been coastally oriented, with shallow water (less than 25-m depths) benthic stations at locations nearest to proposed lease offerings receiving highest priority. As a consequence, very few invertebrate collections have been obtained in the deeper portions of the northeastern Chukchi Sea, and unless otherwise noted, the following description will pertain to the southwestern Beaufort Sea.

8.1 ENVIRONMENTAL PROCESSES

8.1.1 Physical Processes

The physical environment and geology of the southwestern Beaufort Sea have been previously described (Barnes and Reimnitz 1975; DOC 1978; Norton and Sackenger 1981; DOI 1983; Barnes *et al.* 1983; Craig, Sherwood, and Johnson 1985). Benthic fauna generally reflect the sediment composition of the substratum (Lie 1968), and most infaunal surveys have incorporated this environmental variable into their analyses. The surficial sediments of the southwestern Beaufort Sea consist predominantly of mud-clay and silt-sized particles (Figure 8.2). In the present sedimentary regime, the intensity of ice gouging, the wave and current activity, and the composition of sediment delivered from rivers and coastal bluffs are the

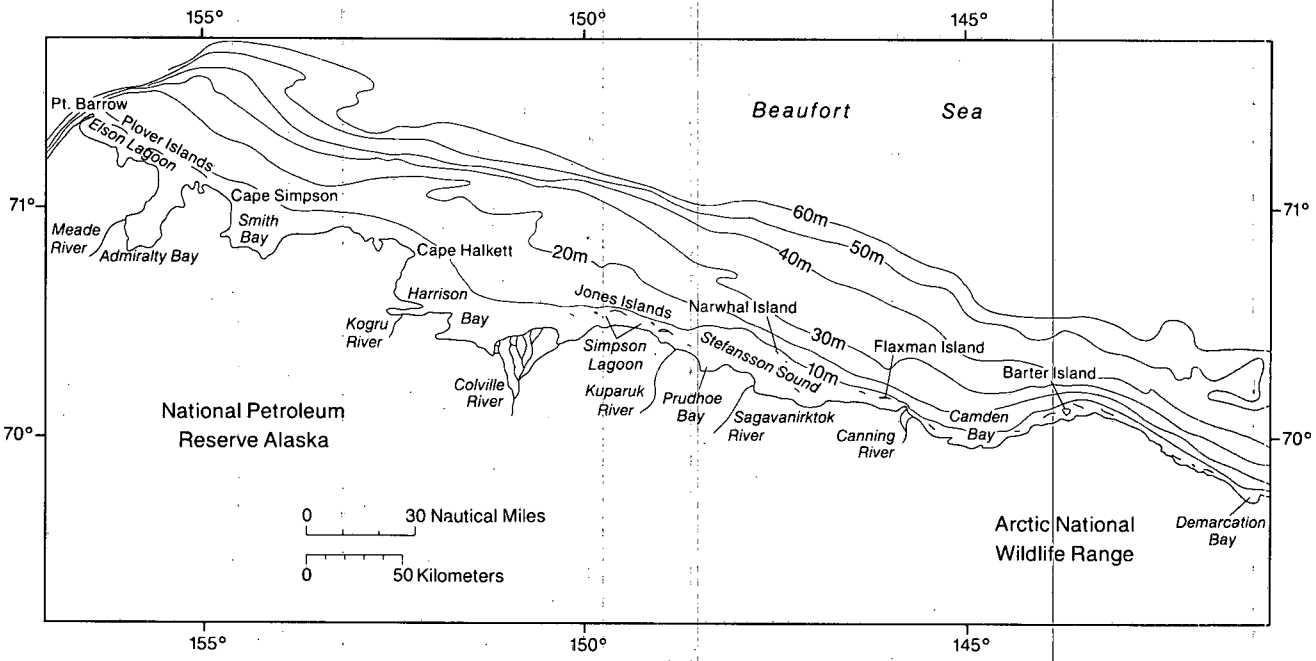

Figure 8.1—The coast and shelf of the Alaskan Beaufort Sea (from Norton and Weller 1984).

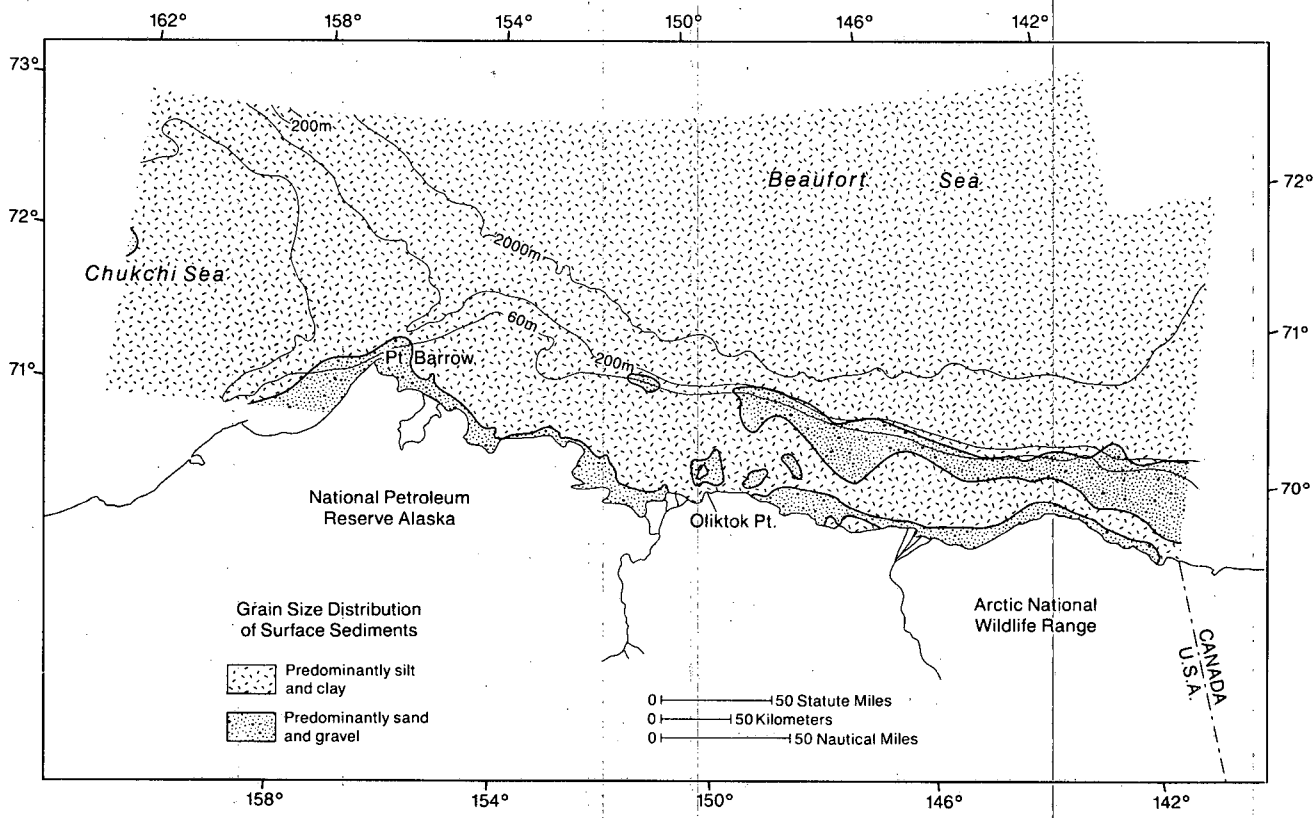

Figure 8.2—Generalized distribution of coarse-grained (sand and gravel) and fine-grained (silt and clay) surface sediments in the Beaufort Sea Planning Area. Coarse-grained sediments on the outer shelf may occur as thin, discontinuous glaciomarine lag deposits overlying finer-grained sediments (from Craig *et al.* 1985).

most important factors affecting sediment composition and texture (Craig, Sherwood, and Johnson 1985). Three generalized shelf zones have been described based on surficial sediment texture and depositional environment: the inner shelf, central shelf, and shelf break. The inner shelf lies between the coast and the 20-m isobath and is characterized by moderately to well-sorted silts and fine sand. This area lies in the fast ice zone and is relatively unaffected by ice gouging. Sediments of the inner shelf are derived primarily from coastal erosion and river effluents. The central shelf lies from the 20-m isobath to the shelf break and is characterized by sediments that are predominantly gravelly muds. Sediments in the central zone are greatly disrupted by ice gouging. The shelf break zone is located between the 60- and 200-m isobaths. Sediments are characterized by a 5- to 20-cm thick unit of muddy gravel overlying a clayey silt.

Wind, water movement and transport, and sea ice dynamics are the main physical processes affecting coastal food webs (Truett 1984a). During the open-water season (mid-July to late September), prevailing winds are from the east and the water transport is along the coast and to the west. The coastal movements result in a well-mixed water column to about the 20-m contour. Under low synoptic conditions, prevailing winds promote the flushing of bays and lagoons. However, coastal landforms such as barrier islands, spits, submerged bars, and causeways will influence coastal flow (Truett 1984a). The following abbreviated description of the physical processes in the Arctic has been taken in context from Truett (1984a).

Cross-shelf water mass transport and exchange (particulate carbon and nutrient sources, accumulation of peat and detritus, transport of invertebrates) may be the most influential physical processes affecting the nearshore ecology of the Diapir Field lease area. The mechanisms for cross-shelf exchange include upwelling in deep shelf waters, estuarine exchanges near river mouths, wind- and tide-driven exchange in shallow shelf waters, and thermohaline exchange under ice. *Upwelling* events appear to be common along the coast (Hufford 1973; Hufford 1974a,b; Hufford *et al.* 1974; Aagaard 1981), with saline water from 200 m and deeper being moved onto the shelf and landward. During periods of peak river discharge, a freshwater lens forms over more saline waters, resulting in an *estuarine-marine* exchange. The freshwater can extend 10-15 km offshore in front of the Colville River (largest Alaskan river discharging into the Beaufort Sea) and may entirely replace seawater in some bays and lagoons fronting intermediate or larger-sized rivers (Matthews 1979, in Truett 1984a). Although longshore water movements are dominant in the open-water season, cross-shelf exchange is probably common (Truett 1984a). Landward *thermohaline* flow at the bottom would occur when winds are from the east and the sea level is lowered, resulting in brackish coastal water being pulled offshore. During periods of ice coverage, thermohaline flow would be opposite the summer condition, with highly saline water flowing seaward along the bottom and less saline water moving landward higher in the water column (Truett 1984a). Other sources of water mass exchange include marine intrusions from the Bering/Chukchi Sea and from the Canadian Arctic.

Sea ice effects on the seafloor and associated marine life are most severe in the very nearshore waters (less than 2-m depth) and coastal waters, most notably in the stamukhi zone (transition zone between relatively stable land-fast ice and highly mobile pack ice), at depths between 18 and 30 m. Ice coverage in the Sale 87 area can be as long as nine months each year (October to June) and has a dramatic effect on regional productivity, *i.e.*, clearness of ice and effective penetration of light into the water column.

8.1.2 Biological Processes

Typical biological energy sources, nutrient regimes, and the annual effective illumination available for phytoplankton production in Harrison Bay and other parts of the southwestern Beaufort Sea (at depths not exceeding 10 m) have been described by Schell and Horner (1981). A total particulate carbon budget of 460 × 10^6 kg C/yr was estimated, with 43% of the carbon source attributed to primary production, 50% to terrestrial runoff, and 7% to coastal erosion. Nutrients, mainly nitrogen and phosphorus, are probably at an annual maximum in March prior to their uptake by ice algae and phytoplankton. Nitrate, ammonia, and phosphate concentrations in ice-covered waters in Harrison Bay ranged between 4-7 μg-atoms nitrate, 1-3 μg-atoms ammonia, and 0.6-1.5 μg-atoms phosphate, respectively, in March. These elevated levels result from *in situ* regeneration (heterotrophic production followed by mineralization of organic nitrogen) during winter periods of decreased biological activity. Schell (1974) reported combined ammonification and nitrification rates of 0.05 μg N/l·hr during the winter in the Colville River delta channels and eastern Harrison Bay. Additionally, he estimated a rate

of 0.13 μg N/l·hr in the overall water column in areas of high organic matter (especially detrital peat). Ammonification rates for the coastal Diapir Field lease area in August have been estimated at 0.012-0.019 μg N/l·hr (Alexander 1974). Schell and Horner (1981) describe the annual effective illumination for phytoplankton production in a 10-m photic zone as 1200 hr between 20 July and 30 September.

Ammonium nitrogen is greatly depleted from the shallow Alaskan Beaufort Sea by late spring and early summer. Uptake rates differ with depth, depending on the effective penetration of light through the water column. Ice algae and phytoplankton remove almost all of the preferred nitrate and ammonia from the water column as summer commences (Schell and Horner 1981). Arctic rivers, such as the Colville River in the central portion of the Beaufort Sea and the Angun River in the northeastern Chukchi Sea, provide important additional sources of nitrogen (and in lesser amounts phosphate) to coastal waters (Schell and Horner 1981; Kinney 1985). *In situ* regenerative processes and advection of nutrients onto the shelf also contribute to nitrogen availability in coastal waters during the open-water season. Nitrogen is typically less than 1.0 μg-atom N/l during this period, and coastal waters are nitrogen-limited (Schell and Horner 1981). Shelf waters are highly stratified, with low nutrient levels near the surface (Hufford 1974b; Horner 1981) resulting in low biological productivity (Schell *et al.* 1982).

The reduced light levels and low nutrient availability characteristic of this environment are reflected in the region's relatively low rates of primary productivity. The seasonal primary productivity is typically between 0-2 g C/m^2·yr for ice algae, and 5-20 g C/m^2·yr for phytoplankton in nearshore waters to depths of about 10 m (Schell *et al.* 1982). Seaward of barrier islands, and in deeper waters, ice algal production increases to 2-6 g C/m^2·yr and phytoplankton increases to about 16-36 g C/m^2·yr. It has been suggested that farther offshore still (beyond 200 km), where the ice pack is perennial, phytoplankton productivity decreases to less than 1 g C/m^2·yr (Appolonia 1959; English 1959). For comparative purposes, *i.e.*, between regions, it is cautioned that these productivity rates be viewed with discretion, as they represent depth-integrated values of the entire water column and not just the photic layer.

The phytoplankton community is widely dispersed across the southwestern Beaufort Sea. Some species, however, are associated with specialized environments or distinct water masses and are patchily distributed in space and time (Carey *et al.* 1984). Schell *et al.* (1982) described a band of higher productivity (35-40 g C/m^2·yr) from Point Barrow east to 152° W along the 20-m contour, and additionally characterized the eddies north of the Plover Islands (143° W) as having annual productivity rates approaching 50 g C/m^2. Areas east of 151° W have annual productivity rates between 15-27.5 g C/m^2 (Schell *et al.* 1982). The higher productivity of the western portion of the southern Beaufort Sea may be due, at least in part, to advection of Bering Sea water (nutrients, phytoplankton cells, and zooplankton) into the area (Johnson 1963; Horner 1980; Divoky 1984). Divoky (1984) characterizes the Bering Sea Intrusion as consisting of two water masses: the Alaskan coastal water, which mixes with arctic surface water soon after passing Point Barrow; and Bering Sea water, which moves east to the Plover Islands region. In other areas of high estuarine influence, such as the Colville River delta, annual productivity rates of 10-15 g C/m^2 have been related to local effects of enhanced nutrient contributions from the riverine system (Horner and Schrader 1982). The Barter Island nearshore area in the eastern Beaufort Sea is another region of suspected increased nutrient and organic matter input, as evidenced by a rich benthos found there.

The relatively low annual primary production of the southwestern Beaufort Sea is reflected in low zooplankton abundance (Horner 1981). In the southeastern Beaufort Sea, Frost and Lowry (1984) have estimated an average total secondary consumer biomass of 28 g C/m^2. It is unlikely that the transfer of energy from the ingestion of phytoplankton produced *in situ* can account for this biomass (even with ecological efficiencies of 60-70%, Schell *et al.* 1982), suggesting that the zooplankton are feeding off other carbon sources such as locally derived or advected detrital material, or are themselves assembled in other places.

8.2 ZOOPLANKTON

The zooplankton community of the Diapir Field region remained poorly known until the early 1970's. Even then, after several years of surveys, information regarding the species composition, succession, biomass, and numerical abundance was scattered and fragmentary in nature (Carey 1978a). Species-specific data are still largely lack-

ing, but surveys conducted over the past decade or so have provided reasonable qualitative coverage of some gross patterns of distribution and abundance in relation to hydrographic conditions.

Little new information is currently available from the southwestern Beaufort Sea relative to what was previously presented for the Harrison Bay Sale 71 lease area (Norton and Sackenger 1981). More recent data have, however, been reported from seasonal surveys conducted in the central portion of the coastal Beaufort Sea, including Harrison Bay, Stefansson Sound, and offshore Narwhal Island between November 1978 and August 1980 (Schell and Horner 1981; Horner and Schrader 1982, 1984). These surveys have confirmed earlier plankton results; zooplankton distribution and abundance are affected by hydrography (Horner 1980).

There are at least 37 species of zooplankton common to the southwestern Beaufort Sea (Horner and Schrader 1982). Correlations between dominant zooplankton and broad environmental zonations are possible according to abundance and overlap of species in differing water masses, *i.e.*, Bering/Chukchi seas and Arctic Ocean waters (Table 8.1). In addition to the species listed in Table 8.1, Grainger (1975) reported small numbers of characteristic species of the deeper Atlantic layer of the Arctic Ocean (200-900 m) in surveys of the southeastern Beaufort Sea: *Chiridius obtusifrons, Gaidius tenuispinus, Heterorhabdus norvegicus, Spinocalanus* sp., *Scaphocalanus magnus,* and *Scolecithricella minor.* Actual abundance estimates are not presented here but are available in data listings provided elsewhere (Grainger 1975; Carey 1978a; Schell and Horner 1981; Horner and Schrader 1982). The observed variances in annual estimates of zooplankton abundance that are probably related to sampling biases (and other sources masked in natural variability) make time and space comparisons, beyond those already portrayed, extremely tenuous. These sources of variation in zooplankton abundance lie in the various methods of plankton collection, quality of time series data

Table 8.1—Environmental zonation of the dominant zooplankton of the southwestern Beaufort Sea*.

Dominant Species (no./1,000 m^3)	Expatriates from Bering/Chukchi Seas	Common Throughout Arctic Basin	Nearshore Less Saline	Meroplanktonic Life Stages
Copepods	*Calanus cristatus* *Eucalanus bungii*	*Euchaeta glacialis*	*Pseudocalanus elongatus* *Acartia longiremis* *Pseudocalanus major* *Eurytemora herdmani* *Acartia clausi* *Derjuginia tolli* *Limnocalanus macrurus* *Acartia bifilosa* *Harpacticus uniremis*	
		Calanus hyperboreus *Metridea longa* *Microcalanus pygmaeus* *Calanus glacialis* *Oithona similis*		
Euphausiids	*Thysanoessa raschii?*	*Thysanoessa raschii* juvenile euphausiids		
Amphipods		Juvenile Amphipods		
Other Taxa	Barnacle larvae	Mysids Larvaceans Chaetognaths		Barnacles Polychaetes Hydrozoans Gastropods Decapods†

* **Sources:** Carey 1978a; Schell and Horner 1981; Horner and Schraeder 1982; Divoky 1984.
† Primarily shrimp of the family Hippolytidae.

obtained, and numerous environmental variables, including season, water depth and salinity (especially freshwater influence), ice condition, and predator-prey relationships. The spatial distribution of zooplankton is patchy for the species common to the littoral and continental shelf waters (Carey 1978a). This patchiness has been attributed to biological interactions (food requirements, mortality, and sinking rates) which may exert more direct influence than hydrographic processes (Redburn 1974).

Copepods are the predominant zooplankton, though larvae of benthic decapods and barnacles are numerous, particularly over the shelf (Carey 1985). The zooplankton community appears to comprise individually large, efficient grazers of phytoplankton, which, in turn, are important prey for vertebrate consumers (Truett 1984a; Frost and Lowry 1984). The annual rate of vertebrate consumption of the zooplankton has been estimated at 22.6 g/m^2 (Griffiths and Buchanan 1982). It has further been estimated that in August and September in the southwestern Beaufort Sea, 90% of the bowhead whale diet is composed of zooplankton; nearly twice as many euphausiids (45,000 t, 65%) are consumed compared to copepods (20,812 t, 35%) (Frost and Lowry 1984). These zooplankton groups also provide major forage for both seabirds and arctic fishes, those apex predators of the arctic pelagic/planktonic food web.

A more recent estimate of the annual consumption of zooplankton by bowhead whales occurring in the Alaskan Beaufort Sea is 400,000 t (Richardson 1986). This value is higher than previous estimates of Frost and Lowry (1984) and is based on (1) the caloric content of zooplankton sampled in the eastern Alaskan Beaufort Sea, and (2) an estimated 4,417 bowhead whales feeding in the Alaskan and Canadian portions of the Beaufort Sea for 130 days. An annual food requirement of 400,000 t suggests that the bowhead whales are feeding in areas where zooplankton biomass averages 1.7 g/m^3. Richardson (1986) does not estimate the consumption of zooplankton from the Diapir Field area but suggests that feeding by whales in the region of upwelling in the eastern Alaskan Beaufort Sea may contribute less than 1 percent of the bowhead food requirement.

Detailed life history information for zooplankton species of the Diapir Field lease area is either lacking or is generally unavailable in published reports. Results of the most recent surveys indicate only one new species' range extends into the Beaufort Sea, that of *Acartia bifilosa*. The likelihood of nearshore breeding by the copepods *Pseudocalanus elongatus* and *Derjuginia tolli* in Harrison Bay in August was reported by Schell and Horner (1981). *Pseudocalanus elongatus* was the most abundant zooplankton species in Harrison Bay, Stefansson Sound, and off Narwhal Island in the 1978-1980 seasonal surveys.

8.3 BENTHOS

8.3.1 Ecological Zonation

Spatial and temporal features of benthic distribution and abundance seaward of the Beaufort Sea coast can be constructed with reasonable confidence using available data. Similarity analyses have formed a picture of community structure that reflects depth-stratification of most arctic species (Wacasey 1975; DOC 1978; Johnson 1981; Norton and Sackenger 1981). In the Canadian portion of the southeastern Beaufort Sea, the estuarine influence of the Mackenzie River extends far offshore and results in a broad transitional zone of reduced temperature and salinity (and intense ice gouging) not evidenced in the west (Figure 8.3). A classification system that defined fewer (four) invertebrate zones than were recognized by Carey (1978a) was adapted to the Harrison Bay Sale 71 area. These zones were based on bathymetry, geomorphology, biomass, and species similarity characteristic of the south-central Beaufort Sea. The Harrison Bay zonation included the following: a nearshore zone (0-2 m isobath); an inshore or coastal zone (2-20 m isobath); an offshore or shelf zone (to about the 70-m isobath); and a slope zone (to about the 200-m isobath, Broad *et al.* 1981). The nearshore zone was considered independently of the littoral zone (usually 0-10 m depth) due to the seasonality of its characteristic fauna (this zone is characterized by low species diversity and low biomass). The seasonality was attributed to the harshness of this environment with its periodic sea ice and salinity stresses (Broad *et al.* 1981). However, Broad *et al.* (1979) did not distinguish a nearshore zone but instead discussed the shallow sublittoral as a habitat of annual recolonization by species from adjacent waters during summer months. This recolonization is thought accomplished through directed species migrations or recruitment mechanisms. Carey *et al.* (1984) were able to define nearshore, inner and outer shelf, and slope assemblages of polychaetes and gammarid amphipods. These assemblages are comparable to previous depth-

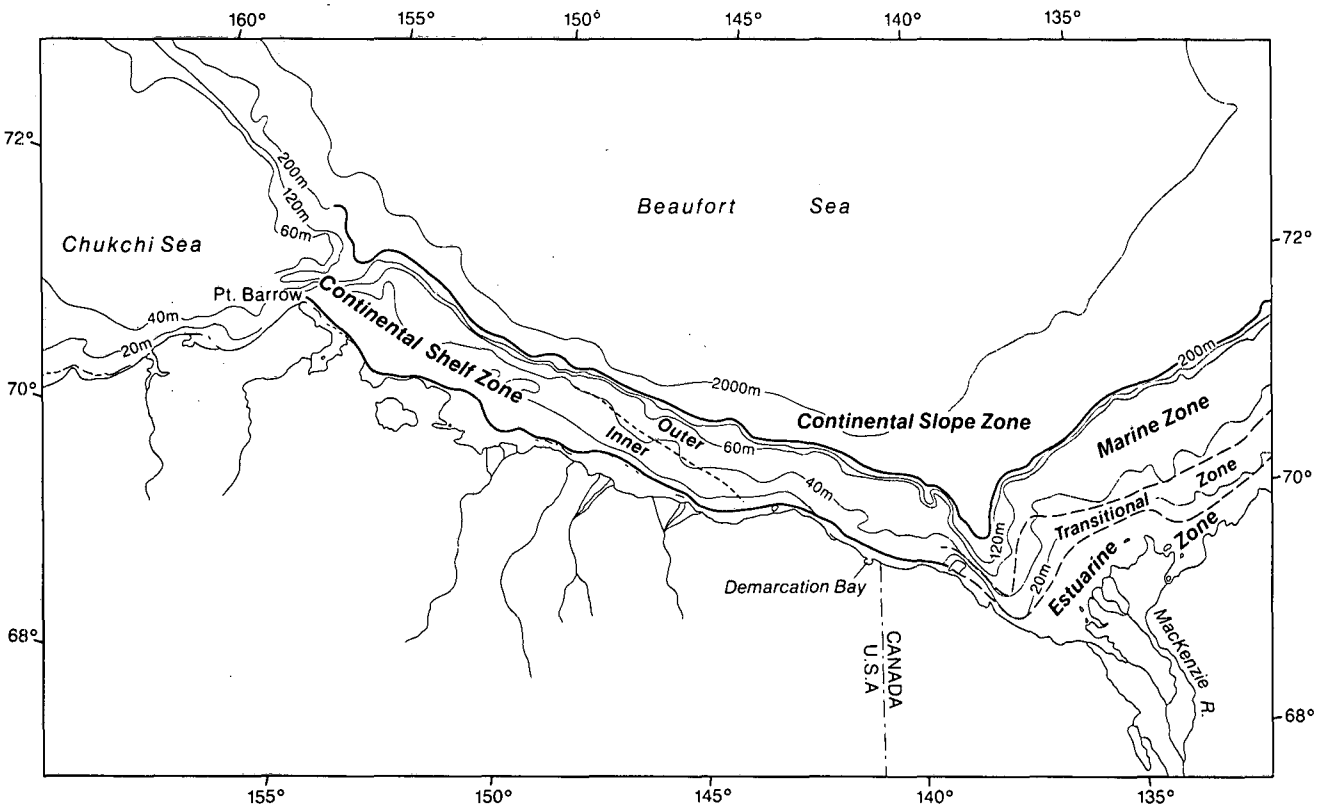

Figure 8.3—Benthos environmental zones (from Carey 1978a).

related abundance patterns. A zone of depressed invertebrate abundance is found in the stamukhi zone.

The above zones are generally sufficient for invertebrate descriptions from most coastal and offshore portions of the Diapir Field lease area. Some nearshore habitats, such as arctic lagoons or areas of enhanced biota, require additional discussion. Other areas that have received special research emphasis because of their proximity, or suspected vulnerability, to ongoing or planned OCS developments are also treated in greater detail.

In view of the geographic boundaries of the Diapir Field, it is significant that both the nearshore northeastern Chukchi Sea (north of Point Hope) and the southwestern Beaufort Sea have the same invertebrate fauna (Broad *et al.* 1979). A statistical comparison of species diversity and mean biomass of infaunal and epifaunal organisms from each area supports this regional similarity (Truett 1984b).

8.3.2 The Littoral Zone

Broad *et al.* (1979) collected 232 species of infaunal and epifaunal invertebrates during a two-year survey in the Point Barrow to Barter Island region. Organisms were sampled at 44 stations across the coast. The infauna was represented by 59 species of annelids (mostly polychaetes) and 28 bivalve mollusks. Amphipods (with 54 species, mostly gammarids) dominated the epibenthic fauna. Five mysid and 4 isopod species were collected.

Surficial nearshore sediments (0-2-m isobath) are composed of sand, silt, and gravel with large amounts of terrestrially derived peat (Broad *et al.* 1981). The principal invertebrates are chironomid larvae and oligochaete worms. The isopod *Saduria entomon* and the amphipods *Gammarus setosa* and *Onisiumus litoralis* are the dominant motile epibenthos. Throughout this zone, biomass and diversity are low; biomass averages 3.1 g/m^2 and ranges 0-21 g/m^2 (Broad *et al.* 1981).

Deeper portions of the littoral zone have a seafloor consisting of silty deposits, with much sandier bottoms in delta areas. The infauna has been characterized as rich, displaying greater species diversity than found inshore (Table 8.2). The estimates are comparable to similar data presented for Harrison Bay (9-43 species, average biomass 30 g/m^2, biomass range 1-160 g/m^2, Broad *et al.* 1981). These standing stock estimates are higher than those found in the more temperate waters of the Pacific Northwest or the Gulf of Alaska, and are thought to result from diminished wave activity in the southwestern Beaufort Sea (Carey *et al.* 1984).

Table 8.2—Average wet weight biomass and density of macrobenthic infauna of the littoral zone (0-10 m) of the Alaskan Beaufort Sea in August 1977 (data from Broad *et al.* 1979).

Taxonomic Group	Biomass (g/m^2)	Density (No. Individuals/m^2)
Polychaetes	9.57	1999.59
Oligochaetes	.03	114.28
Gastropods	.65	53.26
Bivalves	11.49	505.34
Isopods	6.33	5.97
Amphipods	.58	96.27
Other	1.32	447.32
Total	29.97	3222.03

Diversity: 1-43 species per station

Polychaetes, bivalves, and isopods are the most abundant infauna, and they all exhibit patchy distributions. High degrees of spatial variability in biomass of individual species are common along the coast and reflect depth and bottom-related influences (Table 8.3). Other environmental factors that affect geographic patterns of animal density and size include salinity and temperature regimes, nutrients, depth of light penetration, and the grazing rate of zooplankton. All variables considered, the invertebrates of the littoral zone have been described as sparse but exhibiting a patchy distribution (Broad *et al.* 1979).

The numerically abundant infauna of the deeper littoral zone include, in declining abundance, the following (Broad *et al.* 1979):

Polychaetes

Prionospio cirrifera, Tharyx sp., *Chone* sp., *Terebellides stroemi, Ampharete vega, Scolecolipides arcticus, Melanis loveni, Spio filicornis, Praxillella praetermissa, Scoloplos armiger, Sternaspis scutata, Nephtys caeca, Sphaerodoropsis minuta.*

Bivalves

Portlandia arctica, P. intermedia, Liocyma fluctuosa, Boreacola vadosa, Macoma loveni, M. calcarea, Cyrtodaria kurriana, Astarte borealis, Axinopsida orbicualata.

The dominant epibenthos can be similarly characterized based on gross estimates of biomass derived from limited coastal trawling (Table 8.4). Mysids, amphipods, isopods, and other motile crustaceans were relatively abundant. The abundance of these organisms varied by geographic location (Table 8.5). Seasonal fluctuations in abundance have been reported in arctic lagoons and have been related to coastal transport and seasonal migrations (Truett 1984a). In order of decreasing abundance the dominant epibenthos include the following (Broad *et al.* 1979):

Mysids

Mysis litoralis, M. relicta.

Amphipods

Acanthostepheia behringiensis, Onisimus glacialis, Rozinante fragilis, Gammarus zaddachi, Boekosimus affinus, B. plautus, Monoculopsis sp., *Apherusa megalops, A. glacialis, Halirages* sp., *Weyprechtia pinguis, Acanthostepheia incarinata, Gammaracanthus loricatus.*

Isopod

Saduria entomon.

Copepod

Calanus hyperboreas.

Euphausiid

Thysanoessa raschii.

The dominant epibenthos of the littoral zone are scavenging or detritus-feeding organisms. Some, like *Gammarus setosa,* are known to ingest large amounts of detrital peat; however, their ability to digest cellulose has not been demonstrated.

Whereas *Gammarus setosa* and *Onisimus litoralis* were the most abundant species at 0-2 m depth, they were less frequently encountered in the deeper part of the littoral zone.

During the open-water season, polychaete and amphipod populations of the littoral zone remain fairly stable. They do, however, show increasing numbers in early summer and decreasing numbers, although with increased individual sizes, as the season progresses. Broad *et al.* (1979) tentatively suggested that such trends may reflect species' migrations or recruitment of young in the nearshore in early summer, followed by a period of growth. The abundance patterns are further affected by predation and/or emigration effects in August and September. The mobile crustaceans are least abundant early in the ice-free season, with populations peaking by mid-summer. This could also reflect population movements into warmer, less saline waters during summer in search of enhanced food and warmer temperature regimes for growth. The notion of recruitment of young into the zone in early summer is consistent with life history patterns observed for some arctic polychaetes and burrowing amphipods which show late-winter or spring reproduction with recruitment tied to the summer

Table 8.4—Relative abundance of the dominant littoral epibenthos (0-10 m) of the Alaskan Beaufort Sea. Average wet weights (g) and numerical abundances (no. of individuals) summarized from 5-minute epibenthic sled net tows (approximately 50 m; 1.05 mm mesh size) at 39 stations in 1977 (data from Broad *et al.* 1979).

	Grams/ 50-m Tow	Numbers/ 50-m Tow
Mysis litoralis	2.50	273.28
Mysis relicta	1.83	216.51
Saduria entomon	2.01	1.05
Calanus hyperboreus	.09	113.56
Thysanoessa raschii	.03	.69
Amphipods/ other Crustacea	3.08	56.1
Others*	.91	88.1
Total	10.45	749.29

* Others: See footnotes p. 1-66 in Carey *et al.* 1979; 17 taxonomic or species grouping (fish and bivalves).

season (Broad *et al.* 1979). A similar general trend was noted for the isopod *Saduria entomon;* individuals were larger later in summer, although both biomass and density had decreased.

8.3.3 Cross-Shelf Community Structure

The taxonomic composition and seasonal abundance of the major infaunal components of the southwestern Beaufort Sea are known. Descriptions of community structure have been characterized from the synthesis of WEBSEC and OCSEAP data collections taken in 1971-1972 and 1975-1978 (Carey 1976, 1978a,b; Carey and Ruff 1977; Carey 1979; Carey *et al.* 1981; Broad *et al.* 1981; Carey *et al.* 1984). The WEBSEC benthic surveys, sponsored by the National Science Foundation, were designed to provide more information on polychaete ecology in the Beaufort Sea. In 1975 a review of published and unpublished information on arctic invertebrates was initiated by NOAA (Carey 1976), and a year-round temporal study of benthos off Pitt Point was begun (5 sampling peri-

Table 8.5—Average weight (g) and number of dominant epibenthic organisms at several Beaufort Sea stations in 1977 (data from Broad *et al.* 1979). Data are standardized for a 50-m tow.

	Weights (g) Per Station						
	C4F	HOA	HOB	I3H	N1A	P2D	P2F
Mysis litoralis	1.88	21.57	.13	9.46	1.12	.20	
Mysis relicta							
Saduria entomon	9.03			5.89			
Calanus hyperboreus	1.02	.34					.01
Thysanoessa raschii							
Amphipods/other Crustacea	.19	.26		.69	.95	.07	
Other		1.36			8.55	.21	.06
Total	12.12	23.53	0.13	16.04	10.62	0.48	0.07
% Total Ave. Catch	99	97	76	98	99	98	70
	Numbers Per Station						
	C4F	HOA	HOB	I3H	N1A	P2D	P2F
Mysis litoralis	206	3,354	31	999	159	48	
Mysis relicta							
Saduria entomon	1			2			
Calanus hyperboreus	2,274	295					12
Thysanoessa raschii							
Amphipods/other Crustacea	21	45			230	4	
Other		314		84	370	43	21
Total	2,502	4,008	31	1,085	759	95	33
% Total Ave. Catch	99	97	74	97	98	98	92

Table 8.3—Average wet weight biomass and density number of individuals per m² of macrobenthic infauna at selected littoral stations along the Alaskan Beaufort Sea coast, August 1977 (data from Broad *et al.* 1979).

Location	Barter Island		Heald Point		Heald Point		Smith Bay		Pt. Barrow		Pt. Barrow		Pingok I.	
Station	C4F		HOA		HOB		N1A		P2D		P2F		T3F	
Depth (m)	5		2		5		5		2		6		5	
Bottom °C	0.2		1.5		0.9		5.5		6		5		1.5	
Salinity (‰)	28		34.3		27		29		27		26.5		31.5	
Bottom Sed.	sand/mud/peat		sand/peat		sand/gravel/shell		mud/peat		gravel/sand		sand/gravel		clay/mud/peat	
	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²	g/m²	No./m²
Polychaetes	7.18	1,716	4.99	339	9.63	844	6	1,489.33	0.01	7	1.95	271.33	2.69	177
Oligochaetes							<0.01	10			0.04	43.33		
Gastropods			<0.01	16.67	0.09	26.67	2.14	53.33			0.15	10	<0.01	3.33
Bivalves	2.30	160	4.61	60	8.36	270	43.69	2,103.33			0.64	60		
Isopods	7.53	3.33	2.29	3.33			7.92	6.67			1.28	3.33	25.39	3.33
Amphipods	1.17	103.33	0.16	296.67	0.14	86.67	0.62	13.33	0.14	108.33	0.99	20	0.02	16.67
Other	0.82	20	0.13	10	0.66	36.67	0.23	190	0.92	15,843.67	0.42	3.33	0.68	46.67
Total	19.00	2,002.66	12.18	725.67	18.88	1,264.01	60.60	3,865.99	1.07	15,959.00	5.47	411.32	18.88	247.00

ods over a 13-month period). Seasonal changes in infaunal density, biomass, productivity, and species composition were examined at 5 stations located between 25 and 100 m (Carey *et al.* 1981). The shelf data (25-70 m) were compiled from 3 OCS icebreaker cruises from the 1976-1978 summers and the slope data (70-200 m) from the 1971 WEBSEC and 1978 OCS cruises (Carey *et al.* 1984). Inshore extensions of the offshore transects complemented the shelf-sampling effort, providing shallow water (5-25 m) benthic collections in 1976 (Figure 8.4). Benthic sampling at all stations consisted of at least 5 quantitative grabs with a 0.1 m^2 Smith-McIntyre bottom-sampling device. Distributional patterns by depth and distance offshore were examined only for infauna greater than 1 mm in body length.

Trends in density and biomass of the infauna distributed along the centrally located transect off Pingok Island (off Harrison Bay) serve as typical illustrations for the Diapir Field lease area (Table 8.6 and Figure 8.5). By far, the three most abundant animal groups include the annelid polychaetes, pelecypod mollusks, and gammarid amphipods. All discussions therefore pertain to these groups. Nearshore, shelf, and slope assemblages have been statistically determined for the Pitt Point transect (Carey *et al.* 1984). In each case, broad transect lines could be extended across shelf and slope zones by grouping data sets obtained in different years. This synthesis and

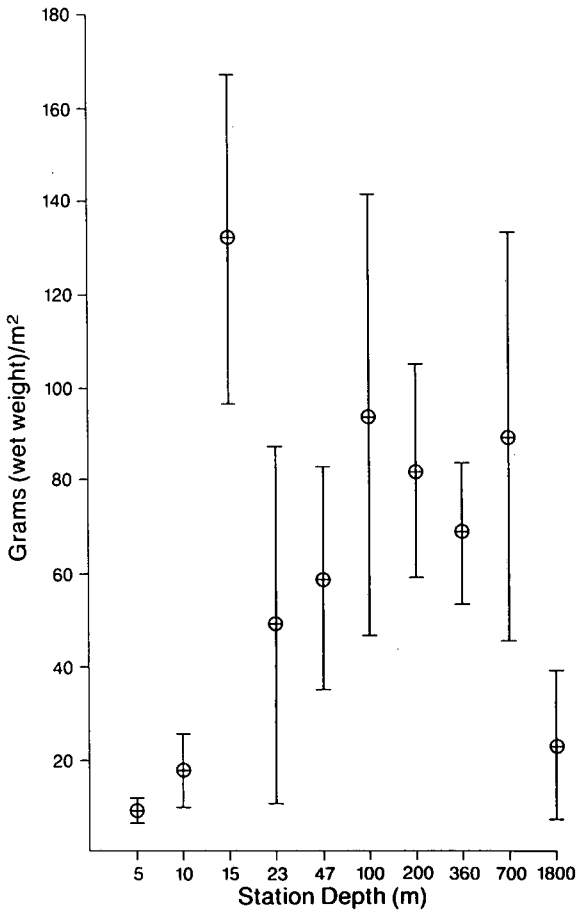

Figure 8.5—Standing stock biomass (wet-preserved) weight of benthic macrofauna on the Pingok Island cross-shelf transect. Means ± 1 standard deviation. N = 5 per station (from Carey *et al.* 1984).

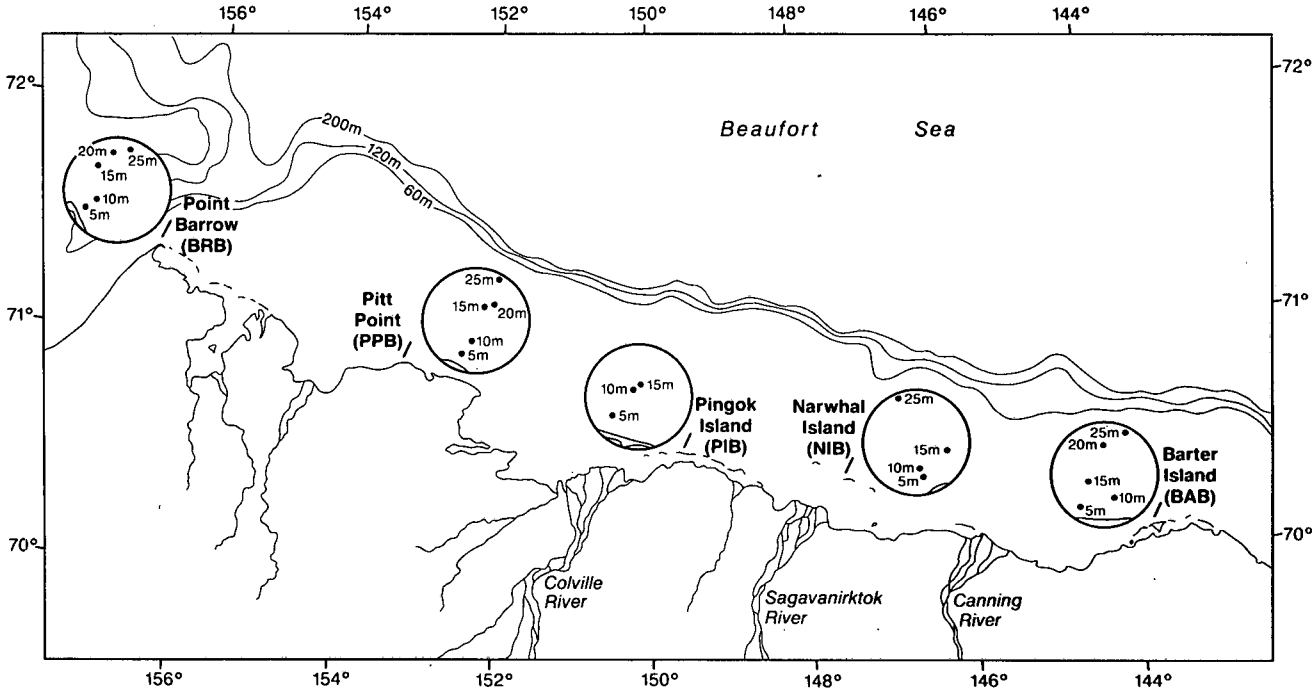

Figure 8.4—Transect lines occupied across the shallow shelf of the Beaufort Sea between Point Barrow and Barter Island. Insets show the relative positions of the stations (from Carey *et al.* 1981).

Table 8.6—Cross-shelf trends in relative abundance (% frequency of occurrence, rounded to nearest whole or + when <1) of major benthos (macrofauna > 1.00 mm) off OCS Pingok Island transect (from Carey *et al.* 1984).

	DEPTH (m)									
	5	10	15	23	47	100	200	360	700	1800
CNIDARIA										
Anthozoa			+		+		1			
ANNELIDA										
Oligochaeta									7	
Polychaeta	88	85	42	41	42	31	85	87	71	39
ARTHROPODA										
Amphipoda	5	+	6	1	28	7	3	2	2	2
Isopoda	1	+	+	+	1				+	+
Cumacea	1	+	+		3	1	+	+	+	3
Ostracoda		1	+		8	16	+	5	3	+
Tanaidacea		+	+		2	4	+	+	3	4
Pycnogonida		+	+		+				+	
MOLLUSCA										
Pelecypoda	+	12	23	35	13	35	5	3	13	48
Gastropoda		+	3	17	+	1	+	+	+	+
ECHINODERMATA										
Ophiurodea				2	+	3	3	+	+	+
Holothuroidea	+	+	+	+						+
CHORDATA										
Ascidiacea			18			+				
OTHER*	4	+	1	+	+	+	+	+	+	1

N = 649 (5 m); 3,601 (10 m); 949 (15 m); 799 (23 m); 1,226 (47 m); 1,185 (100 m); 1,494 (200 m); 1,181 (360 m); 2,273 (700 m); 673 (1800 m)

* "Other" refers to following groups by depth:
5-15 m: Priapulida, Hemichordata, Nemertina;
23-200 m: Echiuroidea, Sipuncula, Aplacophora, Brachiopoda, Priapulida, Nemertina;
360-1800 m: Aplacophora, Sipuncula, Scaphopoda.

comparison of data from several years was possible because of low interannual variability observed in three years of density and biomass indices (Carey *et al.* 1984).

More than 300 species of invertebrates have been sampled in the Alaskan Beaufort Sea. The infauna are distributed roughly into a nearshore group, and more widely into an inner and outer shelf, and upper slope group. The most dominant forms tend to exhibit broad distributions, with optimum depth zones in which they are markedly more abundant (Figures 8.6 to 8.8). A number of species exhibit a bimodal pattern of abundance, with the minimum centered in the region of greatest ice disturbance (20-40 m). An examination of the total density from infaunal samples reveals a bimodal distribution with maxima at 10 m and 700 m and minima at 5 m and 1800 m (Carey *et al.* 1984). At most stations polychaetes are the most abundant taxon, although bivalves are more numerous at 23 m, 100 m, and 1,000 m depths. Carey *et al.* (1984) noted that the abundance of infaunal biomass increases with depth to the outer shelf and upper slope areas, and decreases to low-standing stocks at 1,800 meters. High bivalve biomass estimates at 15 m were thought to be caused by the thick shell of *Astarte montagui*.

Polychaetes are widely and uniformly distributed across the continental shelf, with some species having high numerical abundance in more than one region. For example, *Minuspino cirrifera* is very abundant at both 10 m and 700 m, while *Chone* nr. *C. murmanica* is most abundant at 47 meters. Polychaete numbers are depressed at 15 m and may be related to ice gouging of the seafloor. Such variation across the shelf is indicative of the

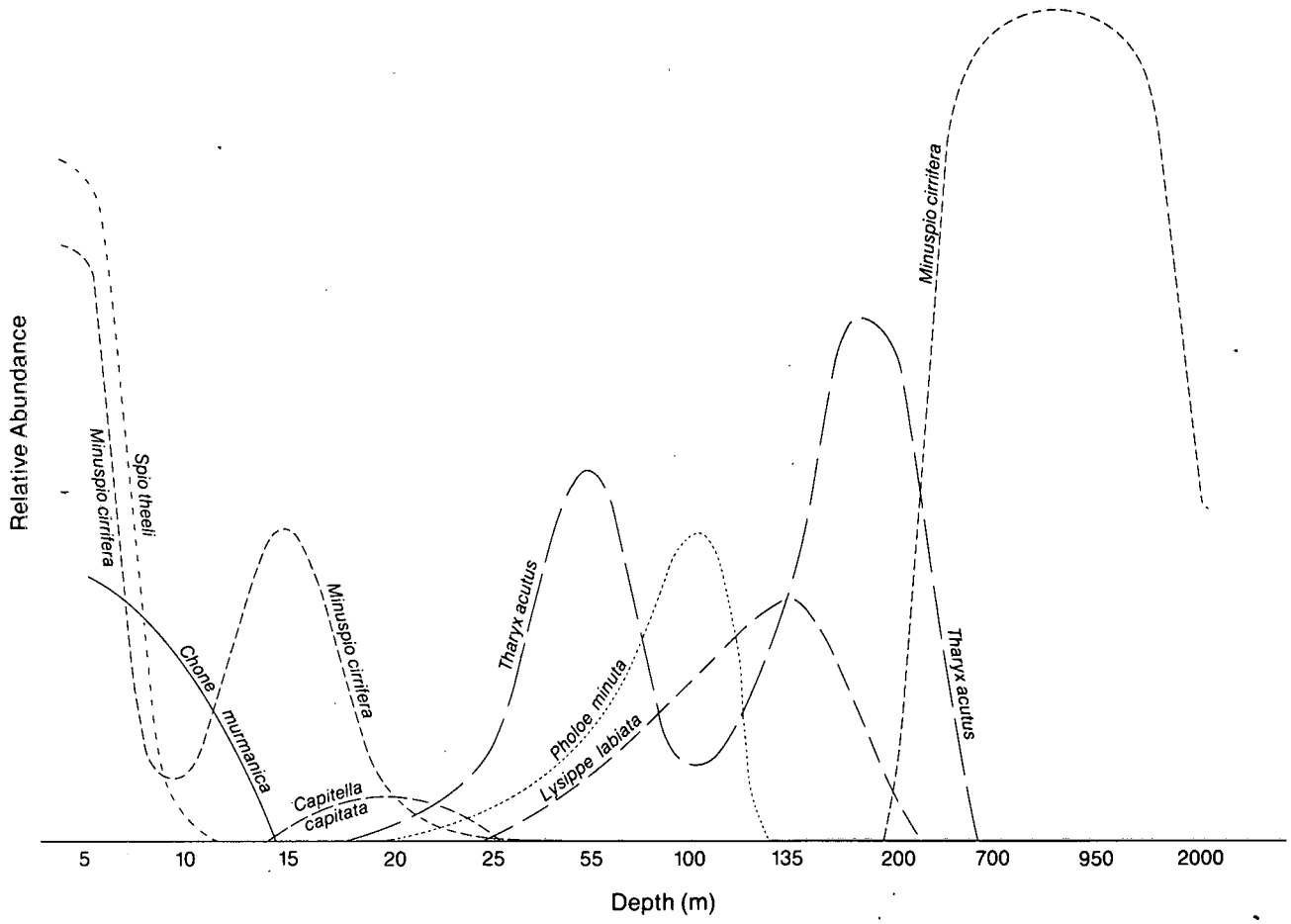

Figure 8.6—The relative abundances of the dominant polychaete annelids across the Pitt Point line from 5 to 2,000 m (from Carey *et al.* 1981).

patchiness of the fauna (Carey *et al.* 1984). Within the area of ice gouging, *Capitella capitata*, a species noted for its occurrence in areas of environmental disturbance, is commonly found.

Bivalves are also broadly dispersed across the southwestern Beaufort Sea. Unlike the polychaetes, the bivalves have rather narrow zones of greatest abundance. The bivalves can be categorized into a nearshore group (5-15 m depth) and an outer shelf group. An assemblage consisting of *Cyrtodaria kurriana, Axinopsida orbicula, Macoma calcarea, Boreacola vadosa,* and *Liocyma fluctosa* occurs primarily in shallower waters. *Liocyma fluctosa* and *M. calcarea* exist across the shelf but are most abundant between 5-10 m depths. Other species, such as *Nucula belotti, Astarte montagui, Thyasira gouldii, Astarte crenata,* and *Portlandia frigida,* predominate within outer-shelf sediments.

Gammarid amphipods can be grouped into nearshore, inner-, and outer-shelf assemblages. The most abundant amphipod of the nearshore (5-15 m), *Onisimus litoralis,* exists in low numbers out to the 100-m isobath. An inner-shelf assemblage is represented by nine species (Animal Ave. No./m^2): *Protomedeia fasciata,* 63.3; *Harpinia serrata,* 66; *Haploops laevis,* 22.7; *Byblis arcticus,* 103.3; *Unciola leucopsis,* 21.3; *Paraphoxus oculatus,* 36.0; *Photis vinogradova,* 18.7; and *Melita dentata,* 48.0. Average densities for all amphipods were 44.8 animals/m^2 and 39.8 animals/m^2 at 55- and 70-m depths, respectively. *Byblis arcticus* was the dominant species at the shallower depth, and *M. dentata* in deeper waters. The outer-shelf assemblage, located at 100 m, is composed of fewer species, including *Tiron spiniferum* (388/m^2), *Podoceropsis lindahli* (148/m^2), and *Guernia nordenskjoldi* (64/m^2).

Several hypotheses explaining the observed cross-shelf distributional patterns of arctic infauna have been offered. They are suggested in the bimodality exhibited in estimates of numerical abundance and their correlation with select environmental factors. The nearshore peak in

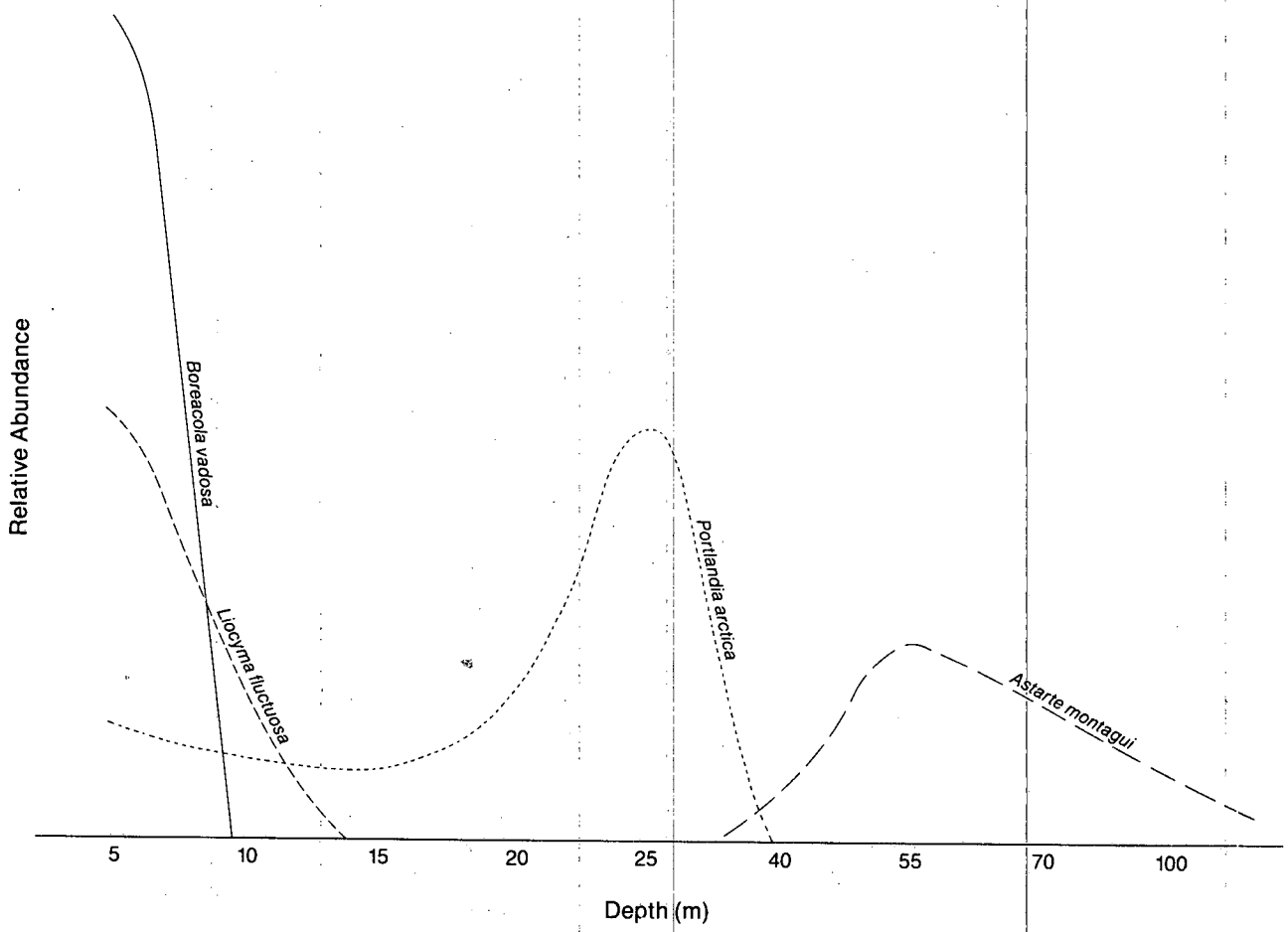

Figure 8.7—The relative abundances of the dominant bivalve mollusks across the Pitt Point line from 5 to 100 m (from Carey *et al.* 1981).

abundance may be associated with high inputs of terrestrial peat from coastal erosion and river runoff, while the maxima near the shelf edge may lie in a region of low-current energies resulting in a sink for oceanic detritus and fine sediments. In either case, the bacterial and meiofaunal community acting upon the various detrital forms is an important, but poorly defined, component of the benthic food web.

A study of polychaete feeding strategies emphasizes the increasing importance of subsurface deposit feeders with increasing depth (Figure 8.9; Carey *et al.* 1984). Surface deposit feeders are most common along the shelf edge and decrease in abundance down to 1,800 meters.

Epifaunal macro-invertebrates, largely dominated by echinoderm groups, are most abundant on the outer shelf and upper slope (Figure 8.10; Carey *et al.* 1984). Brittle stars are most numerous, especially *Ophiacantha bidentata*, *Ophuira sarsi*, and *Ophiocten* sp. This band of epifaunal abundance lies between the 70- and 100-m contours and overlies regions of high sedimentation. A negative correlation was found between ophiuroid density indices and infaunal abundance, suggesting the possible predation of brittle stars on shelf and slope infauna (Carey *et al.* 1984).

In a broad-scale trawl survey conducted in the northeastern Chukchi and southwestern Beaufort seas in 1976, Frost and Lowry (1983) identified 238 species of arctic invertebrates. The species composition included 49 gastropods, 34 amphipods, 28 polychaetes, and 27 echinoderms (mainly brittle stars and crinoids). In most instances, the echinoderms represented about 75% of the total biomass. Survey data were not presented by station, but some regional patterns in animal distribution were apparent.

At least two major epifaunal communities were qualitatively described from collections taken across the southwestern Beaufort Sea at depths of 40-400 m. West of 154°, brittle stars (usually *Ophiura sarsi*) were most abundant, but as a group the ophuiroids were least diverse. The soft corals

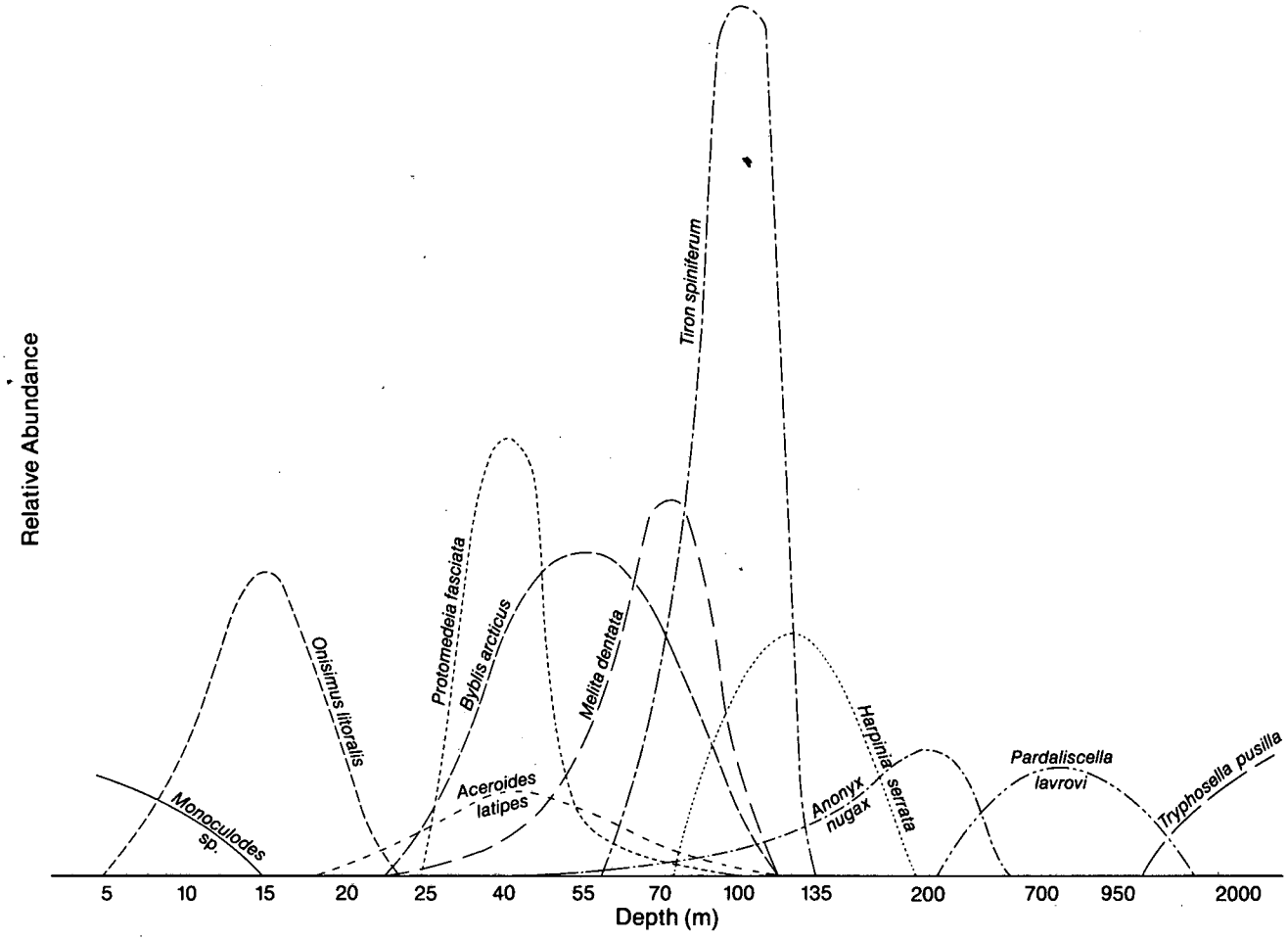

Figure 8.8—The relative abundances of the dominant gammarid amphipods across the Pitt Point line from 5 to 2,000 m (from Carey *et al.* 1981).

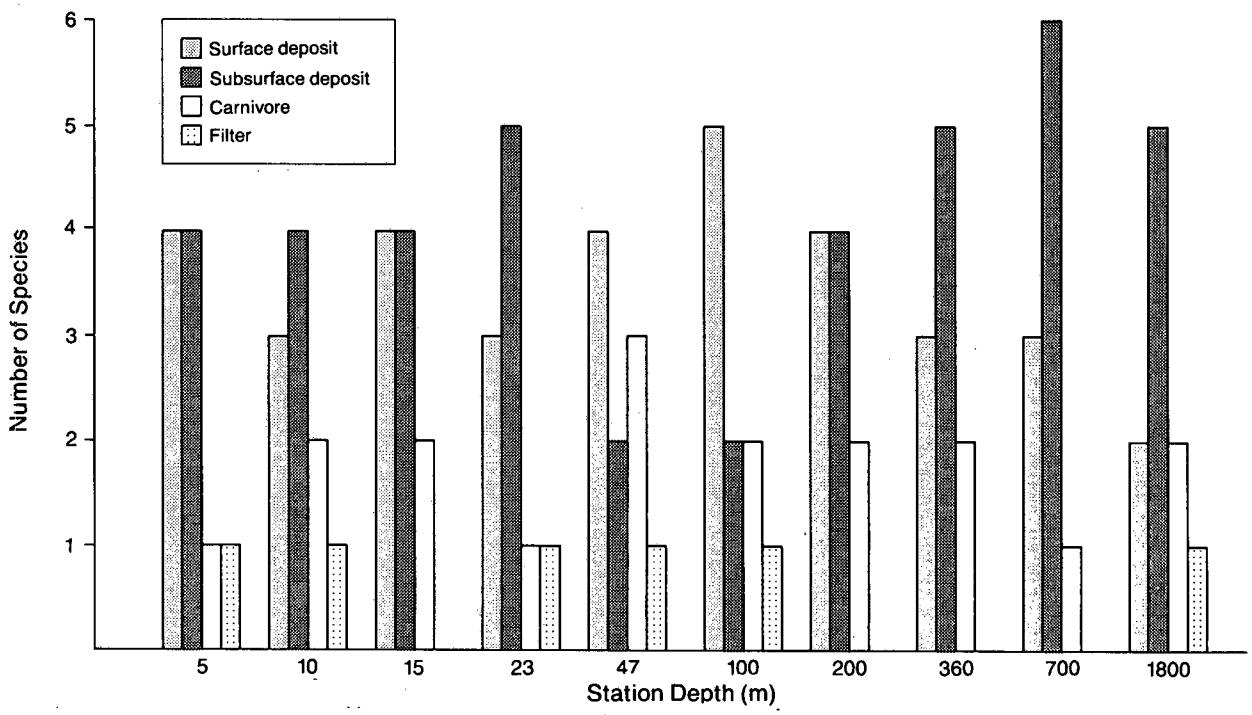

Figure 8.9—Feeding types of the 10 most abundant polychaete species on the Pingok Island cross-shelf transect (from Carey *et al.* 1984).

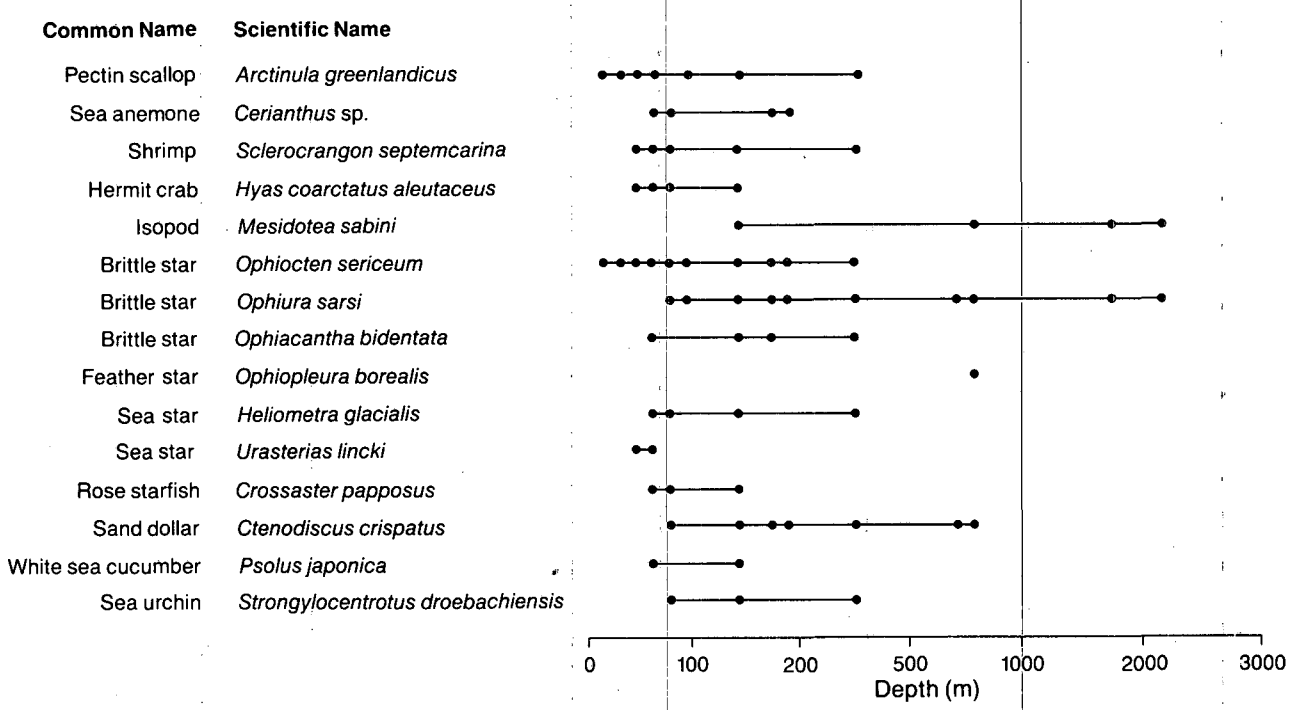

Figure 8.10—Distributional pattern of mega-epifauna (>1.3 cm) on the Pingok Island cross-shelf transect. Data derived from both otter trawl collections and bottom photography (from Carey *et al.* 1984).

Eunehthya sp. and the sea cucumbers *Psolus* spp. and *Cucumaria* sp. were also frequently taken in areas of brittle star abundance. These species were typically associated with a muddy seafloor. The shelf epifauna of the western Beaufort Sea appears to be similar to that of the northeastern Chukchi Sea but different from central and eastern Beaufort regions (Truett 1984b).

East of 150° W, the epifaunal community was characterized by the presence of the scallop *Delectropecten groenlandicus* and the crinoid *Heliometra glacialis.* Sea cucumbers (*Psolus* sp.), sea urchins (*Strongylocentrotus droenbachiensis*), several species of brittle stars, and the shrimp *Sabenea septemcarinata* were usually captured with the dominant species. This community was associated with rocky/pebbly bottom habitats found most frequently in the survey area between 158°-162° W. Other, more tenuous, distributional patterns were noted in trawl samples (Table 8.7).

Interestingly, *Chionoecetes opilio,* a Tanner crab harvested commercially in the Bering Sea and in great abundance in the southern Chukchi Sea, was also found in the Beaufort Sea east of Point Barrow. These crabs were generally of small size and poor reproductive condition, suggesting that they may be reproducing elsewhere. Greater numbers of ovigerous females were observed in catches west of Point Barrow. These crabs, or others located in more southern spawning areas, may be the source of pelagic larvae being transported into the Beaufort Sea.

8.3.4 Benthic Community Functions

Invertebrate production in the shallow waters of the southwestern Beaufort Sea (5-25 m) is a primary concern in understanding how the coastal ecosystem functions (Carey 1978a,b; Divoky 1984; Conners 1984; Frost and Lowry 1984; Craig *et al.* 1984). This coastal zone is an extreme environment subject to seasonal disturbances associated with ice gouging and sediment disruptions, variations in salinity and temperature, turbidity, and currents (Carey *et al.* 1981). Polychaetes, bivalves, and gammarid amphipods predominate; these groups collectively represent a broadly distributed and speciose group, with 105, 31, and more than 100 species reported in coastal sampling, respectively (Carey *et al.* 1981).

Infaunal abundance is greatest nearshore at 5- to 10-m depths. Polychaetes compose 70-85% of the total infaunal density (Carey 1978a), ranging from 159-2,448 worms per station (Carey *et al.* 1981). There were no significant differences in the number of individuals by depth or by transect (Carey *et al.* 1981). Carey (1978b) ranked the most numerous polychaete families in terms of their percentage of the total polychaete fauna from 5-15 m along five

Table 8.7—Dominant epifaunal and occasional distributional patterns noted from 33 trawls in northeastern Chukchi Sea and southwestern Beaufort Sea in 1977, 40-400 m (from Frost and Lowry 1983).

		Observed Distribution
Brachyuran crabs	*Chionoecetes opilio*	west of 155°W
	Hyas coarctatus	50% west of Pt. Barrow 18% east of Pt. Barrow
Shrimp	*Eulaus gaimardi*	less abundant east of Pt. Barrow
	Sabenea septemcarinata	east of Pt. Barrow
	Eualus macilenta	most abundant >100m
	Spirotocaris spini	
	Sclerocrangon boreas	west of Pt. Barrow
	Pandalus goniurus	east of Pt. Barrow
Amphipods	Lysianidae	
	Ampelisidae	
Gastropods	*Margarites costalis*	
	Buccinum spp.	
Bivalves	*Delectopecten groenlandicus*	
	Bathyarca glacialis	
	Nuculana pernula	
Polychaetes	*Antinoella sarsi*	
	Eunoe nodosa	
	Gattyana cirrosa	
Echinoderms	*phiura sarsi*	
Sea stars	*Crossaster papposus*	
	Leptosterias groenlandicus	
Sea urchins	*Strongylocentrotus droenbachiensis*	
	Heliametra glacialis	
Other Groups	Sponges	
	Anemones	
	Flatworms	
	Nemerteans	
	Bryozoans	
	Tunicates	

transects between Point Barrow and Barter Island (Table 8.8). Certain densities did vary across the region; *i.e.*, representations of the family Spionidae appeared to be ubiquitous across the shelf, whereas members of the Pectinaridae predominated off Point Barrow and were rarely found elsewhere. Carey *et al.* (1981) found that *Cistenides hyperborea* numerically constituted 53% of all polychaetes along the Point Barrow transect, but less than 1% along the Barter Island transect. Some depth-stratified differences were also observed; *Minuspio cirrifera* represented 39% of the polychaetes present at 5 m, but only 2% at 25 meters. In all, the 14 families ranked were suggestive of the heterogeneity of habitats occurring within the relatively confined depth range of the coastal environment (Carey 1978b).

Biological information on the feeding types of polychaetes revealed much more about the depth-related distributional patterns of polychaete worms than did singular analysis of frequency of occurrence. Polychaetes were grouped on the basis of feeding morphology (Carey *et al.* 1981):

Tentacular Feeders. These are selective deposit feeders acting on the surface layer (48 species).

Burrowers. These are non-selective deposit feeders (28 species).

Predators. These are carnivores, herbivores, and scavengers (29 species).

Tentacular feeders compose a major portion of the number of polychaete individuals by depth and transect, ranging from 41% of the organisms sampled near Barter Island to more than 88% off

Table 8.8—The most numerous families arranged in terms of percentage of the total polychaete fauna. The percentages are derived from grab samples taken along transects occupied by the *Alumiak* in 1976. Five grab samples were taken at each of the stations represented (from Carey 1978b).

	5 meters	10 meters	15 meters
Barrow Transect:	49% Spionidae	77% Pectinariidae	77% Pectinariidae
	18% Nephtyidae	5% Flabelligeridae	6% Polynoidae
	12% Hesionidae	3% Capitellidae	4% Spionidae
Pitt Point Transect:	41% Spionidae	34% Sabellidae	86% Spionidae
	16% Ampharetidae	17% Spionidae	4% Capitellidae
	13% Orbiniidae	14% Cirratulidae	3% Paraonidae
Pingok Island Transect:	31% Maldanidae	80% Spionidae	56% Spionidae
	14% Cirratulidae	7% Sabellidae	28% Ampharetidae
	11% Spionidae	4% Sphaerodoridae	6% Sabellidae
Narwhal Island Transect:	40% Spionidae	53% Spionidae	25% Cirratulidae
	21% Hesionidae	27% Ampharetidae	13% Spionidae
	13% Sabellidae	6% Cirratulidae	7% Capitellidae
Barter Island Transect:	27% Spionidae	66% Spionidae	17% Cirratulidae
	24% Ampharetidae	7% Ampharetidae	17% Spionidae
	15% Sphaerodoridae	6% Cirratulidae	15% Nephtyidae

Pitt Point (Carey *et al.* 1981). This group displayed a decreasing abundance with increasing depth, although numbers of species remained fairly constant between 5 and 15 m. Seven species accounted for 92% of the total tentacular feeders in this depth range: *Ampharete vega, Cistenides hyperborea, Chone* aff. *C. murmanica, Marenzellaria wirens, Minuspio cirrifera,* and *Terebellides stroemi.* These same species represented 30% and 60% of the tentacular feeders between 55 and 100 m, respectively.

A total of 5,000 bivalves representing 31 species was collected in the coastal zone (Carey *et al.* 1981). No general patterns of bivalve dispersal were revealed in analyzing total numerical densities, species richness, or species composition. Numbers of species were generally low: 14 off Pitt Point, 1 off Narwhal Island; and 64% of the stations had fewer than 200 individuals/m^2. The most abundant, in order of decreasing density, were *Boreacola vadosa, Axinopsida orbiculata, Portlandia arctica, Liocyma fluctosa,* and *Macoma calcarea.* Although most of the numerically dominant species were present throughout this zone, two species, *B. vadosa* and *Cyrtodaria kurriana,* exhibited depth-partitioned distributions. The former species was found at stations shoreward of 15 m, while the latter was found exclusively at 5-m depths.

Regional variation in the composition of the shallow-water bivalve mollusks was statistically examined by Carey *et al.* (1981) through pairwise comparisons of expected versus observed occurrences of dominant species by depth and geographic location. A "common" species pool was established from species accumulation curves; 31 species were included. Subsequent analyses indicated that the community found at 5 m and those found along the Pingok Island transect were most representative of the southwestern Beaufort Sea. Cluster analysis revealed an assemblage of 12 species representing a mix of deposit and filter feeders that are equally likely to be found at any station between 5-25 m depth (Table 8.9). These include *Macoma inflata, M. moesta, M. calcarea, Crenella decussata, Thracia devexa, Astarte montagui, Portlandia atica, Arctinula groenlandica, Axinopsida obiculata, Nucula bellotii, Pandora glacialis,* and *Liocyma fluctosa.* Abundance patterns across the Pingok Island coastal and shelf habitats are depicted in Figure 8.11.

Distinct distributional patterns differ between the suspension- and deposit-feeding mollusks. Station comparisons of sediment type indicate an increase in the patchiness of silt and clay deposits with depth and a corresponding increase in the occurrence of deposit-feeding organisms (Tables 8.9 and 8.10). Suspension-feeders constitute the major portion of bivalves (93% suspension-feeders) in shallow, sandy (65-97% sand) stations, with decreasing presence in silty and clayey sta-

Table 8.9—Environmental parameters, bivalve abundance, and bivalve feeding types in the Beaufort Sea coastal zone (from Carey *et al.* 1983).

	Environment						Bivalve Fauna				
Transect	Depth (m)	Sediment Type	Gravel %	Sand %	Silt %	Clay %	% Organic Carbon	No. of Species	No. of Individuals	% Suspension Feeders	% Deposit Feeders
Pt. Barrow (BRB)	5	Sand	1.4	96.6	1.1	0.9	0.10	4	44	100	0
	10	Silty sand						11	215	88	12
	15	Sandy silt						2	5	20	80
	20	Sandy silt						3	22	45	55
	25	Sandy silt					0.47	5	58	14	86
Pitt Point (PPB)	5	Silty sand	0.0	38.0	39.2	22.8	0.81	14	2454	94	6
	10	Silty sand	0.0	65.8	26.3	7.8	0.17	10	243	60	40
	15	Clayey silt	0.0	71.0	19.2	9.8	1.0	4	40	2	98
	20	Clayey silt	0.0	8.1	51.2	40.7		4	98	1	99
	25	Clayey silt	0.0	4.3	49.1	46.6	0.78	10	217	4	96
Pingok Island (PIB)	5	Sand	0.0	73.2	16.9	9.9	0.09	2	4	0	100
	10	Silty sand	0.0	53.3	38.8	7.9	0.03	11	422	54	46
	15	Sandy silt						12	215	73	27
Narwhal Island (NIB)	5	Gravel-sand	15.9	71.8	6.4	5.9	<0.01	1	1	100	0
	10	Sand	0.3	85.8	7.0	6.9	0.08	7	53	92	8
	15	Gravel-sand	27.0	54.0	10.3	8.7	<0.01	12	35	66	34
	25	Sand-silt-clay	9.6	27.9	27.7	34.8	0.15	12	36	31	69
Barter Island (BAB)	5	Sand-silt-clay	0.0	29.2	38.6	32.2	<0.01	5	19	74	26
	10	Sand	0.0	92.5	4.5	3.0	0.03	7	97	60	40
	15	Silty sand	0.0	64.8	22.5	12.7	0.17	10	378	66	24
	20	Silty Sand	0.0	47.0	25.7	27.3	0.31	13	245	73	27
	25	Sand-silt-clay	0.0	37.6	24.8	37.6	0.34	8	99	33	67

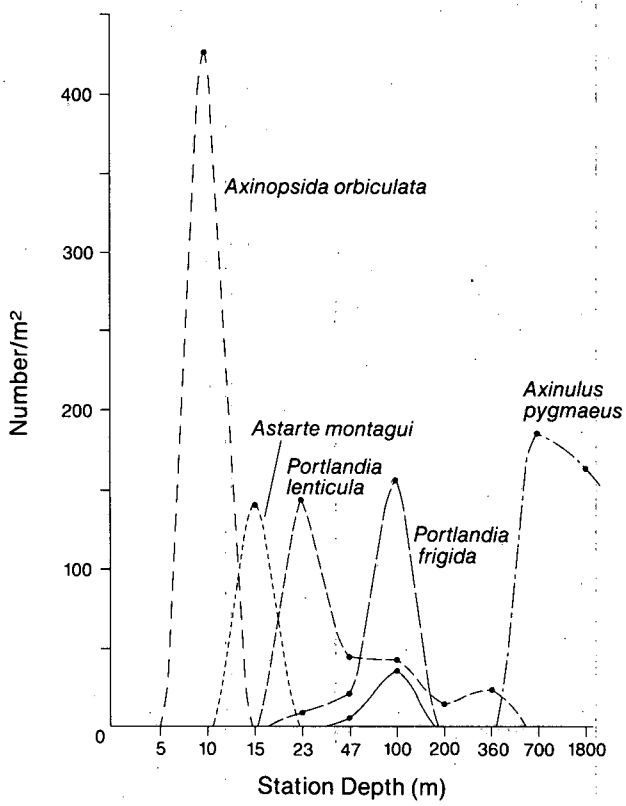

Figure 8.11—Patterns of distribution and abundance of dominant pelecypod species on the Pingok Island cross-shelf transect. Mean of 5 samples per station (from Carey *et al.* 1984).

tions. Conversely, deposit-feeders increased in numbers with increasing depth, from 7% at 5 m to 85% at 25 m (Carey *et al.* 1983).

The lack of wave activity in the arctic nearshore may be responsible for the high molluscan densities and species richness of the exposed Beaufort Sea coast (Carey *et al.* 1983). The decrease in species richness observed at 5-m depth stations probably results from river runoff and ice-related salinity effects rather than from wave scouring. Lower species richness at similar depths in more temperate waters has been attributed to higher energy surf zones (Carey *et al.* 1983).

Gammarid amphipods form a nearshore assemblage in the coastal habitat. Regionally, amphipod numbers are low but are greatest between 5- and 20-m depths. The shallow water affinities of some dominant amphipods are depicted in Figure 8.12. Although some species are filter-feeders, many are omnivorous, scavenging on detrital peat as an indirect food source. *Onisimus litoralis* was most abundant at 15 m and is clearly the dominant amphipod of the shallow-water benthos:

Depth(m)	Dominant Species	Density(#/m²)
5	*Monoculodes* sp.	2.2
10	*Onisimus litoralis*	7.1
15	*O. litoralis*	29.7
20	*O. litoralis*	8.2
25	*Aceroides latipes*	2.7

Throughout the 5-25 m depth range the most abundant species had mean densities ranging from 1-50 animals/m² as follows (Animal Ave. No./m²): *Canthostephe malgreni*, 1.2; *Pontporeai femorata*, 7.6; *Ampelisca macrocephala*, 2.8; *Monoculopsis longicornis*, 11.2; *Onisimus litoralis*, 49.2; *Acanthostepheia behringiensis*, 2.0; *Rozinante fragilis*, 4.0; *Aceroides latipes*, 6.8; and *Haploops tubicola*, 5.2 (Carey *et al.* 1981). Two species, *A. lapites* and *H. tubicola*, are also abundant at 40 m, with mean densities of 32 and 6 animals/m², respectively. The benthic amphipods found at 25 m are low in numbers, and species similarity analysis reflects poorly correlated associations. The variability in abundance at this depth is thought to reflect the variable nature of bottom habitat in an area of intense ice gouging and sediment disruption.

Trophic analysis of the major epibenthic crustaceans indicates that, on the whole, this group relies heavily on detrital carbon sources (Schneider and Koch 1979; see text table below) of a marine origin (Schell *et al.* 1982). Most species appear to be trophic generalists:

Species	Principal Foods
Amphipods:	
Onisimus glacialis	crustacean parts, diatoms
O. litoralis	diatoms, crustacean parts
Gammarus setosa	peat, diatoms, crustacean parts
Apherusa glacialis	diatoms, dinoflagellates, peat, crustacean parts
Mysids:	
Mysis relicta	peat, diatoms, crustacean parts
M. litoralis	diatoms, peat, crustacean parts
Isopod:	
Saduria entomon	diatoms, polychaetes, peat

Table 8.10—Bivalve feeding types (from Carey *et al.* 1983).

A. Percent feeding type by depth and by transect. Based on total number of individuals collected at each station.

Depth (m)	Total No. of Individuals	% Suspension Feeders	% Deposit Feeders
5	2,539	93	7
10	1,030	57	43
15	673	70	30
20	365	52	48
25	410	15	85
Transect			
Pt. Barrow	344	76	24
Pitt Point	3,052	81	19
Pingok Island	641	60	40
Narwhal Island	125	67	33
Barter Island	838	68	32

B. Percent of species: feeding type by depth and by transect.

Depth (m)	Total No. of Species	% Suspension Feeders	% Deposit Feeders
5	15	80	20
10	18	55	45
15	20	55	45
20	14	36	64
25	18	44	56
Transect			
Pt. Barrow	12	58	42
Pitt Point	20	60	40
Pingok Island	16	56	44
Narwhal Island	18	56	44
Barter Island	18	50	50

8.3.5 Pitt Point Temporal Study

Five stations located between 25 and 100 m along the Pitt Point transect were seasonally or annually reoccupied between 1975 and 1978 to study the temporal variability of benthic communities across the shelf. Preliminary analyses (Carey 1978b; Carey *et al.* 1981) suggested that seasonal changes in species densities and biomass of the soft-bodied infauna could be accounted for by a "knife-edge" form of recruitment of juveniles to the benthos in the early portion of the open-water period (Ricker 1975). Such a peak in numerical abundance, followed by rapid summer growth (high numerical abundance in May and peak standing stock levels in August) was consistent with the littoral trends described by Broad *et al.* (1979) and knowledge of infaunal reproductive strategies.

This hypothetical recruitment was further related to the seasonal spike of particulate carbon and nitrogen made available to the benthos when ice-associated pennate diatoms are transported to the seafloor during spring melt. Research off Narwhal Island demonstrated that there was no sudden influx of organic matter to the benthic environment during spring, but instead a generally high and continual rain of organic matter occurred over the spring bloom (Carey *et al.* 1984). The total flux of carbon and nitrogen does not seem to be affected by the accelerated loss of the ice algal community in early June. Carbon flux remained between 29 and 48 mg $C/m^2 \cdot d$, with no significant increase or correlations with environmental events. Nitrogen flux was low, 1.5 to 6.2 mg $N/m^2 \cdot d$, and erratic through the season. Carey *et al.* (1984) also

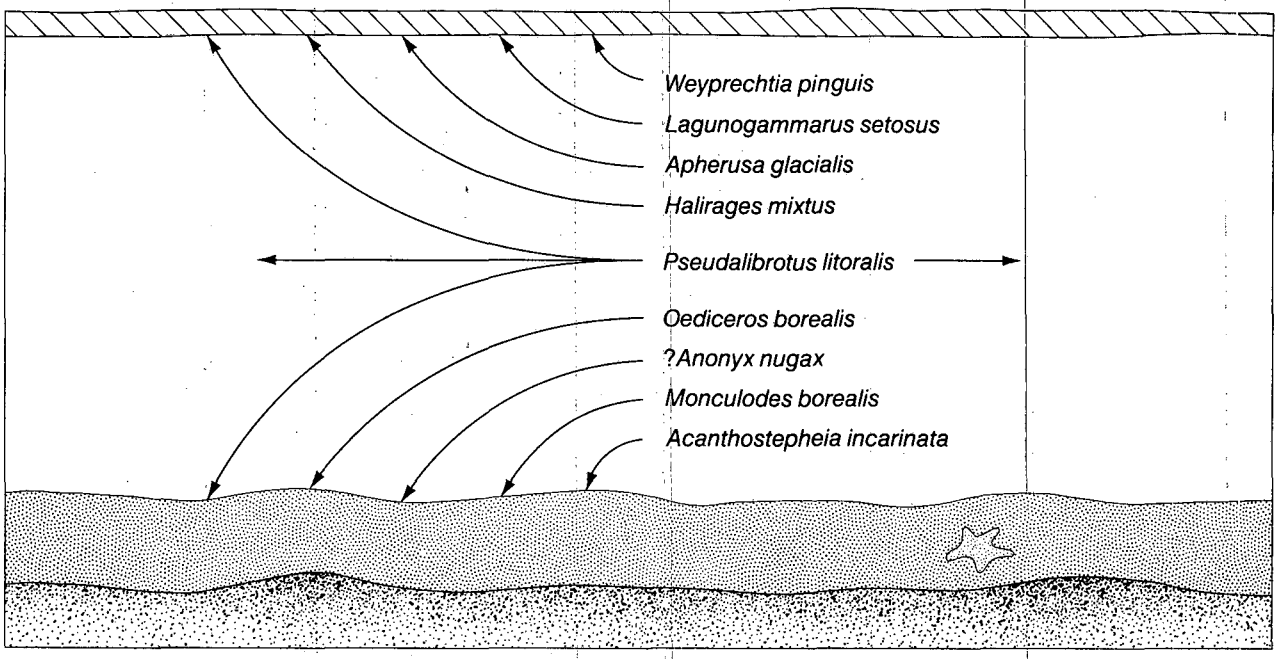

Figure 8.12—Affinities of gammarid amphipod species in the shallow Beaufort Sea. *Pseudalibrotus litoralis* is abundant in the under-ice, mid-water, and benthic environments (from Carey *et al.* 1984).

observed an increase in the fecal pellets of *Pseudalibrotus litoralis* on the seafloor in late May. This gammarid amphipod dominates the ice macrofaunal community on the inner shelf (ice coverage seaward to about 10-m depths).

A more recent analysis of the population structure of dominant polychaete and bivalve species (*Microphythys mimita, Pholoe minuta, Terebellides stroemi, Sternapsis scutata;* and *Nucula belotti, Astarte montagui,* and *Portlandia arctica*) does not support the proposed recruitment type (Carey *et al.* 1984). It appears as if these species are slowly reproducing over most of the year by producing small numbers of lecithotrophic (yolky) eggs. This is in contrast with the amphipods and mysid populations that appear to be breeding during the winter period.

Analysis of species diversity, abundance indices, and compositional similarity of the soft-bodied infauna along the Pitt Point transect resulted in the clustering of inner-shelf (25-40 m) and outer-shelf (40-70 m) benthic communities (Carey *et al.* 1981; Carey *et al.* 1984). Little variation in species dominance within benthic communities was found over the three-year study. Rank-order analysis showed that, even though there were changes in population densities from year to year, the most abundant organisms remained numerically dominant each year.

The inner-shelf assemblage, and especially those organisms found at 25-m depths, are adapted to episodic disruption and are characterized as opportunistic species with asynchronous reproductive cycles (Carey *et al.* 1984). It is thought that their reproductive potential is mostly affected by physical disturbances associated with sea ice (Carey 1978a,b). The benthic community at 40-m depths, the outer edge of the ice-gouging zone, reflects a transitional environment that could be expected to provide habitat to many species with various life histories (Carey *et al.* 1984). As an example, 20 species of polychaetes compose 90% of the total annelid density at this depth. The outer-shelf group was characterized as a community accommodated to a seasonal input of food. Carey (1985) indicates that although reproduction and growth of the shelf edge organisms are low, they do have large standing stocks, suggesting adequate food supplies. Advection of detrital carbon into the southwestern Beaufort Sea from the Bering/Chukchi seas, active sedimentation of this advected material along the upper continental slope, plus enhanced primary production caused by upwelling of nutrient-rich deeper water during open-water conditions could all contribute to maintaining these benthic communities.

Annual fluctuations in density and biomass were found within all infaunal communities during the

three-year study, but variation was greatest in the outer-shelf group (Carey 1978a,b; Carey *et al.* 1981; Carey *et al.* 1984). These changes undoubtedly reflect population-regulating mechanisms, *i.e.*, growth, predation, and mortality operating within a dynamic benthos. Carey *et al.* (1984) reported an increase in populations of meiofauna (harpacticoid copepods and nematode worms) and what perhaps was recruitment of juveniles to the benthic communities. The summer-fall decrease in abundance of larger organisms (polychaetes and gammarid amphipods) implies high mortality rates caused by predation (Carey *et al.* 1981). Although the benthic communities were observed to undergo seasonal cycles, the overall density remained fairly constant from year to year.

8.4 SPECIAL NEARSHORE HABITATS

The utilization of arctic lagoons and coastal waters by invertebrates, especially epibenthic crustaceans and zooplankton, has been of key importance in identifying energetic pathways and major vertebrate foraging areas in the Diapir Field (Schneider and Koch 1979; Griffiths and Dillinger 1981; Truett 1984a; Frost and Lowry 1984; Johnson 1984; Kinney 1985; Craig, Griffiths, Haldorson, and McElderry 1985). The sessile nature of many infaunal species has made them attractive candidates for "monitoring stocks," *e.g.*, biological indicators of environmental change in community structure associated with industrial developments (Houghton *et al.* 1984). Invertebrate standing stocks in Prudhoe Bay (Feder and Schamel 1976; NORTEC 1981) and near the Sagavanirktok River delta (Gallaway and Britch 1983) have been studied in conjunction with planned causeway developments and potential environmental impacts. The Stefansson Sound Boulder Patch is unique to the Beaufort Sea and houses a rich biota, making a significant contribution to annual carbon budgets of local coastal habitats (Dunton and Schonberg 1979, 1981; Dunton 1984; Truett 1984a). While not unique to the Beaufort Sea or Diapir Field study area, the epontic algal community has been extensively studied in Stefansson Sound in order to better understand its energetic contribution to the coastal benthos during spring melt (Carey *et al.* 1981; Carey and Montagna 1982; Carey *et al.* 1984).

Harrison Bay was recently leased under OCS Sale 71 for oil and gas exploration and development. As such, this area has previously been the focus of an OCSEAP information synthesis, and its invertebrate fauna has been well characterized (Norton and Sackenger 1981). No additional discussion of Harrison Bay will therefore be provided.

8.4.1 Arctic Lagoons

Nearshore lagoons provide important late-summer and early-fall foraging habitat for many vertebrate consumers. Two types of lagoons have been described in the coastal Diapir Field: the open system and the closed, or "pulsing," system (Truett 1984a). An open lagoon is coastally bound by low-lying barrier islands and is characterized by a relatively high flushing rate. Closed lagoons, conversely, have a much more restricted exchange with the coastal waters through narrow channels formed between barrier islands and/or spits. Barrier islands have been estimated to parallel approximately 50% of the Beaufort Sea coastline between Point Barrow and Demarcation Point (Truett 1984a). Open lagoons tend to be more common in the central portion of the southwestern Beaufort Sea (Simpson Lagoon, Stefansson Sound including Prudhoe and Foggy bays, and lagoons and bays landward of Stockton and Maguire islands), with closed systems found to the east and west (Elson Lagoon, Beaufort Lagoon, and other small bays and lagoons from Barter Island to Demarcation Point). Peard Bay, in the northeastern Chukchi Sea, is also part of the coastal Diapir Field, and has been categorized as a closed lagoon.

Three of the aforementioned lagoons have been the focus of detailed OCS ecological research. This has made possible regional comparisons of invertebrate standing stocks between lagoon systems and more oceanic waters.

Unlike coastal waters, where polychaetes and bivalve mollusks predominate, the most important invertebrates in lagoons are amphipods, mysids, copepods, and other motile crustaceans. These species form the bulk of the diets of arctic fishes, birds, and marine mammals. Mysids and amphipods are particularly abundant, though their numbers and biomass vary with location, season, and presence of predators. In Simpson Lagoon, seasonal and annual shifts in abundance have been reported (Truett 1984a). These can be related to the environment as well as to population-regulating mechanisms, although in the latter case, growth and mortality alone could not account for the observed changes in mysid density and biomass. A possible seasonal onshore-offshore migration of mysids corresponding to summer and winter periods could explain these changes.

Even though a significant degree of interannual variability has been observed in the invertebrate prey base, epibenthic crustacean food resources are not limiting. As an example, in 1978 the biomass of mysids and amphipods available to key vertebrate consumers remained one to two orders of magnitude greater than their estimated daily nutritional requirement, even though the epibenthic crustacean standing stock was approximately a half to one order of magnitude less than in 1977 (Griffiths and Dillinger 1981).

In addition to a directed seasonal migration, seasonal changes in abundance of epibenthic species may be accounted for by passive transport parallel to the coastline and through open lagoons. During the open-water period, the mysid *M. relicta* is most abundant in brackish waters of Simpson Lagoon, whereas there does not appear to be any difference in the abundance of *M. litoralis* either inside of or offshore of the barrier islands. It has been postulated that either the mysids leave the lagoons in winter and recolonize their waters during summer, or that they simply die (Griffiths and Dillinger 1981). However, the few mysids that have ever been captured in lagoonal waters in February appeared to be in breeding condition. Amphipods were more restricted to the lagoons and also appeared to be breeding during the winter months. If mysid emigration occurs in late winter, it is probably triggered by environmental cues associated with salinity, temperature, or local current regimes. A comparison of mean density and biomass estimates for epibenthic crustaceans collected near the Sagavanirktok River delta and Simpson Lagoon demonstrated that there were no significant differences in mysid and amphipod abundance between the open lagoon and nearby exposed coastal waters (Gallaway and Britch 1983). These results suggest coastal transport of the dominant epibenthos. If this is the case, the entire nearshore area within its bays and lagoons is important for growth and reproduction of these species (Truett 1984a).

In a very general manner Truett (1984a) noted that the epibenthos of the open lagoons is much more abundant overall (although not necessarily per unit area) than that of other lagoonal systems. This, in part, explains the increased use of the open lagoons by higher trophic levels observed by many investigators. Other comparisons are possible between the open and closed lagoons when selected physical and biological information is reviewed for Simpson Lagoon, Beaufort Lagoon, and Peard Bay (Table 8.11). High levels of ammonia were reported in Peard Bay. Considering the bay's size, depth, water residence time, and enhanced nutrient and particulate organic matter inputs, these levels may account for the area's high *in situ* phytoplankton production compared to that of the Beaufort Sea lagoons (Kinney 1985).

Lagoon waters are diluted by river runoff and are correspondingly less saline (4-5 ‰) and warmer (4-10° C) than adjacent coastal waters. These differences become less apparent as the year progresses; and by September, oceanic amphipods species, *e.g.*, *Halirages mixtus*, *Pontoporeia affinis*, and *Parathemisto* sp., move into Simpson Lagoon.

Food web and carbon isotopic studies have revealed much about the utilization of arctic lagoons by invertebrate and vertebrate species. Although detrital peat can form a 2-cm-thick mat on the seafloor of Simpson Lagoon, radioactive carbon tracing has shown that 60-70% of the carbon consumed by mysids and amphipods is of marine origin (Schell 1984). In this lagoon, *Onisimus glacialis* is the dominant amphipod. In Beaufort Lagoon, similar studies have identified terrestrially derived carbon sources to be more prominent in the tissues of some vertebrate consumers, *e.g.*, arctic flounder. In Beaufort Lagoon, *Gammarus setosa* is the dominant amphipod. This species is known to ingest large amounts of peat, probably indicative of its feeding on meiofauna and heterotrophic bacteria associated with the peat. These peat-associated organisms are able to digest cellulose and assimilate carbon from the peat (M. J. Hameedi, NOAA, OAD, Anchorage, AK, pers. comm., June 1986).

There are differences in the epibenthic standing stocks of Simpson and Beaufort lagoons. Biomass estimates for mysids and amphipods were compared for 1978 and 1982 sampling in Simpson Lagoon and 1982 collections in Beaufort Lagoon (Figure 8.13). Mysid biomass greatly overshadowed that of the amphipods in Simpson Lagoon, but they were nearly equal in Beaufort Lagoon. Mysids and amphipods were found in great abundance in both years in Simpson Lagoon, although total biomass was different between years. However, Truett (1984a) cautions against extrapolations from the small 1982 data set from Simpson Lagoon. Standing-stock estimates of these epibenthic groups may be smaller in Beaufort Lagoon due to this system's limited estuarine-marine exchange and low *in situ* primary production. Amphipods were more abundant in Beaufort

Table 8.11—Comparisons of the major environmental features and invertebrate fauna of Simpson Lagoon, Beaufort Lagoon, and Peard Bay (from Truett 1984a and Kinney 1985).

Feature	Simpson Lagoon	Beaufort Lagoon	Peard Bay
Type	open	closed	closed
Area	125 km^2	31 km^2	240 km^2
Ave. Depth	2-3 m	3-4 m	2-7 m
Ave. Flushing Rate	3-4 d	8-10 d	15 d
Annual Production	5-7 g C/m^2	1.6 g C/m^2	10 g C/m^2
Salinity:			
Summer	20-26 ppt	16-20 ppt	14.5-30.6 ppt
Winter	35-68 ppt	> 35 ppt	41-48 ppt
Temperature:			
Summer	0-14°C	16-20°C	3.5-8°C
Winter		—	-1.9-1°C
Ice:			
Thickness	2 m	—	2 m
Ice Free	15 July	1 July	15 July
Sediments	sand, silt mud, detritus	sand, gravel mud	silt, clay peat, mud
Dominant Species:			
Infauna	*C. kurriana*	*P. cirrefera*	*C. kurriana*
	A. vega	*C. duneri*	*L. fluctosa*
	P. cirrifera	*N. aphrodictiodes*	*A. carinatus*
	S. arcticus	*S. filicornis*	*S. filicornis*
	Tharyx sp.		*C. duneri*
			C. occulata
			M. turnida
Epibenthos	*M. litoralis*	*G. setosus*	*Mysis* sp.
	M. relicta	*M. litoralis*	*S. entomon*
	O. glacialis	*M. relicta*	*G. loricatus*
	G. setosus	*Corophium* sp.	*Gammarus* sp.
	S. entomon		*O. litoralis*

Lagoon, which might reflect their adaptation to a different carbon source in peat and other terrestrial detritus (Truett 1984a).

The epibenthic species that inhabit the Peard Bay seafloor are similar to those found in the Beaufort Sea lagoons, especially Simpson Lagoon, even though relative abundance differs (Kinney 1985). The deeper portions of Peard Bay were dominated by *Atylus carinatus*, whereas *Gammaracanthus loricatus* and *Onisimus litoralis* were more abundant in the shallower depths (2-3 m) skirting the deeper central basin (>7m). Differences in infaunal composition, while not great, probably reflect differing habitats such as bottom type, and *in situ* detritus available as food. The bivalve *Cyrtodaria kurriana* was most abundant in Peard Bay, Simpson Lagoon, and most shallow coastal stations in the Diapir Field.

8.4.2 Stefansson Sound Boulder Patch

The Boulder Patch lies in Stefansson Sound (Figure 8.14), some 20 km northeast of Prudhoe Bay. The boulders and cobble substrates and associated macroalgal kelp beds form an unusual, if not unique, habitat in the Diapir Field lease area. The Boulder Patch covers an area of approximately 20 km^2 and averages 2-9 m in depth. Rocks cover more than 40% of this area. Freeze-up normally occurs by 15 October, and ice is typically gone by early July. Annual bottom temperatures range from

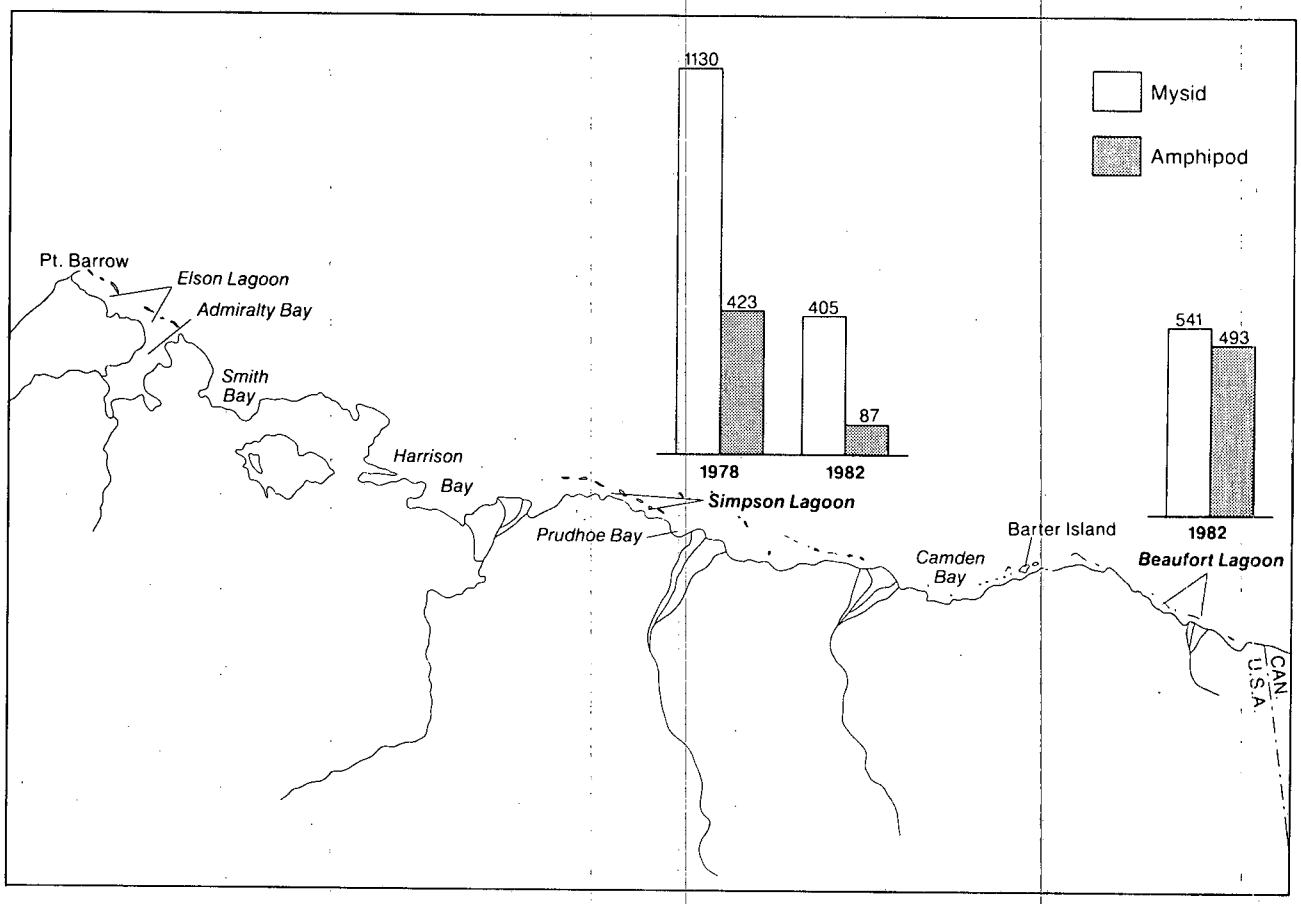

Figure 8.13—Biomass estimates (mg wet wt/m²) of mysids and amphipods in Simpson Lagoon (3 August 1978 and 4 August 1982) and Beaufort (Angun) Lagoon (28 July 1982). *Mysis litoralis* and *M. relicta* composed essentially all the mysid biomass in all cases. Among amphipods, *Onisimus* spp. dominated in Simpson Lagoon, and *Gammarus setosus* dominated in Angun Lagoon. Data from Griffiths and Dillinger (1981) and Jewett and Feder (1984) (from Truett 1984a).

−1.9 to 7° C, and salinities range from 14-35 ‰ (Dunton 1984).

The Boulder Patch community is characterized by the dominant brown alga *Laminaria solidiungula* and the herbivorous chiton *Amicula vestata*. Other organisms, such as several species of anemone and a pink soft coral, are conspicuous members of this habitat. In general, the community has been described as stable. Biological features of the community, as well as kelp productivity, are known (Dunton *et al.* 1982; Dunton 1984; Houghton *et al.* 1984).

The Boulder Patch has often been referred to as a biological oasis within a more desolate arctic coast. Indeed, more than 300 marine species have been identified there (Dunton and Schonberg 1981; Dedera 1982). In addition to the species mentioned above, polychaete fanworms and scale worms (*Spirobis granulatus*, *Potamilla neglecta*, *Actionoella sarsi*), nematodes, and nemerteans are found in sediments between boulders and cobble. Mollusks, especially the gastropods *Neptunea*, *Natica*, *Margarites*, and *Plicifulus*, are abundant, and *Buccinium* eggs have been found here. The largest mobile crustacean, *Hyas coartatus alutacus*, is usually associated with heavy kelp coverage. Sea stars (*Leptaserias* spp. and *Crossaster papposus*), sea spiders (*Nymphon grossipes*), bryozoans, and ascidians (*Molgula griffithsii*) are dominant members of the epifauna. Relative abundance indices for densities and biomass are provided in Dunton and Schonberg (1981). The rocks and boulders of this area provide refuge to invertebrates from intense ice gouging and may, in part, explain observed animal abundance and use of this habitat.

The dominant invertebrates of the Boulder Patch are largely sessile organisms and include an assemblage of polychaete worms, tiny crustaceans, and mollusks. Of these, roughly 65% are fil-

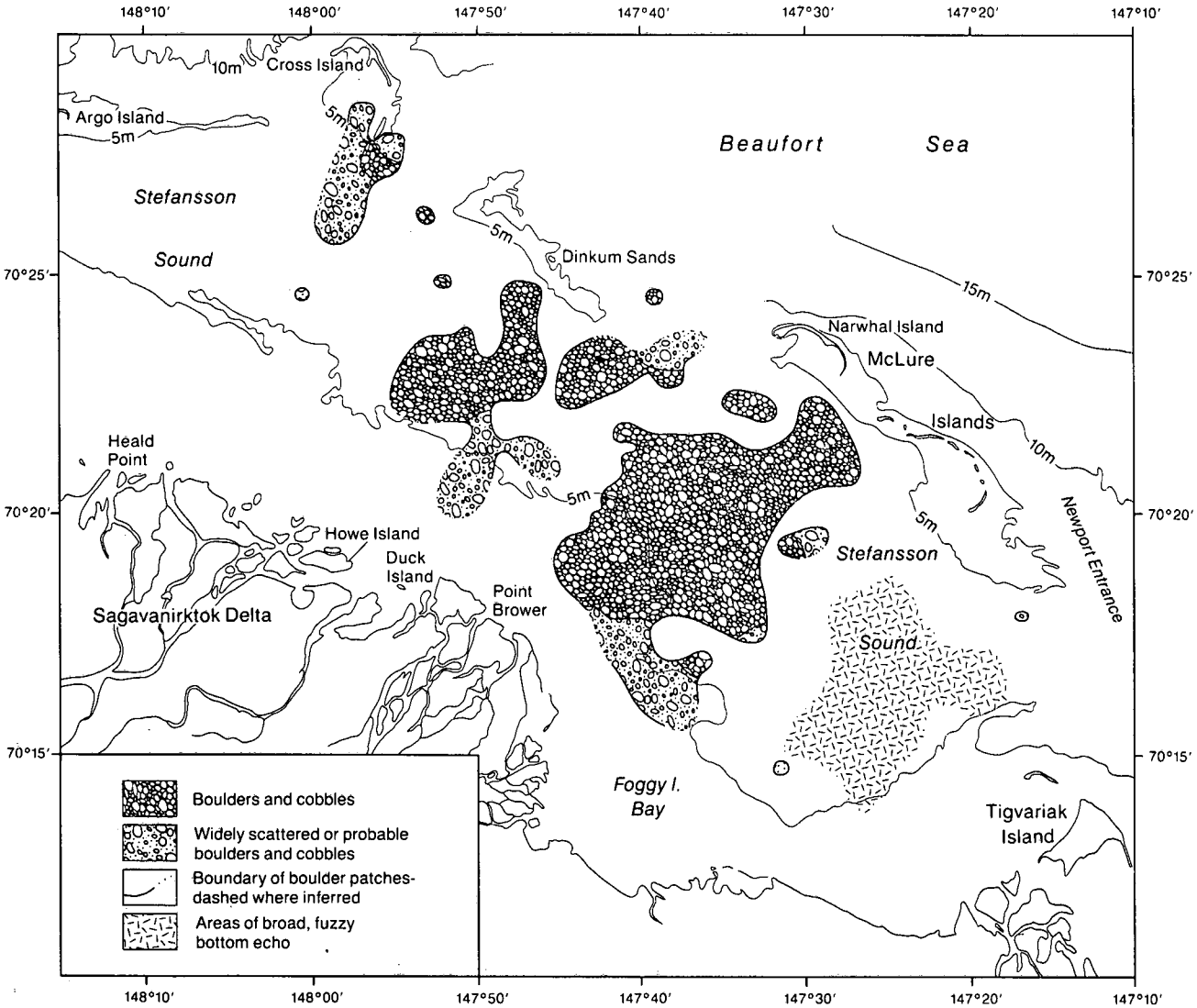

Figure 8.14—Stefansson Sound Boulder Patch (from Dunton and Schonberg 1981).

ter-feeders (Dunton 1984). Filter-feeding is important since as much as 98% of the particulate organic carbon (POC) is derived from Boulder Patch kelp or marine phytoplankton production (Dunton 1984). The magnitude of POC contributions from each of these sources varies annually and largely as the result of differing ice conditions. About 60% of the total carbon released into the benthic environment is in particulate form (Dunton 1984).

In years of turbid ice, the spring bloom is either greatly diminished or non-existent. It is of interest that the dominant inshore amphipods of the Beaufort Sea, *Onisimus litoralis* and *Gammarus setosa*, were absent from the Boulder Patch. The absence of these amphipods from the Boulder Patch habitat may reflect their inability to compete with the filter-feeding fauna for detrital food sources.

8.4.3 Prudhoe Bay and Barrier Islands

Surveys designed to characterize the shallow-water infauna of the Prudhoe Bay area and investigate changes in its infaunal community structure with distance from shore were made in 1974 through 1975 (Feder and Schamel 1976). Sandy substrate types were frequently found at inshore depths less than 1.5 meters. Muddy, sandy, and detritus-littered seafloors were associated with greater depths. Mean wet-weight biomass was 1.74 g/m^2 in 1974, 20.69 g/m^2 in 1975, and 55 g/m^2 in 1979 (NORTEC 1981; Gallaway and Britch 1983). Unlike the previous studies, the 1979 survey consisted exclusively of infaunal sampling in deep Prudhoe Bay waters (2-7 m). Thirty-eight infaunal species from 8 phyla were identified in 1974 and 1975. Of these, polychaetes and amphipods represented

26 species. In 1979, greater numbers, biomass, and diversity of benthic organisms were observed—165 invertebrate taxa belonging to 13 phyla. Polychaetes (71 species) dominated the fauna, while mollusks and epibenthic crustaceans totaled 67 species.

Species diversity, numbers, and biomass tend to increase with distance offshore. Most of the polychaetes and a number of amphipods collected in shallow waters were sessile tube-dwelling species; the polychaetes were primarily deposit-feeders, whereas the amphipods represented deposit and scavenging species (*Pseudalibrotus onisimus* and *Gammaracanthus loricatus*). Amphipod abundance, especially that of *Pontoporeai affinis*, tended to increase with distance from shore; but decreases in biomass were observed farther offshore. The bivalve *Cyrtodaria kurriana* and the isopod *Saduria entomon* were never found shoreward of 1.5 meters. The Prudhoe Bay area is considered to be an open lagoonal system, and the fluctuating levels and numbers and biomass of mysids and amphipods may reflect natural changes in populations, or the migrational and passive transport movements of coastally occurring invertebrates discussed earlier.

The shallow waters along the seaward coasts of barrier islands are subject to intense ice scour and strong wave action for much of the year. The organisms within this zone must be able to tolerate these conditions as well as low levels of dissolved oxygen in the winter. It is an impoverished habitat, with low species richness in depths less than 3 m (Feder and Schamel 1976). *Saduria entomon, Preiospio cirrifera,* and *Chone duneri* have been sampled in low numbers off Gull Island (<1 m). At similar depths off Niakuk Island, *S. entomon, Pontoporeia affinis,* and *Monoculopsis longicornis* were found in low abundance. Eleven species were sampled off Argo Island at slightly greater depths (2-3 m): an unidentified oligochaete, an unidentified bryozoan, an unidentified tunicate, *Amphareta vega, Halicryptus spinulosa, Chaetozone setosa, Sphaerodoropsis minuta, Airatulus cirratus, Castolia* sp., *Terebillides stroemi,* and *Haploscoloplos elongata*. The three last-mentioned species were not sampled inside Prudhoe Bay in either the 1974 or 1975 surveys, possibly attributable to estuarine influences in the bay area.

8.4.4 Epontic Community

Alexander (1974) considered the role of ice algae in the energetics of the coastal Beaufort Sea as a way in which the growing season was effectively lengthened by 2 months. More recently Schell *et al.* (1982) described the ice algae as food for grazing organisms and as a trap for nutrients. The flux of nutrients to the seafloor associated with spring melt was studied off Stefansson Sound, as described earlier in this chapter (Carey *et al.* 1984).

Algal productivity in the sea ice and ice-edge was included in a recent review of primary production in arctic waters (Subba Rao and Platt 1984). Using available data collected over the past 10 years, a revised estimate of total arctic primary production was 210 × 10^6 t C/yr. Of this total, 6 × 10^6 t were attributed to ice-biota. In the Diapir Field region there is a considerable range in similar production estimates: 1.4-164 g C/m^2·yr in the Chukchi Sea, 5-10 g C/m^2·yr in the Beaufort Sea, 0.7 g C/m^2·yr at Narwhal Island, and 5 g C/m^2·yr at Point Barrow (cited in Subba Rao and Platt 1984). The rates are similar in magnitude to the 10 g C/m^2 yr for the Antarctic (Subba Rao and Platt 1984).

In the coastal or littoral portions of the Diapir Field, the sea-ice biota consists of large numbers of meiofaunal organisms in lower ice levels (Kern and Carey 1983). Over 90% of the individuals sampled were less than 1.0 mm body length. Invertebrate numbers and densities were low relative to abundance estimates from the seafloor below. Reported densities were lowest within the pulpy under-ice layer. Densities from the ice under surface peaked in June at approximately 50,000 individuals/m^2.

The ice meiofaunal assemblage included polychaetes, nematodes, rotifers, and crustaceans. The crustaceans consisted of calanoid copepods, nauplii, two species of harpacticoid amphipods, and a cyclopoid amphipod (Carey and Montagna 1982). The ice meiofauna is apparently derived from both benthic and pelagic environments.

Nematodes, copepods, and turbellarians were numerically dominant on the ice under-surface. *Cyclopira glacialis* and *Harpacticus* sp. were the most abundant copepods. These organisms were of special interest with respect to possible recruitment to and reproduction on the sea ice habitat (Kern and Carey 1983; Carey *et al.* 1984). The former species appeared to be constantly reproducing throughout the spring study period. All *Harpacticus* sp. sampled in early spring consisted of juvenile stages. By June the species was evidently mature and possibly breeding, although no gravid females were observed. It has been hypothesized that during spring the under surface of the ice acts as a substrate for benthic recruitment and

nourishment (Carey and Montagna 1982). The meiofauna is, however, too sparse to be of significant importance in nearshore arctic food webs.

8.5 SUMMARY

The relative distribution and abundance of benthic and pelagic invertebrates of the Diapir Field area are reasonably well-known from studies over the past decade. Life history information for most species is lacking, although population features of selected dominant forms are becoming clearer. The vulnerability of any one particular species to planned or ongoing OCS oil and gas activities is thus best addressed at present through an analysis of habitat utilization.

Invertebrate habitat utilization in the Sale 87 area is greatly influenced by the seasonal presence of fast ice in the very nearshore zone and intense gouging of the seafloor by ice in a transitional zone farther offshore. Along the coast the presence and configuration of barrier islands and other landforms affects nearshore salinity and temperature regimes and prevailing coastal transport mechanisms—all are environmental features that affect the occurrence and abundance of the arctic invertebrates. The underlying surface of the seasonal ice pack forms an important, but poorly understood, habitat for the growth and recruitment of several meiofaunal organisms. Upon spring melt, these organisms and associated microalgae are thought to provide an additional, but localized, source of energy to regional food webs.

Two kinds of invertebrate food webs can be described for the Diapir Field area: a nearshore regime, and a pelagic regime. The nearshore regime includes the many coastal embayments and lagoons and is dominated primarily by motile epibenthic crustaceans. These areas are used as the prime foraging habitats for many vertebrate predators during the open-water period. The abundant crustacean prey resources are not considered limiting. The pelagic regime is characterized by arctic cod, bowhead whales, and seabirds, all of which consume euphausiids and copepods. Although patchy in distribution, this invertebrate prey efficiently crops the annual primary production and is fairly abundant throughout the region.

Cross-shelf trends in benthic community structure and temporal variability in stock size and composition have been the focus of OCSEAP invertebrate studies in the Alaskan Beaufort Sea. Polychaetes, pelecypods, and gammarid amphipods are dominant invertebrate groups and have depth-stratified dispersal patterns across the shelf. Whereas there are differences in their abundance from east to west along the coast, a common species pool can be established which allows reasonable predictions of species occurrence by depth or within a particular substratum. For most species, reproduction is apparently occurring throughout the year, with low recruitment rates. This was evidenced by the consistent dominance of 3 or 4 species in several benthic communities over a three-year period.

Biological information on the feeding morphology of invertebrate species, especially bivalve mollusks, in relation to other environmental characterizations, proved more meaningful in understanding invertebrate distributional patterns than did numerical analysis of samples by depth alone. There is an increase in deposit-feeding organisms with depth, with greater numbers of suspension-feeders found inshore.

The invertebrates, on the whole, are probably not particularly vulnerable to offshore oil and gas development in the Diapir Field area. Truett (1984a) discussed the vulnerability of various coastal habitats to possible OCS developments and concluded that lagoonal habitats and possibly "closed" lagoonal systems may be most sensitive to spilled oil. Causeway construction in nearshore waters may alter local current patterns and possibly affect the passive transport of amphipods, mysids, and copepods along the coast.

Some other invertebrate habitats are of additional concern with regard to proposed OCS oil and gas activities and associated coastal developments in the Diapir Field area. The Stefansson Sound Boulder Patch is clearly a unique and important habitat to invertebrates and vertebrates alike, and will receive the special attention of resource managers empowered to adequately ensure its safeguard. Other nearshore areas noted in this chapter for their enhanced invertebrate productivity include the shallow waters in the vicinity of Barter Island and those fronting the Colville River Delta. Although cursory surveys have been conducted in these areas, their ecological significance in the functioning of coastal ecosystems is not fully known.

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Chapter 9

Fish Use of Coastal Waters of the Alaskan Beaufort Sea: A Review

by Peter C. Craig

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Research over the past decade has greatly expanded our knowledge of anadromous and marine fish populations in coastal waters of the Beaufort Sea. Studies have progressed from an initial need to inventory what is present, to an examination of the physical and biological processes that support fish populations. This review summarizes our current understanding of fishes of the Alaskan Beaufort Sea and their uses of coastal habitats.

The study area is a relatively uniform aquatic region in terms of oceanography and fish fauna. To the east is the Mackenzie River, which dominates coastal oceanography and supports a more diverse fish fauna than occurs in the study area (Corkum and Hart 1981). To the west is the Chukchi Sea, which differs from the Beaufort Sea in circulation patterns and source of water. The Chukchi Sea is warmer, more productive, and also supports a more diverse fish fauna than occurs in the study area (Morris 1981; Craig and Skvorc 1982; Craig 1984).

Arctic fish communities, like other arctic animal communities, have fewer species than their lower-latitude counterparts. In Alaskan coastal waters of the Beaufort Sea, 62 species have been recorded; additional species presumably occur offshore. McAllister (1977) reports that 104 species in 20 families occur in marine and brackish water of arctic Canada. For comparison, over 300 species inhabit the east and west coasts of southern Canada (Leim and Scott 1966; Hart 1973).

The fish fauna of the Alaskan Beaufort Sea is typical of the "Inuit fauna" (McAllister 1962), which is a fairly distinct assemblage of marine and anadromous species extending from the central Canadian Arctic westward through Chukchi and Siberian coastal waters. To date, 37 species have been collected in nearshore brackish waters and 40 in offshore marine waters (Table 9.1). These are mostly anadromous and marine species, but several freshwater species are infrequent visitors when salinities are low.

This review is organized by habitat: freshwater drainages, brackish coastal waters, and offshore marine waters. Freshwater systems are included because of their direct contribution of anadromous fish stocks (char, ciscoes, whitefishes) to coastal waters. Nearshore and offshore waters of the Beaufort Sea represent distinctly different aquatic habitats for fish. Offshore waters are cold and marine, and receive year-round use by marine fish species such as cods, sculpins, eelpouts and snailfishes. Nearshore waters are warmer and less saline (brackish) than offshore waters and are used extensively by anadromous fishes.

9.1 FRESHWATER HABITATS

The life cycle of anadromous fishes provides a linkage between freshwater and coastal habitats because these fishes make repeated migrations between the two habitats. Anadromous species generally spawn in the larger North Slope rivers in fall and winter. Their young remain in fresh water for a variable period; Arctic cisco, for example, may enter coastal waters during their first summer while Arctic char usually remain in streams for several years before smolting. Thereafter, the fish enter coastal waters each summer to feed and return to streams and lakes in fall to overwinter, and when mature, to spawn. Most fish probably return each winter to their natal streams although some straying into other streams has been recorded for Arctic char (Craig and McCart 1976) and possibly Arctic cisco (Gallaway *et al.* 1983).

Table 9.1—Fishes of the Alaskan Beaufort Sea. Species are arranged according to principal life history patterns. × indicates presence, ×× indicates species is widespread and abundant (where data are available).

		Occurrence	
		Brackish Nearshore	Marine Offshore
	Anadromous		
Lampreys			
Lampetra japonica	Arctic lamprey	×	
Salmonids			
Coregonus autumnalis	Arctic cisco	××	
Coregonus sardinella	least cisco	××	
Coregonus laurettae	Bering cisco	×	
Coregonus clupeaformis	lake (humpback) whitefish	××	
Coregonus nasus	broad whitefish	××	
Oncorhynchus gorbuscha	pink salmon	×	
Oncorhynchus keta	chum salmon	×	
Oncorhynchus tshawytscha	chinook salmon	×	
Oncorhynchus nerka	sockeye salmon	×	
Oncorhynchus kisutch	coho salmon	×	
Salvelinus alpinus	Arctic char	××	
Stenodus leucichthys	inconnu	×	
Smelts			
Osmerus mordax	boreal (rainbow) smelt	××	
Sticklebacks			
Pungitius pungitius	ninespine stickleback	×	
Gasterosteus aculeatus	threespine stickleback	×	
	Freshwater		
Salmonids			
*Prosopium cylindraceum**	round whitefish	×	
*Thymallus arcticus**	grayling	×	
Cods			
*Lota lota**	burbot	×	
	Marine		
Herring			
Clupea harengus pallasi	Pacific herring	×	
Smelts			
Mallotus villosus	capelin	×	×
Lanternfishes			
Benthosema glaciale	glacial lanternfish		×
Cods			
Arctogadus glacialis	polar cod		×
Arctogadus borisovi	Siberian cod		×
Boreogadus saida	Arctic cod	××	××
Eleginus gracilis	saffron cod	××	×
Gadus morhua ogac	ogac		×
Sculpins			
Artediellus scaber	rough hookear sculpin	×	×
Artediellus uncinatus	smooth hookear sculpin		×
Gymnocanthus tricuspis	Arctic staghorn sculpin	×	×
Icelus bicornis	twohorn sculpin	×	××
Icelus spatula	spatulate sculpin		×
Myoxocephalus quadricornis	fourhorn sculpin	××	×

Table 9.1—*Continued.*

		Occurrence	
		Brackish Nearshore	Marine Offshore
Myoxocephalus scorpius	seascorpion		×
Myoxocephalus scorpioides	Arctic sculpin	×	
Triglops pingeli	ribbed sculpin		×
Algonus acipenserinus	sturgeon seapoacher		×
Alligator fishes			
Asidophoroides olriki	Arctic alligatorfish		×
Lumpfishes and Snailfishes			
Eumicrotremus derjugini	leatherfin lumpsucker		×
Liparis tunicatus	kelp snailfish	×	×
Liparis fabricii	gelatinous snailfish	×	×
Liparis gibbus	dusky snailfish		×
Sand lance			
Ammodytes hexapterus	Pacific sand lance	×	
Pricklebacks			
Eumesogrammus praeciscus	fourline snakeblenny		×
Lumpenus fabricii	splender eelblenny	×	×
Lumpenus macultus	shanny	×	×
Lumpenus medius	stout eelbenny		×
Eelpouts			
Gymnelis viridis	fish doctor		×
Lycodes mucosus	saddled eelpout		×
Lycodes polaris	Canadian eelpout	×	× ×
Lycodes turneri	polar eelpout		×
Lycodes rossi	threespot eelpout	×	×
Lycodes endipleurostictus	doubleline eelpout		×
Lycodes squamiventer	scalebelly eelpout		×
Lycodes jugoricus	shulupoaluk		×
Lycodes sagittarius	archer eelpout		×
Lycodes seminudus	longear eelpout		×
Lycodes raridens	eelpout		×
Lycodes pallidus	pale eelpout	×	×
Flatfishes			
Liopsetta glacialis	Arctic flounder	× ×	×
Platichthys stellatus	starry flounder		×
Limanda aspera	yellowfin sole		×

Sources: Walters 1955; McAllister 1962; Griffiths *et al.* 1975, 1977, 1982; Carey 1977; Able and McAllister 1980; Craig and Haldorson 1981; McAllister *et al.* 1981; Dunton *et al.* 1982; Griffiths and Gallaway 1982; Frost and Lowry 1983; Schmidt *et al.* 1983; Griffiths *et al.* 1977; Bendock 1979; Griffiths *et al.* 1983.
* Incidental.

Southern Beaufort Sea drainages support nine principal species of anadromous fishes: Arctic char, broad and lake (humpback) whitefishes, Arctic and least ciscoes, chum and pink salmon, rainbow smelt, and inconnu (Table 9.2). This list excludes a species occurring east of the Mackenzie River—the eastern Arctic form of Arctic char (McPhail 1961; McCart and Craig 1971)—and incidental catches of other species such as chinook (king) and sockeye salmon and ninespine sticklebacks. Additionally, Bering cisco are combined with Arctic cisco because the distributions of these similar-looking species overlap west of the Colville River, causing some uncertainty about the identity of recorded species (McPhail 1966; Craig and Haldorson 1981; Schmidt *et al.* 1983). The *Coregonus clupeaformis* complex (McPhail and Lindsey 1970; Scott and Crossman 1973) is presented herein as the

Table 9.2—Principal stocks of anadromous fishes in Beaufort and northern Chukchi sea drainages.

		Anadromous Fish Species								
Locale	Drainage	Arctic Char	Broad Whitefish[a]	Lake Whitefish	Least Cisco	Arctic or Bering Cisco	Chum Salmon	Pink Salmon	Rainbow Smelt	Inconnu
Canada	Mackenzie	×	×	×	×	×	×		×	×
	Blow	×	×	×						
	Babbage	×	×	×						
	Spring	×	×	×						
	Firth	×								
	Malcolm	×								
	Fish	×								
U.S.-Canada Border	Clarence	×								
	Kongakut	×								
	Egaksrak	×								
	Aichilik	×								
	Hulahula	×								
	Canning	×								
	Shaviovik	×								
	Sagavanirktok	×	×							
Prudhoe Bay	Colville	×	×	×	×	× *	×	×	×	
	Fish		×	×	×					
	Ikpikpuk		×	×	×	×		×		
	Oumalik			×	×					
	Topagoruk		×	×	×					
	Meade		×	×	×		×			
	Inaru		×	×	×					
Point Barrow	Kuk				×		×	×	×	
	Utukok					×		×		

Sources: McPhail and Lindsey 1970; Alt and Kogl 1973; Scott and Crossman 1973; McCart *et al.* 1974; Ward and Craig 1974; Craig and McCart 1976; Hablett 1979; Corkum and McCart 1981; Craig 1977; Bendock and Burr 1980; Smith and Glesne 1982.

[a] In the Mackenzie drainage; humpback whitefish in the other drainages.

* Supports overwintering but not necessarily spawning populations (Gallaway *et al.* 1983).

humpback whitefish (low-count gill-raker form *C. pidschian*) in Alaskan Beaufort Sea drainages and the lake whitefish (high-count gill-raker form *C. clupeaformis*) in the Mackenzie River area (Morrow 1980). The *Salvelinus alpinus* complex here comprises the western Arctic form of the Arctic char *S. alpinus*, which is considered synonymous with the northern form of the Dolly Varden *S. malma* (McPhail 1961; Armstrong and Morrow 1980; McCart 1980).

The two largest drainages, the Mackenzie and Colville rivers, support the most anadromous species; each system has spawning populations of Arctic char, ciscoes, whitefishes, and smelt, and relatively small runs of salmon. Between these two large rivers, for a distance of 400 km there are no anadromous stocks except for Arctic char (Table 9.2; minor runs and incidental catches are excluded). Streams in this region have been classified as "mountain streams" because they originate in the Brooks Range (Craig and McCart 1975). A common feature of mountain streams is the presence of perennial springs that are associated with the spawning grounds of Arctic char.

Streams to the west of the Colville River do not originate in the Brooks Range and they differ significantly from mountain streams in both habitat and fish populations. These streams drain the tundra-covered slopes of the Arctic Foothills and Coastal Plain physiographic provinces (Payne *et al.* 1952), and support spawning populations of whitefishes, ciscoes, and salmon rather than Arctic char. The absence of Arctic char may be because the Coastal Plain streams lack the perennial springs associated with this species' spawning grounds. The presence of the other species here but not in mountain

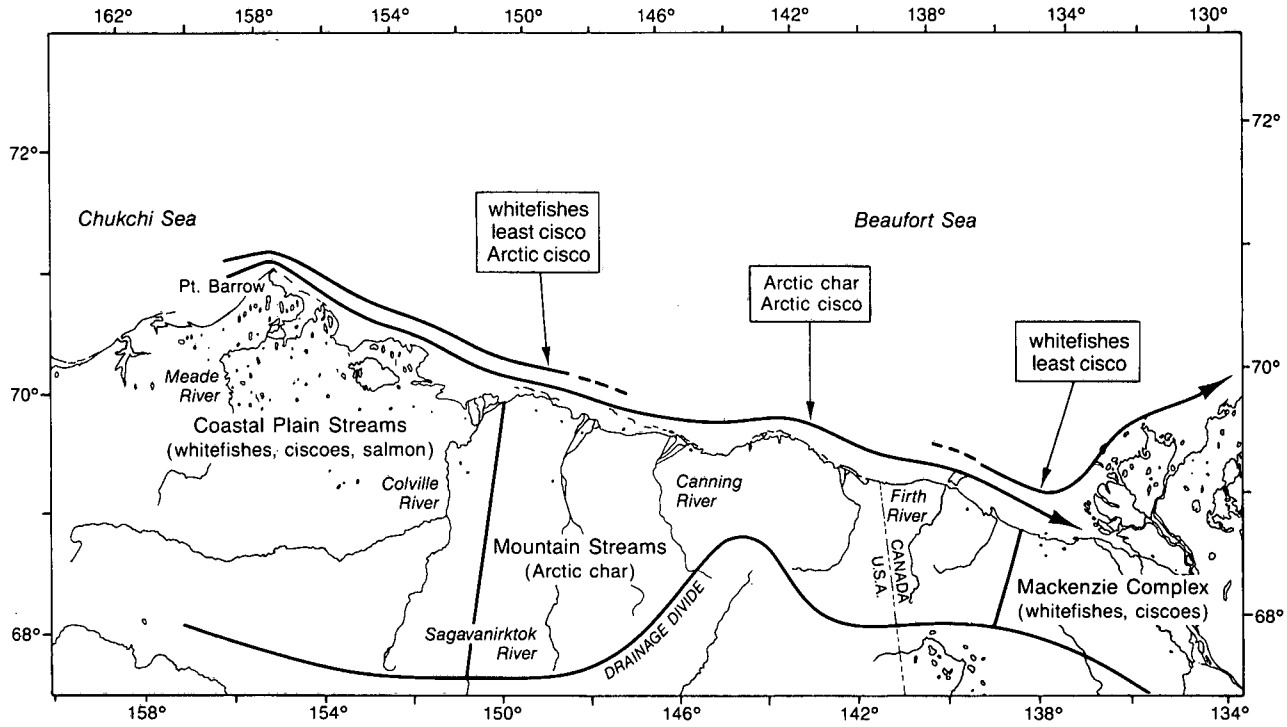

Figure 9.1.—Freshwater sources and coastal dispersal patterns of the principal anadromous fishes occurring along the Beaufort Sea coastline.

streams presumably is due to the presence of more suitable habitat in the form of larger, slower-moving rivers that meander through a network of lakes.

The boundary between the Mountain (Arctic char) and Coastal Plain (whitefishes, ciscoes, and some salmon) streams lies in the vicinity of the Colville River (Fig. 9.1). Some overlap occurs: whitefish occur in the Sagavanirktok River and Arctic char occur in the Colville River.

Smaller streams flowing directly into coastal waters do not support anadromous fish stocks and they represent a negligible contribution to the fish resources of the Beaufort Sea. These small, meandering streams, 30-65 km in length, depend upon tundra runoff; they flood at breakup, their water levels recede through the summer, and they freeze solid in winter. Some of these streams may support small populations of grayling, slimy sculpin (*Cottus cognatus*), and ninespine stickleback, but most receive little summer use by anadromous species other than sticklebacks and occasional juvenile Arctic char.

9.2 BRACKISH NEARSHORE HABITATS

Shallow nearshore waters along the Beaufort Sea coastline provide important habitat for many fish species, including those harvested by man. Despite the variety of species present (Table 9.1), a few species dominate the nearshore fauna. In terms of numerical abundance or use by humans, the important species are Arctic and least cisco, Arctic char, Arctic cod, and fourhorn sculpin. Proportions of these five species vary from site to site and according to sampling gear used, but they account for over 90% of all fish caught along the Alaskan and western Yukon Territory coastlines (Roguski and Komarek 1972; Furniss 1975; Griffiths *et al.* 1975, 1977, 1982; Kendel *et al.* 1975; Bendock 1979; Craig and Haldorson 1981; Griffiths and Gallaway 1982; Griffiths 1983; Schmidt *et al.* 1983; WWC 1983; Moulton and Fawcett 1984). Anadromous broad and lake whitefishes are also important species along the western Beaufort Sea coastline and near the Mackenzie River (Fig. 9.1).

9.2.1 Importance of Brackish Water Habitats

Nearshore waters of the Beaufort Sea are a complex mixture of river runoff and seawater. Nearshore fishes, particularly the anadromous ones, are more abundant in the relatively warm, turbid, brackish, and shallow waters directly along the coastline than in the colder marine waters which may intrude at times very close to the shoreline. In Simpson Lagoon, for example, fish were 5-98 times more abundant (species combined, seasonal average) at

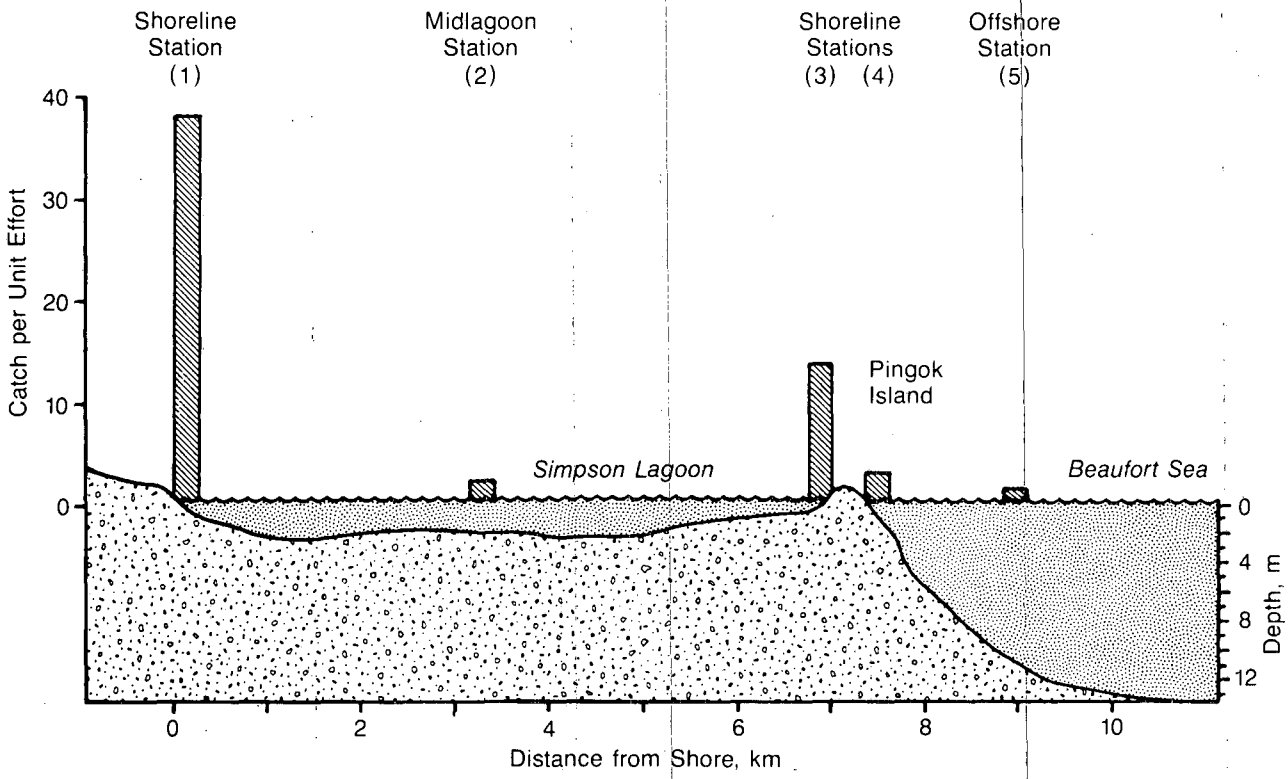

Figure 9.2.—Cross-section of Simpson Lagoon area showing relative numbers of fish caught at five sampling stations during the 1977 open-water season. The catch per unit of effort represents a seasonal average for combined species caught in 7-10 24-hour gill-net sets. (Adapted from Craig and Haldorson 1981.)

various nearshore stations than at the offshore station where no anadromous fish were caught (Fig. 9.2). Other studies have also documented the absence or very low densities of anadromous fish in offshore marine waters, although the overall sampling effort in this zone has been low (McAllister 1962; Griffiths *et al.* 1975, 1977; Percy 1975; Galbraith and Hunter 1979; Frost and Lowry 1983). Arctic anadromous fish remain in nearshore habitats and do not undertake the impressive oceanic migrations of some southern salmon stocks.

The distribution of anadromous fishes can probably be explained by their preference for warm water temperatures. Juvenile Arctic cisco prefer temperatures (11.5-15.4°C) which approach or exceed the warmest temperatures naturally occurring in coastal waters (Fechhelm *et al.* 1983). Because a fish's preferred temperature generally approximates the optimal temperature for its growth and other activities (*e.g.*, Jobling 1981) and because food is abundant in nearshore waters (discussed later), Fechhelm notes that juvenile Arctic cisco are ecologically and physiologically positioned in the warm brackish waters to make optimal use of their limited feeding season.

The occurrence of a band of turbid, brackish (10-25‰), and relatively warm (5-10°C) water is a characteristic feature of the Beaufort Sea coastline during the open-water season (Weller *et al.* 1978; Truett 1981; Matthews 1983). The band is variable in width and depth, depending on freshwater input to coastal waters, nearshore currents, prevailing winds, and topographic features. In view of its dynamic nature, a description of the brackish water band (from Truett 1981) is presented to explain variations in the nearshore distributions of anadromous fishes.

The brackish water band is formed during spring breakup when floodwaters from North Slope rivers flow to sea. Intense flooding lasts less than 2 weeks, after which some shallow lagoons and bays contain nearly fresh water. In the following weeks, nearshore waters mix with incoming cold marine water to create the brackish-water systems that prevail along the coast through the summer. In waters only a few meters deep, the entire water column is usually brackish due to continual mixing; in deeper waters a two-layered system develops, with a lens of surface brackish water overlying a wedge of colder marine water (Fig. 9.3).

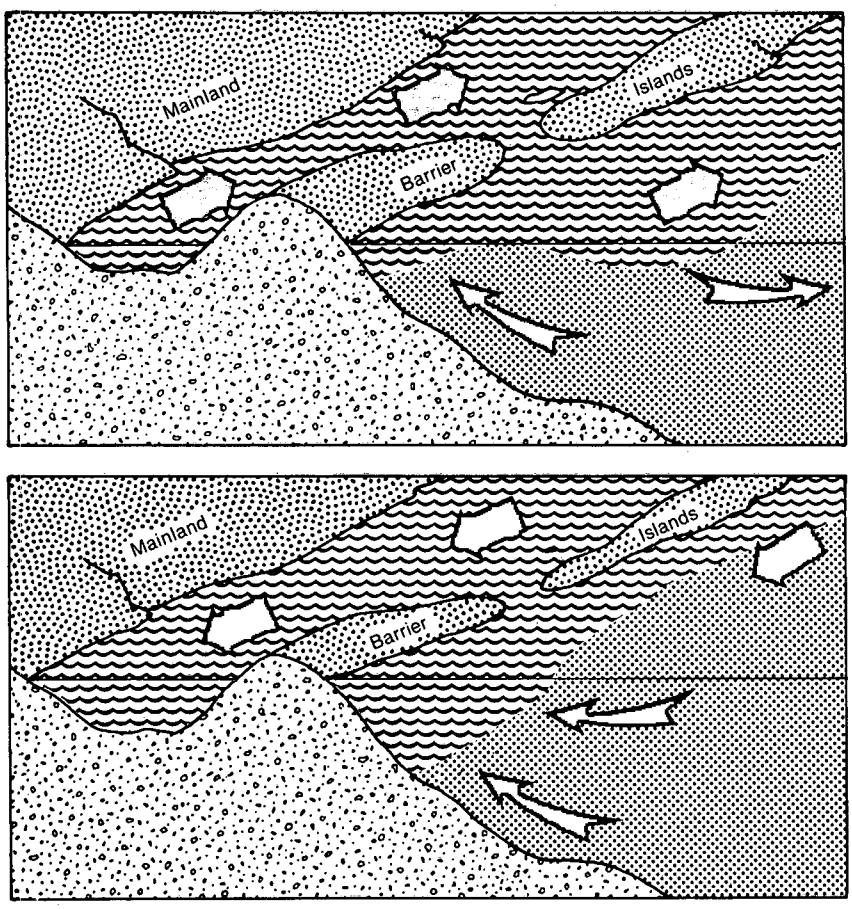

Figure 9.3.—Effects of wind direction on the nearshore band of brackish water along the Beaufort Sea coast. *Above:* Winds parallel to the coast from the east tend to depress sea level, draw brackish water seaward, and cause upwelling near the land margin. *Below:* Winds from the west hold the brackish water against the shore and raise the sea level. (Adapted from Truett 1981.)

A variety of factors influence how far the warm, brackish waters and their associated anadromous fish fauna extend seaward. Barrier islands tend to restrict exchange between brackish and marine water masses; consequently, the shallow waters behind the barrier islands may be brackish while conditions a short distance seaward of the islands are marine. In other areas directly influenced by the discharge of North Slope rivers, a brackish plume of surface water may extend 20-25 km offshore. At such locations, anadromous fish may likewise be dispersed seaward. For example, Arctic char have been caught as far offshore as Cross Island, which lies 18 km off the mouth of the Sagavanirktok River (Bendock 1979). In this same area, Tarbox and Moulton (1980) observed that the brackish layer varied from 2 to 9 m in thickness and extended seaward at least 6 km (the seaward limit of their sampling effort) throughout the summer of 1979.

Winds are a dominant influence on the nearshore environment and may change the width of the brackish water band on almost a daily basis (Weller *et al.* 1978; Truett 1981). Under the conditions of prevailing winds from the east, the sea level is lowered, the warm and brackish waters are pulled seaward as a surface lens, and colder, saline waters intrude landward at the bottom (Fig. 9.3). Winds from the west typically raise coastal waters by pushing water into bays and lagoons, thereby holding the brackish waters against the coast.

9.2.2 Summer Distribution and Movements

Seasonal use of nearshore waters by anadromous and marine fishes differs (Bendock 1979; Craig and Haldorson 1981; Griffiths and Gallaway 1982). Anadromous fishes begin to arrive with the first signs of spring breakup (5-20 June), disperse along the coastline in the brackish-water band, and return by fall to river drainages to spawn or overwinter. Marine species tend to increase in nearshore waters as the open-water season progresses and salinities increase. These fishes are not restricted to nearshore waters and probably do not migrate parallel to the coastline to any appreciable extent as do the anadromous species.

Within the nearshore brackish-water region, it is apparent that fish are not uniformly distributed but are more concentrated along mainland and island shorelines than in lagoon centers (Fig. 9.2).

Seasonally averaged catches along the mainland shoreline in Simpson Lagoon were 19 times greater than in the lagoon center. Similarly, in Kaktovik Lagoon, shoreline gill nets caught 30 times more fish than midlagoon sets on three dates when paired sets were made (Griffiths *et al.* 1977). The same pattern has been observed along the Yukon coastline (McAllister 1962; Kendel *et al.* 1975). It should be noted, however, that the central waters of lagoons and other open areas probably accommodate as many anadromous fishes as do shoreline habitats—fish densities in open areas may be low but the areas are generally large.

Many fish travel parallel to the shore along a very narrow corridor. Highest concentrations are often within 100 m of the shoreline (Fig. 9.4), although this apparently occurs only under certain conditions. Preliminary evidence suggests that fish move farther from shore when water conditions are rough or when shoreline waters are excessively shallow, but such factors are not well understood. Marine species do not display a similar attraction to shorelines (Fig. 9.4).

Several factors influence the assemblage of anadromous fishes in coastal waters: (1) proximity of freshwater sources of anadromous fish stocks, (2) migration timing, and (3) daily responses to temperature and salinity fluctuations in the nearshore environment. As discussed in "Freshwater Habitats," there are major geographical differences in the locations of anadromous fish stocks in North Slope

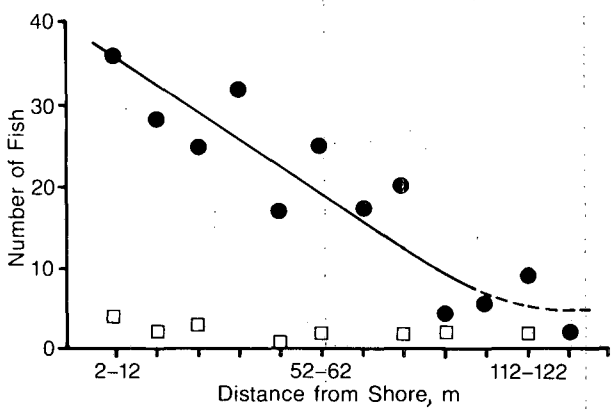

Figure 9.4.—Fish abundance in relation to distance from shore under selected conditions; data represent the sum of seven sets of a 122-m-long gill net. Nets were set for 1-7 hours on six dates, July-September 1978, off points of land in a moderately calm sea. Anadromous fishes (solid circles) and fourhorn sculpins (open squares) are indicated. (From Craig and Haldorson 1981.)

rivers, and this is partially reflected in the coastal distributions of some species (Fig. 9.2). In particular, whitefishes and least ciscoes do not disperse very far from their rivers of origin; consequently, these species are most common near the Mackenzie River and west of the Sagavanirktok River, with relatively few in between. At Barter Island, for example, least ciscoes accounted for only 1% of the total season's catch and no broad or humpback whitefishes were taken (Griffiths *et al.* 1977). In contrast, Arctic ciscoes, and at least some Arctic char (Fig. 9.5), disperse widely from their streams of origin and they are usually common across the entire Alaskan Beaufort Sea coastline.

Migration timing clearly affects the numbers of fishes in coastal habitats, but the effect is complex. According to tagging data, anadromous fishes entering coastal waters disperse in both eastward and westward directions (Fig. 9.5). This results in broad migratory waves of fishes (each lasting a few weeks or so and perhaps with juveniles behaving differently from adults) radiating along the coastline from each river containing anadromous stocks. Tagging data also indicate that the net longshore movement of anadromous fishes is some 3-6 km/day (Craig and Haldorson 1981). At present, whether more or less time is spent in selected habitats is unknown.

The day-to-day pulses of anadromous fishes in nearshore waters are probably responses to fluctuations in temperature and salinities, although these fishes are to some degree euryhaline. They are able to cope, at least for short periods, with conditions ranging from nearly fresh to salt water, temperatures ranging from 0 to 14°C, and clear to very turbid water (Table 9.3). However, tolerance of a wide range of conditions does not imply that these conditions are equally suitable for the fish. Fechhelm *et al.* (1983) found that juvenile Arctic ciscoes prefer the warmest temperatures that occur in Beaufort Sea coastal waters. In general, the abundances of most anadromous species are correlated with warm temperatures and low salinities (Griffiths and Gallaway 1982; Griffiths *et al.* 1983), although not all studies bear out this relationship (Craig and Haldorson 1981). Such correlations, where they do exist, are usually difficult to confirm because catch rates may be influenced by events beyond the boundaries of the sampling area. For example, fish numbers may increase as temperatures decrease, counter to what is expected, if the fish are vacating areas that have even colder waters. However, there have been some recent advances in the develop-

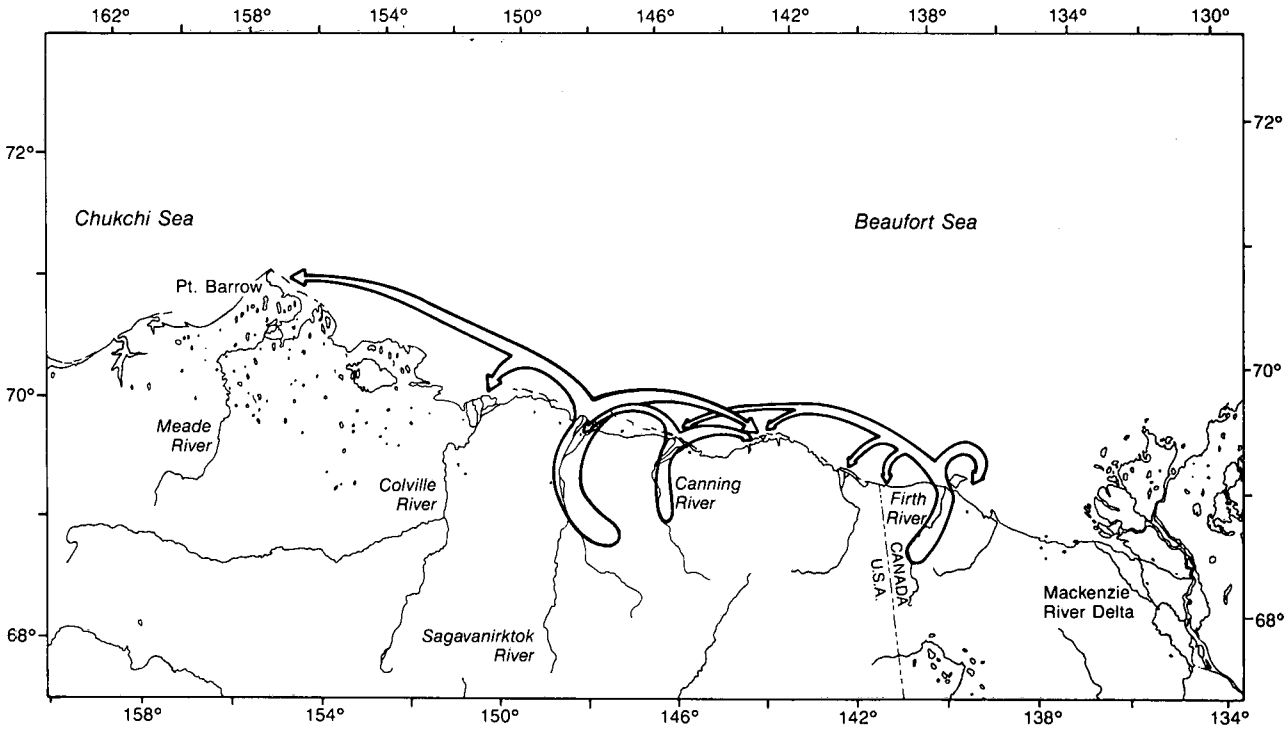

Figure 9.5.—Summer movements of Arctic char based on tagging data from the Sagavanirktok, Canning, and Firth rivers.

ment of computer models to simulate the movements and distribution of anadromous fishes (specifically juvenile Arctic ciscoes) in response to changes in temperature and salinity in the nearshore environment (Fechhelm and Gallaway 1983; Neill *et al.* 1983). To date, the results of simulations generally agree with independently monitored catch rates (Fechhelm and Gallaway 1983). It thus appears that the dynamic temperature-salinity structure of nearshore waters plays an important role in the distribution of anadromous fishes.

Affinity for the mainland shoreline, where water temperatures are typically highest and salinities lowest, varies among the anadromous species (Bendock 1979; Craig and Haldorson 1981; Griffiths and Gallaway 1982; Griffiths *et al.* 1983). Least ciscoes and broad and humpback whitefishes are not commonly found anywhere but near the mainland shore, while Arctic ciscoes and Arctic char are distributed more widely in brackish waters and are commonly present along the lagoon-side beaches of barrier islands. Arctic char are the most abundant anadromous fish on the seaward side of barrier islands, indicating their greater tolerance to varying temperature and salinity (Griffiths and Gallaway 1982; Griffiths *et al.* 1983).

9.2.3 Winter Distribution

Winter information is limited, but it is clear that species composition and distribution in nearshore waters differ from summer patterns. In general, most anadromous fishes leave coastal waters. Marine species remain under nearshore ice but eventually they too leave shallow areas as the ice thickens to a depth of 2 m by late winter.

Most anadromous fishes return to North Slope rivers and lakes in late summer and fall (late August to September), the remainder probably returning by early winter (October). These fish spawn or overwinter in lakes, deep channels, or near perennial springs where a supply of unfrozen water is assured. Overwintering sites have been located in North Slope drainages (Craig and McCart 1974; Bendock 1979; Smith and Glesne 1982), but anadromous fishes demonstrate some flexiblity in their overwintering requirements. Several species may overwinter in slighty brackish coastal waters (5-8‰) off the Mackenzie River delta (Kendel *et al.* 1975; Percy 1975; Galbraith and Hunter 1979) and also in the very brackish waters (18-32‰) within the Colville River delta (Craig and Haldorson 1981; Bond 1982). Both anadromous and marine species were

Table 9.3—Observed temperature, salinity, and turbidity conditions where fishes were caught. Summer (late June-September) values include data from Simpson Lagoon and Prudhoe Bay; winter (November-April) data are from various coastal and freshwater locations.

	Summer Conditions			Winter Conditions	
Species	Temperature (°C)	Salinity (‰)	Turbidity (NTU)*	Temperature (°C)	Salinity (‰)
Arctic cisco	0-13.5	2-32	1-146	−1.7	5-32
Least cisco	1-14	2-32	1-146	−1.7 to 0	0-32
Arctic char	0.5-14	2-32	1-146	0 to 2	0
Broad whitefish	1-14	2-30	2-146	0	0
Humpback whitefish	1-12	2-28	4-146	0	0
Arctic cod	0-13.5	3-28	1-146	−2.0	23-31
Fourhorn sculpin	0-13.5	2-31	1-146	−1.7	5-32
Arctic flounder	0-13.5	2-31	1-82		5-30
Rainbow smelt	1-13.5	1-29	2-140	−2 to −1	1-32

Sources: Summer—Craig and Haldorson 1981; Bendock 1979. Winter—Kogl and Schell 1974; Mann 1974; Percy 1975; Bendock 1979; Craig and Haldorson 1981.

* Nephelometric turbidity unit: 1 represents clear water with >1-m visibility; 146 represents very turbid water, about 5-cm visibility.

caught at the later site: Arctic and least ciscoes, rainbow smelt, fourhorn sculpin, and saffron cod. One anadromous species, rainbow smelt, also normally overwinters in the marine enviroment. This species is a spring-spawner; apparently its winter concentration in Harrison Bay is a prelude to a spring migration into the Colville River (Haldorson and Craig 1984).

Marine species continue to inhabit, feed, and reproduce in nearshore waters during the 9-month winter season. Most marine fishes spawn during the midwinter period. Egg stages are demersal and adhesive (sculpin, snailfish) or pelagic (cod), and hatching may begin by late winter. By winter's end, no fish occupy the shallow waters that received extensive summer use because coastal waters freeze solid to a depth of about 2 m. In addition, unfrozen pockets of water in shallow areas with restricted circulation become unsuitable for fish habitation—hypersaline conditions (50-180‰) may develop because of salt exclusion during freezing of seawater (Schell 1974).

The most intensive winter sampling in Alaskan coastal waters has been conducted in the central region between the Colville and Canning rivers. During two winters, over 330 under-ice net sets were made and 2,870 fish of six species were caught: rainbow smelt, Arctic and saffron cod, fourhorn sculpin, Arctic flounder, and an unidentified snailfish species (Craig and Griffiths 1981a; Craig and Haldorson 1981). Apart from the previously mentioned rainbow smelt, which was caught only in Harrison Bay, the dominant fishes in coastal waters were fourhorn sculpin (80% of the winter catch of marine fishes) and Arctic cod (15%). However, under-ice sampling is biased for selected fish shapes or activity patterns (Craig *et al.* 1982); therefore, relative abundances of winter-caught fish are approximate and additional marine species are presumably present.

Arctic cod were widely distributed in nearshore waters, but their winter catch per unit of effort (CPUE) was greatest offshore (Craig *et al.* 1982). In a late-winter collection when a single type of sampling gear was used, the CPUE was more than 30 times greater at a sampling station 175 km offshore than nearshore in Stefansson Sound near Prudhoe Bay.

In Prudhoe Bay winter samples, Tarbox and Thorne (1979) caught four species of fish: Arctic cod, kelp snailfish, fourhorn sculpin, and slender eelblenny. The abundance of these fishes was low based on capture rates, diver observations, and hydroacoustic measurements. The latter method indicated fish densities of only 0.0006 to 0.0007 fish/m^3. Tarbox and Thorne concluded that these densities were at least an order of magnitude lower than those typically observed in other southern coastal marine environments, and that estimated winter fish densities also appeared significantly lower than those recorded in the Beaufort Sea open-water season.

9.2.4 Trophic Relationships

Coastal waters of the Beaufort Sea are used by anadromous and marine fishes for one main pur-

pose, namely, feeding on the abundant supply of food organisms in nearshore habitats. The food habits of nearshore fishes are surprisingly similar; epibenthic mysids and amphipods usually account for over 90% of the diets of Arctic and least ciscoes, Arctic char, and Arctic cod (Craig and Haldorson 1981; Craig *et al.* 1983). Other fishes also feed heavily on these prey but additional preferences are apparent: rainbow smelt and, at times, Arctic char eat fish; fourhorn sculpin and Arctic flounder eat isopods. Nearshore fishes do not commonly eat infaunal organisms.

Major prey species are two mysids: *Mysis litoralis* and *M. relicta*; and several amphipods: *Onisimus glacialis, Pontoporeia affinis, Apherusa glacialis,* and *Gammarus setosus.* Proportions of prey species available and eaten are likely to vary by location and year. These invertebrates may be present throughout the water column, but they are 25 to 200 times more abundant in the region 0-20 cm above bottom substrates than in the entire 2 m of water above (Griffiths and Dillinger 1981).

The abundance of epibenthic organisms in Simpson Lagoon in 1977 and 1978 exceeded by about 50 times the total daily food requirements of all vertebrate consumers present (fishes and birds). This abundance apparently was maintained throughout the open-water season by a continual immigration of epibenthos into the lagoon from offshore areas, which supported a similarly high density of epibenthos (Griffiths and Dillinger 1981; Craig *et al.* 1983).

Secondary productivity in Simpson Lagoon is linked to offshore marine areas in even a more fundamental way. Isotopic studies indicate that the fish ultimately obtain 80-90% of the carbon in their tissues from modern marine primary production which occurs outside of the lagoon (Schell *et al.* 1982). Although the lagoon also is supplied with a large input of terrestrially derived organic carbon from coastal erosion and fluvial transport, relatively little of this carbon enters trophic pathways leading to fish in the marine ecosystem (but note Schell's discussion about the important role of terrestrial carbon in the freshwater phase of anadromous fishes).

9.2.5 Human Use of Fish Resources

Anadromous fishes, particularly ciscoes, whitefishes, and Arctic char, are the focal point of several fisheries along the Beaufort Sea coastline in Alaska. Some Arctic cod also are exploited in late fall and winter. Principal areas where fish are taken include: (1) subsistence fisheries in the vicinity of Barrow, the Colville River delta (Nuiqsut Village), and Barter Island (Kaktovik Village); (2) a commercial fishery in the Colville delta; (3) sport fishing at villages, distant-early-warning (DEW line) stations, and oil camps. The overall harvest is low and the sustainable yield is unknown.

The commercial fishery in the Colville delta has an average annual harvest of 47,000 ciscoes and 18,000 whitefish. The Nuiqsut harvest is undocumented but is thought to be similar to that of the commercial catch (Craig and Haldorson 1981). Fish are also an important subsistence resource at Barrow and Kaktovik (Pedersen *et al.* 1979; Wentworth 1979; Jacobson and Wentworth 1982) but harvests are largely undocumented. Approximately 570 (3,000 kg) Arctic ciscoes and Arctic char were taken one summer at Kaktovik (Griffiths *et al.* 1977).

Because of the migratory nature of anadromous fishes, harvests at any coastal location usually consist of fish that originate from several different North Slope drainages. Tagging studies have shown, for example, that the Arctic char caught at Kaktovik originated from at least three drainages: the Sagavanirktok, Canning, and Firth rivers (Glova and McCart 1974; Furniss 1975; Craig 1977). Conversely, fish tagged at a single location in central coastal waters were recovered in subsistence, commercial, and sport catches across the Alaskan Beaufort Sea coastline (Fig. 9.6).

In recent years, there have been marked fluctuations in numbers of Arctic cisco available to the commercial fishery. Using mark-recapture data, Craig and Haldorson (1981) estimated that numbers of Arctic ciscoes overwintering in the Colville delta had declined by 86% between 1976 and 1979. This observation was supported by the commercial catch data which declined 87% from a high of about 71,000 in 1973 to a low of 10,000 in 1979. Gallaway *et al.* (1983) examined this situation and presented a hypothesis that could have important ramifications for the fisheries. They suggest that the Arctic ciscoes caught in the Colville delta are actually fish from the Mackenzie River stock, in which case the existing fisheries in the Colville delta might have little impact on population levels of this species. Furthermore, the commercial and subsistence fisheries in the Colville delta would continue to fluctuate radically over the years due to either the density of Mackenzie River spawners or the success of juvenile dispersal from the Mackenzie River to the Colville delta—such dispersal might be obstructed during the occasional "bad ice year" when sea ice does not move off the mainland shore for most of the summer.

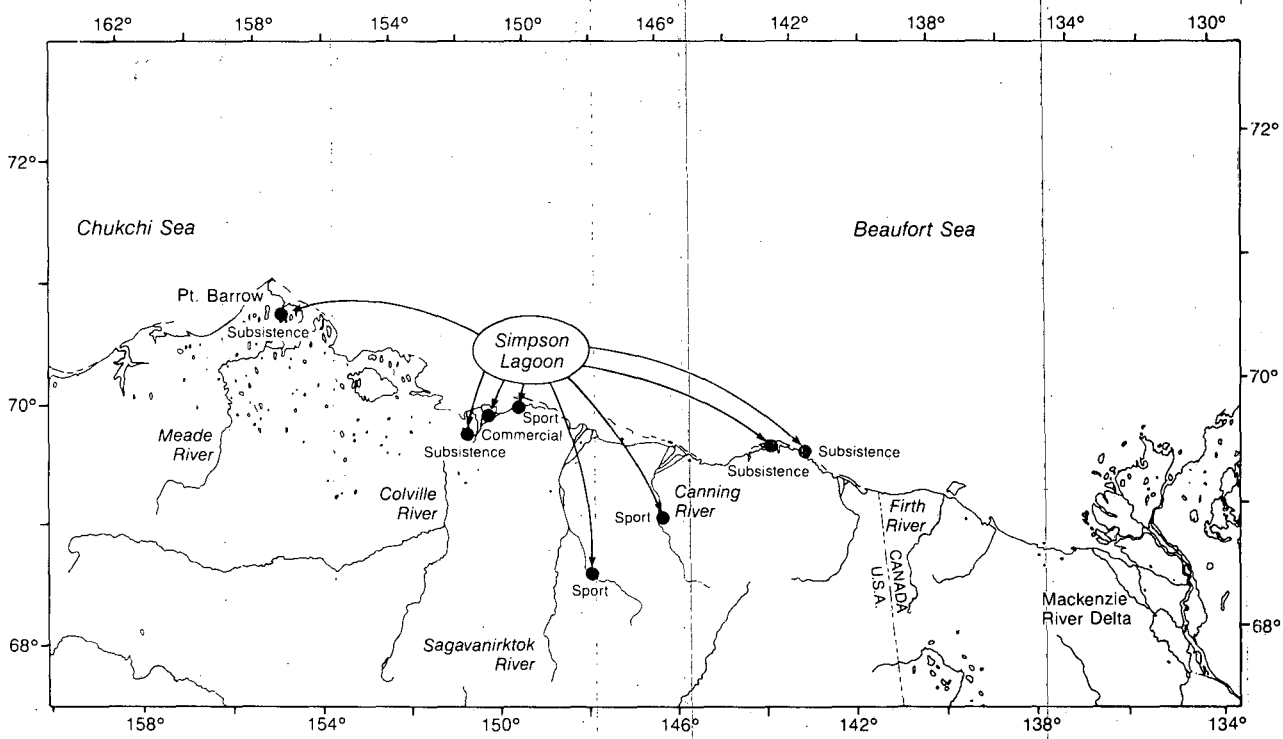

Figure 9.6—Recapture locations of fish tagged in Simpson Lagoon and recovered in commercial (n = 83 recoveries), subsistence (n = 9), and sport fisheries (n = 5).

9.2.6 Important Habitats

Beyond the general statement that nearshore habitats are important to anadromous fishes, it is difficult to single out any particular habitat as being more important than others. This situation reflects our current understanding of what fish do when they enter coastal waters. Anadromous fishes enter estuarine coastal waters to feed and, while in these waters, they may travel considerable distances. They apparently do not feed in particular habitats; rather, it is the zone of brackish water adjacent to the entire coastline that is of particular biological importance to these fish.

There are exceptions, however, in which particular habitats are of special importance to. These are the deltas of the larger rivers, which are overwintering areas for ciscoes, whitefishes, and Arctic char, as well as important migratory pathways and spawning areas for some fish. The Colville River delta is of special significance; the large stocks of fish that overwinter there support both commercial and subsistence fisheries.

Because mud and sand substrates predominate in the Beaufort Sea, an area of rocky bottom near Prudhoe Bay (the Boulder Patch in Stefansson Sound) has received considerable attention and been identified as an important habitat because of its diverse assemblage of plants and invertebrates (Broad *et al.* 1980; Dunton *et al.* 1982). However, this habitat does not appear to be equally important for fishes. The diversity and abundance of fishes in the Boulder Patch are low, although the area does provide habitat for marine species that spawn on hard substrates. Dunton *et al.* (1982) collected three fish species in the Boulder Patch: kelp snailfish; fourhorn sculpin; and fish doctor.

9.3 MARINE COASTAL HABITATS

In the present context, marine coastal waters describe a habitat identified by water-mass characteristics rather than distance from shore. These waters are generally cold (−1 to 3°C) and saline (27-32‰), conditions varying with the degree of mixing with river effluent and ice-melt waters (Hufford *et al.* 1974). Although marine waters are themselves made of several subcategories of water types, it is expedient at this stage to contrast this relatively cold and saline water mass with the much warmer brackish waters adjacent to the coastline. Marine coastal water in offshore areas occupies the complete water column and may extend into nearshore bays and lagoons as a subsurface wedge of water under a lens of brackish water. Because of

the previously discussed dynamic relationship between the marine and brackish water masses, there may be almost daily fluctuations in the distribution of the marine fish fauna in nearshore waters.

Information about fishes inhabiting marine coastal waters is limited. To date, 40 species have been collected in Alaskan offshore waters (Table 9.1), but the sampling effort has been low. Several papers provide general or taxonomic information about these fishes (Andriyashev 1954; McAllister 1977; Able and McAllister 1980; McAllister *et al.* 1981) or information about marine fishes off the Mackenzie River or farther east (Tyler 1978; Galbraith and Hunter 1979; Bond 1982; M. Lawrence, Freshwater Institute, Winnipeg, Manitoba, pers. comm.).

In Alaskan coastal waters, very few studies have examined fish use of marine habitats. Frost and Lowry (1983) conducted a trawl survey in waters 40-400 m deep near the southern edge of the ice pack. Catches were low; an average of 18 fish of four species were caught in each 5- to 10-min trawl (n = 35). In all, 17 species were collected, and 3 (Arctic cod, Canadian eelpout, and twohorn sculpin) accounted for 65% of the catch. Some life-history data are available for these and other abundant marine fishes in offshore habitats (Able and McAllister 1980; Lowry and Frost 1981; McAllister *et al.* 1981; Craig *et al.* 1982; Frost and Lowry 1983). One species, the Arctic cod, has been described as a "key species in the ecosystem of the Arctic Ocean" because of its abundance, widespread distribution, and importance in the diets of marine mammals, birds, and other fishes (*e.g.*, Andriyashev 1954; Quast 1974; Bain and Sekerak 1978; Craig *et al.* 1982; Sekerak 1982). Several authors have suggested that Arctic cod influence the distributions and movements of marine mammals and seabirds in arctic waters (Klumov 1937; Bradstreet 1980; Davis *et al.* 1980; Finley and Gibb 1982). Frost and Lowry (1984) calculate that Arctic cod are by far the most important consumer of secondary production in the Alaskan Beaufort Sea.

9.4 DISCUSSION

Although the distinctiveness of the brackish and marine water masses and their fish fauna have been emphasized in this review, it should be recognized that this generalization has its share of qualifiers and exceptions. Neither the habitats nor the fishes adhere to strictly defined patterns or definitions. The habitats change both spatially and temporally during the open-water season. The brackish-water band along the coastline exists only during the open-water season and it usually varies in width by a few kilometers due to the influence of weather, topographical features, and the freshwater input of rivers.

As the summer progresses, the nature of the brackish water changes, owing to decreasing terrestrial runoff, and consequently, to increasing salinities and cooler temperatures. It is also probable that, at times and places, the brackish and marine waters mix extensively, thereby creating a gradient of temperature and salinity changes rather than maintaining relatively distinct entities.

The fishes inhabiting nearshore waters are euryhaline to varying degrees as might be expected in such an environment. The occasional "freshwater" species enters coastal waters and some "marine" species inhabit brackish waters or may even enter the lower reaches of rivers. Despite these variations, the brackish-water band is a persistent and biologically significant feature of the Beaufort Sea coastline. What distinguishes it from many estuaries at other latitudes is that it is continuous for 750 km rather than a disjunct series of estuaries.

A final comment concerns the vulnerability of Beaufort Sea fishes to industrial developments, a topic that seems appropriate because it was the discovery of arctic oil and gas that spurred the past decade of research. To evaluate vulnerabilities, it is useful to examine the important biological activities of fish that occur in Beaufort Sea coastal waters. Four broad categories of fish activity are spawning, feeding, movements and migration, and overwintering. The last category, though less an activity than a requirement for suitable habitat, represents an annually critical event in the lives of arctic fishes.

With minor exceptions, coastal waters of the Alaskan Beaufort Sea are used only for feeding and migration by the species of subsistence or commercial interest to man. These are the anadromous species which spawn in fresh water. Their young usually remain in streams or lakes for some months or even years before migrating into coastal waters. They also return each fall to streams, deltas, and lakes to overwinter. Thus, the stages of a fish's life cycle considered to be most vulnerable to disturbance generally occur in freshwater systems: (a) spawning, (b) eggs incubating in stream gravel, (c) newly emerged fry and their period of early development, and (d) fish overwintering in typically confined sites where they may not be physically able to avoid perturbations.

In Alaskan coastal waters, anadromous fishes would encounter oil spills or other contaminants during their less-vulnerable stages; *i.e.*, when the larger juveniles and adults enter coastal waters to feed in summer. Large fish are generally less sensitive than eggs or larvae to stresses caused by pollutants (*e.g.*, Hyland and Schinder 1976), and they often are able to avoid or emigrate from polluted areas. In Beaufort Sea coastal waters, anadromous fishes are widely distributed and mobile. Tagging data indicate that these fish are neither territorial nor restrictive in movements but move actively along the coast at a net rate of 3-6 km/day (Craig and Haldorson 1981).

In addition, these fish inhabit an estuarine environment that is maintained at an early stage of ecological succession because of widely fluctuating physical factors (for example, temperature and salinity fluctuations, substrate gouging by ice and resuspension, and periodic freezing). Successful species in this shallow, frequently wind-churned and turbid environment tend to be mobile and tolerant of a wide range of conditions (Craig and Haldorson 1981; Griffiths and Dillinger 1981; Craig *et al.* in press). This, in turn, suggests that—at least in summer—the relatively few species tolerating these conditions would not be overly sensitive to related types of small-scale physical perturbations that might result from industrial activities. However, at least two industrial activities do not fall within this category and may significantly affect anadromous fish populations in coastal waters:

1. *Habitat alterations*. Craig and Griffiths (1981b) discuss potential problems regarding alterations of coastline features with long, solid-fill causeways that would connect offshore docks and drilling platforms to land-based operations. The principal concern is that causeways might alter the along-shore flow of brackish water, thereby changing temperature and salinity patterns in nearshore habitats. For example, the existing Atlantic Richfield Company (ARCO) causeway in Prudhoe Bay has altered temperature and salinity regimes in local habitats by deflecting westward-flowing brackish waters seaward. The brackish waters are replaced by a wedge of more marine water on the lee (west) side of the causeway; consequently, water temperatures tend to be cooler and salinities higher on the lee side. Although the impacts of this particular change are local in nature, the cumulative effect of a series of causeways on nearshore temperature and salinity patterns may be of consequence to anadromous fishes.

2. *Seawater intakes*. Large volumes of seawater are pumped into oil fields to maintain well pressures. The first seawater intake constructed is located at the seaward end of the ARCO causeway, and future intakes probably will be similarly situated on other solid-fill causeways (USACE 1980). Juvenile fish migrating along the coastline and encountering a causeway presumably will continue to move along the causeway shoreline and thus be directed towards the seawater intake. Although best-guess estimates of fish mortality in one seawater intake are low, the cumulative effect of several seawater intakes again may be consequential.

Marine fishes are year-round residents in the Beaufort Sea, and all of their previously mentioned biological activities occur in marine waters; however, their vulnerability to industrial activities appears low. Marine species are widely distributed, and although the available evidence is limited, it suggests that their spawning, feeding, migrating and overwintering areas are likewise widely distributed in the Beaufort Sea. Furthermore, life-history characteristics of one important marine species, the Arctic cod, indicate an adaptation or "strategy" for life in the arctic that is quite unlike that of anadromous species (Craig *et al.* 1982). Whereas anadromous populations tend to be slow-growing, late-maturing, and long-lived, the Arctic cod is a small, short-lived fish that matures at an early age. It has been suggested that species with a high rate of population turnover would be able to withstand higher levels of mortality than would those with a slow turnover rate (Adams 1980). This, in turn, implies that species like the Arctic cod also might recover more quickly from other kinds of perturbations (*e.g.*, oil spills) than would the anadromous species.

In summary, it appears that anadromous and marine fishes will not be seriously affected by most small-scale industrial developments in coastal waters, particularly when each development is viewed in isolation; however, the cumulative impacts of coastwide development as currently envisioned may affect anadromous fish populations both directly (mortality of juveniles in seawater intakes) or indirectly (habitat alteration due to artificial structures that change nearshore circulation patterns).

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Chapter 10
Coastal and Marine Birds

by Stephen R. Johnson, Peter G. Connors, George J. Divoky, Rosa Meehan, and David W. Norton

Previous OCSEAP synthesis reports have discussed the avifauna of the northeastern Chukchi and Alaskan Beaufort seas (Weller *et al.* 1978, 1979; Norton and Sackinger 1981). However, the earlier reports presented information on bird use of representative habitats as if the region were relatively homogeneous. During the Sale 87 synthesis meeting in January 1983, participants in the working group on avifauna determined that they were significantly better prepared than during earlier meetings to discuss relatively distinct subdivisions in the region between Peard Bay and Demarcation Point, Alaska. Consequently, we developed an interpretive and synthetic overview of avifaunal use of coastal and marine systems in the region, using the six geographic areas described by Divoky (1983) (Fig. 10.1). In addition to offshore areas I-VIa, the corresponding coastal areas were subdivided into units A-K (Fig. 10.1). These 11 coastal areas vary in size and shape, and also in available scientific information on birds. Where a section of coast is not included within one of the 11 areas, the expectation of new information that could significantly affect decisions about offshore petroleum development was thought to be low.

In this chapter, we review and reiterate some important information from earlier synthesis volumes concerning zoogeography and seasonal habits of birds in the northeastern Chukchi and Alaskan Beaufort seas (Weller *et al.* 1978, 1979; Norton and Sackinger 1981). In addition, we present the most current information on the distribution, abundance, and habitat use of birds in the six marine and coastal regions, including the pelagic (waters deeper than 20 m) and nearshore habitats (waters shallower than 20 m), and insular, tundra, and specific coastal areas from Peard Bay in the west to Demarcation Bay in the east.

10.1 REVIEW

Birds are highly visible organisms that are often of public interest and concern. The birds of the northeastern Chukchi and Alaskan Beaufort seas are clearly an international resource, whose value is recognized and protected in North America by international treaties. With few exceptions, their presence in arctic Alaska is a transient phenomenon. Some species that breed in this region spend the winter as far away as Antarctica (Arctic Tern, *Sterna paradisaea*) and South America (Pectoral Sandpiper, *Calidris melanotos*; Lesser Golden Plover, *Pluvialis dominica*); individuals of other species may overwinter in the northern Bering Sea or southern Chukchi Sea (Oldsquaw, *Clangula hyemalis*; eiders, *Somateria* spp.). Some also migrate to this area from wintering grounds on South Pacific islands (Ruddy Turnstone, *Arenaria interpres*) and from Asia (Dunlin, *Calidris alpina sakhalina*) (MacLean and Holmes 1971; Norton 1971).

Most birds are present in this area of Alaska only from May through September, the breeding season of all arctic birds. This is a crucial phase in the life cycle of these birds; they cannot abandon a disturbed area during the breeding season without a significant loss of energy invested in eggs or young. Although low densities of nesting birds are typical of this region, they are distributed over a broad area and total populations are often large.

In his review of birds of the Barrow area, Pitelka (1974) listed 151 species, of which 22 are species that regularly breed there. At a coastal tundra site near Prudhoe Bay, Bergman *et al.* (1977) recorded the presence of 71 species, of which 25 were breeding. Because there are no trees, shrubs, or cliffs along the northeastern Chukchi and Beaufort sea coasts, few birds that nest in these habitats are

present. Birds breeding in this area are typical wetland or tundra-nesting species such as loons (*Gavia* spp.), waterfowl, shorebirds, and ground-nesting passerines.

Birds are found on the tundra throughout the entire breeding season, beginning in late May and early June. In late June and early July, after nesting, many adults leave tundra areas and move to coastal habitats. Peak use of the coastal zone occurs in August, when juveniles also abandon tundra areas to join and/or replace adults. In some habitats, however, such as the coastal lagoons between the Colville River delta and Demarcation Bay, diving ducks may remain in large numbers until late September.

10.2 SPRING MIGRATION

Eastbound spring migrant water birds generally follow a coastal route to their breeding areas. There is some evidence that many birds migrate primarily within 10 km of the coast (Flock 1973; Richardson *et al.* 1975; Richardson and Johnson 1981; Woodby and Divoky 1982), but not all migration is restricted to a narrow coastal strip. Migrants are commonly recorded 40 km out to sea (Divoky 1983), as well as 140 km inland on the coastal plain and in mountain passes (Williamson *et al.* 1966). King Eiders (*Somateria spectabilis*), for example, probably migrate far out to sea from Point Barrow to Banks Island (Barry 1968; Richardson and Johnson 1981), coming near shore only when offshore leads close.

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; Woodby and Divoky 1982); whereas in the Beaufort Sea, these leads are used most heavily in early June (Schamel and Mueller 1976). By then, rivers are beginning to flow and open water is available at river deltas. These habitats provide an opportunity for migrants to rest and feed. Similarly, shorebirds use snow-free areas of tundra during spring migration. Such sites may be abundant both along the coast and inland during some seasons, or limited to the headwaters of streams in other seasons. In any given locality, the pattern of habitat availability may be similar from year to year, but the timing may vary considerably.

10.3 POSTBREEDING SEASON

The period of greatest use of the coastal zone by birds occurs during the postbreeding season, when many tundra species move to the coast to feed prior to migration. Beginning in mid-July, Oldsquaws concentrate in bays and lagoons near barrier islands, where they feed and rest during their feather molt (Johnson and Richardson 1981). In late July they are joined by juvenile Red Phalaropes (*Phalaropus fulicarius*) and Red-necked Phalaropes (*P. lobatus*) which move to the coast from the adjacent tundra (Schamel and Mueller 1976; Connors and Risebrough 1977, 1978, 1979; Divoky 1978; Schamel 1978; Johnson and Richardson 1981). These phalaropes are often abundant along barrier islands and spits, and appear to be most numerous near the Point Barrow-Plover Island area (area II) and in the Point Franklin--Seahorse Islands (area I) (Connors 1977; Divoky 1978). These two areas also provide important staging habitat for juvenile Sabine's Gulls (*Xema sabini*), Arctic Terns (Divoky 1978), and other shorebirds (Connors and Risebrough 1977, 1978, 1979). Farther east, the barrier islands and coastal lagoons along the central and eastern Alaskan Beaufort Sea coasts are also important for staging juvenile phalaropes and other shorebirds, gulls, and especially for molting Oldsquaws (Johnson and Richardson 1981; U.S. Fish and Wildlife Service 1982, 1983).

Many birds migrate into the northeastern Chukchi and Alaskan Beaufort region from breeding grounds elsewhere. They concentrate at staging areas located here before continuing their outbound migration. Black Brant (*Branta bernicla*) feed in brackish marshes during their migration in August. Numerous river deltas between Prudhoe Bay and Demarcation Bay may be important to substantial numbers of these geese (Koski 1975, 1977; USFWS 1982, 1983). Approximately 40,000 geese congregate annually in the area north of Teshekpuk Lake (about 75 km east of Point Barrow) to undergo wing molt (Derksen *et al.* 1979). The majority are Brant, but large numbers of Canada Geese (*Branta canadensis*) and Lesser White-fronted Geese (*Anser albifrons*) also are present. Some of the Brant come here from Wrangel Island, U.S.S.R.

Between 160,000 and 400,000 Lesser Snow Geese (*Anser caerulescens*) breed on Banks Island, Kendall Island, and in the Anderson River delta in northwest Canada, then migrate to staging areas along the eastern North Slope of Alaska, in and near the Arctic National Wildlife Refuge (Koski 1977; USFWS 1983) before returning east and south down the Mackenzie River to their wintering grounds in southern North America.

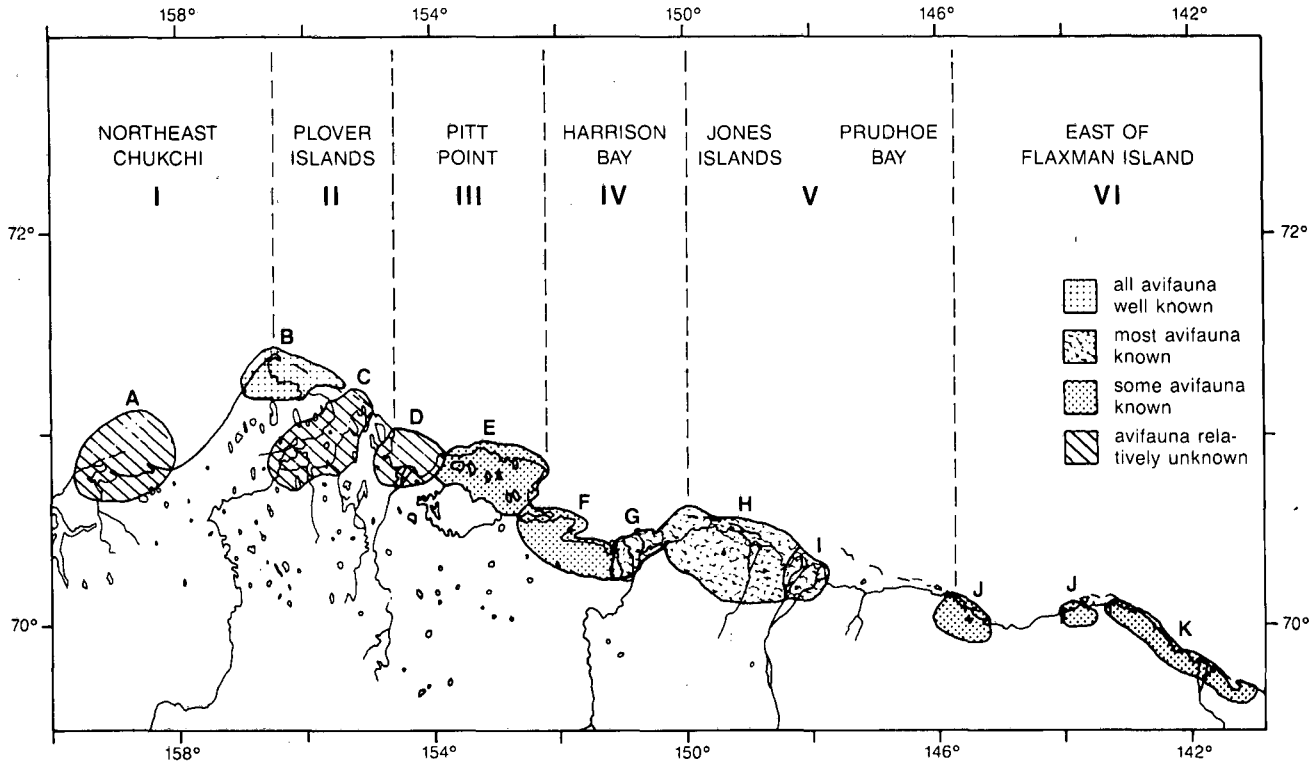

Figure 10.1—Pelagic, nearshore, and coastal regions of the northeastern Chukchi and Alaskan Beaufort seas (Diapir Field OCS Planning Area). Roman numerals designate geographic regions according to Divoky (1983). Capital letters designate specific regions along the coast that are discussed in the text.

Another important postbreeding movement is that of male eiders. Beginning in early July, shortly after the females of these seaducks have laid their eggs, males return westward from nesting grounds in Canada and Alaska to molting areas presumably in the Chukchi and Bering seas. There is some evidence that few, if any, stop before reaching the Chukchi Sea (G. J. Divoky pers. comm. 1978). At least a few concentrations of these molting eiders have been found in the northeastern Chukchi Sea near Peard Bay (Lehnhausen and Quinlan 1982).

10.4 DISCUSSION

In the northeastern Chukchi and Alaskan Beaufort seas, the largest numbers of birds in pelagic, nearshore, and coastal regions are supported in or near ecotones, areas where boundaries of two or more distinctly different habitats or ecosystems meet. The area between Peard Bay and the Plover Islands, an area influenced by the Bering Sea intrusion, is a good example of this phenomenon. Other good examples are the ice edges that provide rich feeding areas for marine birds and the barrier island-lagoon systems, which represent an exceptionally wide band of shallow and protected habitat lying along the marine-terrestrial interface.

10.4.1 Birds in the Pelagic Region

The pelagic waters (waters deeper than 20 m) of the northeastern Chukchi and Alaskan Beaufort seas have complete or nearly complete ice cover from late November through mid-May. During this period seabirds are absent from most areas. The persistent nearshore lead system present in the northeastern Chukchi Sea and extending into the extreme southwest Beaufort Sea supports small numbers of wintering Black Guillemots (*Cepphus grylle*) and is the only area where birds are regularly encountered during this period. When spring migration begins in mid-May, this lead system is the location of exceptionally high bird concentrations. Large numbers of eiders, Oldsquaws, and Glaucous Gulls (*Larus hyperboreus*) use it as a migratory pathway (Woodby and Divoky 1982). The more extensive lead system east of Point Barrow is less well defined, and these species apparently continue their migration farther offshore and over a broader front (Richardson and Johnson 1981).

Bird use of the pelagic region is low during June and July, when ice cover remains extensive and most birds are involved in breeding activities in or near terrestrial habitats. A limited amount of cen-

susing in the pelagic region has been conducted during this period. Nonbreeding Glaucous Gulls and Black-legged Kittiwakes (*Rissa tridactyla*) are present in low densities. Smaller numbers of the species that are more common later in the summer also are present in the pelagic region at this time (Divoky 1978, 1983).

From late July through September, the pelagic waters of the northeastern Chukchi and Alaskan Beaufort seas are used by large numbers of tundra-nesting species during their postbreeding migrations westward toward the Pacific Basin (Divoky 1983). Extensive shipboard censusing during this period has shown that bird densities average less than 10 birds/km^2 in all six areas, except in the extreme southwest Beaufort (region II, Plover Islands; Table 10.1), where densities average over 38 birds/km^2. Observations of feeding and migratory activities by birds indicate that the pelagic waters north of the Plover Islands are regularly used for feeding and premigratory staging, while in other areas birds appear to migrate through without stopping to feed. The extreme southwest Beaufort Sea (area II) appears to be more biologically productive than other areas, because here an intrusion of Bering Sea water advects into the Beaufort Sea and mixes with colder Arctic Ocean water. Low bird densities in the Chukchi Sea directly west of Point Barrow suggest that it may be the mixing of these water masses, rather than the actual intrusion, that increases productivity.

The two easternmost regions (V and VI) had remarkably low bird densities. During shipboard transects, birds were encountered there in only 55% of all observation periods.

The species most abundant in the pelagic region during late summer are Glaucous Gulls, Black-legged Kittiwakes, jaegers (*Stercorarius* spp.), Arctic Terns, Sabine's Gulls, and Red Phalaropes. Loons, eiders, and Oldsquaws are present primarily as migrants in September. Short-tailed Shearwaters (*Puffinus tenuirostris*) are present sporadically and normally only as far east as the Plover Islands, but their maximum densities may reach 1,000 birds/km^2, the highest recorded for any species in the pelagic region.

Birds prey primarily on Arctic cod in pelagic waters, although zooplankton is often locally important, especially in the area influenced by the Bering Sea intrusion.

10.4.2 Birds in the Nearshore Region

Birds are absent from the nearshore region of the northeastern Chukchi and Alaskan Beaufort seas from approximately late October through late May because of the nearly complete ice cover. When open water becomes available at river deltas and in shore leads, in late May and early June, these areas are occupied by loons, Oldsquaws, and eiders. During the period of nearshore ice decomposition, from mid-June through late July, the most common birds in the nearshore region are postbreeding male Oldsquaws. During this period, and during most of the open-water period, Oldsquaws are abundant along the entire portion of the coast protected by barrier islands.

Avian use of the nearshore region is highest during late July and August, when birds move from tundra habitats after the completion of breeding. Censusing from vessels in August indicates that the nearshore region supports rather uniform moderately high densities of birds in the six geographic regions (Fig. 10.1, Table 10.1) with the exception of Harrison Bay (area IV), where densities are low apparently because of shallow and turbid waters with a high freshwater input. Densities of birds in the area east of Flaxman Island (area VI) are probably low because of incomplete censusing in this

Table 10.1—Average densities (birds/km^2) of seabirds in the pelagic and nearshore areas of geographic regions I-VI (see Fig. 10.1) of the Diapir Field OCS Planning Area.

	I Northeastern Chukchi Sea	II Plover Islands	III Pitt Point	IV Harrison Bay	V Jones Islands/ Prudhoe Bay	VI East of Flaxman Island
Pelagic	6.5	38.1	6.9	4.1	3.7	9.0*
Nearshore	—	98.9	144.9†	28.6	75.0	25.9

Source: Divoky 1983.
Note: All censuses were conducted from ships; littoral zones were not included in nearshore censuses.
* Migrant waterfowl constituted 7.7 birds/km^2.
† Migrant eiders constituted 73.4 birds/km^2.

area. No nearshore censusing has been conducted west of Point Barrow; densities have been reported to be moderate to high in Peard Bay (Lehnhausen and Quinlan 1982).

High bird densities recorded in the nearshore region, compared with the pelagic region, are attributable to the presence of large numbers of diving ducks (Oldsquaws, eiders). The high standing stocks of available epibenthic crustaceans that support these diving ducks appear to vary little in composition and availability among geographic regions during the open-water period.

The distribution of surface-feeding birds in the nearshore region, like the pelagic region, is affected by the Bering Sea intrusion. The Plover Islands support the highest densities of all regularly encountered surface-feeding birds in the northeastern Chukchi and Alaskan Beaufort seas (Divoky 1983).

Prey consumed by birds in the nearshore region differs from that in the pelagic region. Species that feed primarily on Arctic cod in offshore waters switch to zooplankton in the nearshore region (Divoky 1983); diving birds, on the other hand, feed primarily on epibenthic crustaceans, as well as some molluscs and small fishes.

10.4.3 Birds in Insular Habitats

The barrier islands lying along the Alaskan coasts of the northeastern Chukchi and Beaufort seas do not support large breeding populations of seabirds. Nevertheless, they represent a distinct habitat and assemblage of species that are not found nesting elsewhere in the Alaskan Beaufort Sea. The principal islands known to support nesting colonies, and numbers of nests known in recent years, are listed in Table 10.2. The only colony that may be considered truly unusual, and of special significance with respect to Alaskan populations, is Howe Island. Howe Island and nearby Duck Island support the only known Snow Goose nesting colony in the United States (Johnson 1983a).

Cooper Island, located at the extreme west end of the Beaufort Sea in the Plover Islands group, supports unusually large breeding populations numbering hundreds of Black Guillemots and Arctic Terns (Divoky 1983).

A system of ranking is useful when considering other barrier islands. If it is necessary to disturb an island along the northeastern Chukchi or Alaskan Beaufort coast, islands lacking sizable breeding populations of birds should be selected in preference to those islands listed in Table 10.2. Islands that support breeding colonies should be subjected only to low levels of disturbance that do not permanently alter the suitability of the island to nesting birds. After any use, barrier islands should be rehabilitated as much as possible to resemble their natural condition, with original height contours, similar amounts and distribution of vegetation and driftwood, and absence of activity and associated noise and disturbance. Under these conditions, it is possible that recolonization by species tempo-

Table 10.2—Approximate numbers of bird nests on islands along the coast of the northeastern Chukchi Sea and Alaskan Beaufort Sea.

	Approximate Numbers of Nests								
	Common Eider	Glaucous Gull	Arctic Tern	Black Guillemot	Black Brant	Snow Goose	Oldsquaw	King Eider	Approx. Total
Pt. Franklin and Seahorse Islands	>20	—	40	<5	—	—	<5	—	>70
Cooper Island	0	—	150	250	—	—	—	—	400
Thetis Island	41	6	2	—	9	—	—	—	58
Egg Island	35	21	5	—	—	—	1	3	65
Howe Island and Duck Island	<5	20	—	—	—	78	—	—	<103
Cross Island	139	4	2	—	—	—	—	—	145
Pole Island	64	3	2	—	—	—	1	—	70
Narwhal Island	35	3	1	—	—	—	1	—	40

Sources: Schamel 1974; Gavin 1976; Divoky 1978, pers. comm.; J. W. Helmericks pers. comm. 1980; Johnson and Richardson 1981; Johnson 1982; U.S. Fish and Wildlife Service 1982; P. G. Conners pers. comm. 1983.
Note: Total numbers of nests of each species on each island are the maximum numbers recorded.

rarily displaced may eventually occur. Irreversible disturbance, however, should be avoided on all islands that support significant breeding colonies (Table 10.2).

10.4.4 Birds in Tundra Habitats

Most species of birds that occur in coastal and marine habitats of the northeastern Chukchi and Alaskan Beaufort seas nest in tundra habitats on the Arctic Coastal Plain in June and July (Wahrhaftig 1965). Onshore developments such as roads, construction pads, or gravel mining associated with coastal and offshore developments may therefore affect coastal bird densities. Fortunately, most tundra-nesting species occur widely along the Beaufort Sea coast in habitats which are similar or the same at many sites. Disturbances at a single site probably would not eliminate a disproportionate fraction of the total populations of any one species, but cumulative effects of widespread development could become a serious problem. Studies of the effects of roads on tundra bird populations, through loss of habitat, the effects of dust, activity and noise disturbance, and hydrological changes, are continuing on the Arctic Coastal Plain of Alaska, mainly near Prudhoe Bay (Connors and Risebrough 1979; Troy and Johnson 1982; Troy *et al.* 1983). Some species, especially Brant and other geese, nest in limited areas and depend on other limited areas of tundra (*e.g.,* coastal salt marshes; Teshekpuk Lake area and surrounding tundra) during the postbreeding season. Tundra developments in these apparently preferred areas might therefore have disproportionate effects on populations of birds.

The density and biomass of most bird species in tundra habitats decrease in late summer (Bergman *et al.* 1977; Myers and Pitelka 1980), as most birds move to molting or staging areas along the coast, or depart on southward migrations (Johnson *et al.* 1975; Connors *et al.* 1979; Johnson and Richardson 1981). At this time the densities and biomass of many species, especially shorebirds, become very high in coastal habitats such as salt marshes, mud flats, and along gravel beaches (Connors *et al.* 1981).

As spring extends through summer into fall, one very significant exception to the general trend of decreased bird densities and biomass is the appearance of hundreds of thousands of Lesser Snow Geese on the Arctic Coastal Plain of the Arctic National Wildlife Refuge (Koski 1977; USFWS 1983). These birds nest in the western Canadian arctic, on Banks Island and in the Anderson River delta, and begin to move westward toward coastal and upland tundra habitats along the North Slope of Canada and northeast Alaska during late August. They feed in these habitats until late September or early October when they migrate back to the east and then south along the Mackenzie River valley.

A few other trends in tundra bird distribution are apparent. Since some species reach the limits of their ranges along the Beaufort Sea coast, the species mix or diversity changes somewhat from east to west. The extent of low wetland habitat changes from east to west, since the coastal plain is broad near Barrow and very narrow in the eastern Alaskan Beaufort. As a result, wetland and tundra birds are more numerous in the west and central area than in the east (Pitelka 1974; Salter *et al.* 1980). Additionally, a north-south gradient in habitat types is thought to be responsible for higher densities of birds near the coast compared to areas farther inland (Pitelka 1974; Myers and Pitelka 1980).

10.4.5 Birds in Coastal Habitats

Area A: Seahorse Islands and Point Franklin

The Seahorse Islands and Point Franklin form a cusp similar to that formed by the Plover Islands and Point Barrow. The largest of the Seahorse Islands has vegetated dunes that are unusual for the area in the Chukchi Sea north of Cape Lisburne. The dunes are about 5 m high and all birds breeding on the island are on or adjacent to dunes. A census of the island in 1977 (Divoky 1978) indicated that approximately 40 pairs of Arctic Terns and smaller numbers (less than 5 pairs) of Black Guillemots, Oldsquaws, and Common Eiders nested there. Common Eiders and Arctic Terns also nest on Point Franklin (P. G. Connors pers. comm. 1983). The density of nests in this area appears to be much higher than on typical barrier islands in the northeastern Chukchi or Beaufort seas. The dune system provides one of the few areas where burrowing species of marine birds can breed north of Cape Lisburne. Two Horned Puffins (*Fratercula corniculata*) were associated with the dunes in 1981 (G. J. Divoky pers. comm. 1983).

The spit that makes up Point Franklin supports large numbers of feeding and roosting birds during the postbreeding staging and migration period (August-September). In early August, approximately 12,000 Red Phalaropes, 6,000 Arctic Terns, and 800 Sabine's Gulls were recorded along a

shoreline transect on Point Franklin. Large numbers of the same species were recorded during this same period on the Seahorse Islands. The spit is also an important staging area for brant later in the fall (Lehnhausen and Quinlan 1982). This area is typical of the combination of islands and spits associated with a coastal cusp or point of land which create eddies offshore. These areas appear to create a productive habitat that attracts certain species of birds during premigratory staging.

Area B: Point Barrow, Elson Lagoon, and Plover Islands

Point Barrow, Elson Lagoon, and the Plover Islands are among the better known regions of the Alaskan Beaufort coast, primarily because of studies of (1) tundra-nesting birds at Barrow (many authors; see Pitelka 1974; Myers and Pitelka 1980), (2) shorebird use of shoreline habitats near Barrow (Connors *et al.* 1979), (3) eider migration at Point Barrow (Thomson and Person 1963; Johnson 1971; Timson 1976), and (4) nesting and migration at Cooper Island, one of the Plover Islands (Divoky 1978, 1983, pers. comm. 1983).

The gravel shorelines and adjacent waters of Point Barrow consistently support very high densities of shorebirds, gulls, terns, and some waterfowl in late summer. These are nonbreeding or postbreeding adults and juveniles of tundra-breeding species, and to a lesser extent island breeders. Densities of most species peak in August prior to their southward migration. The most abundant species include Red and Red-necked Phalaropes, Dunlin, Ruddy Turnstone, Sanderling, Arctic Tern, Sabine's Gull, Glaucous Gull, Black-legged Kittiwake, Ross' Gull (occasionally), Oldsquaw, King and Common Eiders, and Black Guillemot. Other shorebird species are common in salt marshes and mud flats in this area.

Although the Plover Islands lack the two most common birds nesting on barrier islands in other regions of the northeastern Chukchi and Beaufort seas (Common Eider and Glaucous Gull), the Arctic Tern population consists of about 100 to 200 pairs and the Black Guillemot population consists of about 200 to 300 pairs. Breeding occurs primarily on Deadman, Cooper, and Igalik islands, and the other islands support few or no breeding birds.

During the period of postbreeding dispersal, the Plover Islands are an important feeding area for Arctic Terns, Sabine's Gulls, Red Phalaropes, and Glaucous Gulls. These species, and smaller numbers of other surface-feeding species, are more abundant in the nearshore and littoral zones of the Plover Islands and immediately adjacent areas than elsewhere in the Alaskan Beaufort or northeastern Chukchi seas. Nearshore densities average over 75 birds/km^2, and shoreline densities frequently over 250 birds/km. Large flocks of feeding birds are encountered regularly near the islands. The food consumed by birds near the Plover Islands appears to come from two main sources. The rapid decomposition of multiyear pack ice near the Plover Islands apparently makes under-ice zooplankton (primarily *Apherusa glacialis*) more available, while the Bering Sea intrusion also provides a source of food for birds in this area. The large wash-ups of euphausiids that occur on the Plover Islands and Point Barrow appear to be related to the Bering Sea intrusion. In years when food is not abundant near the Plover Islands, they are used as roosting sites by birds that fly farther offshore to feed. The Plover Islands appear to be an important area where staging birds can accumulate fat reserves during fall prior to their southward migrations from the Arctic Basin. The high densities of many bird species recorded in this area (area B) place it among the most sensitive along the Beaufort coast to potential impacts associated with coastal oil development. This particular area was listed as sensitive by Weller *et al.* (1978); subsequent work corroborates this designation.

Area C: Admiralty Bay to Meade River Delta; Area D: Smith Bay to Ikpikpuk River Delta

Relatively little information is available on bird use of areas C and D. However, weekly summer surveys (June to mid-August) of the Meade River delta wetland habitats by Derksen *et al.* (1981) indicate that species composition of breeding birds at their site on the delta is similar to that of East Long Lake (area E). The study site and surrounding area have numerous river channels, oxbows, shallow ponds, and larger lakes. Wetland composition within the study site is similar to that of Island and East Long lakes (area E). Habitat types include wet meadows, deep-open lakes, perched ponds, and lakes breached by river channels adjacent to the study area. The sedges (*Carex aquatilis*) and grasses (*Arctophila fulva*) associated with these habitats provide an important food source for waterfowl.

The most common breeders in the area include Arctic Loon (*Gavia arctica*), Black Brant, White-fronted Goose, Oldsquaw, Spectacled Eider (*Somateria fischeri*), Red Phalarope, Pectoral Sandpiper,

Dunlin, Semipalmated Sandpiper (*Calidris pusilla*), and Sabine's Gull (Derksen *et al.* 1981). No breeding birds were characteristically associated with fluvial waters. Yellow-billed Loons (*Gavia adamsii*), Arctic and Red-throated Loons (*G. stellata*), Whistling Swans (*Olor columbianus*), and Greater Scaup (*Aythya marila*) were found to actively feed and rest on river channels and oxbows.

Area E: Smith Bay to Cape Halkett

The area from the east side of Smith Bay to Cape Halkett is only moderately well studied, and appears to include several areas of productive salt marsh, mud flat, and tidal slough, similar to the area in the vicinity of Lonely.

In late summer, shorebirds of several species (especially Dunlin, Semipalmated Sandpiper, Pectoral Sandpiper, Long-billed Dowitcher, and Ruddy Turnstone) are common in these habitats, and Red and Red-necked Phalaropes forage near some beach areas. Densities of most of the spit and island species that are common near Barrow (phalaropes, gulls, and terns), however, are markedly lower in this region.

Area F: Southwest Coast of Harrison Bay

The area west and southwest of Harrison Bay is moderately well studied. Investigations of shorebird use of littoral areas, primarily on Fish Creek delta and other salt marsh areas in 1980 (Connors *et al.* 1981), indicate high use of these habitats in late summer by shorebirds and waterfowl, including several species of geese. Densities of phalaropes, terns, and gulls appear to be low along the shores of inner Harrison Bay. This region of the coast, along with the Colville River delta, contains some of the most extensive areas of salt marsh and mud flat habitat on the Beaufort coast. Several of these areas are especially important to bird populations and are potentially very sensitive to coastal oil development (Norton and Sackinger 1981).

Area G: Colville River Delta

This area is best known from studies of waterfowl conducted by the U.S. Fish and Wildlife Service during the summers of 1981, 1982, and 1983 (Rothe *et al. In prep.*). Current information indicates that densities of most waterfowl are higher in the Colville delta than at other locations on the Alaskan North Slope. Densities of breeding loons are also very high, and it is the only place where large numbers of Yellow-billed Loons breed. The density of Tundra Swans in the central part of the delta is three times higher than in other parts of the Arctic Coastal Plain. There is a postbreeding influx of swans that brings the total number in the area to approximately 400 birds; this represents at least 10% of Alaska's North Slope population. The nesting density of Lesser White-fronted Geese is approximately three times higher in the Colville delta (6.3 nests/km^2) than in other areas of the Alaskan North Slope and is the highest in Alaska of Lesser White-fronted Geese that use the Central Flyway. Four major Brant colonies contain approximately 350 breeding pairs and represent the only major nesting concentrations of this species on the Alaskan North Slope.

Other studies in and near the Colville delta indicate that this is an important staging area for spring migrants when most adjacent areas are still covered with snow and ice (Divoky 1978, 1983; Johnson and Richardson 1981). Large numbers of post-breeding gulls and shorebirds congregate on the mud flats and in the shallow waters of the delta during late summer and early fall, where they feed prior to southward migration.

Area H: Simpson Lagoon to Prudhoe Bay

The coast from Simpson Lagoon to Prudhoe Bay has been the focus of much biological research since the early 1970's (Alexander *et al.* 1975; Bergman *et al.* 1977), but is best known from recent investigations of barrier island-lagoon ecosystem processes (Johnson and Richardson 1981) and monitoring studies associated with the International Biological Program (Norton *et al.* 1975) and the Prudhoe Bay Waterflood Project (Troy and Johnson 1982; Troy *et al.* 1983).

Key avian species identified in the Simpson Lagoon studies were Oldsquaws, Red and Red-necked Phalaropes and, to a lesser extent, Glaucous Gulls. Other less common species included Common and King Eiders; Arctic, Red-throated, and Yellow-billed Loons; several species of shorebirds such as Sanderling (*Calidris alba*), Dunlin (*C. alpina*), Semipalmated Sandpiper (*C. pusilla*), and plovers (*Pluvialis* spp.); and various other diving and surface-feeding marine birds. The high density and large biomass of birds using barrier island-lagoon ecosystems are supported by an exceedingly abundant invertebrate fauna that consists mainly of epibenthic mysids, amphipods, isopods, and, to a lesser extent, of bivalves and cnidarians.

Table 10.3 illustrates the relative importance of Simpson Lagoon to Oldsquaws, the key avian species using lagoons along the Alaskan Beaufort Sea coast. The average density and biomass of this species in Simpson Lagoon appears to be greater

Table 10.3—Comparison of average densities of Oldsquaws along various sections of the Alaskan Beaufort Sea coast.

Area	Years	Average Density (birds/km²)	Sources
Harrison Bay, Sale 71 area	1977-80	<50	2
Simpson Lagoon	1977-82	~225	1, 2, 3
Stump I. Lagoon	1978-82	50	1, 2, 3
Prudhoe Bay to Flaxman Island	1978-80	50-75	5
9 lagoons in Arctic National Wildlife Refuge	1981-82	~100	4

Sources: (1) Johnson and Richardson 1981, (2) Johnson 1982, (3) Troy *et al.* 1983, (4) U.S. Fish and Wildlife Service 1983, (5) Johnson unpubl. data.

than for any other location along the north coast of Alaska.

Several thousand juvenile Red and Red-necked Phalaropes concentrate along the shorelines of barrier islands to feed during August; the period of peak abundance is during the middle of the month. Along this portion of the Beaufort Sea coast, Red Phalaropes outnumber Red-necked Phalaropes by a ratio of about 4:1. They feed on mysids, amphipods, copepods, and soft-bodied invertebrates (cnidarians), substantially increasing their fat reserves prior to fall migration out of the Beaufort Sea in September (Connors and Risebrough 1977; Johnson and Richardson 1981).

Area I: Sagavanirktok River Delta

Recent studies of birds in the Sagavanirktok River delta by Gavin (1970, 1972, 1980), Herter *et al.* (1983), Johnson (1983a), Troy (1982), Troy *et al.* (1983), Welling *et al.* (1981), and Welling and Johnson (1982) have emphasized the importance of this area to birds, primarily for nesting, molting, and staging waterfowl and, to a lesser extent, for staging shorebirds.

At least 10 species of waterfowl nest in the Sagavanirktok delta, including four species of geese. The Snow Goose nesting colony on Howe and Duck islands in the outer Sagavanirktok delta is the only nesting colony of these geese in the United States. Snow Geese rear their young in relatively discrete areas of the delta, and appear to prefer wetlands south and southwest of the nesting islands (Johnson 1983a).

In addition to waterfowl, the avifauna of the Sagavanirktok delta includes a number of other species, most of which are also associated with wetland or marine habitats. This group includes loons, shorebirds (plovers, sandpipers, phalaropes), and larids (gulls, terns, and jaegers). The shorebirds compose the largest group (with respect to numbers of individuals and diversity of species) of breeding birds. While wetlands are generally preferred as breeding habitat, a few species also choose dry habitats. However, all species of shorebirds rely to some extent on wet or moist tundra for feeding. In August, flocks of shorebirds gather to feed along shorelines prior to fall migration. Phalaropes and Sanderlings prefer islands (Johnson and Richardson 1981), Dunlins and Semipalmated Sandpipers apparently prefer mud flats on the Sagavanirktok River delta (Troy 1982).

The importance of mud flats and salt marshes to shorebirds prompted Conners *et al.* (1981) to recommend avoidance of these areas when planning development activities.

Area J: Canning and Okpilak River Deltas

The Canning River delta is at the western boundary of the Arctic National Wildlife Refuge. Most habitats in this portion of the refuge were extensively studied by the U.S. Fish and Wildlife Service in 1979 and 1980 (Martin and Moitoret 1981). The results of research in the Canning River delta and in the Okpilak River delta, farther east near Barter Island (Spindler 1979), provide the best information on bird use of river delta habitats in the coastal portion of the Arctic National Wildlife Refuge.

Waterfowl used the open water of the Canning River delta extensively during spring migration and prior to nesting on the tundra. Throughout the nesting season, shorebirds were common along the mainland shorelines, but were most common in salt marshes. Waterfowl, primarily Oldsquaws, were present along spits and barrier islands more often than along mainland shorelines. Oldsquaw numbers increased in the Canning delta area in late July and remained high throughout August; some fluctuations that occurred were attributed to local movements.

The greatest densities of nesting shorebirds in the Canning River delta were found in the mosaic of wet sedge and dry sedge tundra, presumably because of the variety of habitats available to birds and the overall greater abundance of prey in these habitats. An increase in shorebird numbers in August was noted in salt marsh, lowland, and

mosaic habitats. The seasonal mean density of waterfowl in the Canning delta was relatively high in relation to other North Slope study sites. The habitat types that received the greatest use by waterfowl were class VI (drained basin complexes) and class VII (coastal salt marshes), as described by Bergman *et al.* (1977).

Farther east, in the Okpilak River delta, 57 bird species were observed; 23 were recorded as breeding. The most abundant species were (in descending order) Lapland Longspur, Pectoral Sandpiper, Red and Red-necked Phalaropes, and Semipalmated Sandpiper. Bird populations varied approximately twofold between the most productive and least productive habitat types censused. Ranked in descending order of total bird population, the four habitat types censused were (1) flooded tundra, (2) mosaic wet sedge-dry tundra, (3) upland sedge-tussock tundra, and (4) wet sedge tundra.

The total bird population ranged from about 112 to 245 birds/km^2. Nesting density ranged from about 45 to 97 nests/km^2. Features such as wetland characteristics and interspersion of microhabitat and microrelief best characterize coastal plain habitats in the Okpilak River delta area. These features, combined with information on patterns of snowmelt, are probably the best predictors of avian density and productivity. In the Okpilak delta area, flooded polygonal tundra and a mosaic of wet and dry and high and low polygonal tundra generally supported more birds than dry tundra with less relief. This pattern is typical of other areas on the Arctic Coastal Plain of Alaska and the Yukon Territory.

Populations of large birds in the Okpilak River delta were censused in a 50-km^2 area. The most abundant species were Oldsquaw, Brant, Glaucous Gull, Red-throated and Arctic Loons, and Tundra Swan. The total density of large birds was 21.7 individuals/km^2, but nesting density was low, about 3.5 nests/km^2. On two wetland areas regularly censused, total bird populations were lower but stabilized early in the summer (June); later, numbers occasionally were high, but sporadic. Patterns of habitat use by large birds in the Okpilak delta were similar to those observed at Storkerson Point, near Prudhoe Bay (Bergman *et al.* 1977). In both of these areas, highest bird use was recorded in diverse wetland complexes (drained basins) and large, deep *Carex*, shallow *Arctophila*, and deep *Arctophila* wetlands. All were recognizable and separable during aerial surveys or from aerial photographs taken in August.

Area K: Barter Island to Demarcation Point

Bird use of the extensive barrier islands and lagoons in the eastern portion of the Arctic National Wildlife Refuge has been investigated in recent years by the U.S. Fish and Wildlife Service (USFWS 1982, 1983) and others (Johnson 1983b). Nearshore habitats in this region support populations of birds similar to those reported for barrier island-lagoon systems farther west, along the central Alaskan Beaufort Sea coast.

Important species in these coastal habitats were Oldsquaw, Glaucous Gull, Sabine's Gull, Arctic Tern, phalaropes, Sanderling, and plovers, and a variety of other shorebirds and diving and surface-feeding marine birds.

As shown in Table 10.3, the average density of Oldsquaws in barrier island-lagoon systems along this eastern part of the Alaskan Beaufort Sea coast was markedly lower than in Simpson Lagoon, but notably higher than in the Sale 71 lease area (Harrison Bay) and in the area between Prudhoe Bay and the western boundary of the Arctic National Wildlife Refuge. These results suggest that the eastern Beaufort coast is important to a large proportion of the total population of Oldsquaws that molt in lagoon habitats along the north coast of Alaska (Table 10.3).

Shorebird use of the barrier island-lagoon systems east of Barter Island is similar to that in areas west of Barter Island; phalaropes, Sanderlings, and plovers were most abundant. Red Phalaropes were notably less common than Red-necked Phalaropes along this part of the Beaufort Sea coast by a ratio of about 1:4. This ratio is consistent with information available on the overall breeding distribution and general abundance of the two species (Pitelka 1974; Johnson *et al.* 1975; Salter *et al.* 1980). Furthermore, use of the eastern Beaufort lagoons by phalaropes appeared to be more prolonged than in other areas of the Alaskan Beaufort, with relatively high densities recorded along barrier island beaches throughout August and September (Johnson 1983b). In general, however, shorebird use of barrier island-lagoon habitats in the eastern Beaufort was approximately one order of magnitude less than along the western or central portions of the Beaufort coast (Connors and Risebrough 1977, 1978, 1979; Connors *et al.* 1981; Johnson and Richardson 1981; Johnson 1983b).

Analyses of invertebrates and of prey consumed by key bird species in eastern Beaufort lagoons indicate that epibenthic crustaceans, mainly mysids,

amphipods, and copepods, along with small fishes and to a lesser extent molluscs, are the primary prey consumed by key bird species (Oldsquaws and phalaropes). Thus, the invertebrate community that supports avian consumers in eastern Beaufort lagoon systems is very similar to that which supports similar avian consumers farther west along the central Alaskan Beaufort coast (Griffiths and Dillinger 1981; Johnson and Richardson 1981; Griffiths 1983; Johnson 1983b).

As mentioned earlier (section 10.4.4), several hundred thousand Lesser Snow Geese concentrate to feed in tundra habitats on the Arctic Coastal Plain of the Arctic National Wildlife Refuge each year from mid-August through late September (USFWS 1982, 1983). Flocks of these birds occasionally rest on coastal lagoons or in nearshore marine waters. These geese are especially sensitive to aircraft disturbance during this critical fall staging period when they accumulate fat (Patterson 1974) for the southward migration (see section 10.6).

10.5 MARINE TRANSPORTATION AND DEVELOPMENT AT ECOTONES

Marine transportation of equipment, fuel oil, and personnel via shipping lanes through the northeastern Chukchi and Alaskan Beaufort seas and potential marine transportation of crude oil or petroleum products through this region are important considerations within the scope of this synthesis. Most barge traffic bound for Prudhoe Bay passes through feeding habitat used by many species of seabirds in the pelagic zone of the Alaskan Beaufort Sea. Future barge and tanker traffic no doubt will follow similar routes. Unless specific precautions are taken, fuel from small spills or chronic leaks and bilge waste may become increasingly common pollutants in these areas and pose threats to seabirds feeding there.

The ecotones (interfaces) between open-water and ice-covered marine habitats (ice edges), marine and terrestrial habitats (shorelines), and marine and freshwater habitats (river deltas, lagoons, estuaries) often support the highest densities and biomass of available food and vertebrates found in the northeastern Chukchi and Alaskan Beaufort regions. The sites of various development activities, especially onshore support facilities (such as terminals), in these habitats along the northeastern Chukchi and Beaufort sea coasts must be chosen with caution to minimize potential impacts on organisms that concentrate in these interface habitats.

10.6 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 the season, species, and level and type of disturbance. Gollop *et al.* (1974) reported that noise from aircraft contributed to abandonment of nests and lowered fledging success of Lapland Longspur (*Calcarius lapponicus*) in tundra habitats. Schamel (1974) found laying-stage Common Eiders on barrier islands would flush at the approach of aircraft; during incubation, however, these same species remained on their nests, even when aircraft approached to within 5 m. Similarly, brood-rearing female waterfowl on coastal wetlands did not relocate or abandon their broods after repeated overflights, but nonbreeding waterfowl did abandon such disturbed areas (Schweinsburg *et al.* 1974).

Postbreeding waterfowl vary considerably in their reaction to aircraft and noise. Snow Geese are perhaps the most sensitive. Salter and Davis (1974) reported that flocks of staging Snow Geese flushed in response to fixed-wing aircraft overflights at altitudes up to 3,000 m. Gas compressor sound-simulators disrupted normal flight behavior of Snow Geese and excluded foraging birds from a radius of about 800 m around the noise source (Wisely 1974). Low-flying helicopters in 1977 caused nesting Snow Geese to abandon Howe Island, in the delta of the Sagavanirktok River (Gavin 1980). In contrast, helicopter overflights were found to have little effect on molting Oldsquaws (Ward and Sharp 1974). Birds dived in response to low-altitude overflights, but this was only a momentary disturbance and birds soon resumed predisturbance activities. Moreover, frequently disturbed areas were not abandoned (Ward and Sharp 1974; Johnson and Richardson 1981). Results of similar recent studies (Johnson 1982, 1983c) have suggested that the responses of molting Oldsquaws to various levels of man-made disturbances are not substantially different from their responses to various natural phenomena (winds, rough water, harassment by predators).

Major alterations of nearshore habitats that affect water circulation patterns and transport regimes have the potential to affect the availability of invertebrate organisms in these nearshore habitats. The indirect effects of this type of gross habitat modification pose the most serious threat to birds by affecting their food supply (prey base) in nearshore habitats.

10.7 SUMMARY

The avifauna of the northeastern Chukchi and Alaskan Beaufort region is transient in nature; most species are present there only from May through September. During this period, marine, coastal, and upland areas provide habitats for fulfilling various functions in the life cycle of each species. These include nesting habitat, migration pathways, summering areas for nonbreeders, and postbreeding staging habitat.

The most important habitats appear to be ecotonal in nature. Ecotones often support the highest densities and biomass of available food. Although many species of birds occur along the Beaufort coast, few are common in marine habitats. The marine areas that do support concentrations of pelagic feeding or staging birds appear to be associated with ice edges and areas of intrusion by Bering Sea water. The coastal habitats associated with barrier islands, lagoons, brackish marshes, and river deltas are also ecotonal in nature. Each of these provides habitat that sustains relatively large concentrations of birds.

Important habitats for resting and feeding migrants include shore leads, river deltas, and snow-free tundra. The pattern of habitat availability is similar from year to year, but the timing of availability varies. Most species of birds that breed in the Alaskan arctic nest in the tundra. However, the coastal zone provides the most important postbreeding habitat for feeding and staging.

Of the 11 areas examined in the northeastern Chukchi and Alaskan Beaufort the greatest amount of avifaunal information was available for Point Barrow to Elson Lagoon and the Plover Islands (area B, Fig. 10.1). The pelagic waters north of the Plover Islands support the largest concentrations of pelagically feeding and staging birds in the Alaskan Beaufort Sea and are therefore designated an important and sensitive area for the support of bird populations. Other areas deemed as very important and most sensitive are the salt marshes and mud flats in southwest Harrison Bay (area F), the Colville River delta (area G), and the Sagavanirktok River delta (area I).

The most serious concern relative to the effects of OCS oil and gas activities on bird populations is the potential for alterations of nearshore coastal habitats, particularly activities that could affect the availability of food. Development activities should be conducted in a manner that will minimize alteration of nearshore coastal habitats and impacts on organisms that concentrate in these habitats.

Data and information gaps still persist. These gaps are geographically illustrated by coastal area A (Seahorse Islands and Point Franklin), area C (Admiralty Bay-Meade River delta), and area D (Smith Bay-Ikpikpuk River delta) (Fig. 10.1). On a nongeographic basis, more information would be desirable to (1) integrate avian studies with those of fishes, invertebrates, marine mammals, and physical processes; and (2) help determine true vulnerabilities or responses of arctic avifauna to activities associated with offshore petroleum development (*i.e.,* monitoring studies).

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the shear zone is caused by the huge forces working against each other. The first sight of the region is of a sheer wall of ice stretching east-west almost from horizon to horizon. Behind this wall lies an area criss-crossed with pressure ridges and leads. Usually its landward boundary, a band about 40 km wide, is found between the 15- and 20-m contours (Prichard and Stringer 1981) and parallel to the coast (Stringer 1981). This is the area where polar bears and bearded seals are most abundant.

Not all of the forces working on the winter ice are dissipated by activities in the shear zone: pressure ridges develop and leads appear in shorefast and pack ice. Since the pack ice is mostly composed of multiyear ice and the shorefast ice is mostly composed of first-year ice, the latter is generally the smoothest and flattest of the three regions, although it too contains pressure ridges and surface deformations. The snow drifts that form on the lee side of these features are favored locations for ringed seal lairs. During the winter the highest density of ringed seals is found in the shorefast region.

Satellite photos have shown that north of the east-west-trending shear zone, an extensive system of interconnecting north-south rectilinear leads develops in the spring. The shear zone, and perhaps this extensive lead system to its north, appear to be the principal corridors in which bowhead and belukha whales travel from the Alaskan Beaufort Sea into the Canadian Beaufort Sea. As seen in Figures 11.1a and b, the leads are far offshore and almost interconnected all the way to Banks Island. These leads coincide with the sightings of whales from aerial surveys conducted from Point Barrow eastward (Fig. 11.1c). Easterly winds in the Canadian Beaufort Sea during spring, in concert with the clockwise rotation of the Beaufort gyre, cause a major north-south lead west of Banks Island and another (and often connected) lead north of the landfast ice of the Tuktoyaktuk Peninsula. During spring, the ice in Amundsen Gulf begins to break up to form a major polynya, which expands and becomes continuous with the leads off Banks Island and the Tuktoyaktuk Peninsula (Braham, Fraker, and Krogman 1980), allowing the whales access to the nearshore region of the eastern Canadian Beaufort Sea. This explains the nineteenth century whalers' observations that bowheads were first seen near Cape Bathhurst, rather than to the west at the whalers' overwintering site in the vicinity of Herschel Island (Fraker and Bockstoce 1980). Recent aerial observations by Davis *et al.* (1982) have also found whales in the vicinity of Banks Island and Cape Bathurst before they are seen in the vicinity of the Mackenzie Delta.

During June, rising temperatures and ice melting allow the bottomfast ice inside the 2-m isobath to float (Pritchard and Stringer 1981), and soon afterward the fast ice starts to drift. Most of the larger, grounded ice formations melt slowly or may be broken up by waves and currents. The thicker floes persist while the area of open water increases.

When the shorefast ice melts and the pack ice retreats, the polar bears follow the ice. Spotted seals and other summer residents enter the Beaufort Sea from the Chukchi Sea.

During the open-water season, the pack ice loosens and chunks of multiyear ice drift into the coastal region, where they may become grounded in very shallow water. Currents and winds carry the floes along similar trajectories, and when the largest floes ground, others blow into them, frequently forming a series of parallel ridges. Summer storms may break up or consolidate these grounded ridges. Lowry, Frost, and Burns (1978a) identified these and other remnant ice features as important substrate for seals and birds in the summer.

By late August to early September the pack ice is at its annual minimum, and the location of the pack ice edge, while highly variable, may be tens to hundreds of kilometers offshore. However, shifts in winds and currents can combine to drive the pack ice toward shore (Pritchard and Stringer 1981).

As freeze-up begins in the fall the summer visitors have already departed; bowheads move westward through the planning area, much closer to shore than on their spring migration, and belukhas may be found moving westward along the edge of the pack ice. Again, the Beaufort Sea is left to the resident seals, polar bears, and arctic foxes. Ringed seals again establish home ranges and set up their breathing holes, which they will maintain through the coming winter. Female polar bears move in toward the coastal region and establish their dens. The cycle starts anew.

The following account of species of concern is based upon discussions held in the Marine Mammal Workshop, Diapir Field Synthesis Meeting, January 1983. In addition to the published literature and contract reports, the following agencies have supplied unpublished data or internal reports: Alaska Department of Fish and Game (Marine Mammal Project), Fairbanks, Alaska; Minerals Management Service, Environmental Studies, Anchorage, Alaska; National Marine Fisheries Service, National Marine Mammal Laboratory,

Chapter 11
Marine Mammals

by Guy W. Oliver

The Diapir Field Lease Area contains important marine mammal habitats and migratory corridors. The most common species are bowhead and belukha whales; ringed, bearded, and spotted seals; polar bears; and arctic foxes. At least for the bowheads, belukhas, and polar bears, the area contains biologically critical habitat. Besides these most common species, the lease area and adjacent waters, especially to the east, are utilized as important feeding grounds by gray whales and walruses. Although at least eight other species have been reported in the Beaufort Sea, these do so far less regularly and are generally individual animals well beyond their typical range.

Although other chapters discuss the physical oceanography, meteorology, and ice conditions in detail, the physical environment so shapes the ways that various species can use the area that it is important to review the annual ice cycle and some of the factors relevant to the principal marine mammals.

In the planning area and throughout the Arctic Basin, sea ice is the dominant condition affecting the distribution and abundance of marine mammals. The mammals inhabiting the planning area for all or parts of the year exhibit a high degree of synchrony with the annual ice patterns. To a large extent, the distribution and abundance of these species may be generally determined on the basis of ice conditions.

Ringed seals, bowhead whales, and polar bears are the most ice-adapted, ranging over wide areas of the Beaufort Sea, while less ice-adapted but still pagophilic (ice loving) species, such as bearded seals and spotted seals, are more regionally restricted temporally and spatially. For example, bearded seals cannot maintain breathing holes in the fast ice, thus they are found only where leads and cracks are kept open by ice movement, while spotted seals can only use the area during the open-water period.

On the average, the Beaufort Sea is covered with ice 9 months of the year, has varying amounts of open water for 2 months, and is in the transitional periods of break-up and freeze-up for the remaining month. The ice cover of the Beaufort Sea is far from homogeneous. Within the Diapir Field the three principal zones—the pack ice, the shear zone, and the landfast ice—differ in their physical characteristics and in the types of habitats existing within them. Predictably there is faunal segregation in use of these zones.

The pack ice is a persistent feature of the Arctic Ocean, covering the largest portion of the planning area. It is composed of floes of multiyear ice consolidated and supplemented by each year's annual ice. In the Beaufort Sea the pack ice is at its annual maximum extent in early May, and at its annual minimum extent in late August and early September. In summer the pack ice is rarely motionless, whereas in winter it may not move for extended periods.

The shorefast ice is very stable. Along the Beaufort Sea coast, the seaward floating portion may extend from 25 to 75 km offshore. During the first stages of freeze-up (late September to late October), multiyear floes may become grounded as they enter the nearshore region. As freezing continues, the new ice locks these multiyear ice features in place like rounded blue islands set in the flat, new ice. As the new ice thickens, the thicker grounded features become strong points, anchoring the ice, obstructing flow, and making the ice shorefast.

Between the fast ice and multiyear floes lies the shear zone, where compressional and shearing stresses are created by the pack ice pushing against the immobile fast ice. The jumbled appearance of

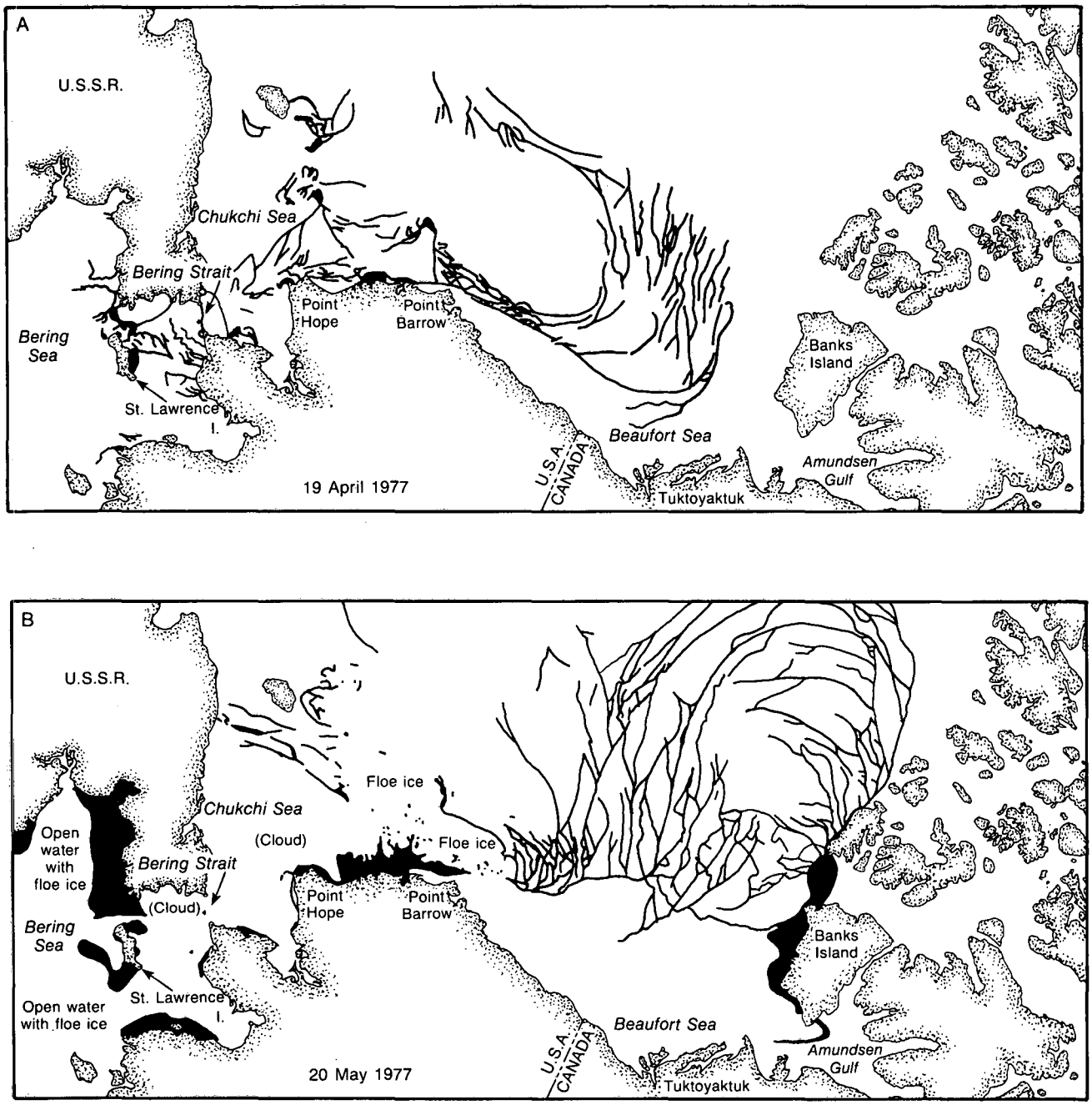

Figure 11.1a, b—The development of the lead system across the Beaufort Sea typically follows the pattern observed by satellite in April (a) and May 1977 (b). Black areas represent open water (adapted from Braham, Fraker, and Krogman 1980).

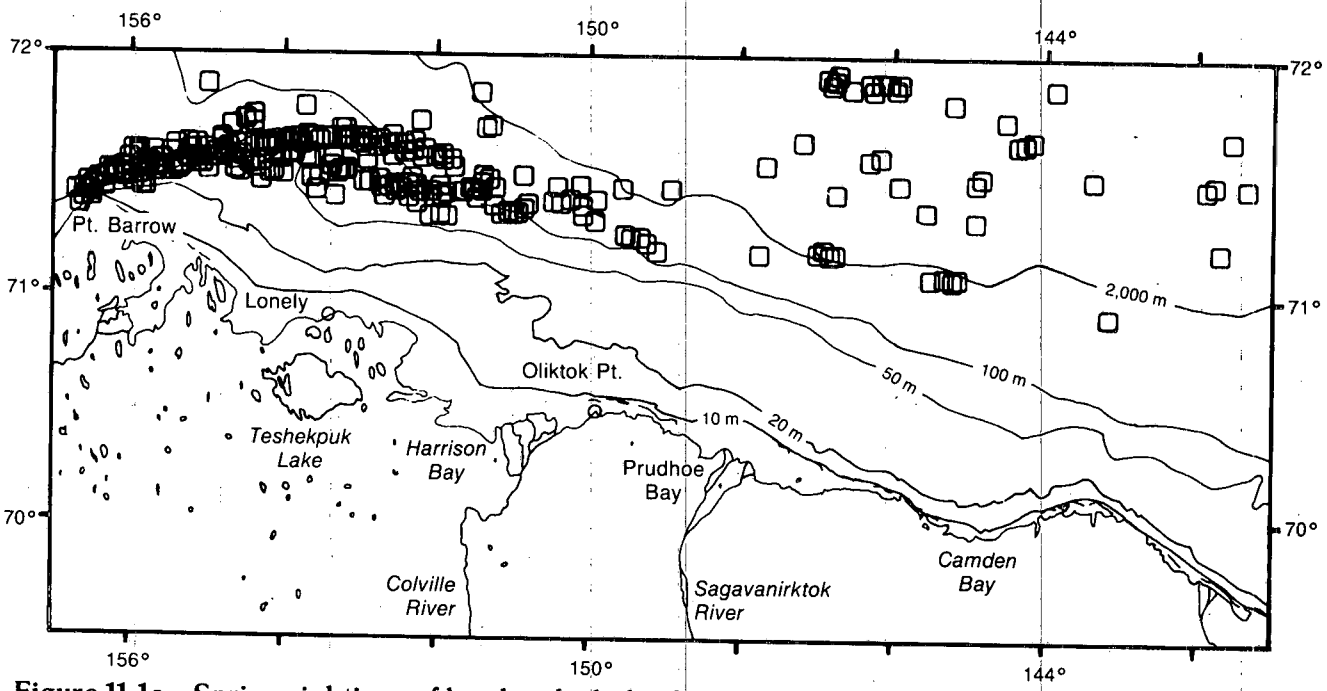

Figure 11.1c—Spring sightings of bowhead whales from aerial surveys conducted by Ljungblad and coworkers between 1980 and 1983. (Ljungblad 1981; Ljungblad, Moore, Van Schoik, and Winchell 1982; Ljungblad, Moore, and Van Shoik 1983, 1984).

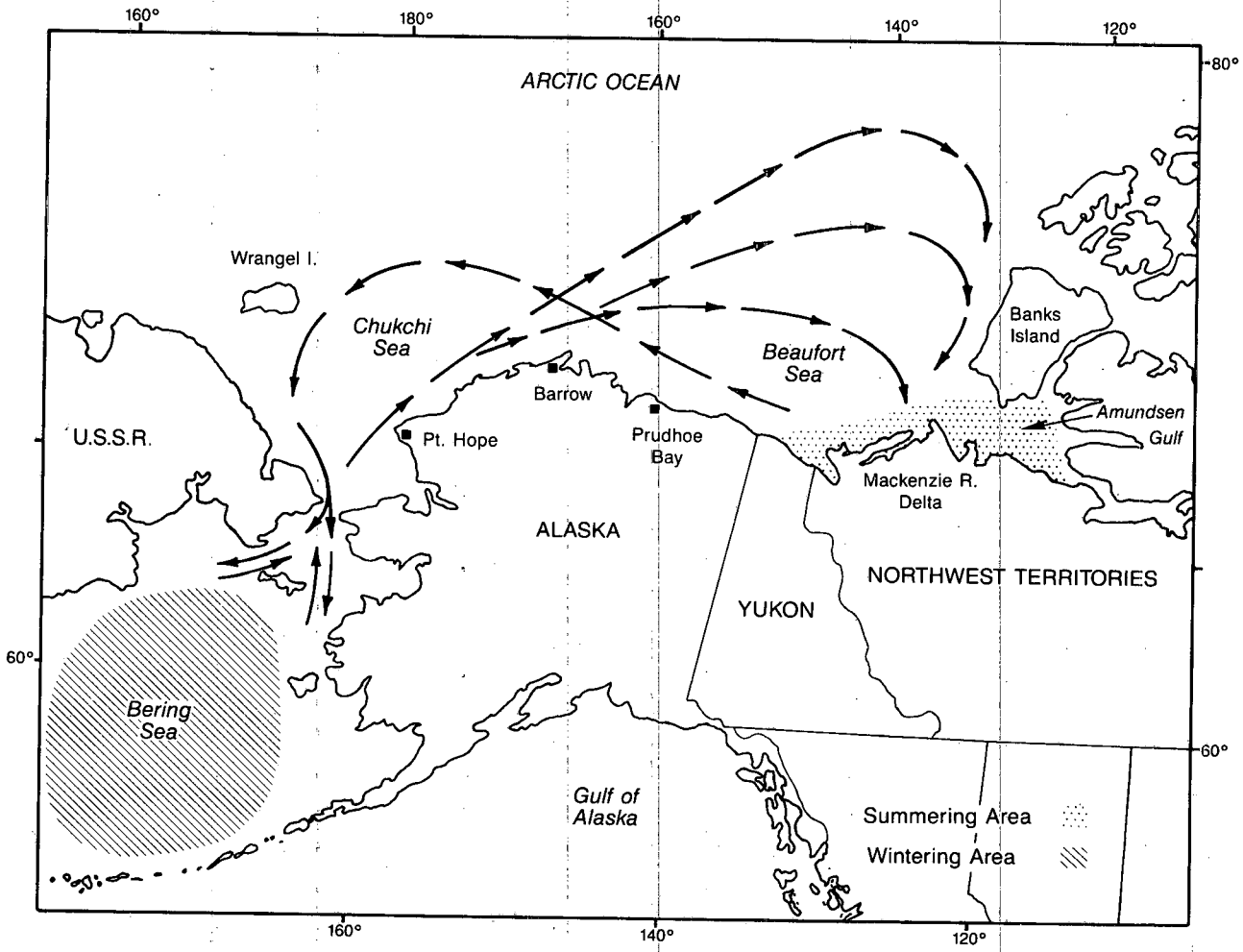

Figure 11.1d—The annual migratory route of the bowhead whale in the western Arctic (from Fraker 1984).

Seattle, Washington; NOAA, Ocean Assessments Division (OCSEAP), Anchorage, Alaska; North Slope Borough, Environmental Protection Office, Barrow, Alaska; and U.S. Fish and Wildlife Service (Marine Mammal Project), Anchorage, Alaska. The state of arctic science is such that, since the meeting was held, there have been numerous studies completed and findings reported that were unavailable to the participants. The author has attempted to incorporate the most current information available, while retaining the overall scope of the meeting.

11.1 BOWHEAD WHALE

11.1.1 Stocks and Population Estimates

Prior to exploitation, the bowhead whale, (*Balaena mysticetus*) was circumpolar in distribution, inhabiting arctic and subarctic waters in four principal areas (International Whaling Commission [IWC] 1978): from Spitzbergen west to eastern Greenland; Davis Strait to Baffin and Hudson Bays; the Bering, Chukchi, and Beaufort seas (the "western Arctic" stock); and the Okhotsk Sea. Due to excessive harvesting in the past, all populations are now seriously depressed (IWC 1978; Table 11.1).

The effects of Yankee whaling, which peaked in the 1880's and ceased by 1917, continue today. Bockstoce and Botkin (1983) estimate that over 18,650 bowheads were killed between 1848 and 1917, with over 60% taken in the first 20 years (Fig. 11.2). The population stock is believed to have originally contained about 18,000 whales (IWC 1983). Other estimates have ranged from as low as 9,000 (Breiwick and Mitchell 1983) to as high as 40,000 whales (Bockstoce and Botkin 1983). Although the depleted population size resulted in a severely reduced catch per unit effort, the high market value

Table 11.1—World bowhead stocks: estimates of historic and current population sizes (adapted from Braham 1984).

Stock	Historic Size	Current Size
Spitzbergen-East Greenland	25,000	nearing extinction
Davis Strait-Hudson Bay	12,000	few hundred
Western Arctic	18,000	4417
Sea of Okhotsk	unknown	few hundred

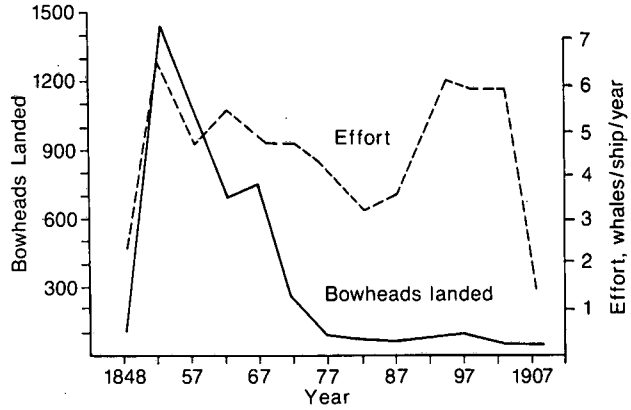

Figure 11.2—Whaling effort and catch of bowhead whales from the western Arctic stock between 1848 and 1907. Most whales were killed between 1850 and 1870, although whaling effort remained high into the 20th century (from Braham 1984).

of bowhead whale products, principally baleen and oil, resulted in a continued high effort to capture bowheads. Whaling for bowheads practically stopped by 1917 with the collapse of the markets for baleen and oil and the increasing scarcity of bowheads. The historic minimum population probably occurred near the end of the pelagic fishery period (about 1914) and has been estimated at between 600 and 1,000 bowheads (Eberhardt and Breiwick 1980) (Fig. 11.3). Protected since 1937 except for the small Eskimo take, recovery from Yankee whaling has been very slow. Breiwick *et al.* (1984) modeled known population life-history parameters and estimated that, in the face of a continued small harvest by Alaskan Eskimos, recovery would be very slow, if at all.

Although the Spitzbergen-east Greenland stock originally had the largest population, today the western Arctic stock is the largest; its population estimate is based on counts of whales during the spring migration near Barrow. These counts are obtained from observers at camps set on the shorefast ice bordering the nearshore lead system. The best estimate of the current stock size is 4,417 bowheads, with 95% confidence limits of 2,613-6,221 animals (IWC, in press).

Population size estimated from aerial surveys of the summer range (Davis *et al.* 1982) is consistent with that assessed near Barrow in spring and is almost double that computed only three to five years earlier; it is believed to realistically reflect more accurate survey methods rather than a rapid increase in population size, considering the very slow reproductive rate of this species.

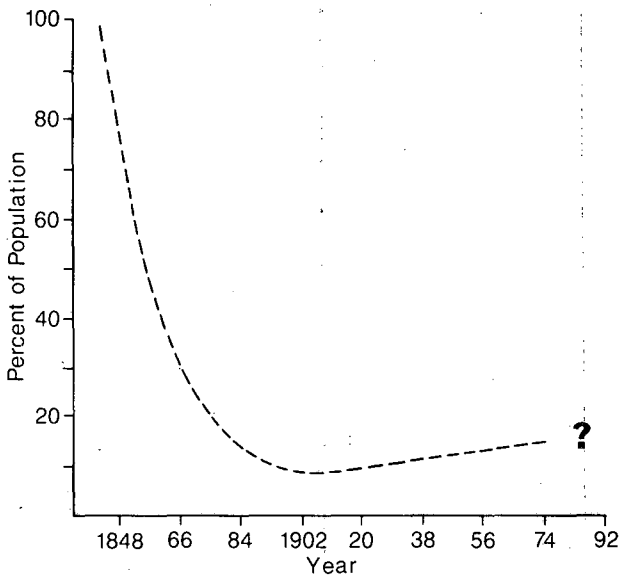

Figure 11.3—The population decline and possible increase of the western Arctic stock of bowhead whales since the end of commercial whaling, as projected by Braham (1984) using information from Townsend (1935), Eberhardt and Breiwick (1980), and Bockstoce and Bodkin (1983).

11.1.2 Spring Migration

Bowheads are seasonal inhabitants of the Beaufort Sea and Diapir Field Planning Area. They overwinter in the ice-infested sectors of the northern and central Bering Sea (Brueggeman *et al.* 1984) and from mid-April to mid-June migrate northward past Point Barrow (though they may occur in low numbers well before and after these dates) (Fig. 11.1d). The general timing and pattern of bowhead movements during the spring migration have been known for a long time (Bailey and Hendee 1926; Tomilin 1957; Durham 1972; Braham and Krogman 1977). For centuries, coastal Eskimos have taken bowheads as they move past their villages soon after openings in the pack ice appear (Braham, Fraker, and Krogman 1980). Until recently, however, the migratory pathway has not been described in detail, especially in the largely frozen Beaufort Sea.

The initiation of the bowhead migration, the migration continuity, and perhaps even the rates of passage of whales past points along the Chukchi coast, are all functions of ice conditions farther south (Braham, Fraker, and Krogman 1980; Fraker, pers. comm.). The migration typically begins around the third week of April (Braham, Fraker, and Krogman 1980), although in some years it may start in March. Eskimos claim that bowheads move in two to three annually occurring pulses and that there is an age-sex segregation during migration (Braham, Fraker, and Krogman 1980); the cows with calves arrive during the last pulse. Pulses have been observed in three years (1976-1978) during which ice camp counts have been conducted (Braham, Fraker, and Krogman 1980; Rugh, pers. comm.). After the camp at Barrow was pulled off the ice in 1982, many calves were reported by whalers at Wainwright (Dronenburg, pers. comm.). Yet Rugh (pers. comm.) contends that the data do not indicate pulses in most years and, other than in 1982, calves were not seen in a pulse at season's end.

Aerial surveys do not support the contention that significant numbers of whales move past Barrow via offshore lead systems (Marquette *et al.* 1982). Some animals have been acoustically detected beyond the visual range of ice camp observers (Clark 1983; Cummings *et al.* 1983), but these whales are believed to be using the nearshore lead system (which is sometimes too wide to survey visually from ice camps) rather than offshore lead systems.

Aerial surveys are the only way to delineate the offshore spring migration route off Barrow (see Fig. 11.1c). Whales appear to follow the same course east of Barrow even though this course is not necessarily along leads (Rugh and Cubbage 1980).

Bowheads are well adapted to survive in the Arctic. The shape of the skull, its massive construction, and its covering of shock-absorbing blubber allows the bowhead to break through overlying ice and penetrate seemingly impassable routes. Bowheads have been observed in the spring north of Barrow migrating through waters that are 100% ice covered, breaking through ice up to a meter thick (Rugh, unpubl. data; Carroll, pers. comm.). The bowheads follow an eastward course after passing Barrow, almost as though they were in single file. Aerial observers have frequently seen areas of the Beaufort 100% covered by ice, with individual and small groups of bowheads separated by minutes, hours, and sometimes even days, following the same course, even surfacing in the same locations as they moved eastward from Barrow. Tomilin (1957) reported that bowheads entered Plover Bay in 1933 when the bay was bound with a 20- to 30-cm-thick ice cover, breaking the ice repeatedly as they surfaced for air. Ljungblad (1983) and Fraker (1984) reported similar "bowhead tracks" along both the Chukchi and Beaufort migration routes.

The 1980-1982 migration into the Beaufort Sea can be portrayed as following a corridor between 71°20′ and 71°40′ north latitude, which broadens east of 149° longitude toward Banks Island (Ljungblad 1981; Ljungblad, Moore, Van Schoik, and Winchell 1982; Ljungblad, Moore, and Van Schoik 1983). In 1983, bowheads rounding Point Barrow thereafter followed a mean heading of 75.8°, with a significant clustering about this mean (Ljungblad *et al.* 1984). Thus, during the migration across the Beaufort Sea, bowheads are as highly directional in their movements as when they follow the nearshore leads through the Chukchi Sea.

Ljungblad *et al.* (1983) found that from Barrow eastward across the Beaufort Sea, bowheads migrate beyond the seaward edge of the shorefast ice in waters deeper than 20 meters. Their data also support the conclusion that there is annual variation in the preferred water depth of the eastern migrations. In some years bowheads appear concentrated between the 20- and 50-m contours and in other years spread out, but in all years they are seaward of the 20-m contour and the shorefast ice. Ljungblad *et al.* (1985) found the eastward migration route to be beyond the 20-m contour and approximately 25 km wide at Barrow, broadening to 50 km from north of Smith Bay to Harrison Bay. East of Prudhoe Bay few whales are seen during the spring until they are sighted in Canadian waters near Banks Island. The few sightings in this region are probably a function of limited survey and ice conditions, which make whales difficult to spot. Ljungblad *et al.* (1983) predicts that the route east of 150°W will be 50 to 100 km wide to the Canadian border. This corridor follows the ice shear zone through the Alaskan portion of the Beaufort Sea.

Whales arrive in the Canadian Beaufort Sea in the vicinity of Banks Island and then move southward. Aerial surveys in the vicinity of Tuktoyaktuk in 1981 showed that bowheads had arrived in large numbers by July; their numbers peaked in early August, and declined thereafter (Table 11.2).

Table 11.2—Estimated number of bowhead whales in the eastern Beaufort Sea during 1981 (from Davis et al. 1982).

Date	Number of Bowheads
July	1300
Early August	3500
Late August	2900
September	2500

11.1.3 Feeding

Once in these Canadian waters, bowhead behavior shifts from the highly directional movement patterns associated with migration to behaviors associated with feeding. Würsig *et al.* (1982) identified four modes of feeding behavior: water-column feeding, near bottom-feeding, skim-feeding, and mud tracking. The first three clearly represent feeding, whereas the function of the last is unclear. There are considerable annual variations in the locations where feeding is observed, and variations in the mode of feeding employed as a function of location. Presumably the different feeding modes are used by whales feeding on different prey. Since much of their diet is composed of mobile zooplankton, they move from patch to patch using the behavioral method most appropriate to capture their prey. All whales usually employ the same feeding mode throughout a widespread area (Würsig *et al.* 1982).

Animals engaged in water column feeding and skim feeding often show a high degree of synchrony in their respiration and movement patterns. Frequently skim-feeding whales swim in an echelon formation, similar to the V-formation of geese. Echelon feeding could increase the feeding efficiency of animals staggered behind and to the side of other individuals by allowing more effective exploitation of concentrated patches of small prey than would be possible if whales were feeding alone (Würsig *et al.* 1982).

Würsig *et al.* (1982) report that they were not able to detect localized dense patches of surface plankton from aircraft, though they do describe linear concentrations of what were probably zooplankton, apparently along boundaries of "fronts" between water masses. Bowheads occasionally were seen near these linear features, but none was observed to feed along the front. In contrast, Watkins and Schevill (1976, 1979) saw northern right whales skim-feeding at the surface on patches of plankton that were visible to observers in aircraft; these right whales appeared to adjust their courses to remain within the densest parts of the patches.

Griffiths and Buchanan (1982) report that the hydrographic structure of water coming from the Mackenzie River may act as a concentrating mechanism for the bowheads' food; the fresh water from the river overrides the denser and more saline ocean water, confining marine prey to a wedge near

the bottom. In recent years, work on a variety of baleen whales has shown that they employ an impressive array of techniques to concentrate their prey (such as humpback's bubble nets [Jurasz and Jurasz 1979] and echelon feeding [Hain *et al.* 1981]) and that the degree of concentration may be as important to these filter-feeders as initially finding prey (Nemoto 1959, 1970).

Aerial surveys conducted by Würsig *et al.* (1982) over the Canadian Beaufort Sea revealed that in localized areas all bowhead whales tend to practice the same feeding mode, but between areas where feeding occurs, different modes might be used.

Three main hypotheses exist regarding the distribution and importance of feeding areas for bowheads:

1. They forage predominantly in the Canadian Beaufort Sea and continue feeding to a significantly lesser degree as they move into U.S. waters.
2. The Canadian Beaufort Sea is the first and perhaps the principal feeding area, but a considerable portion of the energy requirements is met by foraging in the Alaskan Beaufort and Chukchi seas during fall.
3. Bowheads feed to the same extent in the Beaufort, Chukchi, and Bering seas.

The first hypothesis was the most commonly held a decade ago. The tremendous increase in bowhead research over the last decade has resulted in considerable modification of this viewpoint on the foraging patterns of bowheads. Stomach contents of whales taken during fall at Kaktovik and Barrow provide evidence that whales do feed in Alaskan waters: these stomachs contained 0.5-109 l of food (mean = 24.7 l), while other stomachs collected during spring contained very little food (Lowry and Frost 1984). Other inferences include the following: behavioral observations of whales "apparently feeding" (Ljungblad, pers. comm.), including non-directed movement and lack of uniformity of orientation between groups of whales; echelon formation; mud plumes streaming from the mouth and straining of the water (turbid water in front of the whales and clear water behind them); and defecation.

On the basis of the frequency of such behavioral observations along the coast and the stomach contents data, hypothesis #1 has been rejected and at least two feeding areas in the Alaskan Beaufort Sea can be identified: Demarcation Bay to Barter Island, and Barrow to approximately Pitt Point.

Lowry and Frost (1984a) presented the clearest case for hypothesis #2 and state that "the fact that bowheads migrate several thousands of kilometers annually to summer and feed in the Beaufort Sea implies that the quantities and kinds of food available to them there are adequate, and perhaps that feeding conditions are superior to those found in other areas." Although the abundance of the principal bowhead foods, copepods and euphausiids, is not exceptionally high in the Beaufort Sea (Griffiths and Buchanan 1982), their frequent occurrence in predator stomachs indicates that these must occur at least occasionally in dense patches (Frost and Lowry 1981).

Seasonal changes in the caloric value of bowhead prey are great, for these zooplankton accumulate lipids during the summer, which are used during fall and winter for maintenance and reproduction (Percy and Fife 1980, cited in Lowry and Frost 1984a). Thus, these invertebrate prey have a similar seasonal cycle, as do at least one of their principal predators, ringed seals. Physical condition of the zooplankton, when measured as the degree of lipid stores, is at its annual peak in the fall and low point in the early summer. As noted by Lowry and Frost (1984a), organisms with very high energy values are the primary prey of bowheads (*e.g.*, copepods and euphausiids), those with intermediate values are consumed with some frequency (*e.g.*, hyperiid and gammarid amphipods), and those with very low energy values are rarely or never consumed. Bowheads have been observed feeding during September in the Alaskan Beaufort Sea, times at which copepods contain almost 50% more energy than they do in early summer (Percy and Fife 1980, 1981, cited in Lowry and Frost 1984a). The values for caloric content of Frobisher Bay copepods collected in September are the highest published values for any marine organism. Lowry and Frost (1984a) consider that "given equivalent prey densities, late summer prey feeding may be of greater value to the whales than that which occurs earlier in the year."

When assessing the availability of food in the marine environment and the food requirements of whales, previous authors (Klumov 1962; Brodie *et al.* 1978; Brodie 1981; Griffiths and Buchanan 1982) have been forced to conclude that the whales either had to swim at unrealistically fast speeds, or the prey densities were much greater than those found using standard sampling techniques. Lowry and Frost (1984a) conclude that, although some feeding occurs in the northern Bering and Chukchi seas during spring, the major feeding grounds are in the Beaufort Sea and, on the basis of a 130-day feeding season (105 days in the Canadian region

and 25 days in the U.S. portion of the Beaufort Sea), that "bowheads can obtain their annual food requirements . . . if they feed for somewhat over half the time they are on the feeding grounds and concentrate their efforts in areas where prey are relatively abundant." Frost and Lowry (1981) estimated that 0.3-4.4 million tons of zooplankton are produced annually in the Beaufort Sea and estimate that annual consumption is 1.1 million tons (Lowry and Frost 1984a), thus suggesting that "food availability may be limited in years of low production, while in other years a surplus of food may be available." Extensive blubber reserves may help sustain animals through occasional years of low summer productivity. Lowry and Frost (1984a) were very cautious in their extrapolations from a single whale's energy requirements to the food needs of the western Arctic bowhead population. The quantities and kinds of organisms seem adequate, and the extraordinarily high fat content (and energy value) of prey facilitates accumulation of blubber reserves necessary to maintain animals during periods of fasting. Some late summer and early autumn feeding may occur in the Chukchi Sea. Lowry and Frost (1984a) speculate that winter feeding in the Bering Sea, if it occurs, is of little significance in the annual nutrition of bowheads.

The third hypothesis is that bowheads forage opportunistically throughout their range to buffer against the large oscillations of prey availability that occur in the Arctic and subarctic. The evidence to support this view is predominantly circumstantial; it relies on the premise that bowheads forage on their wintering grounds in the Bering Sea. The exact location of the overwintering bowheads is unknown, but the current hypothesis is that they are in the Bering Sea seasonal pack ice from the ice front at least to, and probably concentrated in, the vicinity of the polynyas formed at St. Lawrence and St. Matthew islands (Brueggemann *et al.* 1984). During the winter, observations of bowheads are so few and brief that, unlike in the Beaufort Sea, there are no observations of feeding bowheads in the Bering Sea. This could be because the whales are not engaged in much feeding activity or because observations are so few and brief. Also, there is no active bowhead hunting at this time of year, so stomach content records are lacking, although some information is available from two spring whales taken at Gambell and Shaktoolik.

Four lines of indirect evidence support winter feeding in the Bering Sea:

1. Whales taken in the spring at Barrow are generally larger in each year class than those taken at Barrow the preceding fall (Nerini, pers. comm.).
2. No significant difference in blubber thickness was seen in animals taken at Barrow in the spring versus in the fall (Nerini, unpubl. data on seven whales killed in 1979 and 1980). A difference could be expected if bowheads relied upon their summer-accumulated lipid stores for winter maintenance. This is quite different for gray whales taken off the California coast, where southward migrants were fat and northward migrants lean (Rice and Wolman 1971). There was no significant difference in the blubber thickness of the two groups of gray whales; but, rather, during the winter they depleted their stores of body fat. If this was the case with the bowheads, it is reasonable to assume that the Eskimos of Barrow would have developed specific vocabulary to differentiate between the leaner, spring whale meat and the fatter, fall whale meat. Although spring and fall whales are known by different words (*aguiq* and *ukialliq*, respectfully), such terms are not used to differentiate the meat and *muktuk* from animals taken at different seasons (George, pers. comm. from T. Brower and Adams).
3. Considerable upwelling occurs in polynyas; warmer, nutrient-rich waters are brought to the surface, providing favorable habitat for bowhead prey in the upper portion of the water column. Although little is known about the distribution of zooplankton behind the ice front of the Bering Sea during winter, some Japanese data suggest that dense aggregations do at least occasionally occur and that, at least for euphausiids, they are at a shallow depth.
4. Calanoid copepods and euphausiids utilize the same method of storing energy (by increasing their lipid stores) to overwinter in the Bering Sea as they do in the Beaufort Sea, and thus, if the same prey types are eaten in the winter as in the fall, there is abundant, concentrated, high-energy food available.

One argument against the idea that feeding in the Bering Sea is an important nutritional component centers around the bowheads' long migration; if they feed extensively at the northern end of the migratory route, then it must be energetically beneficial for them to do so, otherwise they would either stay in the Bering Sea, a favored feeding ground for several other species of baleen whales, or starve. Fraker (1983) and others have argued that one rea-

son why the existing bowhead population migrates to the Beaufort Sea is that those portions of the original population that fed in the Bering and Chukchi seas were eliminated by Yankee whalers in the nineteenth century. Townsend (1935) clearly shows that many bowheads were taken in the Bering Sea south all the way to the Pribilof Islands. The only whales that survived the whaling onslaught were those animals that migrated well into the Canadian Beaufort Sea and did not migrate from the area until they were forced to by ice conditions. While only speculative, such behavior could have been responsible for saving of this portion of the population, and that behavior might then be quite conservatively fixed in the behavioral repertoire and/or genetics of the species.

Given the expected relatively short residence time of food in a recognizable state and the low number of sampling locations (Eskimo whaling villages), stomach samples may be more a reflection of local abundances of particular bowhead prey than representative of typical foraging patterns (*i.e.*, a strong geographical bias) over the entire annual range.

Sample sizes and available information are inadequate to determine bowhead prey in detail. Although large amounts of prey have been obtained from Eskimo-harvested whales, it is not known (a) if the throat and esophagus were examined (a difficult procedure given the present day procedures of butchering the harvested animals); (b) whether different prey items were found in different compartments of the stomach, thus possibly representing distinct foraging bouts on highly concentrated prey; and (c) what proportion of the stomach contents were recognizable. Food clearance rates (rates of digestion) are unknown for bowheads; it has been estimated to take about 5 hours for 25-30% of stomach contents to be digested by fin whales (Kawamura 1971). The digestive times for the various prey species, and thus their residence times as recognizable prey, need to be known. Data are also needed on regurgitation: whether bowheads regurgitate their food when startled or chased (several other species do—Kawamura 1971), how long the chase lasts, and whether the length of the chase increases the likelihood of regurgitation.

Lowry and Frost (1984a) have reported data supporting age related differences in diet: whales that had principally eaten copepods averaged 13.1 m in length (range = 10.5-17.4 m, n = 7); those that contained mostly euphausiids averaged 12.0 m (range = 8.5-16.0 m, n = 7); and whales that had eaten only benthic organisms averaged 9.2 m (range = 8.3-10.1 m, n = 5). The differences between the benthic prey feeders and the copepod and euphausiid foragers are significant at the 0.05 level. Animals 9.2 m long are estimated to be 1.25 years old and the others at least over 3 years.

11.1.4 Behavior

Although the Canadian Beaufort Sea has traditionally been characterized as part of the feeding grounds for the bowheads, Würsig *et al.* (1983) found socializing, and perhaps occasional mating, to be important components of bowhead behavior there during summer. Social behavior was defined by Würsig *et al.* (1982) to include situations in which whales were within one-half body length of one another or appeared to be pushing, nudging, chasing, or obviously orienting their activities toward one another. The frequency of mating fluctuates from year to year, but both feeding and socializing occur regularly in the Canadian Beaufort Sea in summer and the Alaskan Beaufort Sea during one or both migration periods. Würsig *et al.* (1982) reported that on many occasions, which lasted from seconds to days, members of widely spaced groups showed an "impressive" degree of synchrony of basic behaviors.

High levels of such social interaction have been observed during the spring migration around Alaska (Rugh and Cubbage 1980; Carroll and Smithhisler 1980). An apparent decrease in social behavior in the eastern Beaufort Sea from early August into September suggested a continuous decrease from the spring levels (Würsig *et al.* 1982).

Würsig *et al.* (1983) also noted hour-to-hour variations in the amount of social activity. Peak social activity occurred at noon, with a secondary peak in the evening. Why whales should engage in more social activities at some times than at other times is unknown, but diel rhythms are well-known in several other marine mammal species (Saayman *et al.* 1973—for bottlenose dolphins; Matsushita 1955—for sperm whales; Schevill and Backus 1960—for humpback whales). Würsig *et al.* (1983) hypothesize that the increased level of socialization may be a reflection of a lowered level of feeding at that time, which Nemoto (1970) reported for baleen whales in general. Since the noon socialization peak coincides with the time of the daily maximum depth of plankton that exhibit diel vertical migration, perhaps the whales socialize at this time rather than forage in a less efficient manner than they could at other hours.

The behavior of bowhead cow-calf pairs in summer appears to be markedly different from that of the closely related southern right whale, *Eubalaena australis*, in austral winter and spring (Davis *et al.* 1983). Taber and Thomas (1981) reported that during the first four months of life, right whale adults and calves in the Gulf of San Jose, Argentina, appeared to maintain very close spatial relationships, and when seen the following year with the young as yearlings, they maintain this close spatial relationship for two to six weeks. Davis *et al.* (1983) reported that in the Canadian Beaufort Sea during August, bowhead calves are frequently separated from their mothers. They speculate that this loose cow-calf pairing is precipitated by adult feeding activities. It is unknown whether the mother-calf bond becomes stronger after feeding subsides, although Ljungblad reports that calves seen in Alaskan waters during August were within one body-length, although farther apart by September.

11.1.5 Fall Migration

The activities seen in the Canadian Beaufort Sea during July, August, and September are also seen in the Alaskan Beaufort Sea as bowheads start moving westward to complete their annual migration cycle. Aerial surveys conducted from 1979 to 1981 concentrated on the nearshore region of the Alaskan Beaufort Sea (Ljungblad *et al.* 1980, 1981; Ljungblad *et al.* 1982) and were unable to account for a large proportion of the western Arctic stock as the whales moved past the Alaskan coast.

In 1981 a limited survey was initiated to determine if bowheads were utilizing an offshore corridor as well as the apparent coastal avenue. These and subsequent surveys showed that the first bowheads seen in Alaskan waters in the fall were, indeed, far offshore.

Ljungblad *et al.* (1983), in describing the 1982 migration, hypothesized that it "can be depicted by a westerly moving, continuous distribution of bowheads in a general trapezoid shape moving west across the Beaufort Sea and dispersing southwest across the Chukchi Sea" (Fig. 11.1d).

Ljungblad *et al.* (1983) suggest that bowheads observed offshore in early August (north of Demarcation Bay at 71°30′N) did not make the complete migration to the Banks Island-Amundsen Gulf area. Rather, these were some of the whales seen migrating past Point Barrow in late May and early June that did not move much farther east but instead exploited an offshore food source that began to falter soon after the peak bloom in July (Schell *et al.* 1982).

Schell *et al.* (1982, p. 81) stated that "the retreat of the pack ice northward in summer, nutrients supplied by terrestrial runoff, and the maximum euphotic depths lead to the maximum productivities observed" in the Beaufort Sea. Further, they indicate that average (1978-1980) annual primary production contours in the Alaskan Beaufort Sea depict gross production of 25-27.5 g C/m^2 occurring from shore to 71°N, where it rises to about 40 g C/m^2 along 141°W longitude, and to 25 to 40 g C/m^2 from shore to 72°N latitude at 157°W longitude. These contours roughly encompass the area of all migratory bowhead distributions in the Beaufort Sea (Ljungblad 1981; Ljungblad *et al.* 1982, 1983). The 1982 observations of early offshore and later onshore bowhead sightings roughly coincide with peaks in primary production in the Beaufort Sea reported by Schell *et al.* (1982). These peaks in primary production are generally followed by peaks in numbers of primary and secondary consumers, the primary bowhead foods.

11.1.6 Life History

Available life history information is summarized in Figure 11.4. Breeding activity appears to be greatest in the northern Bering Sea (Ljungblad *et al.* 1982; Rugh, pers. comm.). Apparent breeding activity during spring migration around Alaska has been described by Everitt and Krogman (1979), Carroll and Smithhisler (1980), Rugh and Cubbage (1980), Johnson *et al.* (1981), and Ljungblad (1981). Some breeding activity and perhaps calving have been observed in the vicinity of the ice camps during 1982 (Dronenburg, pers. comm.) and infrequently in the Canadian Beaufort during August (Würsig *et al.* 1982).

Photogrammetric studies by Davis *et al.* (1983) provide estimates of the length-frequency distribution of the western Arctic stock and allow determination of the bowhead calving dates. They estimate that between 29% and 48% of the calves will have been born after May, when the ice camp censuses are conducted at Barrow. This suggests that considerable calving occurs in the Diapir Field Planning Area during the spring migration.

Since methods of aging bowheads have been largely unsuccessful, the age at sexual maturity and other age-related parameters cannot be estimated (Nerini 1983). Length estimates at various stages of growth are 4-4.5 m at birth, 8-8.5 m at one year, 13.5-14 m at sexual maturity (female), and 18-20 m

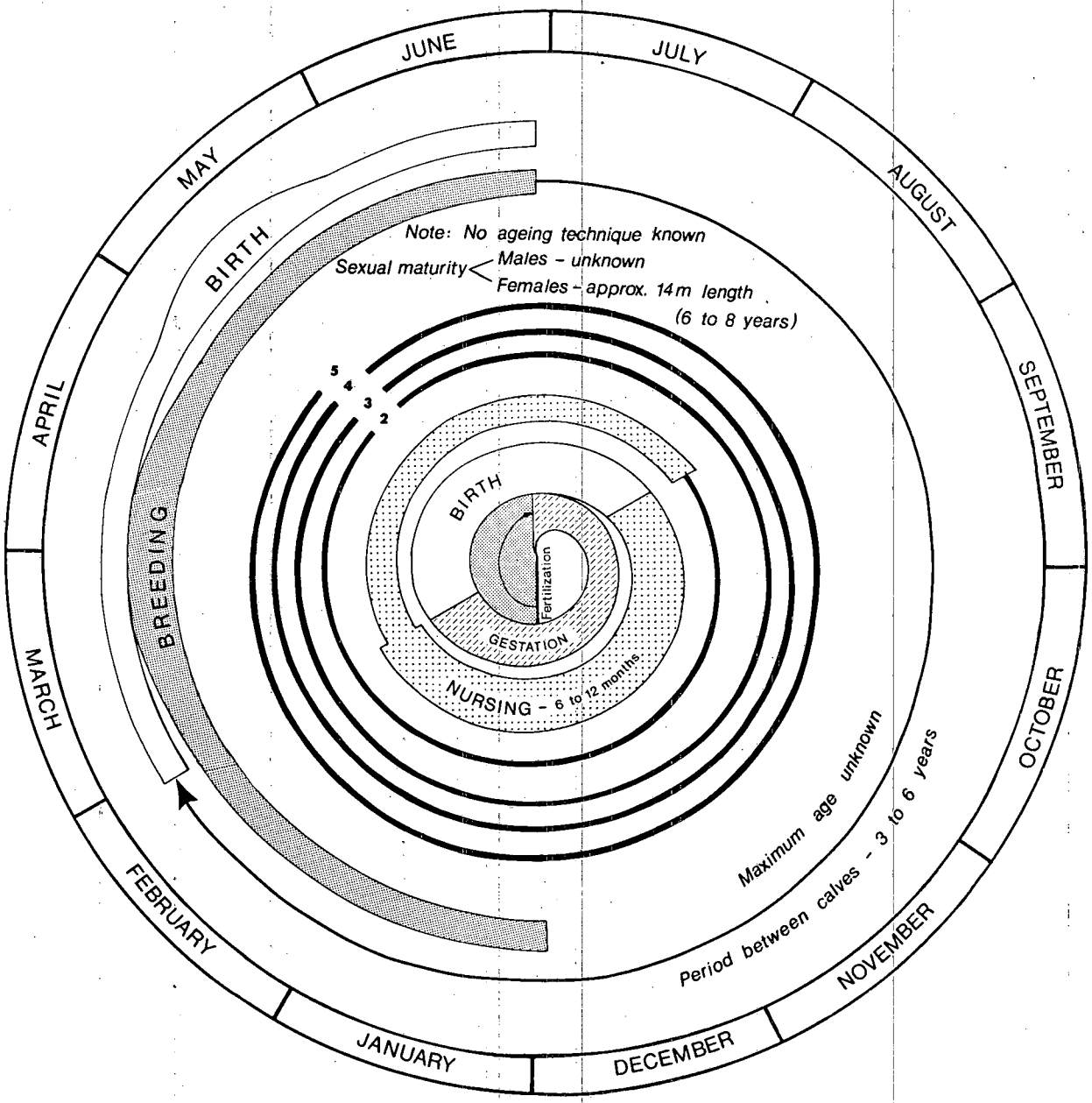

Figure 11.4—Life History of the bowhead whale. To follow the life cycle of a bowhead start in the center, with fertilization occurring in March. Variation in the age at weaning is displayed by changing width of segment, and peaks in breeding activity and births are illustrated by bulges. See text for details and full references. Nerini *et al.* (1984) served as the principle data source.

at physical maturity or maximum length (Nerini *et al.* 1984).

Considerable disparity exists in the estimates of the gross annual recruitment rate for the western Arctic population. Although the percentage of calves observed increases from March until as late as October, there is no convincing evidence that the percentage of spring calves is greater in the Canadian Beaufort Sea than at Barrow. In addition, no near-term fetuses have been found in whales taken at Barrow in the spring, although they have been found in whales landed at Point Hope and Wainwright. Thus, there is no direct evidence that calving occurs east of Barrow. The bowhead calving season may extend from March to August, with the probable peak in May. Yet in 1982, only Ljungblad *et al.* (1983) observed calves between 7 August and 4 October.

Nerini *et al.* (1984) suggest that bowheads do not fit the gestation pattern exhibited by other baleen whales because bowheads do not move into warm water during the winter and they produce their calves just before, rather than just after, the feeding season. They hypothesize that the thermal

disadvantage to the calf, and concomitant demand on the female, of a midwinter birth in arctic waters is a greater cost than an extended gestation. Nerini *et al.* further argue that if lactation is the costliest period of reproduction (Lockyer 1981), then the bowhead has adapted to this demand by timing the onset of lactation to the onset of the feeding season.

Estimates of gross annual reproductive rate (GARR) for bowheads are unusually low relative to other mysticetes (Ljungblad *et al.* 1983), and considerable variation in the GARR has been reported in different studies (Table 11.3). There are four potential causes of this variation: (1) some years have more females breeding than other years; (2) different observation platforms produce different sighting rates for calves; (3) prolonged observations of specific groups increase probability of sighting calves, in contrast to brief reconnaissance of each group; and (4) sexual and perhaps age-related segregation of the population means the various surveys may all have been observing different components of the population.

The time of weaning has not been determined. The only calf (6.1 m) examined during the fall hunt at Barrow was reported to have an empty stomach,

Table 11.3—Bowhead calf sightings: an indication of gross annual reproductive rate.

Survey Dates	General Location	Observational Platform*	Data Source†	Calf Count	Total Bowheads	Percentage Calves
19 Apr-14 Jun 76	Bering/Chukchi	A	1	3	88	3.8
1 Apr-8 Jun 76	Bering/Chukchi	A	1	0	5	0.0
19 Apr-9 Jun 78	Bering/Chukchi	A	1	5	156	3.2
21 Aug-7 Oct 78	E. Canadian Arctic	A+L	2	1-3	46-83	2.2-3.6
7 Mar-12 Apr 79	N. Bering Sea	H	3	0	109	0.0
2-26 May 79	Barrow Vicinity	A	1	1	35	2.9
10 Jul-31 Oct 79	W. Beaufort	A	4	6	250	2.4
23 Jul-18 Aug 79	E. Beaufort	S	5	2-3	54-62	3.7-4.8
17 Apr-27 Jun 80	Bering to Beaufort	A	6	4	857	0.5
4-23 May 80	N. Bering Sea	A	1	3	95	3.2
3-31 Aug 80	E. Beaufort	A	7	5	126	4.0
6-24 Aug 80	E. Beaufort	A	8	6	158	3.8
20 Aug-9 Sep 80	E. Beaufort	A	9	6	179	3.4
20-25 Aug	E. Beaufort	S	9	2	113	1.8
23-29 Aug 80	E. Beaufort	S	9	1	78	1.3
4 Sep-4 Nov	Beaufort to Bering	A	6	1	49	2.0
6-21 May 81	Barrow Vicinity	A	10	3	2	0.0
18 Jul-14 Sep 81	Beaufort	A	10	4	117	3.4
12 Aug-5 Sep 82	E. Beaufort	A	11	42	339	12.4
23 Apr-25 May 82	Bering to Beaufort	A	12	2	265	0.8
10 Jul-17 Oct 82	Beaufort to Bering	A	12	42	724	5.8
15-22 Sep 82	Barter Is. to Demarcation	A	13	28	137	4.9
21 Apr-11 May 83	Bering to Beaufort	A	14	NR	223	NR
31 Jul-19 Oct 83	Beaufort to Bering	A	14	13	172	7.6

* A = aircraft; H = helicopter; L = land; S = ship; NR = not reported

† Data source:

1 = Marquette *et al.* 1982.
2 = Davis and Koski 1980.
3 = Braham, Krogman, Johnson, Marquette, Rugh, Nerini, Sonntag, Bray, Brueggeman, Dahlheim, Savage, and Goebel 1980.
4 = Ljungblad *et al.* 1980.
5 = Hazard and Cubbage 1982.
6 = Ljungblad 1981.
7 = Würsig *et al.* 1981.
8 = Renaud and Davis 1981.
9 = Cubbage and Rugh 1982.
10 = Davis *et al.* 1982.
11 = Davis *et al.* 1983.
12 = Ljungblad *et al.* 1983.
13 = Johnson *et al.* 1981.
14 = Ljungblad *et al.* 1984.

and perhaps to have been recently weaned (Durham 1980). Lack of solid food could also indicate that the animal was still nursing (Nerini *et al.* 1984). Given the size distribution of calves observed in August-September 1982, it would be entirely consistent to expect some of those calves to be weaned and others to be still nursing as they pass Barrow in the fall (Davis *et al.* 1983).

11.1.7 Direct Effects of Oil

The direct effects of spilled oil upon bowhead whales are not known with certainty. Some possible effects (Albert 1981) have been suggested:

- Fouling of baleen would seem likely to alter filtering efficiency and lead to some ingestion of oil. Studies with isolated bowhead baleen (Braithwaite *et al.* 1983) showed a reduction in filtering efficiency of about 10% when coated with Prudhoe Bay crude oil and an even larger reduction when coated with oils of a higher wax content. Another study (Geraci and St. Aubin 1982) using isolated baleen from fin and gray whales noted only temporary reductions in filtering efficiency after contamination with three types of crude oil.
- In an investigation of the effects of the localized application of oil on the skin of bottlenose dolphins (*Tursiops truncatus*) and Risso's dolphins (*Grampus griseus*), exposure for up to 75 minutes produced mild, temporary structural damage with a depression of phospholipid synthesis (Geraci and St. Aubin 1982).
- The skin of the bowhead whale is characterized not only by its great thickness but also by its many (dozens to hundreds) small diameter (1-3 cm) lesions. These are particularly common on the head. The lesions are localized areas of epidermatitis (Migake 1981) with a very rough surface and provide a microhabitat for a large number of bacteria and diatoms (Haldiman *et al.* 1982). Albert (pers. comm.) postulates that spilled oil is more likely to adhere to the roughened areas than to undamaged skin. The effect of adhered oil on the bacteria in the eroded areas is unknown, but Albert speculates that if bacteria continue to grow under the oil film, they may further damage the skin, leading to ulceration with bacteria entering blood vessels of the skin. In addition, if the eroded areas contained pathogenic or potentially pathogenic bacteria, a septicemia could result.
- The conjunctival sac associated with the eye is very large in the bowhead whale, extending approximately two-thirds of the way around the globe (Dubielzig and Aguirre 1981). Albert (pers. comm.) stated that if an irritant such as spilled oil contacted the eye and entered the conjunctival sac, conjunctivitis, ulceration, or perforation of the cornea might result.
- Ingestion of oil could result from ingestion of oiled prey items and from contaminated baleen fragments that break off and are swallowed. Blockage of the gastrointestinal tract is possible if oil-fouled baleen fibers are swallowed. Large numbers of dislodged baleen fibers are found in the gastrointestinal tract of harvested bowheads (Albert 1980), and oil could provide the mechanism to allow ingested baleen fibers to form "hair balls" and block the intestine.

  The bowhead stomach is four-chambered like that of many ungulates. A probable site for a blockage would be the narrow connecting channel (2-3 cm wide and about 20 cm long) between the second and fourth gastric chambers (Sis and Tarpley 1981). Such intestinal blockages are not uncommon in domestic ungulates and can frequently prove fatal (Lowry, pers. comm.).
- Two additional physiological responses to oil were suggested by Albert. First, oil adhering to the tactile hairs located around the blowhole and along the chin or filling the cone-shaped depressions in the skin from which the hairs emerge might impair the tactile sense. Second, repeated inhalation of oil "fumes" and possibly some oil droplets might result in lung irritation that could lead to pneumonia.

11.2 BELUKHA WHALE

The belukha whale (*Delphinapterus leucas*), a circumpolar species, is common, and at times very abundant, in the Diapir Field Planning Area in spring, summer, and fall (Fig. 11.5). In the winter, from late November through March, ice and weather conditions are unfavorable for belukhas. Small numbers of migrating whales may become entrapped by ice during the fall, but the incidence of such events is probably low. Observations of entrapped belukhas in the eastern Arctic (Porsild 1918; Freeman 1968) suggest that attempts to overwinter in arctic waters result in high mortality.

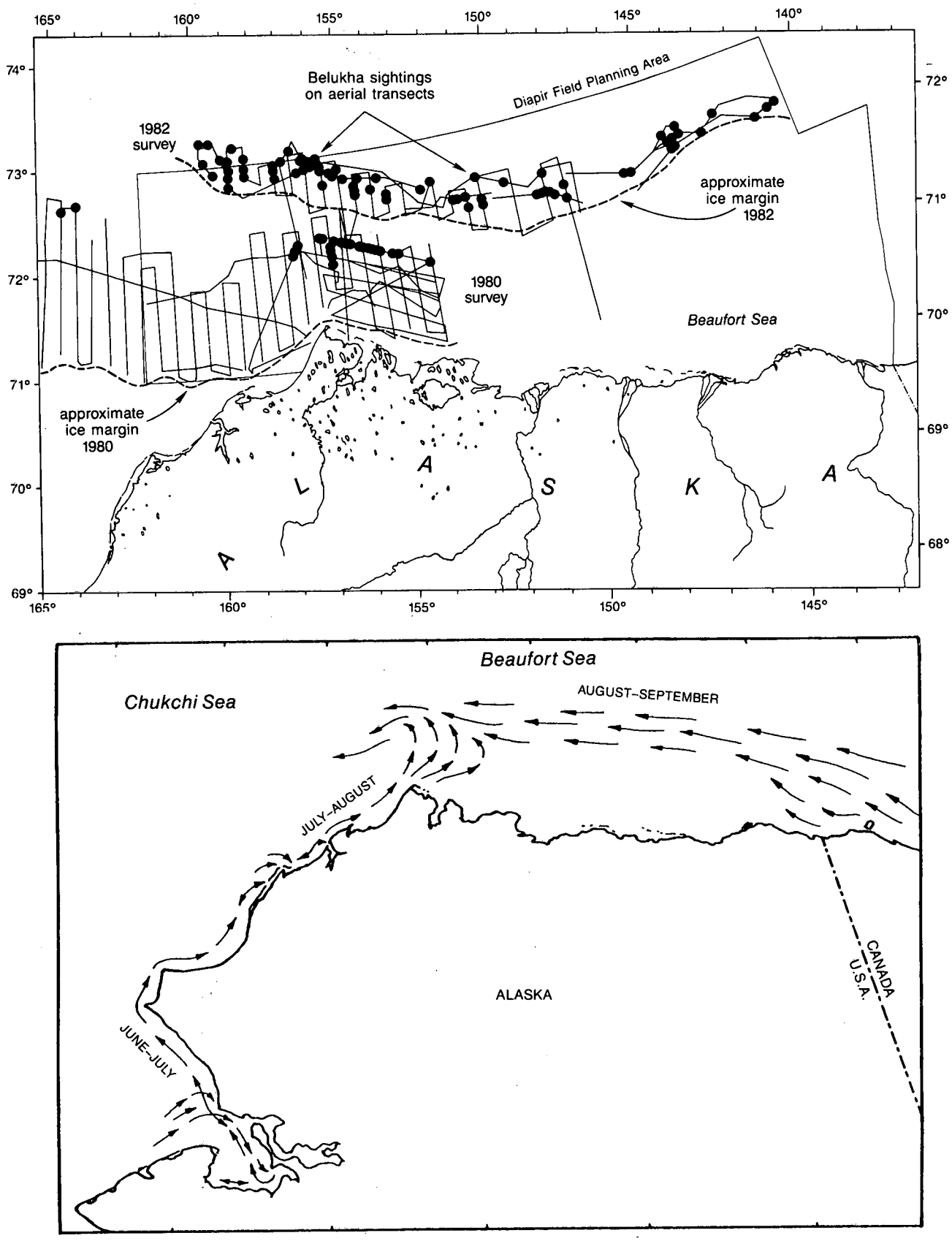

Figure 11.5—The effect of the position of the pack ice front on the distribution of belukha whales north of Point Barrow in the fall(a). Hypothesized migration routes of the eastern Beaufort Sea and eastern Chukchi Sea belukha stocks in the vicinity of the Diapir Field (b) (adapted from Burns and Seaman, in press).

11.2.1 Stock and Population Estimates

Five management stocks in waters off Alaska are recognized by the International Whaling Commission (IWC) (in press) and identified by their summering locations: Cook Inlet, Bristol Bay, Yukon-Kuskokwim Delta, Norton Sound, eastern Chukchi Sea, and Canadian Beaufort Sea. Whether these represent true stocks (discreet breeding groups) or are merely summer feeding groups which intermingle and interbreed to varying degrees in the Alaskan Beaufort Sea is unknown. There have been no large-scale dedicated efforts to determine the size of the Alaskan Beaufort belukha population, although the size of the various management stocks has been estimated (Table 11.4). The two management stocks germane to the lease planning area are the Canadian Beaufort stock, estimated at 17,000 whales (Norton and Harwood, in press), and the Chukchi stock, estimated at 2,500-3,000 (Lowry 1985). Both of these groups spend at least part of their annual cycle within the planning area and, like all but the Cook Inlet group, overwinter in the Bering and southern Chukchi seas. The majority of belukhas occurring in the Beaufort Sea are part of the Canadian Beaufort managment stock (Braham and Krogman 1977; Davis and Evans 1982; Norton and Harwood, in press; Alaska Department of Fish and Game, unpubl. data).

11.2.2 Migration

There are two distinct migrations representing the two northernmost groups. The Beaufort group is the earliest usually seen at St. Lawrence Island in March (Hazard, pers. comm.) and passes Point Hope in mid- to late March. It is probable that belukhas occasionally pass Barrow as early as late March, although the earliest recorded sighting of belukha whales passing Point Barrow was on 2 April 1977 when a Barrow hunter (A. Brower, pers. comm.) sighted over 60 whales moving through a narrow lead of the shorefast ice. Four days later several hundred of the whales were seen.

Belukhas are known to utilize offshore, as well as nearshore, leads during the spring migration through the Chukchi Sea (Braham *et al.* 1979), and it is likely that some belukhas pass Point Barrow unnoticed by local hunters. The peak of the spring migration past Barrow occurs from late April to the third week in May and varies according to ice conditions (Braham and Krogman 1977; Carroll, pers. comm.). The general northward and eastward migration past Point Barrow continues through at least early July. Braham *et al.* (1979) observed belukhas north of Barrow while conducting aerial surveys in late June. Harrison and Hall (1978) observed two groups north of Barrow in the first week of July, and Murdoch (1885) reported whales along the coast of Barrow in mid-July immediately following break-up.

Table 11.4—Belukha whale management stocks and their estimated population sizes in Alaskan waters (Hazard, in press).

Stock	Population Estimate
Cook Inlet	500
Bristol Bay	1,000-1,500
Yukon-Kuskokwim Delta-Norton Sound	1,000-2,000
Eastern Chukchi Sea	2,500-3,000
Eastern Beaufort Sea	17,000

The migration route of belukha whales from Point Barrow to the Canadian Beaufort Sea is described by Hazard (in press) and is similar to the route followed by bowheads. Observations by Ljungblad (1981) confirm that in late May and June 1980 spring migrants utilized pack ice offshore leads that extended northeast from Barrow into the Beaufort Sea. Many are present in the southeastern Beaufort Sea and Amundsen Gulf in late May and June (Braham *et al.* 1979). By late June most of these whales have moved to the shallow, warmer waters of the Mackenzie River estuary, where concentrations in excess of 2,000 whales are observed in some bays (Fraker *et al.* 1979). Some whales have been seen moving eastward in Alaskan waters as late as 27 June (Ljungblad 1981).

Belukha whales have never been observed in large numbers during the summer in the coastal waters of the Alaskan Beaufort Sea. This is in marked contrast to the Canadian portion of the Beaufort Sea, where during early summer up to 7,000 whales have been sighted in the Mackenzie River estuary (Fraker 1980). Long-time residents of the Alaskan mid-Beaufort region (J. and H. Helmericks, pers. comm.), consider belukhas common off the shorefast ice until the ice moves away from the coast, usually between late June and mid-July. During the remainder of the summer belukhas are rarely seen in the ice-free coastal waters of the Alaskan mid-Beaufort Sea (Lowry and Frost 1984b).

During summer, belukhas are occasionally observed in the pack ice or ice-free waters near Bar-

ter Island. In July, these whales are typically observed close to shore moving eastward in small groups of 5 to 15 whales. During August, they occur in groups of similar size. Their direction of movement is more variable, however, as whales are observed moving both east and west parallel to the coast. Residents of Kaktovik on Barter Island often see, and successfully hunt, belukhas during the autumn bowhead hunt, and belukhas are occasionally taken there during the summer as well.

In contrast, belukhas are widely distributed and numerous in the offshore and nearshore parts of the Canadian Beaufort Sea and Amundsen Gulf in mid- to late summer (Davis and Evans 1982). As seen in Table 11.5, the movement into and out of a large area can be be quite tightly clustered. Although the third survey encompassed a smaller area than did the other three surveys, it is apparent that a large number of animals had left the area between the second and third survey periods.

Aerial surveys have resulted in very few sightings of belukha whales in the offshore waters and pack ice of the Alaskan Beaufort Sea during July and early August. Harrison and Hall (1978) saw four whales on 18 August 1976, approximately 75 km north of Cape Halkett, and Ljungblad *et al.* (1982) made three sightings of 26 animals 96, 220, and 270 km north of Prudhoe Bay on 22 August 1981. The considerable effort devoted to offshore aerial surveys in this region (*e.g.*, Harrison and Hall 1978; Ljungblad *et al.* 1980, 1982), indicates that belukhas are rare in the Alaskan Beaufort Sea during summer (July and early August).

Sightings of belukha whales in the Canadian Beaufort Sea become increasingly infrequent in late August and September. Whales are seen headed west past Herschel Island during September; a group of 2,000 was sighted near there on 21 September 1972 (Fraker 1978). It appears that most whales move offshore prior to entering the Alaska Beaufort Sea since they are rarely reported in nearshore waters. Johnson (1979) reported two sightings of whales swimming westward just offshore of the Jones Islands; a group of 75-100 was seen on 15 September 1977, and approximately 35 were seen on 23 September 1978. Oliver (unpubl. data) observed a single individual swimming west within 0.25 mile of the barrier islands east of Barter Island on 18 September 1984. No belukha vocalizations were heard during the period 4-17 September 1984, although a hydrophone array was in place just outside of the barrier islands at Beaufort Lagoon and was monitored 24 hours a day (Oliver, unpubl. data). Cummings (pers. comm.) heard vocalizations of belukha whales near Prudhoe Bay in September 1980.

Table 11.5—Estimated number of belukha whales offshore in the Canadian Beaufort Sea during 1981 (Davis and Evans 1982).

Survey Dates	Survey Location	Estimated Number of Belukhas
July 18-25	Canadian Beaufort & Amundson Gulf	4,389
August 5-17	E. Canadian Beaufort & Amundson Gulf	11,506
August 19-29	E. Canadian Beaufort	138
September 7-14	Canadian Beaufort & West Amundson	633

The majority of belukha whales seem to remain well offshore throughout their westward migration out of the Beaufort Sea, and their distribution in the fall strongly correlates with the location of the edge of the pack ice (Fig. 11.5a) (Burns and Seaman, in press). Large numbers of the whales have been seen on several occasions in September and early October in the region 35-220 km north of Point Barrow (Johnson *et al.* 1981; Burns, unpubl. data). During September they may be dispersed over a wide area. For example, on 21 September 1972, 100 were seen north of Prudhoe Bay and 2,000 were seen near Herschel Island. On 20 September 1980, Burns (unpubl. data) observed numerous belukhas in a band 140 km long in pack ice north and east of Barrow. As discussed in the previous section, the whales are only rarely seen near Point Barrow during autumn.

11.2.3 Life History

The life history of belukhas is shown in Figure 11.6. Females first ovulate just prior to or during their fourth year, and reach sexual maturity, as defined by onset of first pregnancy, when they are five years old (Burns and Seaman, in press). Development in males is slightly slower; reproductive activity begins at about age eight (Burns and Seaman, in press). Breeding activity may occur from late February until June, with the peak occurring in March and April. Gestation is estimated to be 14.5-16 months, and it is uncertain whether there is a delay in implantation or if embryonic development is slow. Calves are born in mid-summer, when belukhas are in the coastal regions and especially in

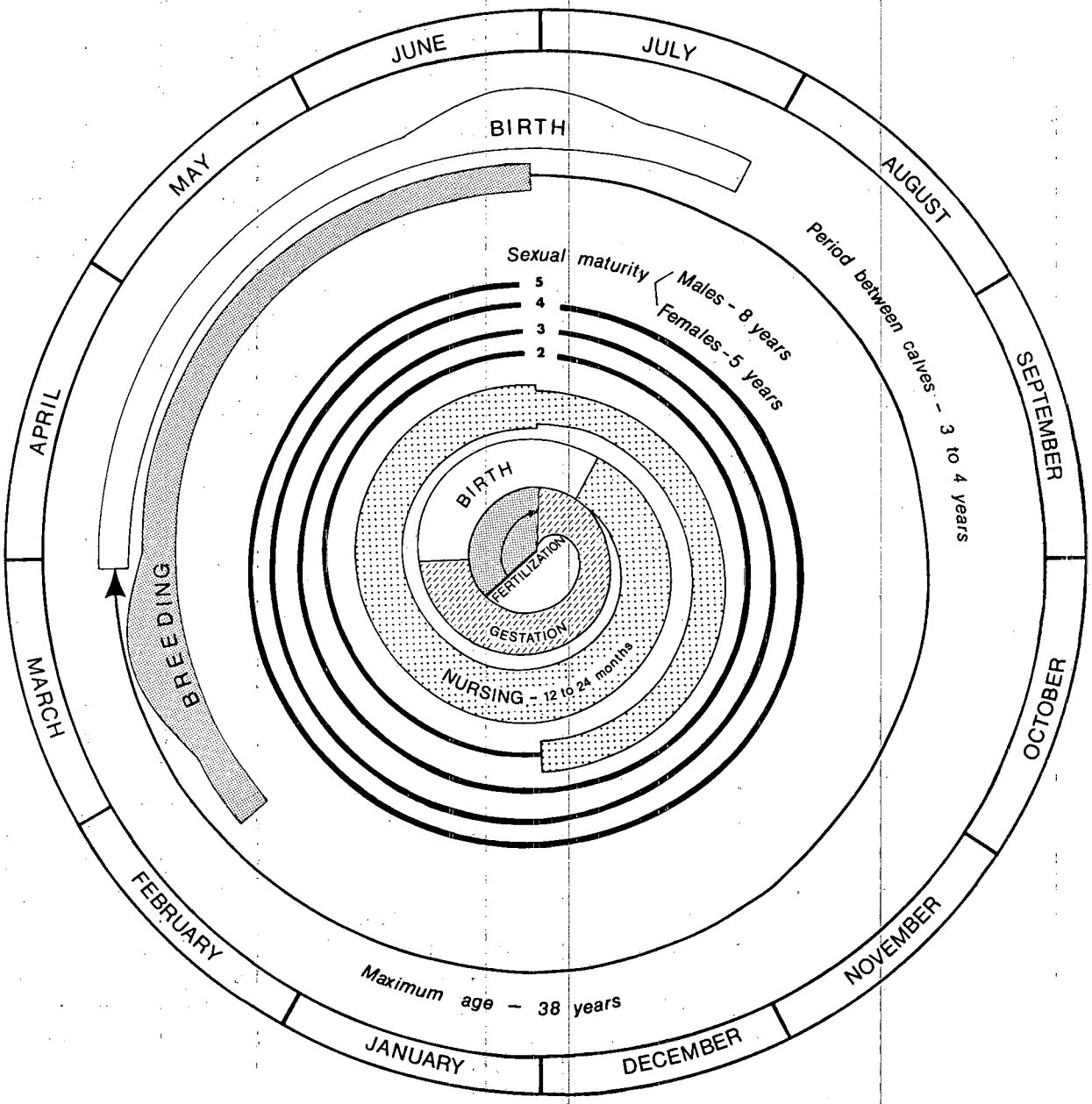

Figure 11.6—Life history of the belukha whale. To follow the life cycle of a belukha start in the center, with fertilization occurring in March. Variation in the age at weaning is displayed by changing width of segment, and peaks in breeding activity and births are illustrated by bulges. See text for details and full references. Nerini *et al.* (1984) served as the principle data source.

the shallow estuaries. Fraker *et al.* (1979) found that whales that were frequently concentrated in the warm and shallow waters of the Mackenzie River delta were usually adult females and calves. At birth the blubber layer of belukhas is very thin. Considerable thermal advantage is gained for the calf maintained in this warmer water until the blubber layer thickens. The period of parental care is protracted, for calves nurse from 12 to 18 months (Burns and Seaman, in press). Breeding normally occurs the year following calving, so the breeding cycle is triennial. Lowry (1985) estimated that the gross annual reproductive rate is about 9%, which relative to annual breeders such as seals is low, but relative to bowheads is high.

11.2.4 Food

No dietary information is available for belukhas in the Alaskan Beaufort Sea. Although a diet based upon the seasonal patterns of abundance and distribution of the common fishes of an area has been shown to accurately portray their diet in the coastal area, this method of reasoning should not necessarily be applied to belukhas when they are in the

waters of the Alaskan Beaufort Sea. There they are found almost entirely in the offshore region, while all available feeding information is from stranded animals or animals hunted in the shallow waters adjacent to coastal communities.

Predation by humans, killer whales, and polar bears is an important cause of belukha mortality. Burns and Seaman (in press) estimate that between 1977 and 1984 in northern and western Alaska, about 220 belukhas were harvested annually, and another 140 were lost to predators.

11.3 POLAR BEAR

11.3.1 Stock and Population Estimates

Polar bears (*Ursus maritimus*) are circumpolar in distribution, and in Alaska are found throughout the Beaufort and Chukchi seas to the St. Lawrence Island area in the northern Bering Sea. The most important factor affecting polar bear distribution is the sea ice; the bears move north in spring as the ice retreats and south in fall when it advances.

Historically, polar bears were common as far south as St. Matthew Island. Over 300 bears were killed in the vicinity of St. Matthew by Yankee whalers in the late 1800's, and paths the bears wore into the hillsides remain. Although ice and prey (seal) distribution appear favorable, it is perhaps due to historically high levels of hunting activity in these areas that bears are generally absent from both Kotzebue and Norton sounds.

Lentfer (1975) described Alaskan polar bears as having two populations (western and northern), with some overlap in the northern Chukchi Sea between Point Lay and Wainwright. Lentfer (1975) distinguished between these populations on the basis of differences in skull measurements and concentrations of heavy metals in tissue samples.

Using mark and recapture techniques, aerial surveys, and reexamination of catch per unit effort by sport hunters, population estimates reveal that the population appears relatively stable and about the same size now as it was 25 years ago. Large numbers of the northern polar bear population have been marked, and the average recapture rate of tagged animals is 20% (Amstrup, pers. comm.). The northern and western Beaufort populations are estimated at 1,500-2,500 each (Amstrup, pers. comm.). Recent evidence suggests that Alaska's northern population is, in fact, a population shared with Canada.

11.3.2 Migration and Movement Patterns

In the Beaufort Sea, bears are largely seasonal visitors to coastal regions: if ice is present, so are bears. Tracking of radio-tagged individuals and aerial surveys support the concept that bears occurring seasonally along the Beaufort coast are largely restricted to a band 241-322 km wide from Barrow to the Tuktoyaktuk Peninsula, N.W.T. (Fig. 11.7). This is an area of approximately 308,210 km^2 (176,120 km^2 in the United States and 132,090 km^2 in Canada). Most bears along the North Slope apparently travel considerable east-west distances, many moving from as far west as Barrow to as far east as Tuktoyaktuk, N.W.T., over the course of several years (Amstrup, pers. comm.).

Density appears to be about one bear every 78 to 130 km^2 (Amstrup *et al.*, in press). Available evidence suggests overall densities in the Bering and Chukchi seas are not much different than in the Beaufort Sea, but more information is needed (Amstrup, pers. comm.). Lentfer (1972) and Amstrup (pers. comm.) reported that density drops off rapidly after 161 km offshore. Bears exist at population levels significantly below the short-term optimum; however, they are adapted to extreme fluctuations of environment on a long-term basis (Burns, pers. comm.). This suggests that the population is below carrying capacity (Amstrup, pers. comm.).

Drifting pack ice off the coast of the Alaskan Beaufort Sea probably supports greater numbers of polar bears than either shorefast or polar pack ice (Lentfer 1972). Polar bears generally occur along the shore of the Alaskan Beaufort Sea from October to March, when shorefast ice enables them to travel easily from drifting pack ice to the beach. Local concentrations of polar bears may occur along the coast of Alaska when pack ice drifts close to the shoreline and shorefast ice forms early in the fall. However, polar bears are capable of swimming many miles in open water and can be found year-round in coastal areas, as they are along the coasts of Hudson and James Bays in Canada (Jonkel *et al.* 1972).

There appears to be considerable sexual segregation during the winter in polar bears. Many of the sexually mature females come into the nearshore region to den with the adult males remaining in the shear zone and beyond. Movement patterns of adult males are not well-known because technical

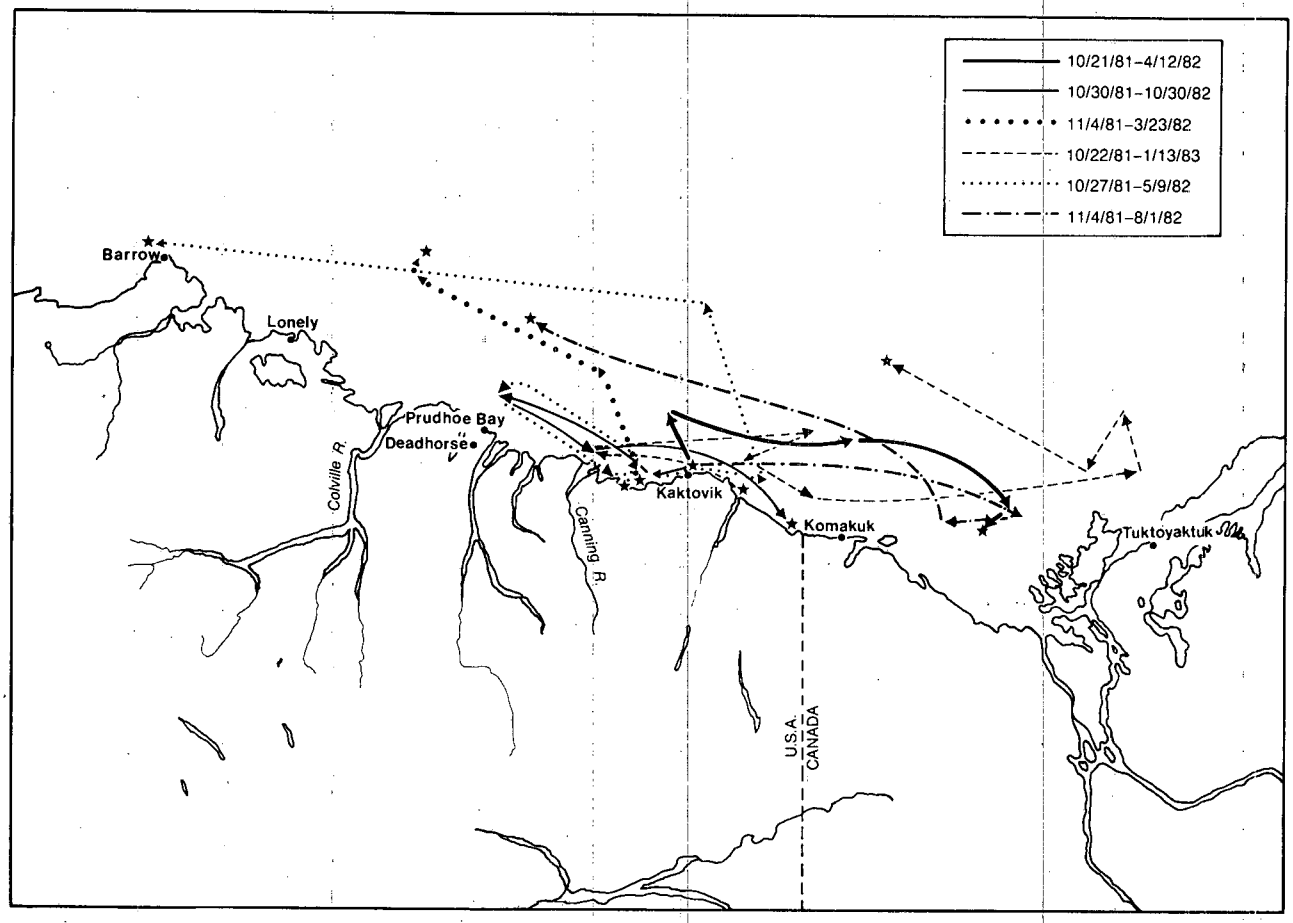

Figure 11.7—Movement patterns of 6 radio-tagged female polar bears. Data were supplied by Amstrup and are currently unpublished.

difficulties have prevented effective radio tagging of the males (their necks are larger in diameter than their heads, so the collars, which are effective on the females, fall off and cannot be used). Knowledge of female patterns is becoming well understood. When the females emerge from their dens, they start to forage right away. If hunting is successful in the immediate vicinity of the den, they tend to remain in the area. If hunting is not successful, they will range widely.

By following individual bears for several years, various trends have emerged. Some animals seem to be very localized in their movement patterns, and others range much more widely upon emerging from their dens; Amstrup (pers. comm.) attributes much of this difference to sampling error due to long delays between relocating bears, which may have masked major movements. Ice conditions and localized prey availability appear to be the major determinants delimiting the bear's movements. The overall foraging strategy appears to be flexible, involving exploitation of localized prey resources for as long as possible and then foraging over a wide area (Amstrup, pers. comm.).

11.3.3 Food

Polar bears off the Alaskan coast feed primarily on ringed seals, and to some extent, on bearded seals (Lentfer 1985; Amstrup, unpubl. data). The polar bear is typically an opportunistic feeder, sometimes frequenting coastal areas to feed on carrion, especially whale carcasses, and also on human refuse when it is available.

11.3.4 Life History

Polar bears reach sexual maturity at five years, and females produce their first offspring in their sixth year (Fig. 11.8). If cubs are successfully raised, they remain with the female for 2.5 years; thus, the average breeding cycle is 4 years.

Pregnant and lactating females with newborn cubs move into coastal areas in late October or early November to construct and occupy dens during early and mid-winter. Dens are located both on the sea ice and on land. Pregnant sows have relatively rigid requirements for denning; major factors appear to be depth of snow cover and existence of pressure ridges (Amstrup, in press). Polar bears

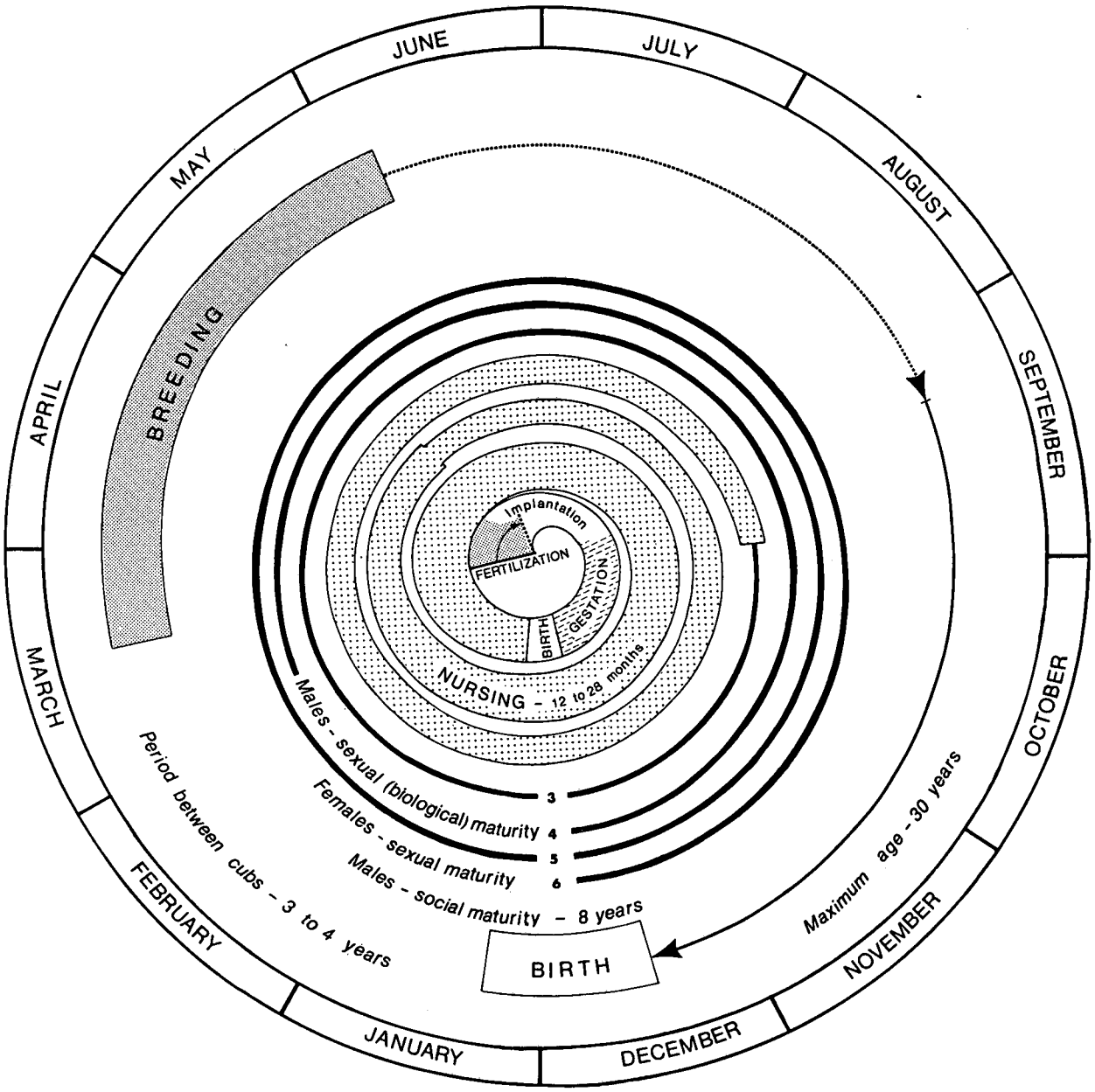

Figure 11.8—Life history of the polar bear. To follow the life cycle of a polar bear start in the center, with fertilization occurring in March. See text for details and full references. Lentfer (1985) and Amstrup (in press) served as the principle data sources.

establish dens for pupping on the pack ice, shorefast ice, and shore. Most terrestrial dens are located close to the sea coast, usually not more than 8-10 km inland (Uspenski and Kistchinskii 1972), although Lentfer and Hensel (1980) found a den 48 km from the coast. According to Lentfer (1972), polar bear dens have been located along river banks in northeast Alaska and on shorefast ice close to islands east of the mouth of the Colville River. Between 1983 and 1985 Amstrup (pers. comm.) located 26 dens along the northern Alaskan coast; 21 of these were on the pack ice, 1 on the fast ice, and 3 on shore, with the remaining den either just on the edge of the fast ice or on shore. Whether fidelity to denning sites occurs is unknown; only two female bears have been radio-tracked through two known reproductive cycles. One bear that denned near Herschel Island and failed to produce any young the first year denned the following year nearby along the Yukon coast and produced a cub. The second bear first denned east of Barter Island, and the next time denned way out on the pack ice (Amstrup, unpubl. data).

Insufficient data exists to accurately quantify the extent of polar bear denning along the Beaufort coast. The existence of concentrated denning

areas comparable to those found on Wrangel and Spitsbergen islands is unknown along the Alaskan coasts. Lentfer (1975) reported that some bears give birth in maternity dens far offshore on the pack ice. The relative importance of denning on the pack ice versus coastal denning remains unknown.

Parturition occurs from early December to late January (Lentfer 1985), and females and cubs break out from the dens in late March or early April.

Principal causes of mortality are cub cannibalism by male bears and hunting by local residents. Natural mortality rates are not well known. Polar bear survivorship typically ranges from 0.88 to 0.94 (Amstrup *et al.*, in press).

Hunting levels from 1925 to 1985 are summarized in Table 11.6. Lentfer (1985) characterized the first four hunting periods as follows: (1) prior to the 1940's, primarily native subsistence hunting with dog teams and the sale of the hides; (2) starting in the late 1940's, guide hunting by aircraft, which continued until stopped by the State of Alaska in 1972; (3) after statehood, Alaskan management of the polar bear hunt, requiring sealing and examination of the hides, and protection of cubs and females with cubs; in 1972, ban of aircraft hunting, and as a result of the Marine Mammal Protection Act, transfer of management authority from the state to the Federal Government; and (4) since 1973, all hunting limited to subsistence use and elimination of all protection to females and their cubs.

In recent years monitoring of the subsistence hunt has been less intense. The recent rise in subsistence take may be due to heightened affluence of the Natives (more time to hunt and increased use of snow machines).

There has been a change in the sex composition of the harvest since 1973: from 1960 through 1972 females composed an average of 24 ± 3.5% of the harvest, but since 1973 they have averaged 42 ± 5.4%. The difference is highly significant ($P<0.005$). The population is relatively small and, with the low reproductive rate of bears, there are understandable concerns for their management if females with cubs continue to be a significant portion of the annual harvest.

Besides being protected by the Marine Mammal Protection Act of 1972, polar bears and their habitats are protected by the International Agreement on the Conservation of Polar Bears of 1976 signed by Canada, Denmark, Norway, the U.S.S.R., and the United States. The agreement states in Article II that "each contracting party shall take appropriate action to protect the ecosystem of which polar bears are a part, with special attention to habitat components such as denning and feeding sites and migration patterns" (Lentfer 1974).

Polar bear distribution can be characterized as patchy, but these patches are transient (*i.e.*, they show a dynamic movement pattern). Temporally, the distribution is spotty, but over time it is even. In the winter, sexual segregation occurs with females and young concentrated in the nearshore areas and adult males farther offshore (Amstrup, pers. comm.). This has been observed through tagging studies in Canada and near Barter Island (Figure 11.7) and is also collaborated by the limited recent harvest data (Amstrup *et al.*, in press; Amstrup, pers. comm.).

11.4 RINGED SEAL

11.4.1 Stock and Population Estimates

Ringed seals (*Phoca hispida*) are circumpolar in distribution, and are the most abundant pinnipeds in the Beaufort Sea. The current world population estimate is in excess of 6,000,000 ringed seals,

Table 11.6—Annual polar bear hunting statistics, 1925-1985. Numbers represent average annual take for each of the 5 time periods.

Years	Subsistence Harvest	Sport Hunting	Northern Population Only	Annual Take (mean ± s.d.)
1925-53[1]				117
1954-60[1]				158 ± 52
1961-72[1]	34	226	81	260 ± 73
1973-79[1]	86	0	26	86 ± 56
1980-85[2]	135	0	38	135 ± 88

Data sources: 1 = Lentfer (1985); 2 = Taylor (pers. comm.).

with Frost's (1985) Alaskan stock estimate at 1,500,000 seals. Only minimally affected by ice conditions, they are the most ice-adapted of all northern pinnipeds. Frost and Lowry (1981) estimated that approximately 40,000 seals inhabit that portion of the planning area extending out to the 200-m isobath between Point Barrow and Demarcation Point during the winter, and estimated that the population swells to 80,000 during the open water season.

In the Bering and Chukchi seas, ringed seal abundance is closely tied to the stability and extent of shorefast ice, the preferred winter habitat (Burns and Eley 1978). However, in the Beaufort Sea, nearshore pack ice is quite stable during the winter months, and ringed seal occurrence on this portion of the pack ice may not be less than on the shorefast ice zone (Frost and Lowry 1981). This is not the situation with the moving pack ice, where ringed seals are less abundant (Lowry, pers. comm.).

Although there has not been a systematic effort to determine the population level in the planning area, there have been several aerial and shipboard surveys concentrated shoreward of the 200-m isobath. These surveys indicate that while the ringed seal is the most abundant pinniped in the Beaufort Sea, its density there is quite low. During winter the fast ice has approximately 5-10 times the density of seals as does the offshore pack ice. Fast ice has 0.43-0.60 seal/km^2, while pack ice has 0.04 seal/km^2 (Burns and Eley 1978; Burns and Kelly 1982). In the area west of Barrow the density of seals is considerably higher: fast ice from Barrow to Point Franklin has 1.46 seals/km^2 (Burns and Kelly 1982); Chukchi pack ice has 0.07 seal/km^2 (Burns and Eley 1978).

During the winter the area of the pack ice in the planning area is several orders of magnitude greater than that of the fast ice. Thus, considerably more animals reside on the pack ice than on the shorefast ice, but their density is much lower. First-year ice has long been recognized as preferred habitat of ringed seals (McLaren 1958; Smith and Hammill 1981). Low ridges on stable sea ice provide optimal areas for ringed seal lair construction. In the Beaufort Sea the density of all ringed seal lairs is very low (Burns and Kelly 1982). Ice conditions, particularly deformation and depth of snow accumulation, appear favorable. Availability of food during winter is unknown, but was suggested by Burns and Kelly (1982) as a possible limiting factor. Studies of radio-telemetered ringed seals have revealed that seals do not range widely during the winter in the Beaufort Sea, but consistently haul out at the same lairs.

11.4.2 Migration and Movement Patterns

During ice break-up there is an influx of seals into the nearshore region (along the cracks and leads) of the Beaufort Sea (Burns and Kelly 1982; Lowry, pers. comm.). The nearshore population is estimated to double during the summer, and seal distribution is very patchy. No systematic population surveys of ringed seals have been performed in summer; however, high densities of seals have been reported to be associated with ice remnants that occur in the planning area (Burns *et al.* 1980).

Concentrations of seals frequently are seen east of Barter Island, north of Prudhoe Bay in the vicinity of Flaxman Island, and east of Barrow. The persistence of these concentrations is unknown but is assumed to be associated with local concentrations of prey, especially euphausiids and hyperiid amphipods. The density of seals decreases offshore (Lowry, pers. comm.). This is similar to the pattern seen along the Yukon coast during the summer, where sightings increase in the nearshore zone and animals are believed to have moved south from the pack ice (Stirling *et al.* 1982). Ljungblad (pers. comm.) reports few offshore sightings, although sightings of ringed seals in the water during an aerial survey concentrating on bowhead whales are unlikely due to sighting difficulties and scan differences.

The annual variation in population size is not known, but is apparently subject to sizable fluctuations. In the Canadian Beaufort Sea the population apparently decreased by 50% between the early and mid-1970's. This decrease has been attributed to the heavy ice years of 1973 and 1974 (Stirling *et al.* 1982). This may also have been observed in Alaska, but the data are confused since the surveys were flown over areas of record seismic exploration. Concurrently, increased densities apparently occurred in the Bering and southern Chukchi seas, and possibly the Alaskan Beaufort Sea. The population in Canada more than doubled in 1978. This is much faster than could be expected to occur through intrinsic reproduction rates alone and thus suggests that immigration occurs (Stirling *et al.* 1982; Lowry, pers. comm.).

As noted and discussed in greater detail in Chapter 19, Noise and Marine Mammals, the winter distribution and abundance of ringed seals is affected by man's activities on the ice. Burns and

Kelly (1982) conclude that some localized displacement of ringed seals occurs in immediate proximity to seismic lines (within 150 m), but overall displacement resulting from this activity in the nearshore Beaufort Sea is insignificant to the Alaskan ringed seal population.

Ringed seal distribution and abundance patterns within the planning area depend on a variety of factors such as ice conditions, food availability, and proximity to human disturbance. Ringed seals have evolved a variety of survival mechanisms and prosper in the Beaufort Sea during winter. One of these is to maintain breathing holes in the ice cover until break-up. As freeze-up occurs the ice cover starts to thicken and small deformations and ridges appear. Ringed seals most often maintain breathing holes adjacent to such deformations. As winter progresses, the seals hollow out snow accumulated in pockets on the lee side of these deformations, in depths greater than their own dorsal-ventral thickness.

Depending on the age and sex of the seal, these structures may range in size and complexity from slightly greater diameters than the breathing hole to elaborate, multichambered, multilair pupping complexes. Intermediate in size and complexity are the more common haulout and birthing lairs. These structures provide the seals with a haven from the severity of the arctic winter. Kelly (unpubl. data) found that the temperature is much higher inside the lair than outside. The seal warms the lair with its presence, and the blanket of snow serves as an effective insulator to prevent the rapid dissipation of body heat. When the seal is absent, the water in the exit/breathing hole becomes another source of heat, for the water temperature is only −1.7°C, considerably above the frequent midwinter air temperature of −40°C. A seal in a lair is also protected from the wind-chill. This may be especially important in late winter to pups whose blubber layer is not as substantial as that of adults. These dens also provide some protection from predatory polar bears and arctic foxes.

11.4.3 Life History

Previously, ringed seals were believed to be monogamous (Burns 1978), but recent radio-tagging studies suggest that males maintain territories that overlap the range of several females; this is strongly suggestive of a polygamous social system. Smith and Hammill (1981) describe territorial breeding habitat that is also strongly suggestive of polygamy in ringed seals. During the reproductive period, however, ringed seals do not form large concentrated herds but remain widely dispersed.

The life history of ringed seals is summarized in Figure 11.9. Peak breeding activity is in mid-March to late April, with an 11-month gestation period including a 3.5 month period of delayed implantation. Pups are born in late February-March and are nursed for 4-6 weeks. They remain in their birth lairs until weaned, then emerge at between 9.07 and 13.6 kgs, ready to shed their dense coat of lanugo and forage for themselves.

Four to six weeks after giving birth most female ringed seals breed. Impregnation rates can vary widely both geographically and annually. Normally 80-90% of adult females are pregnant, but records from the Canadian Beaufort Sea indicate that in 1974 and 1975 these rates decreased to 11% and approached 0% in local areas. Severe ice conditions limiting food availability may have been responsible for this decrease.

There are regional differences in pupping activity. In the Alaskan Beaufort Sea only 7% of all seal structures are pupping lairs, and the density of these lairs is less than 0.07 lair/km^2. Young animals constitute a large percentage of the Eskimo take, so reproduction is obviously occurring (Lowry, pers. comm.). The question is, where are these pupping centers?

In Baffin Bay more ringed seals breed on extensive areas of pack ice rather than on smaller areas of fast ice despite higher density on fast ice (Finley *et al.* 1983). Although the offshore region has not been carefully examined in the Alaskan Beaufort, similarities with Canadian findings in the Canadian Beaufort can be expected. Finley *et al.* (1983) found that in Baffin Bay, Canada, pack ice seals are smaller than their fast ice counterparts and have a different diet and gut parasite load. Pack ice seals probably mix with fast ice seals in coastal areas during the brief open-water season, but morphological and ecological differences suggest the populations are reproductively isolated (Finley *et al.* 1983). In addition to animals moving in toward the coast from the pack ice, Burns (pers. comm.) and Burns and Kelly (1982) suggest that ringed seals enter the Beaufort Sea prior to ice breakup via leads and cracks from the Chukchi. Localized breeding concentrations have been found along the Chukchi coast, with those closest to the planning area being near Point Franklin. In addition, there is circumstantial evidence that when conditions are not favorable in the Canadian Beaufort Sea, some seals move west, seeking more favorable conditions.

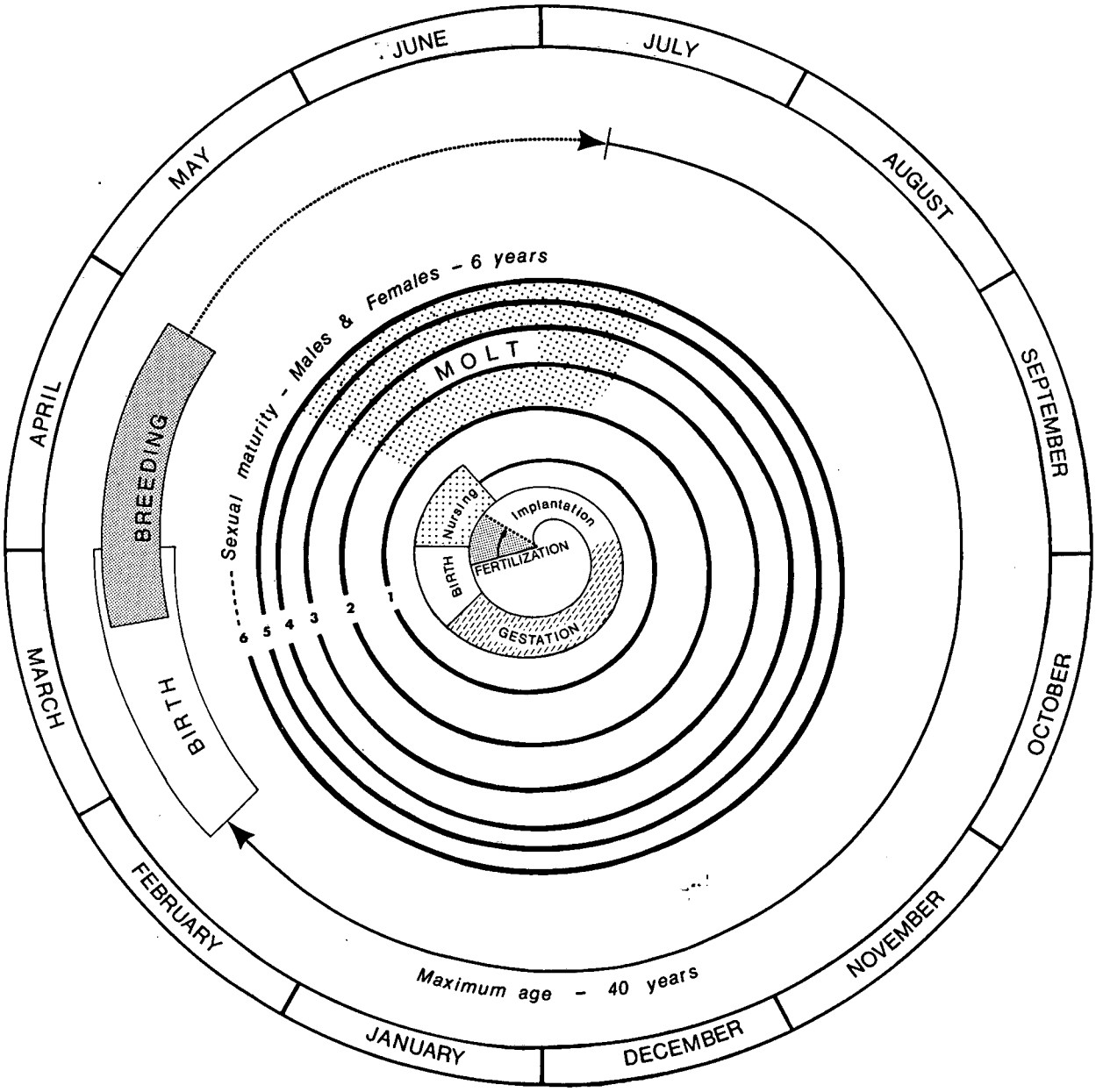

Figure 11.9—Life history of the ringed seal. To follow the life cycle of a ringed seal start in the center, with fertilization occurring in March. Variation in the age at weaning is displayed by changing width of segment, and peaks in breeding activity and births are illustrated by bulges. See text for details and full references. Frost (1985) served as the principle data source.

Ringed seals molt from May through July after the pupping and breeding seasons (Eley and Lowry 1978). During this period ringed seals tend to show greater synchrony in their haulout patterns (Burns and Kelly 1982). Increased warmth and hair growth is attributed to spending much of each day basking on the ice (Feltz and Fay 1966). During the molt, feeding is limited and physical condition, as measured by blubber thickness, decreases to its annual minimum (Frost 1985).

As the leads and cracks start to open up in the nearshore ice, immigration of seals begins. These spring arrivals include ringed seals that have overwintered, and perhaps pupped and bred in the offshore pack ice, and animals from the Chukchi and perhaps even the Bering seas.

11.4.3 Food

Ringed seals consume a large variety of prey that varies seasonally, spatially, and perhaps according to the seal's age and sex. Depending on local availability, ringed seals consume arctic cod, euphausiids, amphipods, mysids, and small pelagic fishes (Frost and Lowry 1981; Lowry *et al.* 1980). During

winter in the Beaufort Sea, arctic cod make up over 80% of the ringed seal diet. Decreased prey availability is considered the primary reason why the winter population is so much lower than the summer population. Large aggregations or herds of ringed seals have been observed to apparently migrate and feed in swarms (Morris, pers. comm.).

11.4.4 Predation

Ringed seals are preyed upon by polar bears, arctic foxes, and man. These seals are the mainstay of the polar bear diet, and it has been estimated that 265,000-530,000 ringed seals are consumed annually by Alaskan polar bears (Frost 1985, adapted from Stirling and Archibald 1977). These figures are, however, based on rather limited data, which Amstrup (pers. comm.) believes may overestimate the importance of ringed seals in the annual diet of the bears. Arctic foxes were found to have marked 32.9% of all seal structures and to have entered 18% of them in 1982 (Burns and Kelly 1982). Fox predation on ringed seals peaks in April and May and is directed at the pups. Foxes also follow polar bears and scavenge the remains of bear kills. Ringed seals constitute as much as 58% of the total seals harvested by subsistence hunters in Alaska (Burns and Eley 1978; Burns and Bennett, Chapter 18, this volume).

11.5 BEARDED SEAL

11.5.1 Stock and Population Parameters

Bearded seals (*Erignathus barbatus*) are circumpolar in distribution and generally restricted to areas where seasonal sea ice occurs over water less than 200 m deep. In Alaska, bearded seals range from the central Bering Sea through the Chukchi Sea and into the Beaufort Sea; Nelson *et al.* (1985) characterize this as the largest continuous bearded seal habitat in the world. The Alaskan seals are believed to form a single stock with an estimated size of approximately 300,000 (Burns 1981). There are no population estimates for the Beaufort Sea alone. Few bearded seals overwinter in the Beaufort Sea; rather, the center of abundance is in the southern Chukchi and northern Bering seas (Burns and Frost 1979; Burns 1981). Densities decrease eastward from Barrow (Lowry, pers. comm.). Unlike ringed seals, which frequent the shorefast ice, the bearded seals are primarily restricted to the pack ice because of their inability to maintain breathing holes and preference for leads and cracks. However, they are occasionally found in winter over deep water (Finley and Renaud 1980; Greene, pers. comm.) and sometimes along cracks in fast ice far from the open pack ice (Finley 1978). During summer in the Beaufort Sea, densities of bearded seals are also low, perhaps one-tenth that of ringed seal densities (Lowry, pers. comm.).

The population is centered in the Chukchi Sea. The region from Point Franklin to Cape Barrow is important to bearded seals. Ice, frequently near shore in this region, moves on and off shore all summer. Bearded seals frequently use this ice as an important haulout (Frost, pers. comm.). Interestingly, however, no bearded seals were observed in aerial and shipboard surveys within 5 km of shore during 1981 or near Peard Bay in 1983 (Oliver, unpubl. data).

11.5.2 Food

Food habits of bearded seals in the Diapir Field Planning Area are not well known. Although generally described as benthic feeders, bearded seals exhibit a high degree of consumer opportunism throughout their range. In the shallow Chukchi and Bering seas, where the bottom is within the range of the seals' diving depth, the seals feed primarily on shrimps, crabs, and bivalve mollusks. Fish are apparently of only minor importance (Burns and Eley 1978; Lowry, Frost, and Burns 1980b). In areas of the Barents and Kara seas, Chapskii (1938) reported that shrimp and mollusks were the predominant prey of bearded seals, although fish, particularly arctic cod, were thought important when they occurred in large concentrations. Fish were important components of the seals' diet in those areas beyond seal diving depths in both the Sea of Okhotsk (Pikharev 1941) and off Greenland (Vibe 1950). Finley and Evans (1983) examined the stomach contents of 34 seals taken during summer in the vicinity of Baffin Bay in the eastern Canadian Arctic. They found that in the coastal waters of the Canadian Arctic, pelagic and benthic fish constituted the bulk of their diet. Even though invertebrates were present in all stomachs, they constituted only about 2% of the wet weight of prey.

Only 20 bearded seal stomachs have been examined from the Beaufort Sea, 16 of these from the Barrow region; therefore, information on spatial and temporal changes in diet for the Beaufort is sparse. Crabs and shrimps were the primary prey items. Clams, hermit crabs, octopus, gammarid amphipods, isopods, and fishes were also eaten (Burns and Frost 1979). Near Barrow, clams were an important component in August, and arctic cod

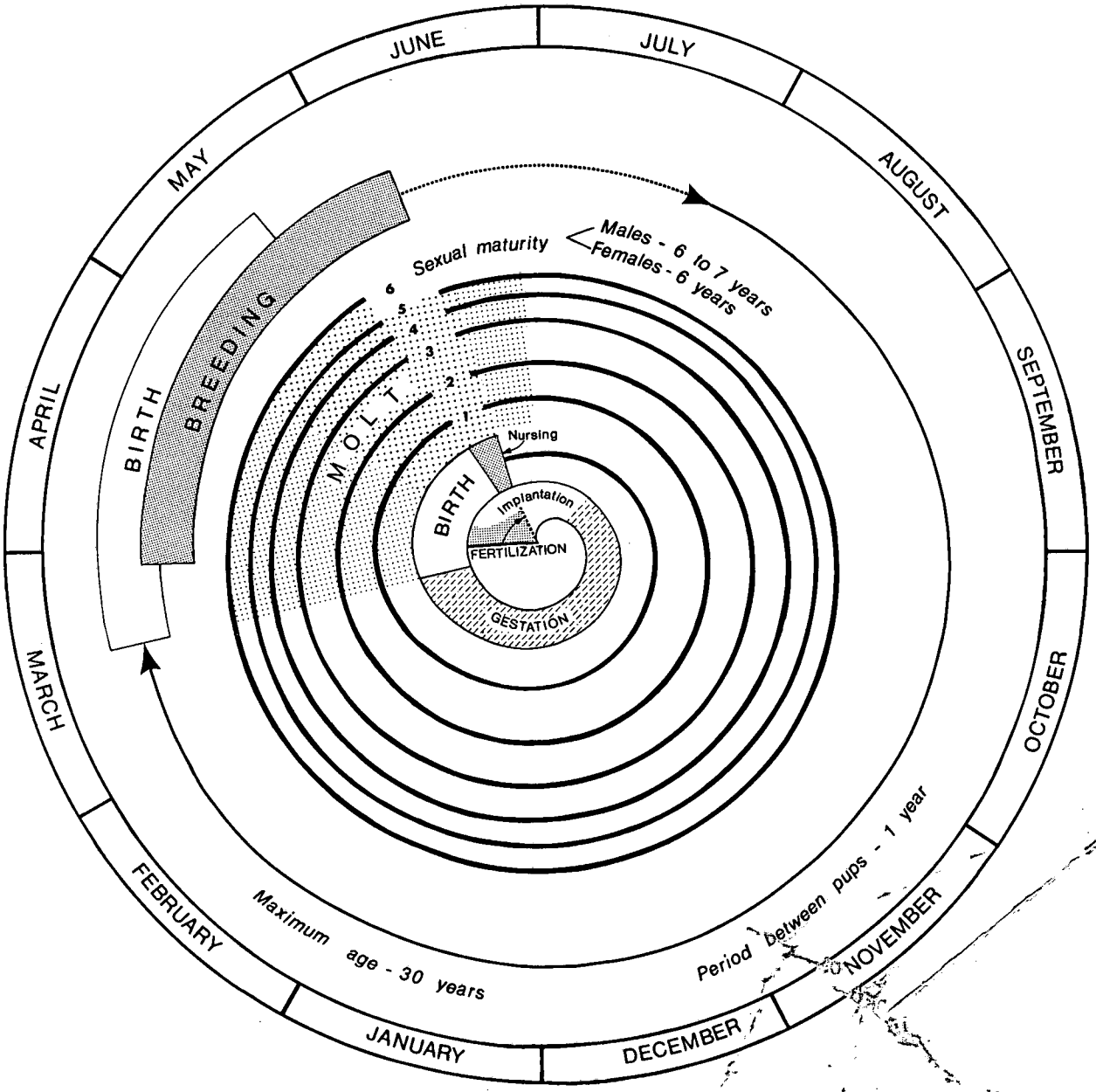

Figure 11.10—Life history of the bearded seal. To follow the life cycle of a bearded seal start in the center, with fertilization occurring in April. See text for details and full references. Nelson *et al.* (1985) served as the principle data source.

during November and February. Burns and Frost (1979) attribute the importance of arctic cod to its abundance in the Beaufort Sea, and its appearance in the seals' winter diet may coincide with its onshore spawning migration during early winter. Overall, the most abundant food species at Barrow were Tanner crab, spider crab, and the shrimp *Sclerocrangon boreas*; in the Prudhoe Bay area, spider crab and the shrimp *Sabenea septemcarinata* were most abundant. The absence of Tanner crab and the difference in shrimp species reflect faunal differences between the two areas. East of Barrow, Tanner crab occur only rarely and *Sabenea* is more abundant than *Sclerocrangon* (Lowry *et al.* 1978b).

11.5.3 Life History

The life history of bearded seals is summarized in Figure 11.10. Sexual maturity is reached at 6 years by females and at 6-7 years by males. Bearded seals breed and pup primarily in the Bering and Chukchi seas. Pupping magnitude in the Beaufort Sea is unknown, but believed small in comparison to the Bering and Chukchi production.

Breeding occurs in April through early June. After a gestation period of 11 months, including a 2-month delay in implantation of the blastocyst, pups are born in mid-March through mid-May and nursed for a very short time (12-18 days), and then females breed again. Most pups reach approximately 63% of their adult length and weight when they are weaned (Burns 1967; Burns and Frost 1979). Reproductive senility is unknown in bearded seals. Over 85% of the adult females collected between 1969 and 1978 (n = 117) were pregnant in the reproductive cycle preceding collection (Burns and Frost 1979). Bearded seals are thought to be monogamous (Burns 1981).

Unlike walrus, harbor seals, and sea lions, bearded seals are not highly gregarious and do not form herds. Loose aggregations of animals sometimes occur, especially during the molt. Burns (pers. comm.) notes that of all the northern pinnipeds, bearded seals have the most protracted hair loss (bald spots can be found year-round). The period of hair regeneration is much more compact though, late March through June, with the peak occurring from May through mid-June.

During this period of regeneration, bearded seals increase the amount of time hauled out, and decrease their foraging activities. This increased haulout behavior keeps the pelage dry, and with both the increased blood flow into the surface layer and the warming effects of the spring sun, rapid hair growth is fostered. These haulout periods also provide an optimal opportunity to conduct annual aerial census surveys of bearded seals.

Like ringed seals, bearded seals are in prime physical condition, as measured by blubber thickness, in the fall and early winter. As winter continues the blubber stores are utilized by the seals, especially those seals pregnant or pregnant and expending nursing energy. Just prior to breakup the molt occurs, with increased haulout time and reduced foraging. By the end of this period physical condition is at its annual minimum, and males may outweigh females. Thickness of the blubber varies from an average of 7.2 cm in late fall through early spring to about 4.9 cm in the summer (Burns and Frost 1979).

Bearded seals are highly vocal, and produce a variety of sounds, including a distinctive song, the nuptial whistle (Dubrovskii 1937). Singing occurs from March to July, with a marked peak during April and May (Dubrovskii 1937; Chapskii 1938; Burns and Frost 1979). Ray *et al.* (1969) suggested that the song is either a proclamation of territory or of breeding condition by mature males. However, Burns (1981) believes that the songs are made by both sexes, since the calls are so common, and almost seem to exceed the number of animals during their population peak. They are one of the principal contributors to the ambient noise spectra of the Arctic.

11.5.4 Predation

Polar bears and man are the primary predators of bearded seals. Bearded seals are important subsistence animals to man, valued especially for their hides (Burns and Bennett, Chapter 18, this volume). Polar bears follow cracks and leads in hunting this species on the pack ice (Richardson, pers. comm.).

11.6 SPOTTED SEAL

Spotted seals (*Phoca largha*) are in the Diapir Field Planning Area only during the open water season. They appear in low numbers along the coast in July and remain until mid-October (Frost, pers. comm.). Peak occurrence is in August and September, when perhaps 1,000 spotted seals haul out on beaches, barrier islands, and remote sandbars on river deltas (Burns *et al.* 1981). Primary haulout areas include the Colville River delta (Helmericks to Lowry, pers. comm.), Oarlock Island in Dease Inlet (Burns, Lowry, and Frost, pers. comm.), and the mouth of the Piasuk River in southwest Smith Bay (Lowry, pers. comm.). Spotted seals are present in unknown numbers during summer and fall in the vicinity of Peard Bay, and especially near the mouth of the Kugrua River (Frost, Lowry, and Burns 1983). Winter and spring periods are spent along the ice front in the Bering Sea where the seals pup, breed, and molt (Burns 1978).

Food habits of spotted seals in the planning area are unknown. They frequently enter estuaries, and sometimes ascend rivers (especially the Kugrua and Colville), presumably to feed on anadromous fishes. Based on available information on prey and food habits from other regions, a diet of anadromous fishes, capelin, and shrimps does seem likely (Frost, pers. comm.).

As the shorefast ice reforms and the pack ice advances southward, spotted seals depart the planning area and move to the Bering Sea ice front, where they pup, breed, and molt in winter and spring.

11.7 OTHER SPECIES

Individual fur seals, hooded seals, minke whales, and harbor porpoises are other marine mammals that appear with less regularity in the Diapir Field Planning Area.

Occasionally, gray whales appear in the Diapir Field; their occurrences have been observed with increasing frequency near Point Barrow (Dronenburg, pers. comm.). Their annual arrival is in the northeast corner of the Chukchi Sea during late spring, shortly after the bowheads have passed through the area (early or mid-June) (Rugh, pers. comm.). Considerable feeding activity has been observed near Barrow throughout the summer until late August or early September (Maher 1960). Gray whales were abundant in the area off Point Franklin and Peard Bay during both 1981 and 1982 (Frost, pers. comm.). Each year from 1980-1982 there have been one to three sightings of gray whales in the Canadian Beaufort Sea (Rugh and Fraker 1981; Richardson, pers. comm.), indicating that these animals traverse the Alaskan Beaufort Sea. Gray whales have been observed as far east as Tuktoyaktuk Peninsula, N.W.T. (Rugh and Fraker 1981), but occurrence east of Point Barrow is considered to be only occasional or rare (Rugh, pers. comm.).

Other occasional inhabitants include walruses, killer whales and narwhals. Walruses appear to have a presence and timing similar to grey whales and arrive in the Diapir Field Planning Area from the west as early as May (Rugh, pers. comm.), but most often in July and later. Sightings diminish in frequency to the east (Rugh, pers. comm.). Killer whales arrive from the west. Narwhals arriving from the east are rarely sighted in the Beaufort Sea (Rugh, pers. comm.).

Although common in the planning area, the arctic fox is not discussed here, but adequate information is provided in Davis and Thomson (1984).

11.8 SUMMARY AND CONCLUSIONS

The Alaskan Beaufort Sea is a traditional feeding ground for bowheads. During the fall, bowheads feed in at least two regions of the planning area: east of Barter Island to the Canadian border and, less frequently, between Pitt Point and Point Barrow. Whether specific feeding areas can be delimited, or whether the entire portion of the Beaufort occupied by bowheads should be considered feeding habitat, cannot be resolved with the existing data. What is important is the recent recognition by the scientific community and management agencies of the predictability of the use of these areas for food.

Polar bears can be characterized as having a patchy, transient distribution, and temporally, this distribution is spotty. Sexual segregation occurs in the winter, with females and young concentrated in the nearshore areas and adult males farther offshore. This has been observed through tagging studies in Canada and near Barter Island and collaborated by recent available limited harvest data (Amstrup *et al.*, in press; Amstrup, pers. comm.). This segregation has obvious and dramatic implications for onshore activities.

Estimating the impact of the above species on the Diapir Field Planning Area environment, their relative importance, and their susceptibility to disturbance, is currently impossible. There are no common denominators for comparison, but it is possible to calculate a relative indicator of the important species using the following formula:

Species Biomass = mean weight of individual × number of individuals × average residence time.

As with any such indicator, its calculation is fraught with simplifying assumptions that may render it questionable, but it is convenient for management purposes. Examination of Table 11.7 reveals a surprising flaw in the workshop discussions: although gray whales and walrus are largely limited to the extreme westward portion of the planning area, their relative importance appears to have been underestimated by the workshop participants due to the focus on the Beaufort Sea portion of the planning area. The low species biomass figure for the polar bear is not surprising since its primary prey are ringed and bearded seals.

No such scale is currently possible for determination of the effects of development on these species. Two useful concepts in such discussions are vulnerability and sensitivity. Vulnerability refers to the individual's or population's geographical and temporal distribution, and sensitivity measures an individual's behavioral and physiological response to a particular condition. Although the effects of development are certainly germane to the workshop discussions, they were not addressed for any species other than the bowhead whale. Chapter 19, Noise and Marine Mammals, in this volume discusses one aspect of these effects in detail. For other topics relating to marine mammals and the effects of development of offshore oil and gas, Braham *et al.* (1982), Davis and Thomson (1984), and Armstrong *et al.* (1984) are recommended.

Table 11.7—Annual species biomass of the principal marine mammal species occurring in the Diapir Field Lease Area.

Species	Weight (kg)	Number of Individuals	Residence (Days)	Biomass (kg/10^6 yr)	Rank
Bowhead whale	40,000	4,000	45	7,200	1
Belukha whale	1,000	20,000	40	800	4
Polar bear	227	2,500	365	207	7
Ringed seal					
residents	50	40,000	365	730	
summer migrants	50	40,000	100	200	
total				930	2
Bearded seal					
residents	200	4,000	365	292	
summer migrants	200	4,000	100	80	
total				372	6
Spotted seal	75	1,000	100	7.5	8
Walrus	800	15,000[1]	75	900	3
Gray whale	20,000	1,000[1]	35	700	5

[1] This is an estimate of the maximum number of animals that might occur in the Chukchi portion of the Diapir Field.

11.9 INFORMATION NEEDS

There are many gaps in the available data base on the marine mammals of the Diapir Field. Those concerning the impacts of development are of a generic need and apply to most other Alaskan continental shelf areas; they have been dealt with in other synthesis volumes and are discussed here as well. Information needs in the Diapir Field were identified on a species-by-species basis and are not given priorities other than to indicate the need for a large-scale study of the feeding ecology of the bowhead whale. Such a study is currently underway.

Bowheads:

Major information needs pertain to feeding ecology, social behavior, reproductive behavior, and the distribution of whales on portions of their migrations. Specific questions needing resolution include:

- What are the residence times and primary activities of bowheads in the Diapir Field during the fall?
- What is the extent of feeding activity in the Diapir Field; what are the characteristics of the feeding areas and the zooplankton upon which they feed; how important is winter feeding to bowheads?
- To what extent does breeding and calving occur in the Beaufort Sea?
- What is the dispersion of the migrants once they are east of Prudhoe Bay in the spring and west of Barrow in the fall?
- In Alaskan waters, are the whales segregated into groups by age or sex, and are these groups differentially affected by man's activities on the continental shelf?

Belukhas:

The distribution, abundance, and feeding ecology of belukha whales in the Diapir Field are poorly known. Further work is needed to determine the following:

- Are the aggregations of whales north of Barrow in September composed of animals that have summered in the Chukchi Sea and its coastal lagoons and the Mackenzie River area?
- What they are doing in the Diapir Field Planning Area?
- What segment of the Alaskan population do they represent? (Frost [pers. comm.] estimates that this could be as high as two-thirds of the Alaskan population.)
- Is this area's consistent use due to particular physical processes that entrain plankton and thus make it an attractive feeding area for belukhas?

Will these same physical factors serve to entrain or accumulate pollutants?

Ringed Seals:

Questions about ringed seals include the following:

What are the factors determining the summer distribution in relation to ice and open water?

Are ringed seals indicators of high biomass—biologically rich areas that are also suitable for bowheads?

What are the factors which caused the large oscillations in abundance observed in the mid-1970's?

Where are the principal pupping areas for the Beaufort Sea population?

Spotted Seals:

In conjunction with ringed seal studies, there is a need to further document spotted seal use of the Beaufort Sea coast in the late summer and fall, and to determine what foods they utilize.

Walruses:

Walrus summer foods and feeding areas are poorly known; but based upon their diet in other areas, Frost speculates that their Diapir Field diet is probably clams, which are locally abundant in the vicinity of Barrow. The area from Wainwright to Barrow can be a "hot spot" for walruses in the late summer and fall if ice conditions are appropriate. This area appears to have a very rich benthic community and should be sampled.

Polar Bears:

Site-specific information on denning, pregnant polar bears, and the movement patterns of male bears throughout the Diapir Field is lacking.

Gray Whales:

The abundance, distribution, and activities of gray whales in the western portion of the Diapir Field are poorly known. Presumably they feed on benthic resources, but the distribution and abundance of the resources are inadequately known.

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Part II

Interdisciplinary Processes Analyses

Chapter 12
Physical Hazards: Interaction with Development Activities

by William J. Stringer and Paul Sellmann

The 1978 interim synthesis report for the Beaufort and Chukchi seas and the synthesis report for Sale 71 provide discussions of hazards to offshore development in parts of the Diapir Field (Sale 87) lease area. The magnitude of these hazards in the Diapir Field, however, will be more variable and subject to more uncertainty due to the large range of water depths, subsea materials, lease area size, and limited data for the Chukchi Sea and the region beyond the coastal zone in the Beaufort Sea.

Recent OCSEAP attention has shifted away from physical hazards investigations, with the result that little additional work has been performed in this area since the last synthesis. One of the chief reasons for this shift of emphasis has been the difficulty in determining a quantitative relationship between a physical hazard (multiyear ice, for instance) and pollutants. Several steps in the process of this evaluation require data which either do not exist or are proprietary property of petroleum companies (for instance, the design strength of drill platforms).

For this reason, OCSEAP has chosen to identify physical hazards and to explore their locations and magnitude to some extent, but not to second-guess the environmental impact resulting from these hazards, such as the failure rate of manmade islands and subsequent spilled petroleum due to ice damage. It is generally assumed that the cost of drilling platforms and other facilities will be high enough to warrant stringent design criteria to reduce the risk of petroleum spills to that of average values within the industry. In this case, OCSEAP's role in hazards assessment is limited to the compilation of a hazards catalog.

In this synthesis of hazards information, we will list the various hazards, describe them briefly, reference complete descriptions, and make comments based on new knowledge (if any).

12.1 STORMS AND WAVES

During the open-water season, the Beaufort Sea coastal areas become prone to storm surges (a general rising of the sea level) and storm-driven waves. Major storm surges in this region are generated by westerly winds associated with storms transported northward from the Bering Sea. The most severe effects occur near the end of the open-water season, when the fetch between the land and pack ice is greatest. The greatest storm surge on record in this area occurred in September 1970, when a surge of 3 m was measured and waves of an additional 3 m were estimated by local observers. This same storm caused significant beach erosion and stranded ice floes of up to 3 m in thickness upon barrier islands along the Alaskan Beaufort Coast (Reimnitz *et al.* 1972).

Because much of the nearshore land surface is low-lying, particularly river deltas, extensive coastal areas are inundated by such surges. They represent, therefore, a significant threat to industrial installations. Bluff retreat of up to 60 m (Weller *et al.* 1978) has been reported to have occurred during a single storm. All but the highest barrier islands are entirely awash and undergo considerable alteration.

The environmental hazard resulting from storms and waves arises from the possibility of destruction of petroleum product storage facilities and petroleum pipelines, leading to introduction of pollutants into the Beaufort Sea and adjoining low-lying ponds and marshes.

To extend the data base into the past is difficult to impossible, although some success was realized through identifying old storm surge debris lines. The existing data are sparse and largely based on visual observations rather than measurements. The only source of new data is from observations of ocean behavior in the future.

12.2 SEA ICE HAZARDS

12.2.1 Ice Islands and Resulting Fragments

Ice islands are actually tabular icebergs. They calve from Canadian ice sheets in the very northernmost portions of the Canadian Archipelago. Systematic observations of these ice features have been limited to the past few decades; therefore, their long-term frequency is not known. The thickness of ice islands can be between 20 and 70 m (Crary 1958); and their extent, as much as 300 km^2 (Koenig *et al.* 1952), although sizes from 0.1 to 1.0 km^2 are much more common. Ice islands have been introduced into the Beaufort Gyre, where they have resided as long as several decades. During summer, the degree of surface melting of these icebergs varies, depending on the latitudinal location of the islands in the gyre. The average annual surface melt appears to be about 0.5 meter.

No observations of ice islands with thicknesses less than 20 m have been reported, which could be due to several factors:

1. Perhaps the ice islands observed are not yet old enough to have ablated beyond 20 m. This could result from:
   a. Lack of calving from the ice shelves for several years prior to those resulting in the oldest ice islands recorded.
   b. The relatively high probability that the islands will exit the gyre into the Greenland Sea and melt. If they remain in the gyre, they can take as few as eight years to reach the exit point again (Hattersley-Smith 1957).
   c. Thicker ice islands are prone to grounding. Once grounded, they are susceptible to breaking up.
2. The thinner the ice islands, the more likely that their drift will be determined by winds rather than the gyre currents. This might increase the probability for grounding or traveling to warmer waters that accelerate the melting process, or wind-drift might place the islands in areas that are less frequently observed.
3. Perhaps as they become thin, the ice islands break up as a result of internal stresses from uneven melting.
4. Perhaps it is no longer feasible to easily discern an ice island from sea ice once the ice island is less than 20 m in thickness.

Additional descriptions of ice islands can be found in Kovacs and Mellor (1974).

Ice islands represent a potential hazard to structures located in waters with a depth greater than 20 m. The mass of these features is such that, even moving at a few cm sec^{-1}, they can possess a momentum great enough to constitute a hazard not only to free-standing structures but, possibly, to manmade islands as well.

Although little direct data exist at present, it appears that ice islands may be responsible for sea-floor gouges observed in 20-m waters. This would indicate a hazard to buried pipelines, either through gouging or by enhanced pressure travelling through the sea bed and impacting pipelines.

Not all ice islands would constitute a hazard to a particular structure. Hence, for each structure design, it would be necessary to define a "minimum hazardous size."

Ice island encounters can be anticipated. They can easily be detected at several weeks' distance from a structure, thereby allowing defensive measures (blasting, for instance) and petroleum spill precautions to be made.

The probability of impact for structures in the United States Beaufort is not known, but it is considered to be "relatively low" by industry engineers. However, even if this is true, based on the present density of ice islands, there is no guarantee that a large calving event will not take place within the next two decades, dramatically changing these probabilities.

If accurate knowledge of ice island origin, size distribution, and frequency is desired for the public domain, a considerable research effort is required. An evaluation of size distribution and frequency of occurrence would require extensive sampling by means of aircraft. However, in 1986 a satellite with an imaging synthetic aperture radar is slated to become operational. This data should be of immense value to an ice-island census.

As mentioned above, there is little direct evidence linking ice islands with deep sea-floor gouging. This is another area where data might be sought.

Data are needed concerning the rate and magnitude of calving events. The design of this analysis would depend upon historical data: calving of ice sheets seems to be highly erratic. The Ward Hunt ice shelf experienced major calving events in 1962, 1946, and probably late in the nineteenth century, but otherwise remained mostly intact. Therefore, a short-term census may have little meaning regarding major calving events.

One of the current objectives of RU 267 (presently 663) is to use both the existing satellite imag-

ery gathered over the past decade and the existing literature in order to conduct an analysis of ice island occurrences along the Alaskan Beaufort coast.

Other analyses exist but are proprietary. In particular, Exxon has performed an estimate of the frequency of ice island encounters and reports that the value is "low."

12.2.2 Multiyear Ice

As this term has been used by OCSEAP investigators, it means ice older than one melt season. There can be a wide range of ice features fitting this general description. However, it is the largest multiyear ice features that are regarded as enough of a potential hazard to offshore oil field operations to possibly lead to adverse environmental impact. These features are multiyear ridges and hummock fields. Kovacs and Mellor (1974) have described multiyear ice features in detail. As their names imply, these two features are simply ridges and hummock fields which have survived one or more melt seasons. During the melt season, brine flushing takes place within the piled or hummocked ice. Along with this, the upper, exposed portions of the ice melt, and the water, thus liberated, tends to freeze in the voids between the ice blocks. As a result of this process, the ice composing the feature becomes "fresh" (and therefore possesses a greater unit strength), and the entire feature becomes stronger as a consequence of increased structural integrity. Multiyear ridges with thicknesses of about 20 m have been commonly observed; extreme thicknesses of 50 m have been reported with widths of 100-150 m and lengths of about 1 km (Wright and McGonigal 1982). Multiyear hummock fields have been described as a collection of multiyear ridges having the spatial dimensions of an ice island; thicknesses as great as 35 m have been measured (Metge *et al.* 1982).

Because of the melting of exposed surfaces during the summer season, multiyear features have a rounded or undulating appearance that certainly aids in their detection; but they are not nearly as detectable as ice islands, which are very clearly identifiable due to their abrupt edges.

These large, fresh-ice features are of sufficient size to present a hazard to offshore structures from two aspects. First, they can possess a large momentum by virtue of their great mass. Second, their strength and size are so sufficiently great that they can act as stress concentrators, bringing pack ice forces summed over their large cross section to bear on their point of contact with a structure.

Furthermore, it is suspected that the frequency of occurrence of large multiyear features is significantly greater than that of ice islands. Therefore, even if ice island collisions can be ignored, the chance of a collision with a multiyear ridge or hummock field must be considered. In addition to their hazard structures, multiyear features can, like ice islands, plow the ocean floor or create overpressures on buried pipelines.

As with ice islands, the probability of a collision between a structure and a multiyear floe can be forecast. However, because multiyear features are harder to identify than ice islands, such forecasting might be somewhat more difficult. For each structure design, there would be a minimum hazardous size of multiyear feature to be monitored.

Because of the predictability of multiyear features, it is possible to design defensive measures into an offshore oil field structure. Such defensive measures would allow a minimization of oil spill hazards following an interaction between multiyear ice and the structure.

Should it be felt that additional data is needed in the public sector to determine the potential risk resulting from these multiyear features, the following data should be collected: frequency vs. size distribution, absolute frequency of occurrence, and accurate measurement of strength.

Some data along these lines have been collected on a proprietary basis by various petroleum concerns; this information could possibly be made public. Otherwise, the data could be obtained by means of a series of aerial photographic sampling flights and surface measurements performed over a span of a few years. At present, two OCSEAP research units are studying multiyear ice *per se*: RU 88 (Weeks/Kovacs) has correlated frequency vs. size (including thickness) distribution, and RU 663 (Belong/Stringer) is in the process of estimating the *absolute amount* of multiyear ice in the Beaufort Sea coastal region, based on old annual ice present at freeze-up. This process could be extended to a determination of areal floe size distribution (but not floe thickness).

12.2.3 Massive Ridging and Piling of First-Year Ice

Large piles and ridges of first-year ice occur in the proposed lease areas. These ice features result largely from interaction between the dynamic pack ice and fast ice. In late fall, these interactions take place in waters around 10 m deep; and as winter progresses, the region of interaction moves out to waters of 20 to 25 m in depth. These ridges have

been studied extensively by Kovacs and Mellor (1974) and Kovacs (1978), who described their geometry; by Weeks (1976), who studied their spatial frequency; and by Stringer *et al.* (1980), who mapped the location of their occurrence. Many other studies have been performed as well.

These features can be either free-floating or grounded. In the latter case, the sail height can be considerably higher than that given by hydrostatic equilibrium. Kovacs and Mellor (1974) reported a 17-m-high sail on a ridge grounded in 15 m of water.

This phenomenon presents two basic hazards. First, if gravity structures are used for petroleum-related operations, it is likely that they would be steep sided. Such structures would require a sufficient freeboard to avoid ice spilling over onto work areas during these occurrences. Second, the keels of these ice features appear to be a major source of sea-floor gouging.

These events cannot be predicted dependably. Thus, very little time would be available to cease operations and initiate environmental risk-reducing actions. Some active defensive measures are possible and have been successfully applied in the Canadian Beaufort in the case of ice piling in the vicinity of grounded drillships. Such defensive measures include ice strengthening or the cutting of slots to cause piling away from the facility. The strength of offshore structures required to withstand forces imposed by these ice features would be superseded by the strength requirement needed to withstand multiyear ice.

There are probably sufficient data in the private sector regarding the nature of ridges and piles in terms of freeboard requirements. The sea-floor gouging data requirement is discussed in another section of this report.

12.2.4 Shoreline Pileup and Override

Although their appearances are quite different, shoreline override and pileup are actually two aspects of the same phenomenon. Both occur as a result of a shoreward motion of the ice adjacent to the shore. In the case of override, the ice, as a single sheet, is pushed up the beach and even as far as 100 m across the adjacent tundra. Shoreline pileup is initiated in the same manner. However, at some point the ice buckles and begins a self-perpetuating pile of ice blocks near or upon the beach. These pileups can accumulate to heights greater than 12 m and widths as great as 35 m. Shoreline lengths of 1,800 m (Kovacs and Sodhi 1979) have been observed for overrides and pileups.

Since override and pileup occur as a result of shoreward ice push, they might be expected to occur at any exposed beach location. Observations over the past several year (Kovacs and Sodhi 1979) and historical accounts (Shapiro and Metzner 1978) support this hypothesis. In general, shoreward ice push occurs most often when the ice is mobile. This condition is usually met in the fall and early winter, before the nearshore ice is firmly grounded, and in early summer, when the ice detaches from shore.

Clearly, shoreline pileup and override can present hazards to structures placed on or near the beach. In addition, these processes can present hazards to facilities placed on manmade islands. The hazards to the environment in these cases would result from the introduction of pollutants into the ocean following damage to facilities.

Although it has not been well defined, shoreline pileup and override are generally considered to be the majority of phenomena described by the Inupiat Eskimo term "Ivu." Historical accounts (Brower 1942) describe deaths in a semi-subterranean house at Barrow early in this century as a result of a shoreline pileup. In this case, the ice had surmounted a reasonably high bluff before piling upon the residence. In addition, recent archaeological excavations at Barrow show strong evidence of this same disaster occurring in prehistoric times, again at the top of the bluff at Barrow (Daily News-Miner 1982).

Override and pileup events are not really predictable, and precautions against their occurrence should be taken at all times. Active and passive defensive techniques have been considered in detail by some members of the petroleum industry (Exxon 1979) and have been used successfully in the Canadian portion of the Beaufort Sea (Dome Petroleum 1983). Although rideup and pileup are initiated under similar circumstances, the factors responsible for determining which process actually takes place are not well known. However, research towards solving this problem is currently underway by the Corps of Engineers, and some success has been informally reported.

It does not appear necessary for the public sector to accumulate further data on these sources of hazard; considerable privately sponsored research is currently underway.

12.2.5 Unusual Shoreward Flaw Formation

The flaw is defined as the boundary between the fast ice and pack ice. This boundary can take many

forms, ranging from a lead or polynya to a line along which the pack ice grinds against the fast ice (often creating a shear ridge). The location of the flaw can be relatively constant in some locations (usually when it occurs quite close to shore adjacent to headlands) and can vary considerably in other locations (such as the region of the Beaufort Sea off Harrison and Prudhoe bays). The location of the fast ice edge has been mapped by several authors at various times. Stringer *et al.* (1980) have compiled statistics on the location of the flaw in late winter, early spring, and late spring in the coastal regions of Alaska.

The location of the flaw represents the boundary between relatively stable and safe fast ice and the unstable and risky pack ice. The pack ice is unsafe for both personnel and equipment. Because the location of the flaw can change rapidly, it is quite possible that operations being conducted upon the fast ice will suddenly be located within the pack ice. In order to prevent this, it is anticipated that surface operations requiring overnight lodging will be confined to statistically safe areas. However, there would yet remain a small chance of flaw formation shoreward of almost any location. Setting aside the risk to personnel, such occurrences would have a high likelihood of introducing petroleum products into the water column as equipment and stored fuels are lost through cracks and leads. These occurrences would then constitute a risk to the environment.

The draft of this report was written in February 1983. At that time, the intention was to state here that the probability of flaw formation can be assigned with a reasonable degree of confidence and that additional data were probably not required. Since that time, an extremely shoreward series of cracks was observed in Harrison Bay, bisecting at least one ice trail (Daily News-Miner 1983). Furthermore, Shapiro and Metzner (1979) reported an interview with Mr. Harold Itta, who stated that in 1928 similar cracks formed within Harrison Bay. Stringer *et al.* (1980), on the other hand, had shown the region within Harrison Bay to be well inshore of the flaw zone for the years 1973 through 1978.

Clearly, the 5-year record compiled to date is insufficient to determine with a high degree of confidence the relative probability of flaw formation. If these statistics are to be improved, the location of the flaw should continue to be monitored.

12.2.6 Summertime Pack Ice Invasions

This hazard source is closely related to storm and wave hazards. It has long been considered possible that at any time during the summer the pack ice could be transported to the Beaufort shore. The most catastrophic event of this sort would accompany a major storm. During the storm of September 1979, the pack ice in the Canadian portion of the Beaufort Sea was transported 160 km southward to the shore. At Babbage Bight, the storm drove a large quantity of sea ice, including extensive remnants of old, multiyear floes and several ice island fragments, into the nearshore areas (Public Works of Canada 1970).

Hazards to the environment can arise from such events because a number of summertime offshore activities are predicated on the concept of ice-free conditions. The most likely source of environmental damage would arise from spilled petroleum products as oil drilling operations are overtaken by advancing ice and equipment and storage facilities are destroyed. Such pack ice invasions can be anticipated to some extent (1-2 days).

Data regarding the frequency and rate of pack ice advances are needed. In addition, analysis relating meteorological conditions to these events should be performed if a predictive capability is desired. (This is a current objective of RU 663.)

12.3 HAZARDS RELATED TO EROSIONAL AND DEPOSITIONAL PROCESSES

12.3.1 Excessive Erosion and Sediment Transport (Littoral Zone)

During ice-free, open-water periods, natural features such as bars, islands, shoals, and coastal beaches can be rapidly modified. Erosion can be even more dramatic on manmade structures, particularly during storms (Barnes and Reiss 1982). High erosion rates observed on manmade structures such as gravel islands and causeways can in some cases be related to the lack of a gradual beach profile, which permits a more direct wave attack.

The common use of manmade islands and causeways and associated erosion problems has focused investigations on various methods for reducing erosion rates, such as slope protection.

Deposition of sediment along the coast and around structures (Barnes and Minkler 1982) can

also create problems associated with reduced water depth, adverse changes in circulation patterns, and modification of the sea-floor temperature regime.

Excessive erosion can be a problem at any location in this lease area. Improved quantitative models are needed in order to predict rates of sediment migration in the nearshore zone and around causeways.

12.3.2 Seabed Sediment Migration (Erosion and Transport)

Problems associated with seabed sediment migration may be greatest in the Chukchi Sea. Currents can be strong enough locally to cause significant movement of bottom sediments, particularly during intense storms in periods of open water. These storms can destroy ice-gouge features and can construct sand waves 1 m or more in height (Barnes and Reimnitz 1979; Reimnitz *et al.* 1980; Barnes and Reiss 1982).

Natural currents also scour around natural features and manmade structures on the seabed. Intermittent depressions 1 to 2 m deep have been observed during detailed surveys of the Beaufort Sea inner shelf. These holes are believed to have formed by current scouring and sediment erosion around grounded ice features. These holes may persist for several years after the ice feature melts (Marine Board Report 1982).

Protection for equipment or facilities that depend on burial could be reduced if currents are great enough to remove some or all of the overlying sediments.

12.3.3 Coastal Thermal Erosion

Ice-rich, fine-grained sediments exposed in bluffs along major segments of the coast are often subject to dramatic erosion rates. These rates often approach 10 m per year, and rates as high as 30 m per year have been observed (Lewellen 1977; Hartz 1978). Greatest erosion is usually associated with periods during which wave and current action directly impact the base of the bluff. This process is characterized by excessive undercutting of the bluffs and failure of large overhanging blocks. In these areas of rapid coastal retreat, ice-bonded permafrost will be near the seabed. The new, warmer marine environment will cause additional thaw of these sediments, including possible thaw settlement. The magnitude of this natural process will depend on the ice volume of the sediments, including distribution of any massive ice bodies.

Rapid coastal retreat and opportunity for thaw settlement will affect development of landfalls for pipelines and any other coastal projects requiring a sea-land transition or a site near the coastline. Thaw settlement can have a great deal of local variability, depending on ground ice distribution. Detailed subsurface data and knowledge regarding a project's influence on sea-floor temperatures will be important in these areas. Coastal thermal erosion will be a common problem along the Beaufort Sea coast, particularly west of Harrison Bay.

12.3.4 Strudel Scour

This Arctic seabed erosion process occurs near river deltas where sea ice is flooded by discharge from a stream during the spring. Seabed erosion is caused by drainage of this surface water through holes or cracks in the ice cover. The resulting jet or stream then scours a pit in the seabed. Pits of this type have been observed to be as much as 4 m deep and 10 m wide. These pits develop annually while the sea ice is intact and stream discharge is high. There is no way to predict their distribution, only the general region in which they will occur (Reimnitz *et al.* 1974). Strudel scour will be most common along the coast from the Canadian border to inner Harrison Bay, and will likely have the greatest influence on the design and location of pipelines.

12.3.5 Ice Gouging

Seabed gouges produced by floating ice masses can vary greatly in depth and frequency of occurrence and are a common phenomenon on the northern Alaskan shelf. Their depth and frequency depend on differences in shelf slope, currents, sediment type and thickness, and, also, on the ice regime. A gouge 5.5 m deep was observed in 38 m of water in the Alaskan Beaufort Sea (Reimnitz *et al.* 1977). Surveys reveal ice gouge furrows at depths of more than 100 m in the Alaskan Beaufort Sea and in up to 58 m of water in the Chukchi Sea (Reimnitz *et al.* 1977). In the Beaufort Sea, gouge frequency peaks in 20 to 30 m of water beneath the ice shear zone. The frequency can be exceedingly high, with total annual reworking of the seabed in some locations and water depths. Knowledge of incision depth and frequency of occurrence are essential factors that will control burial depth, routing, and placement of pipelines and other facilities.

Information on frequency of gouge recurrence is sparse. No quantitative data are available for this process in the Chukchi Sea. Information on distribution and frequency in the Alaskan Beaufort

Sea is restricted to small areas on the middle and inner shelf. Therefore, there are considerable data requirements. The greatest requirements in the Beaufort Sea are for the region with a depth between 20 and 50 meters.

Gouge distribution in the U.S. Beaufort Sea and methods for estimating frequency have been discussed by Barnes and Reimnitz (1974), Reimnitz and Barnes (1974), Reimnitz *et al.* (1978), Thor and Nelson (1981), Reimnitz *et al.* (1977), Lewis (1977), Wahlgren (1979), and Weeks *et al.* (1980).

12.4 SUBSEA PERMAFROST AND SEASONALLY FROZEN SEDIMENTS

A number of government and industry programs have now documented the existence of ice-bonded permafrost in the Beaufort Sea. All confirmed observations suggest that depth and distribution vary greatly. In coastal waters ice-bonded material can be found at very shallow depths extending tens of kilometers from shore, while in an adjacent region it may be significantly deeper or possibly absent. Most of the information on permafrost distribution resulted from analyzing seismic records of the distribution of high-velocity material. Drilling data for control purposes is only available from a very small number of drill holes in the nearshore coastal setting (less than 20 m of water). Therefore, most of our information is of a speculative nature. The information we do have confirms that subsea permafrost is far more complex than permafrost on the adjacent land area.

Variability in distribution, material type, and properties will require careful, site-specific studies prior to any offshore development activities. Hazards that can be anticipated are grouped into three categories and are described below.

12.4.1 Thaw Settlement

Most frozen sediments and some rock will undergo a reduction in volume upon thaw. The magnitude of this change will be related to the volume of ice incorporated in the soil and the freedom for meltwater to drain from the thaw zone. Ice volumes are often greatest in fine-grained material, where ice occurs not only in intergranular voids but also in the form of lenses and masses.

Thaw settlement can be a natural process in the marine environment. Natural thaw settlement should occur along a coast where rapid coastal erosion and inundation are taking place. In these locations, cold terrestrial permafrost will be near the seabed and subject to thaw. Differential thaw settlement is likely to occur in the upper part of the permafrost section, due to variations in material type and the large variations in ground ice volumes that can occur in this zone. Thaw rates can be greater in the marine environment than on land, due to much higher permafrost temperatures and salt contents.

Thaw settlement will also occur offshore due to development activities that cause warming of the ice-bonded permafrost. Settlement could be expected, associated with some seabed structures, pipelines, and casing strings (Marine Board Report 1982).

12.4.2 Thaw Weakening

Frozen materials are noticeably stronger than thawed materials. Marked reduction in strength as frozen soils warm usually begins several degrees below the freezing point and depends on the grain size of the material, which influences the amount of unfrozen water contained in it. Salts also lower the strength of frozen materials at the temperatures usually expected in subsea permafrost. Therefore, because of the salt and warm seabed temperatures, subsea permafrost will consist of materials substantially weaker than similar materials found on land.

For a period of time after thaw, materials can have exceptionally low strength if pore water is not free to drain. Once the pore water has drained and soil particles carry the majority of the overburden pressure, the thawed strength will increase. Thaw weakening is of concern when bottom-founded structures cause melting of ice-bonded permafrost and the thawed strengths are not sufficiently large to resist shear or compressive failure.

12.4.3 Seasonal Freezing, Frost Heave, and Freeze-Back of Thaw Zones

Seasonal freezing is common in the marine environment (Osterkamp and Harrison 1976). It occurs on bars, islands, shoals, beaches, and in shallow water areas when sea ice freezes to the seabed. In Harrison Bay, Osterkamp (unpublished data) found the seabed frozen in a number of holes where it was not in contact with the sea ice. Blouin *et al.* (1979) observed it in Prudhoe Bay, where sea ice formed to or near the bed. Chemical and thermal data from deeper water showed that seabed sediments were partially frozen but ice-bonding was not great enough to increase the strength properties of these materials (Sellmann and Chamberlain 1979). Artificial structures such as islands, causeways, and other earth-filled, bottom-founded

structures are also subject to seasonal freezing. Perenially frozen materials can also form under certain situations, not only in the natural and artificial structures, but also in the seabed materials. The most significant problems related to freezing are frost heave, increased variability in material properties, and high pressures developed when confined thaw zones freeze.

Differential movement associated with frost heave can influence both surface and subsurface facilities and structures. In situations where freezing of the zones around well casings is permitted, the high, non-uniform freezebank stresses developed by ice formation can cause casing failures. In situations where increased performance of a structure depends on the freezing of the earth materials from which it is constructed or founded, the varying material properties caused by freezing will need to be evaluated. This may be of concern on manmade islands or causeways exposed to ice forces.

12.5 OTHER HAZARDS

12.5.1 Shallow Gas

Geotechnical exploration activities have found gas at shallow depths in the Beaufort Sea (Harding-Lawson Associates 1979). Studies based on analysis of shallow high-resolution seismic data (Boucher *et al.* 1981) and information from the upper ends of industry seismic records also suggest that shallow gas can occur locally (Neave and Sellmann 1982).

Problems from unexpected encounters with gas would likely be greatest for shallow drilling projects, since they normally do not have provisions for gas control. The greatest problems might be expected in the Beaufort Sea because of its great sediment thickness.

12.5.2 Deep Gas (Hydrates)

Gas in hydrate form has been found at depths that range from 200 m to over 1,800 m below the sea floor (Marine Board Report 1982). This means that in very deep water beyond the shelf break, hydrates can occur at or near the seabed and have been inferred from seismic profiles in the Alaskan Beaufort Sea (Grantz and Dinter 1980). Any development that upsets their equilibrium will cause the hydrates to decompose, liberating large volumes of gas that will greatly exceed the original hydrate volume and cause problems during exploration drilling and during production (Goodman and Franklin 1982).

Problems that have been recognized as associated with hydrates include: (1) Gas produced by warming of the hydrate zone during exploration drilling can reduce drilling mud density, possibly causing gas release and well-control problems. (2) Hydrate decomposition can occur during production, due to warming of the hydrate zone. If this gas cannot migrate from the thaw zone surrounding the casing, it can cause external pressure buildup on the casing string. (3) In deep water areas where hydrates can occur near the seabed, development that can cause their decomposition could have a significant effect on sea floor stability.

There are requirements for improved means of detecting and characterizing hydrates during routine geophysical observation and test drilling so that proper development and production techniques are used.

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Chapter 13
Ecological Characterization and Processes

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As is true throughout the Arctic, biological events in the Beaufort Sea are characterized by marked seasonality. Annual cycles in meteorological conditions, particularly temperature and day length, induce changes in physical factors such as river flow and sea-ice conditions and biological processes such as primary production. Each species is biologically attuned to an anticipated seasonal cycle, the relationship with which is poorly understood even for well-studied species. Deviations from "normal" seasonal conditions have important consequences for some populations.

During summer and early autumn, lagoons and nearshore areas are usually free of ice, and broken pack ice occurs at variable distances offshore. Most of the annual primary production occurs during this period, since light penetration is no longer limited by ice and nutrient levels are high. Zooplankton and the larvae of many invertebrate species and Arctic cod graze on the primary producers and on each other. For most species, including both benthic and planktonic forms, this is the period of greatest growth. Fishes that have overwintered in rivers move seaward to feed on marine crustaceans, which they share with Arctic cod. Seabirds, shorebirds, and waterfowl arrive after breakup begins; each species feeds, breeds, and rears young in characteristic habitats. Some bird species rely on the region for more subtle, but no less important, life history events or annual events such as premigratory fat deposition and molting of flight feathers. Ringed and bearded seals are found primarily near pack ice; ringed seals feed on crustaceans and Arctic cod, whereas bearded seals eat primarily benthic organisms. Spotted seals move into the coastal zone from the west. Polar bears hunt seals on the pack ice.

Autumn marks a striking transition from the comparatively warm, bright summer to dark, freezing winter. Depleted nutrients, reduced daylight, and the formation of sea ice reduce primary production in the water. In some areas, a bloom of algae may occur in the forming ice. Anadromous fishes move into the river systems, where they will spawn and overwinter (Griffiths and Buchanan 1981). Marine fishes and invertebrates continue to feed in the area as long as adequate food is available; fish and crustaceans such as Arctic cod and mysids begin development of eggs and larvae that will be released during winter or early spring. Spotted seals and virtually all species of birds leave the area. Bowhead and belukha whales and birds which have summered to the east migrate westward through the area.

The ice-covered period includes both the cold, dark months of winter when the sea-ice cover forms and thickens, and the bright, gradually warming spring. Most primary production ceases during winter, and nutrients are regenerated by microbial processes. With lengthening days in spring, primary production of ice-associated algae increases where clear ice is present. Little is known about the zooplankton and benthic organisms during this period. Arctic cod occur in the area and presumably feed and spawn under the ice during winter. Ringed seals bear and nurse their young in snow-covered lairs on the ice during spring. Most of their diet at that time consists of Arctic cod and benthic crustaceans. Pregnant female polar bears construct dens in which they spend November-March while giving birth and nursing their cubs. Other polar bears roam the ice, where they kill and eat ringed seals. Arctic foxes also range far to sea on the ice, feeding on the remains of ringed seals left by polar bears and preying on seal pups.

From late May to early July, river runoff combines with melting and degradation of the ice, causing

the ice to break up. Ringed seals haul out to molt during the last days of stable fast ice. Primary productivity begins in the water column. Epibenthic and perhaps also zooplanktonic species release eggs, larvae, and juveniles. Motile species move into areas from which they had been excluded by bottomfast ice. Many anadromous fishes move seaward to feed, whereas boreal smelt move upriver to spawn. Birds migrate to and through the area, stopping in tundra ponds and nearshore open-water areas to rest and feed. Bowhead and belukha whales pass through the western and northern portions of the Diapir Field during their eastward migration. Polar bears move offshore with the ice, while arctic foxes move ashore to den, feed, and raise their young.

At the synthesis meeting, several major habitats or ecological zones were discussed with respect to their biological characteristics and possible discreteness. It was concluded that although some major differences between zones are evident, boundaries are not sharp and may not exist at all for some species. Furthermore, discussions and conclusions were sometimes based on limited observations and samples, the numbers of which were considered inadequate by many investigators.

The Diapir Field planning area may be classified into four major ecological zones: (1) terrestrial, (2) nearshore and lagoon, extending to about 3 m of water depth, (3) neritic, extending from about 3- to 20-m of water depth, and (4) oceanic, seaward of the 20-m depth contour. Descriptions of each of these zones follow.

13.1 TERRESTRIAL ZONE

The terrestrial zone of the Beaufort and Chukchi coasts includes a variety of distinct habitats which can be broadly classified as mainland tundra, mainland littoral zone, and barrier islands. Coastal tundra varies from low wetlands to well-drained uplands and includes streams, ponds, and lakes. The littoral zone consists of all coastal areas which are periodically or occasionally inundated by salt water. Major habitat types include ocean and lagoon beaches, closed brackish lagoons and sloughs, salt marshes and mud flats, and river delta islands. Barrier islands—and other coastal islands—consist mainly of littoral habitats similar to those of mainland spits and gravel beaches but may include areas of tundra vegetation.

Seasonal patterns of snow and ice cover determine the seasonality of habitat use by most species within the terrestrial zone. On the tundra, for example, almost all bird species return in late May or early June, and plant growth and insect reproduction begin soon after. Aspects of local topography (polygonization, drainage, pond size, and stream type) strongly influence the species of plants, invertebrates, and vertebrates most common at each site.

In the littoral zone, although activities are strongly influenced by the seasonality of ice cover, the nature and extent of the zone are determined primarily by patterns of storm-induced saltwater flooding. Barrier island activities are similarly influenced by the seasonality of ice cover and open-water conditions, and the topography and location of islands are determined by currents and storm surges.

13.1.1 Energy Inputs

Energy sources within the terrestrial zone include primary productivity by tundra plants, freshwater algae, and marine phytoplankton, as well as decomposition of tundra peat. Important invertebrates include insects of many species on tundra and in some littoral habitats, and a variety of freshwater and marine zooplankton. These invertebrates provide the major food sources for many species of birds and fishes feeding on tundra, in lakes and rivers, and in the littoral zone. Other vertebrates are grazers (some ducks and geese, lemmings, and caribou) or higher-level predators preying on small fishes, birds, and mammals (Arctic char, loons, gulls, jaegers, and foxes).

13.1.2 Major Faunal Groups

The most prominent groups of vertebrates in the terrestrial zone vary widely in habitat use, distribution, and seasonality.

Fishes

Freshwater habitats along the Arctic coast support both freshwater and anadromous fishes. East of Simpson Lagoon, the prominence of mountain streams makes this an important region for Arctic char and grayling. From Simpson Lagoon west to Barrow, coastal plain streams support whitefishes, ciscoes, grayling, and salmon. West of Barrow, coastal plain waters are less productive but include some salmon and whitefishes. Overwintering occurs in deep lakes and river pools.

Birds

Shorebirds and passerines compose the largest numbers of nesting birds on coastal tundra. They

are supported by dense insect populations, primarily tipulid and chironomid flies. Other common bird groups include waterfowl (ducks, geese, and loons) and predators (jaegers and owls). Gulls and terns nest along some rivers. Activity is centered in these habitats during the nesting season (June and July), and shifts to littoral and nearshore areas in August. The highest densities of many species in the Arctic occur along beaches near barrier islands, on lagoons, and in salt marshes and mud flats in late summer. These include shorebirds of many species, gulls, terns, and waterfowl, especially Oldsquaws, eiders, and geese. Geese also occur in large numbers in some coastal tundra areas, most notably around Teshekpuk Lake and on river delta islands, as well as in salt marshes.

Barrier island nesting sites vary in their importance to nesting birds. Some islands, such as Thetis Island, support a fair number of nesting eiders, while other islands, such as Cross and Egg islands, support small groups of several species. The Plover Islands, east of Point Barrow, support large numbers of guillemots and gulls. Although the number of nests on these islands is low compared to the overall bird resources of the arctic slope, these nesting sites may be considered unique in comparison to the other barrier islands.

Mammals

Lemmings, weasels, ground squirrels, and arctic foxes occur widely on coastal tundra. Foxes are sometimes stranded on barrier islands during spring breakup. Spotted seals haul out on some islands and sandbars along the coast. Polar bears seldom use the terrestrial zone except in winter when females den in tundra areas with deep snowdrifts, as along riverbanks. Caribou move to the coast in summer in three main herds (Central Arctic herd, Porcupine herd, and Teshekpuk Lake herd) to calve and avoid insects.

As the preceding discussion indicates, seasonality of vertebrate use of terrestrial areas varies depending on species or groups of species. Winter use is mostly limited to polar bear denning and wintering of small mammals and freshwater and anadromous fishes. Early summer is the period of highest activity on the tundra, primarily of birds, whereas late summer is the period of peak shoreline activity for many species of birds.

13.1.3 Interactions with Neighboring Zones

Many biotic relationships connect the terrestrial zone with the more marine zones. Peat from tundra washes into the nearshore zone, providing a carbon and nutrient source as well as the mud substrate of some lagoons and bays. Anadromous fishes, for which most feeding and growth occurs in marine waters, reproduce in freshwater streams. Some tundra-nesting birds (loons and terns) feed during the nesting season on fishes and invertebrates taken from coastal waters. Similarly, barrier island nesters (eiders, gulls, terns, and guillemots) take similar prey from lagoons and ocean waters. Shorebirds feeding along beaches take large numbers of zooplankton, a marine food source. In fact, all the birds which feed in the nearshore, neritic, and offshore zones spend at least the breeding season in some portion of the terrestrial zone, where they all nest. Across seasons they move from one zone to another and also from the Arctic to areas as far away as the Antarctic, thus introducing energy exchange with distant regions. Some marine mammals (arctic foxes, polar bears, and spotted seals) also cross zonal boundaries, denning and/or hauling out on land and feeding in the marine environment.

13.1.4 Research Needs

Principal research needs concerning the terrestrial zone include studies of bird distribution and habitat use around Dease Inlet, Admiralty Bay, and Smith Bay; recovery rates and processes of coastal habitats, especially salt marshes, after oil spills; recovery of waterfowl nesting colonies on barrier islands after disturbance or initiation of colonies on new islands; and responses of birds and mammals to oil spills.

13.2 NEARSHORE AND LAGOON ZONE

The nearshore and lagoon zone has been defined as extending from the shoreline seaward to about 3 m of water depth and includes lagoons and shallow waters along simple coastline and outside the barrier islands. The superficial sediments are sand, silt, and gravel and may contain large amounts of peat. Salinities are low, and the water is usually warmer than the bottom water farther offshore. The ice-free period in the nearshore and lagoon zone is short, lasting approximately 3 months (July-September). Breakup is initiated by floodwaters from coastal rivers and streams in early June. This nutrient-rich runoff initially flows out over the ice in the nearshore area but subsequently drains through strudel holes formed in the ice cover. The formation of open-water leads along the mainland and barrier island shorelines occurs by mid-June. By late June

and early July these leads have widened to about 100 m in width and contain cold (0-4.5°C), clear, and almost fresh waters (2.1-6.0 ‰). Most nearshore ice soon melts or is moved away by winds and currents, and lagoons are 90% free from ice by mid-July.

On the outside of barrier islands and along the exposed mainland shore, ocean ice may hold fast against the shore until mid- or late July, when it is moved offshore by winds. Periodically throughout the open-water season ice floes are blown back to the barrier islands or against the mainland; however, lagoons generally stay ice free for the remainder of the summer.

Freeze-up in the nearshore and lagoon zone typically begins in late September or early October when ice forms in calm, shallow waters. During the winter months, the ice steadily grows and reaches a thickness of about 2 m by late winter (April). Thus, most of the nearshore and lagoon zone that is less than 2 m in depth freezes to the bottom by late winter.

Throughout the short open-water period the waters in the nearshore and lagoon zone are generally warmer (2-4°C) and less saline (4-5 ‰) than the deeper marine waters. For a detailed description of nearshore temperature and salinity patterns during the open-water season, see chapter 9. (This discussion is taken largely from Craig and Haldorson [1981].)

13.2.1 Energy Inputs

A detailed description of nutrient dynamics and carbon sources in the nearshore and lagoon environment is provided in chapter 7.

Schell (1979) reports the depressions in C-14 activity in most organisms from Simpson Lagoon indicate that peat (*i.e.*, old) carbon appears to account for approximately 10% of the carbon in the organisms. Total terrestrial carbon (*i.e.*, peat carbon plus river-transported modern carbon) may account for as much as 30-40% of the carbon composing the organisms in the nearshore and lagoon environment (Schell 1979). If this is the case, then the largest (60-70%) portion of the carbon utilized by nearshore and lagoon organisms comes from marine primary production.

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.

13.2.2 Major Faunal Groups

Invertebrates

In nearshore and lagoon environments, the key groups of epibenthic invertebrates and zooplankton include amphipods, mysids, isopods, and copepods (Griffiths and Dillinger 1981). Collectively, these taxonomic groups dominate the invertebrate fauna 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 recolonize nearshore areas which freeze solid each winter. A list of the most common epibenthic species that occur in these shallow waters between Point Barrow and Demarcation Bay is shown in Table 13.1. Although infaunal invertebrates are present in shallow nearshore waters, they are

Table 13.1—Key species of epibenthic invertebrates occurring in the nearshore/lagoon habitats between Point Barrow and Demarcation Bay.

Mysids	Amphipods	Isopods
Mysis relicta	*Apherusa glacialis*	*Saduria entomon*
Mysis litoralis	*Gammaracanthus loricatus*	
Neomysis intermedia (W)	*Gammarus setosus*	
Neomysis rayii (W)	*Pontoporeia affinis*	
	Onisimus glacialis (E)	

(W) occurs mainly in the western portion of the Alaskan Beaufort Sea.
(E) occurs mainly in the eastern portion of the Alaskan Beaufort Sea.

neither diverse nor abundant. The principal infaunal organisms are chironomid (midge) larvae (which may be important in introducing terrestrial carbon into the marine system) and enchytraeid (oligochaete) worms.

Typically, epibenthic invertebrates occupy nearshore and lagoon areas each year during breakup and continuously move into these waters from offshore areas as the summer progresses. This continuous replenishing from offshore stocks serves to maintain the level of prey organisms required by the vertebrate consumers that utilize these waters during the open-water season. During the winter as the ice thickens, most epibenthic invertebrates either move into deeper offshore waters or perish in the hypersaline waters formed due to salt exclusion (Griffiths and Dillinger 1981). A few species such as the amphipod *Onisimus glacialis* and the isopod *Saduria entomon* are able to complete their entire life cycle in lagoons by moving into the deeper (>3 m) water during winter.

Fishes

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. Species occurring in nearshore waters can be classified in three broad categories: (1) freshwater species, which are also occasionally present in low-salinity areas; (2) anadromous species, which are tolerant of saline water and undertake seaward migrations during their life cycle; and (3) marine species, which remain in brackish or marine waters throughout their lives.

Despite the variety of species present, a very few account for the vast majority of fishes 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*	×	
Least cisco *C. sardinella*	×	
Arctic char *Salvelinus alpinus*	×	
Fourhorn sculpin *Myoxocephalus quadricornis*		×
Arctic cod *Boreogadus saida*		×

Although proportions of these five species vary from site to site and according to sampling gear used, they account for 91-98% of all fishes enumerated at Simpson Lagoon (Craig and Haldorson 1981), Prudhoe Bay (Bendock 1979; Griffiths and Gallaway 1982), 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 whitefishes (*Coregonus nasus* and *C. clupeaformis*) are also important species in some localities (Kendel *et al.* 1975; Craig and Haldorson 1981; Griffiths and Gallaway 1982).

During the open-water season, anadromous and marine fishes utilize nearshore habitats extensively as feeding and rearing areas (Table 13.2). Some fishes arrive with the first signs of spring breakup (approximately 5-20 June), and some are still present when surface ice forms on nearshore waters in early winter (approximately 20 September-10 October). As a generalization, most anadromous fishes 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 water: (1) most fish are found nearshore rather than in 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. Reasons for this habitat preference are thought to result from the presence of slightly warmer and less saline water in these habitats (Griffiths and Gallaway 1982; Fechhelm *et al.* 1983).

Studies conducted across the Beaufort Sea coast between Point Barrow, Alaska, and the Mackenzie River, N.W.T., have shown that the abundances of least cisco, broad whitefish, and humpback whitefish typically decline rapidly (*i.e.*, within 100 km) to the east of the Colville River and to the west of the Mackenzie River. The vicinity of the Sagavanirktok and Colville rivers is probably a major center for spawning and overwintering of these species along the Alaskan Beaufort Sea coast. Arctic char and Arctic cisco range all along the Beaufort Sea coast from Alaska to Canada (Roguski and Komarek 1972; Furniss 1975; Griffiths *et al.* 1975; Kendel *et al.* 1975; Craig and McCart 1976; Griffiths *et al.* 1977; Bendock 1979; Craig and Haldorson 1981). Arctic char are the dominant anadromous species associated with the Sagavanirktok River and other rivers to the east which pro-

Table 13.2—Anadromous and marine fish use of the nearshore/lagoon zone (0 to 3-m depth) from Peard Bay to Demarcation Point.

Area	Species	Timing	Food
Chukchi Sea south as far as Peard Bay	Chum and pink salmon, Arctic char, ciscoes, whitefishes, boreal smelt, Arctic cod, saffron cod, sand lance, capelin, Pacific herring	Summer residence	Invertebrates
Point Barrow to Colville River	Least and Arctic cisco, Arctic char, broad and humpback whitefish	Open-water season—late June to late September	Epibenthic invertebrates, primarily mysids and amphipods
	Fourhorn sculpin and other marine species (*e.g.*, Arctic and saffron cod)	Marine species remain until excluded by thickening ice	
Colville River to Flaxman Island	Least and Arctic cisco, Arctic char, broad and humpback whitefish	Open-water season—late June to late September	Epibenthic invertebrates, primarily mysids and amphipods
	Fourhorn sculpin, Arctic and saffron cod, Arctic flounder	Marine species remain until excluded by thickening ice	
Flaxman Island to Demarcation Point	Arctic cisco, Arctic char—very few least cisco	Open-water season—early July to mid-September	Epibenthic invertebrates, primarily mysids and amphipods
	Fourhorn sculpin, Arctic and saffron cod, Arctic flounder	Marine species remain until excluded by thickening ice	

vide overwintering habitat. Like char, Arctic cisco range widely, but, in contrast to char (and most literature accounts), this species probably does not spawn in Alaskan rivers (Gallaway *et al.* 1983). The individuals in Alaskan waters are most likely from a Mackenzie River stock. However, between the time they are recruited and the time they return to the Mackenzie to spawn, many move west to feed and grow in Alaskan waters. The Colville River is an important overwintering area for these fish.

Marine species (fourhorn sculpin, Arctic cod) migrate farther offshore to spawn and/or overwinter during the winter. Arctic cod remain in nearshore and lagoon areas in early winter but as the ice thickens move into deeper waters.

Birds

Bird use of the nearshore and lagoon environments from Peard Bay to Demarcation Point is summarized in Table 13.3. For a detailed description of bird activity in this zone, see chapter 10.

With few exceptions birds are transient phenomena in the northern Chukchi and Beaufort seas and are present only from May through September. Since they come to this area to breed, they are mostly occupied with caring for their eggs and 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 as well as 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 molting Oldsquaws and migrating shorebirds and larids are found in lagoons and near barrier islands. Since birds migrate linearly along the coast, it is possible that environmental 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.

13.2.3 Trophic Interactions

Nearshore and lagoon waters of the Beaufort Sea are used by vertebrate consumers (anadromous

Table 13.3—Bird use of the nearshore/lagoon zone (0 to 3-m depth) from Peard Bay to Demarcation Point.

Area	Species	Timing	Food	Divoky's Zone*
Chukchi Sea as far south as Peard Bay†	Black Guillemot	15 Jun-10 Sep	Euphausiids and hyperiid amphipods	I
	Arctic Tern	25 Jul-15 Aug		
	Ross' Gull†	25 Sep-10 Oct		
	Sabine's Gull	25 Jul-15 Aug		
	Black-legged Kittiwake	25 Jul-10 Sep		
	Red Phalarope	Aug		
	Oldsquaw	20 Jul-10 Aug		
Point Barrow/Plover Islands to Smith Bay	Same as above	Same as above	Same as above	II
Smith Bay to Cape Halkett	Oldsquaw†	20 Jul-10 Aug 15 Sep-1 Oct	Invertebrates	III
	Red Phalarope	Aug		
	Northern Phalarope	Aug		
	Black Brant	Jul	Vegetation	
Harrison Bay	Oldsquaw†	20 Jul-10 Aug 15 Sep-1 Oct	Mysids, amphipods, bivalves, copepods	IV
	Red Phalarope	Aug	Mysids, amphipods	
	Northern Phalarope	Aug		
	Glaucous Gull	late Sep	Isopods, fishes	
Jones Islands to Flaxman Island	Oldsquaw†	20 Jul-10 Aug 15 Sep-1 Oct	Mysids, amphipods bivalves, copepods	V
	Red Phalarope†	Aug	Mysids, amphipods	
Thetis Island†	Northern Phalarope†	Aug		
Howe Island†	Glaucous Gull†	late Sep	Isopods, amphipods	
Simpson Lagoon†	Arctic Tern	Aug	Hyperiid amphipods, fishes, terrestrial vegetation	
Leffingwell Lagoon†	Snow Goose†	1 Jun-10 Jul		
	Black Brant	1 Jun-10 Jul		
Flaxman Island to Demarcation Point	Oldsquaw†	20 Jul-10 Aug 15 Sep-1 Oct	Mysids, amphipods, bivalves	VI
	Red Phalarope†	Aug	Copepods, mysids, amphipods	
	Northern Phalarope†	Aug		
	Glaucous Gull	late Sep	Isopods, fishes	

*These zones correspond to those delineated by G. Divoky; see chapter 10, this volume.
†Key areas or species.

and marine fishes, and birds) during the open-water period primarily for feeding on the abundant supply of epibenthic organisms found there. The food habits of nearshore fishes and birds are surprisingly similar—they feed extensively on epibenthic and pelagic mysids, amphipods, and copepods, which usually account for over 90% of the diets of key fish species (Arctic cisco, least cisco, Arctic char, Arctic cod, and fourhorn sculpin) and bird species (Oldsquaws, phalaropes, and Glaucous Gulls) (Kendel *et al.* 1975; Bendock 1977; Craig and Haldorson 1981; Johnson and Richardson 1981; Craig *et al.* 1984). Large anadromous fishes, particularly Arctic char, may also feed on small Arctic cod or fourhorn sculpin. Nearshore fishes do not commonly eat infaunal organisms, although approximately 10% of the diet of Oldsquaws is composed of infaunal bivalve molluscs.

Major prey species are two mysids (*Mysis litoralis* and *M. relicta*) and several amphipods (*Onisimus glacialis, Pontoporeia affinis, Apherusa glacialis, Gammarus setosus*). The proportions of prey species available and eaten vary by location and by year. Although these invertebrates may be present throughout the water column, they are 25 to 200 times more abundant in the region 0-20 cm above the bottom than in the entire 2 m of water above (Griffiths and Dillinger 1981).

13.2.4 Interactions with Neighboring Zones

The abundance of epibenthic organisms in lagoons is apparently maintained throughout the open-water season by a continual immigration of epibenthos into the lagoons from offshore areas. Studies conducted in Simpson Lagoon in 1977 and 1978 showed the abundance of epibenthic organisms exceeded by about 50 times the total daily food requirements of all vertebrate consumers (fishes and birds) present.

Productivity in the nearshore and lagoon environment is linked to offshore marine areas in even a more fundamental way. Isotopic studies indicate that the fish ultimately obtain 80-90% of the carbon in their tissues from modern marine primary production (Schell *et al.* 1982). Relatively little of the large input of terrestrially derived organic carbon enters trophic pathways leading to fishes (and birds) in the marine ecosystem (but note Schell's discussion about the important role of peat carbon in the freshwater phase of anadromous fishes and Oldsquaws).

13.3 NERITIC ZONE

The neritic zone of the Beaufort Sea has been defined as extending from the 3-m to the 20-m isobath. It includes large protected lagoons and bays such as Stefansson Sound, as well as open coastal regions. The surface sediments of the neritic zone in most of the Sale 87 area are silt and mud, and peat is a minor component of the bottom deposits. In general, the sediments such as gravels, cobbles, or boulders are infrequent but do occur in the following areas: the northeastern Chukchi Sea coast from Peard Bay to Point Barrow; Point Barrow vicinity; the Boulder Patch in Stefansson Sound; south of Belvedere Island in the Stockton Island chain; north of Narwhal and Flaxman islands; western Camden Bay; and along portions of the eastern Beaufort Sea shelf between Barter Island and Demarcation Bay.

Since a major portion of the neritic zone consists of large coastal lagoons and bays formed by the presence of offshore islands and shoals, physical disruption of the benthos by ice is minimal. Most ice gouging occurs in the shear zone, which is broadly defined as that area located between water depths of 10 and 20 m. However, many rivers empty into the neritic zone, and disturbance of the benthos can be accomplished through heavy sedimentation and strudel scour during the late spring and early summer.

The neritic zone is characterized by a slow transition in salinity, in which a gradient of lower to higher salt concentration occurs in a seaward direction. Mixing is sufficient to prevent the formation of high saline waters on the bottom during the long winter period. In winter there appears to be an onshore movement of water under the ice canopy, with an offshore movement of high-density (high salinity, low temperature) bottom water seaward. During the summer, circulation is generally driven by the wind. Bottom salinities range from 24 to 32 ‰, and water temperatures from -2 to 7°C (Barnes *et al.* 1977).

The topography of the ice surface in the neritic zone depends largely on weather conditions during freeze-up and varies from year to year. In general, a large portion of the ice surface will have vertical relief ranging from 30 to 70 cm. Occasional ridging due to overlapping ice pans is common. The frequency of turbid ice, another common occurrence in the neritic zone, also depends on ice formation conditions during autumn.

13.3.1 Energy Inputs

The major inputs of marine carbon to the neritic zone are phytoplankton, ice algae, benthic algae, and macroalgae. Phytoplankton contributes the bulk (over 80%) of the carbon available to consumers. In some areas, however, the carbon input made by macroalgae, mainly kelp, can be greater than or equal to that of phytoplankton. Areas characterized by significant concentrations of macroalgae (Dunton *et al.* 1982) include Peard Bay; offshore of Skull Cliff (between Peard Bay and Point Barrow); the Boulder Patch in Stefansson Sound; south of Belvedere Island; western Camden Bay; Beaufort Lagoon; and Demarcation Bay.

13.3.2 Major Faunal Groups

Benthos

Except in macroalgae beds, the principal organisms of the benthos in the neritic zone are crustaceans (amphipods, mysids, isopods, and euphausiids), polychaete worms, bivalve molluscs, and priapulids. The predominant species are listed in Table 13.4. Macroalgae beds are dominated by several species of either brown or red algae and by cnidarians and sponges. Areas containing the greatest benthic standing stock (>100 g/m^2) are Stefansson Sound and Leffingwell Lagoon. In most cases, the benthic biomass in the neritic zone ranges from 20 to 60 g/m^2 (Broad *et al.* 1983).

Table 13.4—Primary species of the neritic zone benthos.

Polychaeta:	*Scoloplos armiger*
	Scolecolepides arctius
	Nephthys caeca
	Prionospio cirrifera
	Spio filicornis
	Ampharete stroemi
Oligochaeta:	Tubifacidae—species unknown
Bivalvia:	*Boreacola vadosa*
	Cyrtodaria kurriana
	Portlandia arctica
	Portlandia intermedia
	Lyocyma fluctuosa
Priapulids:	*Halicryptus spinulosus*
	Priapulus caudatus
Crustacea:	
Amphipods:	*Onisimus litoralis*
	Onisimus glacialis
	Pontoporeia femorata
	Pontoporeia affinis
Mysids:	*Mysis litoralis*
Euphausiids:	*Thysanoessa raschii*
Isopods:	*Saduria entomon*
	Saduria sabini

The benthos of the neritic zone is strikingly different from that of the nearshore, where there is the effect of shorefast ice impinging on the bottom. Diversity is greater and biomass is approximately 10 times that of the nearshore zone. The neritic zone is inhabited by many infaunal species that are not abundant in the nearshore zone, and the abundant, infaunal oligochaete worms and midge larvae of the nearshore are not found (or are quite rare) in the neritic zone.

The high biomass of the benthos in areas such as Stefansson Sound and Leffingwell Lagoon is undoubtedly an important food resource to many animals. The high benthic standing stock in Stefansson Sound is probably related to the productivity of the Boulder Patch, but it is not known to what extent. There are virtually no data on the composition or biomass of benthic species in Camden Bay or east of Barter Island.

Pelagic Organisms

Few data are available to describe the fish or invertebrate resources of the pelagic system in the neritic zone. Available data suggest that Arctic cod and copepods are the major fish and invertebrate components, respectively. Anadromous fishes are present in this zone only in small numbers, and then usually in the shallowest regions (Bendock *et al.* 1978).

Marine and Coastal Birds

Several million birds belonging to about 150 species (Pitelka, as cited by Schamel 1978), including seabirds, waterfowl, shorebirds, passerines, and raptors, occur on the North Slope adjacent to the Beaufort Sea. Nearly all of these species are found in the Arctic seasonally, from May through September. Most species inhabit the areas adjacent to Harrison Bay, the Colville River, and east to Simpson Lagoon. The species common to the neritic zone are listed in Table 13.5. These species nest on barrier islands and feed in the nearshore and neritic zones. The timing of ice breakup surrounding a barrier island is critical for determining its importance as a nesting site for marine birds (Divoky 1978). For this reason, islands near large river deltas such as Thetis Island receive the heaviest use. Nesting occurs during May and June and is usually complete by mid-July.

Marine Mammals

Marine mammals which are common to the neritic zone in the Sale 87 area include ringed seals, bearded seals, spotted seals, and polar bears. Ringed seals are the most abundant seals in the Beaufort Sea. During winter and spring, they commonly live nearshore and bear their pups on the shorefast ice. During summer they remain associated with the ice, which in some years is very nearshore and in other years well offshore. Bearded seals are less abundant in the Beaufort Sea. They are primarily restricted to the pack ice of the Bering and Chukchi seas during winter. In summer they may be found in nearshore ice remnants. Spotted seals are present in the Beaufort Sea only in late summer and autumn. They feed in the nearshore and neritic zones on marine and anadromous fishes.

There is substantial annual variation in the seasonal distribution and local abundance of polar bears in the Alaskan Beaufort Sea. The single most important natural factor affecting their distribution is sea ice. Drifting pack ice probably supports greater numbers of polar bears than either shorefast or polar pack ice (Lentfer 1972). Local concentrations of polar bears may occur along the coast of Alaska when pack ice drifts close to the shoreline

Table 13.5—Birds common to the neritic zone, their timing, and area of presence.

Species	Location	Time
Red Phalarope	Smith Bay to Demarcation Bay	Aug
Oldsquaw	Barrow to Demarcation Bay	20 Jul-10 Oct
Glaucous Gull	Harrison Bay to Demarcation Bay	Late Sep
Common Eider	Harrison Bay to Demarcation Bay	Late May-early Sep
Black Guillemot	Barrow (Plover Islands) to Smith Bay	15 Jun-10 Sep
Arctic Tern and Sabine's Gull	Barrow to Flaxman Island	25 Jul-1 Sep
Ross' Gull	Peard Bay to Plover Islands	25 Sep-10 Oct

and shorefast ice forms early in autumn. Some polar bears may den on the shorefast ice.

13.3.3 Trophic Interactions

The primary prey species of the major vertebrate predators of the neritic zone are listed in Table 13.6. A conceptual model of food web structure in the Sale 87 area is shown in Figure 13.1. Not shown in Figure 13.1 is the seasonality of use of major prey items by predators. Birds are absent during most of the period of total ice cover, a period when some marine mammals are common in the neritic zone.

13.3.4 Interactions with Neighboring Zones

The neritic zone is an integral part of the Arctic shelf and interacts intimately and actively with the zones that border it. Summarizing, the major interactions are:

1) Areas characterized by higher than average standing stocks of benthic biota serve as reservoirs of reproductive material that (a) colonize the benthos in highly stressed physical environments inshore, and (b) serve as a food source for organisms living in seaward and/or shoreward zones.
2) There is a small but significant input of marine-produced carbon from the offshore (pelagic) zone.
3) Various marine mammals (particularly seals and polar bears) move freely between the oceanic and neritic zones to feed in biologically productive areas which are not permanent, either in time or in space.
4) Outside the barrier islands and along open coastlines, whales may infringe on the outer edge of the neritic zone, feeding on copepods and euphausiids.

13.3.5 Research Needs

The following statements summarize the major research needs with respect to the neritic zone:

1) Data on the composition, density, and biomass of the benthic biota east of Barter Island and in Camden Bay are nonexistent.
2) There has been no research into the effects of siltation (as caused by offshore develop-

Table 13.6—The primary prey species of vertebrate predators of the neritic zone.

Predator	Primary Prey
Arctic cod	Copepods, mysids, amphipods
Red Phalarope	Copepods, mysids, amphipods
Oldsquaw	Mysids, amphipods, molluscs
Glaucous Gull	Isopods, fishes, amphipods
Common Eider	Molluscs, amphipods, isopods, other crustaceans
Arctic Tern and Sabine's Gull	Amphipods, euphausiids, mysids, copepods
Ross' Gull	Amphipods
Ringed seal	Arctic cod, euphausiids, amphipods, mysids
Bearded seal	Molluscs, crustaceans
Spotted seal	Anadromous and marine fishes
Polar bear	Ringed seals

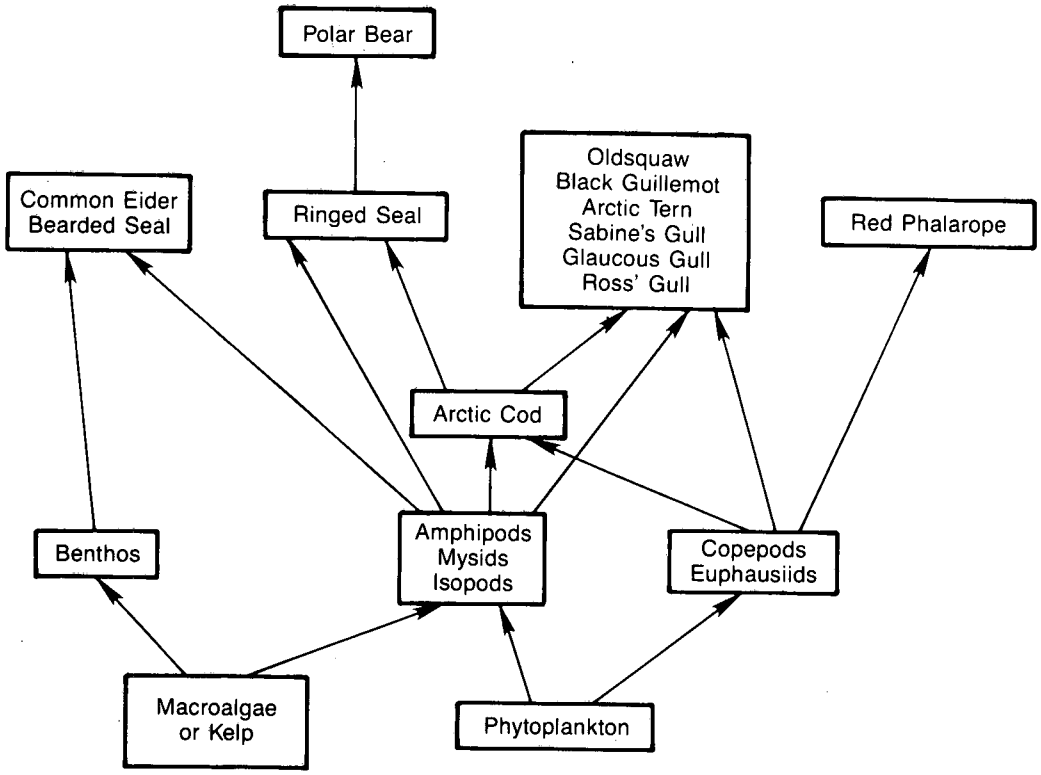

Figure 13.1—Generalized food web structure in the neritic zone, Sale 87 area.

mental activities) on the growth and recruitment of infaunal benthic communities.

3) The importance of the benthos as a food source for many of the important prey species listed in Table 13.6 is underestimated and not accounted for in food web models.
4) Virtually nothing is known about the marine resources of the northeast Chukchi Sea.
5) There is virtually nothing known of the fish use (especially by Arctic cod) of the neritic zone. Areas of reproduction, population dynamics, and patterns of movement cannot even be speculated upon at this time.
6) The role and significance of macroalgae in many areas of the eastern Beaufort Sea cannot be ascertained until more information is collected on the composition and size of the macroalgae beds.
7) No census of the birds inhabiting the area between Point Barrow and Thetis Island has ever been conducted.

13.4 OCEANIC ZONE

The continental shelf of the southwestern Beaufort Sea is shallow and narrow, with the shelf break occurring between 50 and 70 m depth at 55-110 km from shore (Carsola 1954; Sharma 1979). The shelf is characterized by three main physiographic features: (1) the inner shelf, which slopes gently to 30 m, (2) the outer shelf, with a steeper declination to 70 m, and (3) the continental slope, which descends steeply to the Canada Abyssal Plain. There are broad shoals off the river mouths, and sand and gravel barrier islands parallel much of the coastline (Barnes *et al.* 1984). The sediments are generally silts and clays, though sands occur near shore, and patches of relict gravel are found near the shelf edge (Barnes and Reimnitz 1974). Much of the sediment is patchy, particularly on the inner shelf scoured by sea ice (Reimnitz and Barnes 1974). Ice gouging disrupts the surface sediments episodically at depths of 0 to 40 m, causing a reworking of sediments (Barnes *et al.* 1984).

Sea ice dominates the hydrographic and pelagic ecological processes in the Beaufort Sea. The seasonal sea ice zone with continuous ice cover for about 9 to 10 months of the year usually extends from the shoreline out to the shelf edge (Reimnitz *et al.* 1978). Permanent pack ice cover lies beyond the Beaufort Sea shelf.

Hydrographically, the Beaufort Sea is an integral

portion of the Arctic Ocean with three major sources of its water masses: (1) the Arctic surface water (0-200 m), which includes Bering Sea-Chukchi Sea water; (2) Atlantic Ocean water (200-900 m); and (3) the Arctic bottom water (>900 m) (Coachman 1969). There is a substantial transport of Bering Sea-Chukchi Sea water masses around Point Barrow into the Beaufort Sea along the outer shelf and upper continental slope by the Beaufort current (Aagaard 1984; chapter 4, this volume).

13.4.1 Energy Inputs

In contrast to the nearshore and lagoon zone and neritic zone, little terrestrial organic material reaches the oceanic zone over the continental shelf and slope. The major inputs to the food web come from phytoplanktonic and ice algal primary production (Horner and Schrader 1982; Horner 1984); advection of particulate carbon and zooplankton from the productive, shallow Bering and Chukchi seas to the southwest; and migration of fishes, marine mammals, and birds into the area (Johnson 1963). The total energy input into the southwestern oceanic ecosystem is thought to be very low (Nemoto and Harrison 1981).

There appears to be no spring phytoplankton bloom under ice-free conditions, though the period immediately after ice breakup is difficult to sample (Horner 1984). The ice algae production appears to be a small fraction of the total carbon fixed annually.

13.4.2 Major Biotic Groups

Phytoplankton species are widespread throughout the southwestern Beaufort Sea, although some species are associated with specialized environments or distinct water masses (*e.g.*, sea ice or the Bering Sea water intrusion). Standing stock and primary production are variable and patchy in space and time. Diatoms are generally the dominant group, and *Chaetoceros* spp. the dominant taxa, though small flagellates (<10 μm) can be the most abundant organisms. Dinoflagellates are almost always present, but are low in abundance. Ice conditions, which in turn affect light transmission, influence phytoplankton abundance and productivity (Horner 1980).

The distribution and abundance of zooplankton species are affected by hydrography: some species occur in warmer, less saline coastal waters, some occur throughout the area, and others are advected into the Beaufort Sea from the Bering and Chukchi seas. Distributions are patchy and appear to be significantly affected by ice presence and concentration. Copepods are the predominant group, though meroplanktonic larvae of decapod and cirripede benthic invertebrate species are numerous, particularly over the continental shelf (Horner 1980).

West of Prudhoe Bay benthic invertebrate macrofauna are most abundant near shore at about 25 m of water depth and at the shelf edge and upper slope to depths of 700 m (Carey and Ruff 1977; Carey *et al.* 1984). At all depths polychaetous annelid worms predominate, and bivalve molluscs are the second most abundant group. A group of associated polychaete species is found across the shelf to the upper slope, and three associated groups on the upper slope to midslope (Bilyard and Carey 1979).

The benthic mega-epifauna (>2.0 cm) are most abundant on the outer shelf to upper slope (80-195 m). Fewer organisms are present on the inner shelf and the deeper portions of the continental slope (Carey *et al.* 1984).

Oceanic birds (*e.g.*, Glaucous Gull, Short-tailed Shearwater, and Black-legged Kittiwake) are very low in abundance and biomass. The largest densities are found in the Point Barrow region. There is a marked latitudinal gradient in bird densities, presumably because of the intrusion of warm, Bering Sea water with its associated prey fauna (Divoky 1984).

13.4.3 Trophic Interactions

Offshore of the barrier islands, the continental shelf and slope food web is poorly defined. The offshore food sources of large predators (*e.g.*, Arctic cod) are not well known, though they are known to be pelagic feeders probably preying on copepods, euphausiids, mysids, and hyperiid and gammarid amphipods (Frost and Lowry 1984). In contrast to temperate faunas, there may be few predators on the offshore benthic infauna and epifauna (Carey *et al.* 1984). A low predation rate may provide one of the explanations for the existence of the large standing stocks of benthic infauna at the shelf edge and beyond. Most of the benthic invertebrates are deposit-feeding organisms, with a trend toward more subsurface deposit feeders with increasing depth.

The offshore birds are surface feeders, primarily preying on Arctic cod (Divoky 1983, 1984). The Arctic cod are pelagic feeders on zooplankton, particularly small crustaceans (*i.e.*, copepods,

euphausiids, mysids, and hyperiid and gammarid amphipods) (Frost and Lowry 1984).

13.4.4 Interactions with Neighboring Zones

There appears to be less of an energetic connection of the oceanic zone to the nearshore and lagoonal zone, though the neritic zone probably functions as a fundamental unit of the shelf system. Not enough is known of seasonal and/or ontogenic migrations of motile organisms from this shallower zone to conclude whether they are important trophic links in the oceanic zone.

13.4.5 Research Needs

Plankton distributions and abundances before and during ice breakup are unknown and should be investigated. This could be a critical time for a spring phytoplankton bloom, reproductive success of zooplankton, and production and dispersal of ice algae.

Information on the distribution, abundance, and food habits of larval fishes is lacking. These data are needed for fishery management and for environmental assessment.

Lack of data on the offshore food web leaves a significant need for data on the trophic-energetic role of the offshore continental shelf and upper slope in the shallower environments. The role of offshore populations of pivotal faunal groups in the food webs (*e.g.*, amphipod crustaceans and Arctic cod) are not known.

Though the ice biotic community is ubiquitous, if patchy, its role in the oceanic ecosystem is not known. Fundamental data on its patchiness, annual primary production, role in the energetics of benthic and pelagic organisms, and use of its undersurface as another substrate and interface in the ocean are needed to determine the importance of this environment in the polar ecosystems.

The biology and ecology of birds in the productive region just east of Point Barrow needs to be fully investigated because of the effect of the Bering Sea intrusion and the susceptibility of the area to offshore oil exploration.

Before we can conclude how fragile or hardy the Beaufort Sea marine biotic communities are, fundamental information is needed on biological rates of reproduction, growth, repopulation, and predation, and on the basic energetics of the ecosystem.

The influence of Bering Sea water on the ecology of the western Beaufort Sea as it is advected into the area by the Beaufort current is a research topic of great importance.

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Chapter 14
Pollutant Transport
Oil Spill Trajectory Calculations

by Mauri J. Pelto

One of OCSEAP's objectives is to provide the Minerals Management Service (MMS) with the means to assess the risk to the environment from oil spills. To do this, the behavior of oil spills must be described and the probable trajectories of spilled oil found. MMS can then combine the statistics of the trajectories with probabilities that oil will be found and the probabilities of the occurrence of a spill to arrive at an estimate of the risk (Samuels, LaBelle, and Amstutz 1983).

If oil is spilled under ice, as is likely to be the case in the event of an accident in the Beaufort Sea, the ice will probably restrict it to a very small area, and its movement will be determined by motion of the ice (Thomas 1983b). Therefore, modeling oil spill trajectories in the Beaufort Sea, with its nearly year-round ice cover, consists largely of modeling the motion of the ice (Pritchard and Kollé 1981). When the short open-water season arrives, a part of the oil incorporated into annual ice is released and may be tracked as if an open-water spill had occurred.

Oil spill trajectory modeling in the Arctic, therefore, has been divided into two phases. The first phase computes the motion of the ice that encapsulates the spilled oil. Its trajectory is followed until it encounters open-water conditions or until it leaves the modeled area. The second phase consists of following the motion of the oil slick in open water, under the assumption that oil spilled in winter is released from the ice when the ice reaches open water. The oil then spreads and continues to move in response to winds, very much like a spill that originated in open water. A summer spill that originates in open water is modeled in a manner like that used for subarctic spills.

14.1 WINTER TRANSPORT

A winter oil spill in the Arctic immediately brings forth the specter of oil contamination in the presence of ice. I propose here to summarize some of the data on the movement of the ice pack and to examine some of the characteristics of an oil spill occurring when ice is a major environmental factor, as it is during most of the year in the study area.

I will review, briefly, the relevant data on the growth of the ice cover, its movement in response to winds, its interaction with the oil, and the transport of the oiled ice floes prior to the eventual release of the oil during the ice breakup of the following summer. The description will draw heavily on reports to OCSEAP, in particular those on oil-ice interaction, ice trajectories, and the winds that determine to a large extent the motion of the ice.

In the southern Beaufort Sea, ice begins to grow in late September. Rapid growth of ice proceeds from October to December, by which time the ice is sufficiently strong that its motion in response to winds is severely restricted inside the barrier islands and out to about the 20-m isobath (Thomas 1983b). There is a strong tendency for the grounding of ridges and deeper-draft, multiyear ice floes in a zone between the 15- and 20-m isobaths. Inside the 15-m isobath the ice remains very stable from February through early May (Barry 1977). The boundary between stable fast ice and the moving pack ice in the late winter is beyond the 18-m isobath, which has been given as the nominal seaward boundary of the fast-ice zone (Kovacs and Weeks 1979).

At the site and time chosen for the scenario, at about 15-m water depth off of Barter Island, the water will be partly covered with freely drifting, broken ice floes. The ice will gradually increase in strength until December (Thomas 1983b). At that time, shorefast ice will have increased in thickness and in strength and will have ridged and grounded to such an extent that, out to a depth of about 20 m, the ice is largely immobile, with its shoreward edge anchored to the land and many intermediate points by grounded ridges and barrier islands.

During the period of freeze-up, from October to December, before the ice has reached an appreciable thickness, there is a possibility for offshore winds to move the thin, growing ice into deeper water (Kozo 1983, 1984). Thus, ice that originally forms in shallow water can be incorporated into the moving pack ice beyond the 20-m isobath.

Average motion of the pack ice is generally toward the west, with mean speeds varying from 3.7 km/day in the fall to 1.3 km/day in the winter to 3.6 km/day in the summer. Shoreward of the 20-m isobath, the westward drift velocity of the ice decreases, as the ice motion is restricted by the presence of land, barrier islands, grounded ridges, multiyear ice floes, and ice islands grounded in the shallower water. The model used to calculate ice trajectories assumes a linear decrease in the average speed of ice motion as shore is approached. This is consistent with a limited number of observations that even in 60-kt winds the shorefast ice moves but very little (Kovacs and Weeks 1979). While the average motion is towards the west, brief periods of motion to the east in response to westerly winds have been recorded. These events are seen as short, infrequent vectors toward the east in Figure 14.1, which shows a partial summary of results from the ice model.

Figures 14.1 and 14.2 summarize the results of ice trajectory calculations, using an adaptation of the AIDJEX ice model. These trajectories were used to determine the probable locations of subsequent landfalls of spilled oil after its release from the ice. The most important driving force affecting the motion of ice is the wind, although the model also includes the effect of currents. Figure 14.3 summarizes the wind data used in the modeled trajectories. Wind fields were derived from pressure charts (Thorndyke and Colony 1980, 1981) and selected at random according to a transition matrix. As a check, the modeled winds were compared with winds of record in the Climatic Atlas (Brower *et al.* 1977). The bimodality of the wind field in the Beaufort Sea is shown clearly, with easterlies predominating, causing the westerly motion of the pack ice, but with sufficiently frequent occurrence of westerlies that reversals from the monthly mean motions are common.

The principal current field driving the model is a geostrophic velocity field that is assumed to be constant. It has a velocity of 1.0-5.0 cm/s towards the west, beyond the shelf break, with negligible effect on the shelf itself. A shelf-break current described by Aagaard (1981) is also included in the model.

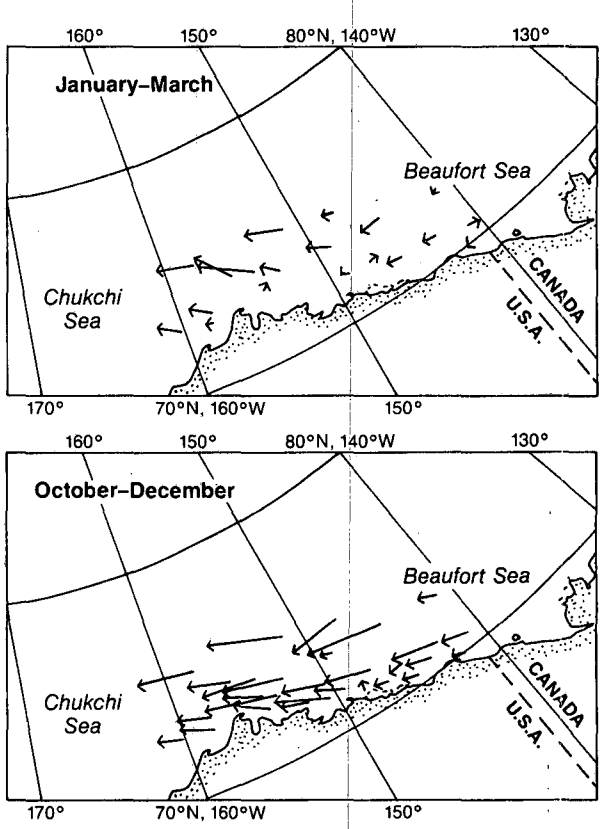


Figure 14.1—Modeled monthly ice motions for the fall and winter season. Modeled trajectories originate at the launch points used in the study (adapted from Thomas 1983a).

This current is a narrow, jet-like feature that is confined to the shelf break. It is bimodal in character, with a net speed to the east of 7 cm/s for a long-term mean. Because of its narrowness, and the time variability of this feature, its effect on the ice field is to cause variability of ice velocities near the shelf break.

14.1.1 Scenario: An Oil Well Blowout in Early Winter

An oil spill in 15 m of water off Barter Island, occurring in October or the early fall, furnishes a setting within which to discuss most of the features that are believed to be descriptive of oil spills in the Arctic in the presence of sea ice. The spill is assumed to have occurred because of a pipeline rupture, or because of a well failure deep under the sea floor, which allows gas and oil to flow through geologic structural faults to a point on the sea floor away from the gravel island. (A wellhead failure that results in a blowout would initiate a spill on the surface of the gravel island and would be easily contained). It should be pointed out that a pipeline rupture results in a minimal loss of oil because at inter-

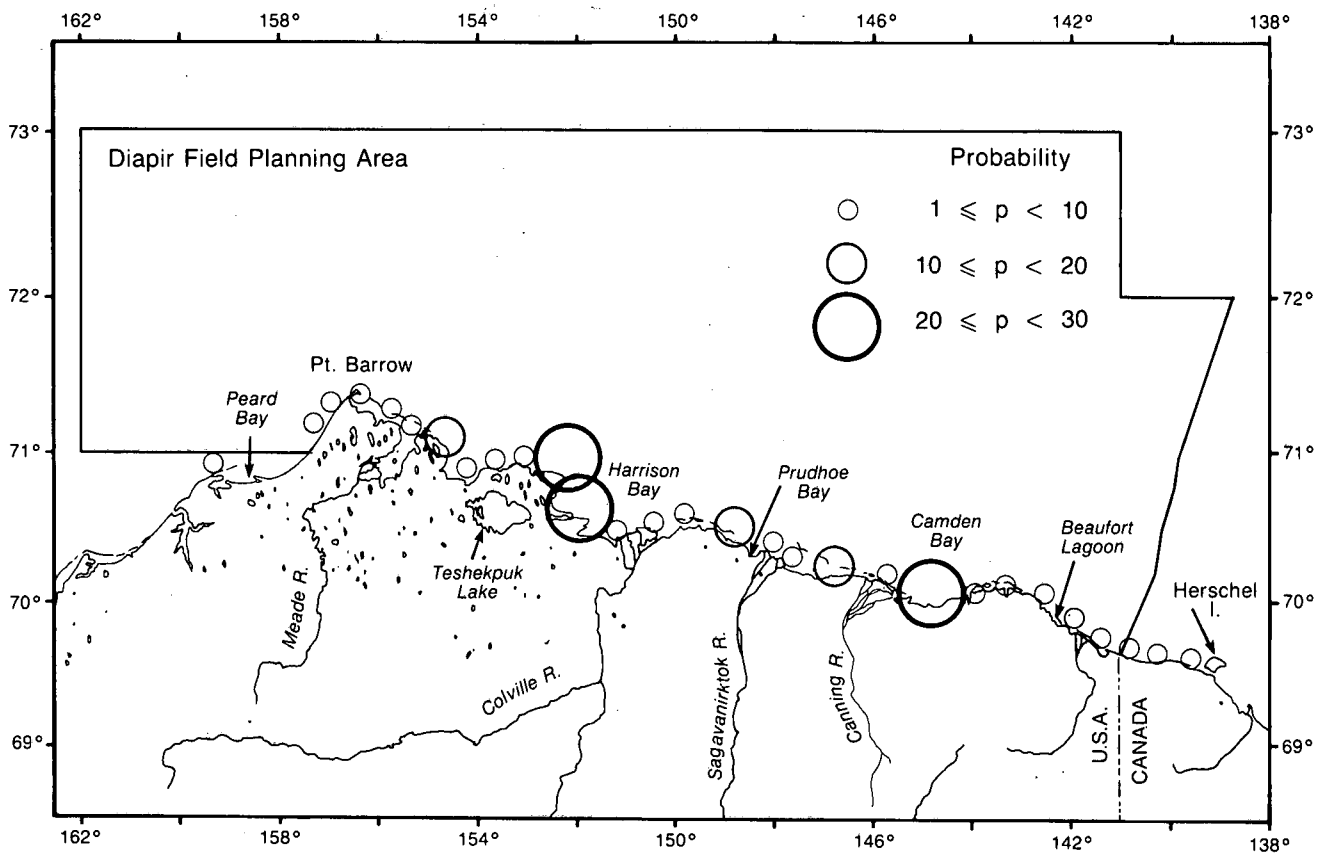


Figure 14.2—Probable location of shoreline impact points from oil spills originating from locations designed by MMS (adapted from Samuels, Banks, and Hopkins 1983).

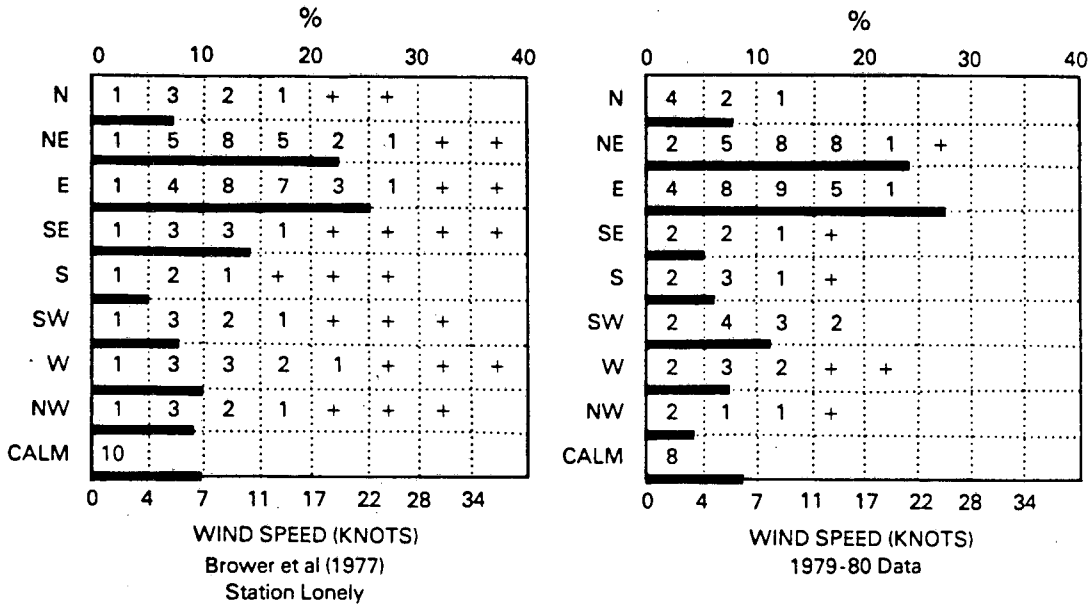


Figure 14.3—Wind speed and direction summaries used in modeling of ice trajectories by Thomas (1983a). Information for Station Lonely is from Brower *et al.* (1977). Offshore winds were computed from the 1979-80 Arctic Ocean Buoy Program pressure data used in trajectory calculation.

vals along its length are values that can be closed in the event of a spill.

A spill with a flow rate of 2,000 barrels per day may be described in order to illustrate the scale of behavior seen in large events. The character of smaller events can be inferred from these by scaling down the description of the pool of oil formed under the ice.

14.1.2 Environmental Considerations

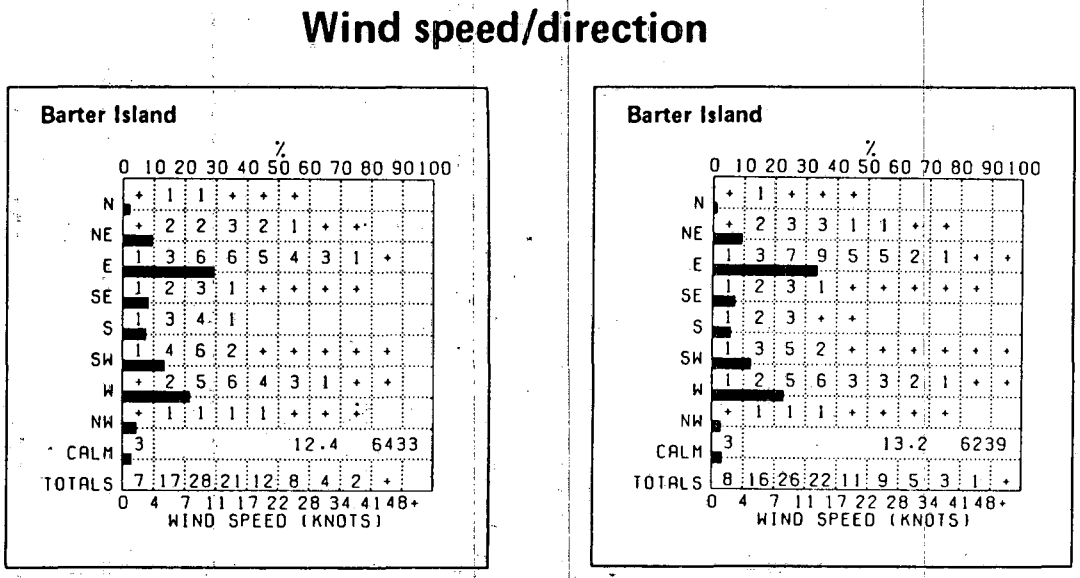
The single most important environmental factor controlling oil spill behavior is the wind and its effect on the motion of the Arctic ice cover. In October, the winds near Barter Island are very nearly bimodal, with a nearly equal probability of blowing from either east or west (Brower *et al.* 1977). Figure 14.4 shows the statistics of winds in the Barter Island area. The resulting ice motion is nearly parallel to the shoreline in response to the wind stress and to the resulting currents, which tend to be parallel to shore.

There is an 80% probability of a storm event of 3-5 days' duration during October and November, which would cause offshore motion of the ice, leaving open water at the site of the oil spill (Kozo 1983). Under these storm conditions, the oil would move offshore with the ice and would become incorporated in newly freezing ice. There it is likely to become incorporated into pack ice, which would move to the west under the prevailing winds (Thomas and Pritchard 1979; Pritchard and Kollé 1981).

After October 15, the prevailing conditions, with winds from either west or east, would result in rapid freezing and the entrapment of oil released on the sea floor under a cover of ice. The location is such that it is possible for the ice cover to either remain in place or to be moved to the west by prevailing winds, depending on the strength of the ice and the winds. Kozo (1984) shows evidence that ice can be moved offshore by strong easterly winds in November, after the formation of continuous shore-fast ice is well under way. There is also a possibility that ridge building will occur in the vicinity of the spill.

14.1.3 Character and Behavior of Oil and Ice

Two extremes of ice motion during the spill may be considered, in order to visualize the oil under the ice. In the case of stationary ice, the oil would form a roughly circular pool that would grow in size and surround the release point. In 60 days, 120,000 barrels would have been released. Were the ice perfectly smooth, and the oil spread to an equilibrium thickness of 1.0 cm, the resulting pool would have a radius of about 0.8 km after 60 days. Since the ice has a considerable roughness, the oil would be thicker in the depressions under the ice and, therefore, the radius would be much less than the 0.8 km for perfectly smooth ice. Presumably, some sort of recovery operation would be feasible under these conditions. Since the ice is generally in motion, the next step in the development of the extreme-case scenario is to assign a velocity to the ice. The most



October **November**

Figure 14.4—Wind climatology near Barter Island (adapted from Brower *et al.* 1977).

likely drift during most of the winter is toward the west, following the coast, with a mean speed of about 2 km/day. This translates to a little more than 2 cm/s. Because of the motion of the ice over the location of oil release, the rising oil forms an elongated plume under the ice.

The maximum width of the plume of pooled oil under moving ice will be considerably less than the dimensions of the pool formed under stationary ice. As a result of turbulence, the rising oil plume will break up to form droplets and larger globules of oil that will spread out to form a plume about 100 m wide, after rising through the 15 m of intervening water column (Thomas 1980). With the ice moving at the assumed rate, a 100-m-wide swath will receive an average thickness of 0.16 cm of oil. While this may seem to be very thin, it must be recalled that the roughness of features will cause some areas to be thicker than elsewhere. On the other hand, if the oil were to rise to the surface in an intact stream to form a thick layer with minimum spreading to the equilibrium thickness of 1.0 cm, as assumed earlier, it would result in a plume width of 16 m. As above, this assumes that the ice moves at a speed of 2 km/day.

It is concluded that the under-ice oil slick will have dimensions of 10-1,000 m in width, with the most likely width in the neighborhood of 100 m. The thickness of the oil will be from about 0.1 cm to a few cm in deep pockets in rough ice.

The length of the resulting oil plume under the ice depends entirely on the rate of ice motion. Pritchard and Kollé (1981) have shown that ice moves approximately 75 km in a 30-day period in areas not unlike those immediately offshore of the location that was selected for this scenario, near Barter Island. It has also been shown that the ice moves in a meandering path, with changes in direction due to shifting winds and tidal currents. Therefore, an oil spill event that continues for 60 days will cause a swath of oil, which could be 150 km in length, under and in the ice floes. The variability of monthly ice motion vectors is very high, so the length of the oiled swath also may vary.

Some additional factors need discussion before the fate of the oil plume can be fully described. These include such phenomena as the effect of currents, the incorporation of oil into the ice as freezing continues, the rate of dispersion into the ice as freezing continues, the rate of dispersion into the water column as dissolved fractions, and the subsequent settling to the bottom, if weathering and accommodation to suspended sediments occur. Oil under ice continues to move with the ice even if the water beneath has a different speed, up to a relative speed of 20 cm/s (Cox *et al.* 1980). While currents under ice as high as 20 cm/s are not unknown, they are uncommon. We therefore conclude that the oil will almost always move with the ice.

Payne *et al.* (1984) have shown that the rate at which oil fractions are dispersed into the water column does not exceed 5.0 g/h/m^2 shortly after the initial release of oil (Table 14.1). At this rate, water column concentration near the swath of oil could be as high as 10 ppb only if the ice and oil moved at exactly the same rate of speed as the water for more than 12 hours, continuously (Pelto *et al.* 1983). After the oil is encapsulated into the ice by water freezing underneath, dispersion of oil into the water column will be greatly reduced. Ice continues to form under the oil during freezing conditions as

Table 14.1—Weathering and spreading of oil. Decrease in volume is due to evaporation and dispersion into the water column. Spreading is according to the model by Payne *et al.* (1984) and does not include the effect of oceanic dispersion, which causes the distance between patches of oil to increase, while the thickness of oil in each patch decreases according to the weathering model.

Time (hr)	Volume (bbl)	Area (m^2)	Thickness (cm)	Mass/Area (gm/m^2)	Dispersion (gm/m^2/hr)
0	83	660	2	18,000	7.7
5	73	12,000	.09	840	3.9
10	70	17,000	.06	580	2.6
15	67	21,000	.05	460	1.8
20	65	23,000	.04	400	1.4
40	60	32,000	.03	270	.5
60	57	38,000	.02	210	.3
80	55	43,000	.02	180	.3
100	54	45,000	.02	170	.2

assumed in our scenario. As a result, the oil will appear as a series of lenses of varying thickness within the ice. The rate of freezing is such that within several hours, encapsulation reduces contact between the oil and the water, and thereafter the oil is subject to incompletely understood weathering processes. These processes are thought to be such that only minor change occurs to the oil between the time of encapsulation and oil release during breakup.

The distance that oil-contaminated ice will travel during the winter before breakup depends on whether the floe in question remains within the fast-ice zone or is carried offshore into the moving ice pack by offshore winds early in the freeze-up period. At the end of December, in the latter case, the oiled ice could be 275 km to the west, still close to the fast ice, but moving with the pack. At the end of May, it may be another 375 km farther west. If the contaminated floe remains inside the boundary separating the moving pack from the fast-ice zone, we must assume its speed to be much less. It could even be immobilized if it is moved shoreward into shallower water where the fast ice is even less likely to move. It is concluded that an oil-contaminated ice floe originating near Barter Island in October could be transported as far as 650 km to the west beyond Point Barrow or, as a minimum and depending on the winds, could remain very close to Camden Bay. A spill that continues for many days or weeks could result in a portion of the oil remaining in place while some of the oil is moved offshore to begin a longer trajectory as part of the moving pack ice.

Wherever the oil-contaminated floes are in May or June, when breakup begins, the oil will be released from the ice in much the same condition as it was when encapsulated. The release at that time will be from widely scattered points, depending on where individual floes may move after the ice begins to break up into freely drifting floes.

One of the concerns of participants at the synthesis meeting was related to the behavior of the oil as it is released from a floe at the edge of a lead, such as might occur if the floe entered the Chukchi Sea beyond Point Barrow. It was concluded that the oil would cross a lead, if it originated on the upwind side, and would be held against the opposite side of the lead by the diverging current in the lead. At the time of the synthesis meeting, there was no model for determining the dispersion of ice floes; therefore, it is not possible to estimate the local density of floes that might contain oil, nor are we able to estimate the rate at which oil flows out of a broken ice floe. Intuition suggests that because of the high viscosity of oil at the temperature of the ice, the rate at which oil is released is not great. It is not possible, therefore, to predict the amount of oil to be found in a lead, should a contaminated ice floe be nearby.

Although ice is known to enter the Chukchi Sea from the Beaufort Sea, this is not the usual behavior; ice usually continues toward the northwest (Aagaard 1983). A concern is that if oil does get into a wide lead along the Chukchi Sea coast, it might be held while the lead contracts and opens as the driving force of the winds dictates. The oil could, therefore, remain in the lead as a hazard to biota for a period of time.

Another concern is the likelihood of contaminated floes grounding near a lagoon and releasing oil into nearshore waters destined to enter a lagoon. Again, without an estimate of the dispersion of contaminated ice, it is impossible to say what the probability is for a given amount of oil to enter a lagoon. It is known, however, that floes enter lagoons and that winds and tides cause a pulse-like entry of surface water into lagoons (Hachmeister and Vinelli 1983).

14.2 OIL SPILL TRAJECTORIES IN SUMMER

Figure 14.5 shows the location of spill sites selected for calculation of trajectories to be used as inputs to the Oil Spill Risk Analysis model operated by the Minerals Management Service (Samuels, Banks, and Hopkins 1983). Some of the launch points are the locations where winter trajectories become open-water trajectories, and some are spill sites selected by MMS for simulation of oil spills in the summer or open-water season.

Trajectories from a few of the sites are illustrated in Figure 14.6. In all, 30 trajectories were computed from each site. The mean motion is to the west as a result of the prevailing easterly winds paralleling the shore, though a few trajectories will hit the shoreline with probabilities as shown in Figure 14.2. Statistics of the winds that drive the oil are shown in Figure 14.7, as they were incorporated into the trajectory mode.

14.2.1 Open-Water Trajectory Model

Oil spill trajectories under open-water conditions were calculated with the Rand Corporation's oil spill model, which utilizes response functions obtained from a multi-layer circulation model to determine the surface currents in the presence of

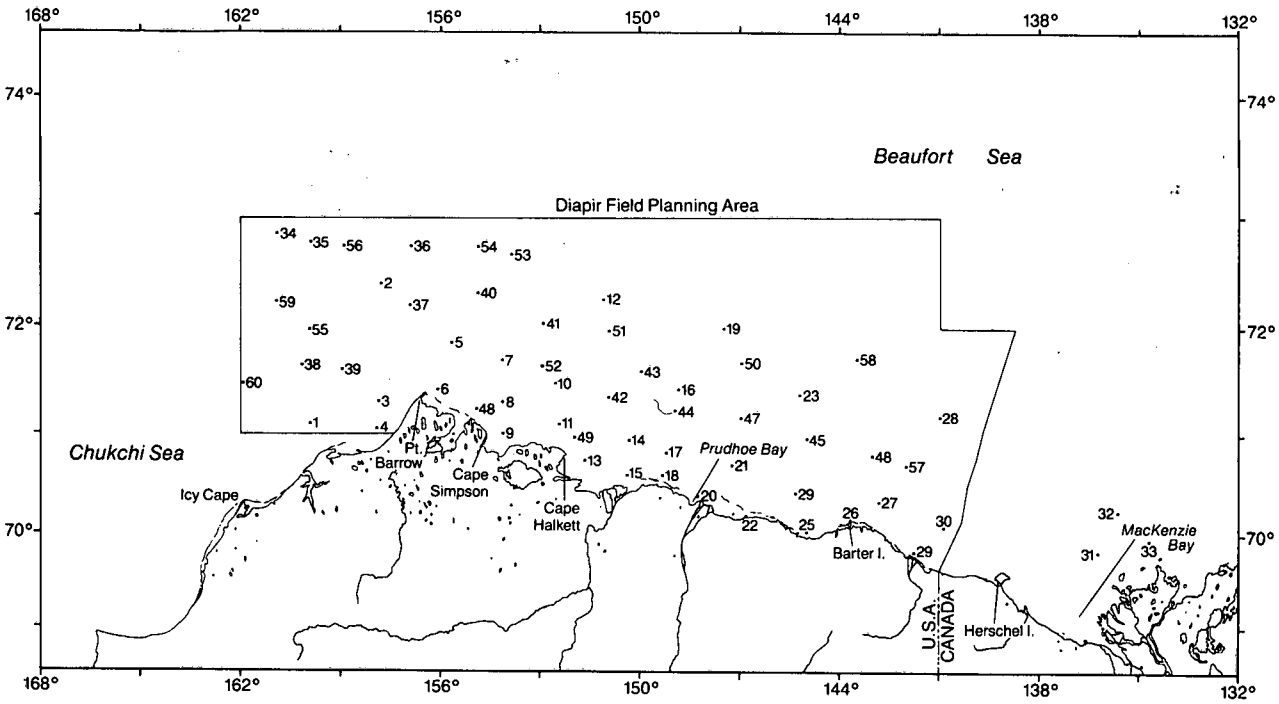


Figure 14.5—Location of hypothetical spill sites designated by MMS for investigation of trajectories and location of landfalls (Liu and Leendertse 1983).

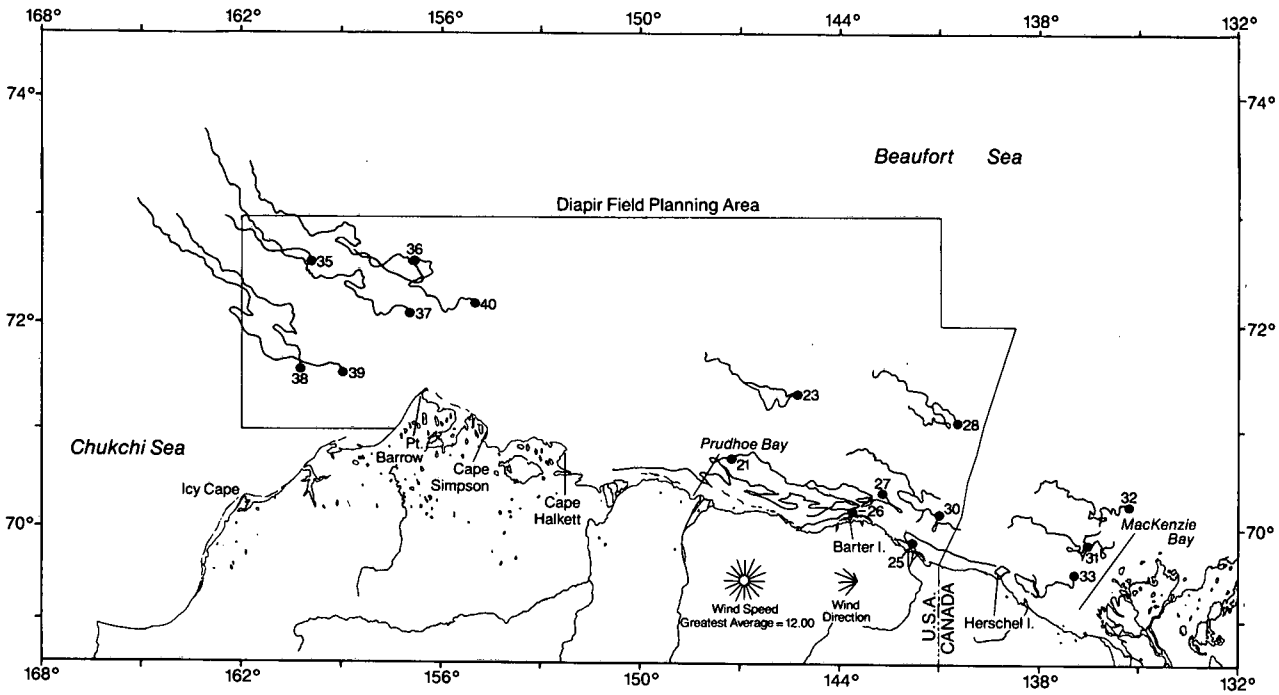


Figure 14.6—Typical oil spill trajectories calculated by the Rand model. Summer conditions, with nominally open water, are depicted (Liu and Leendertse 1983).

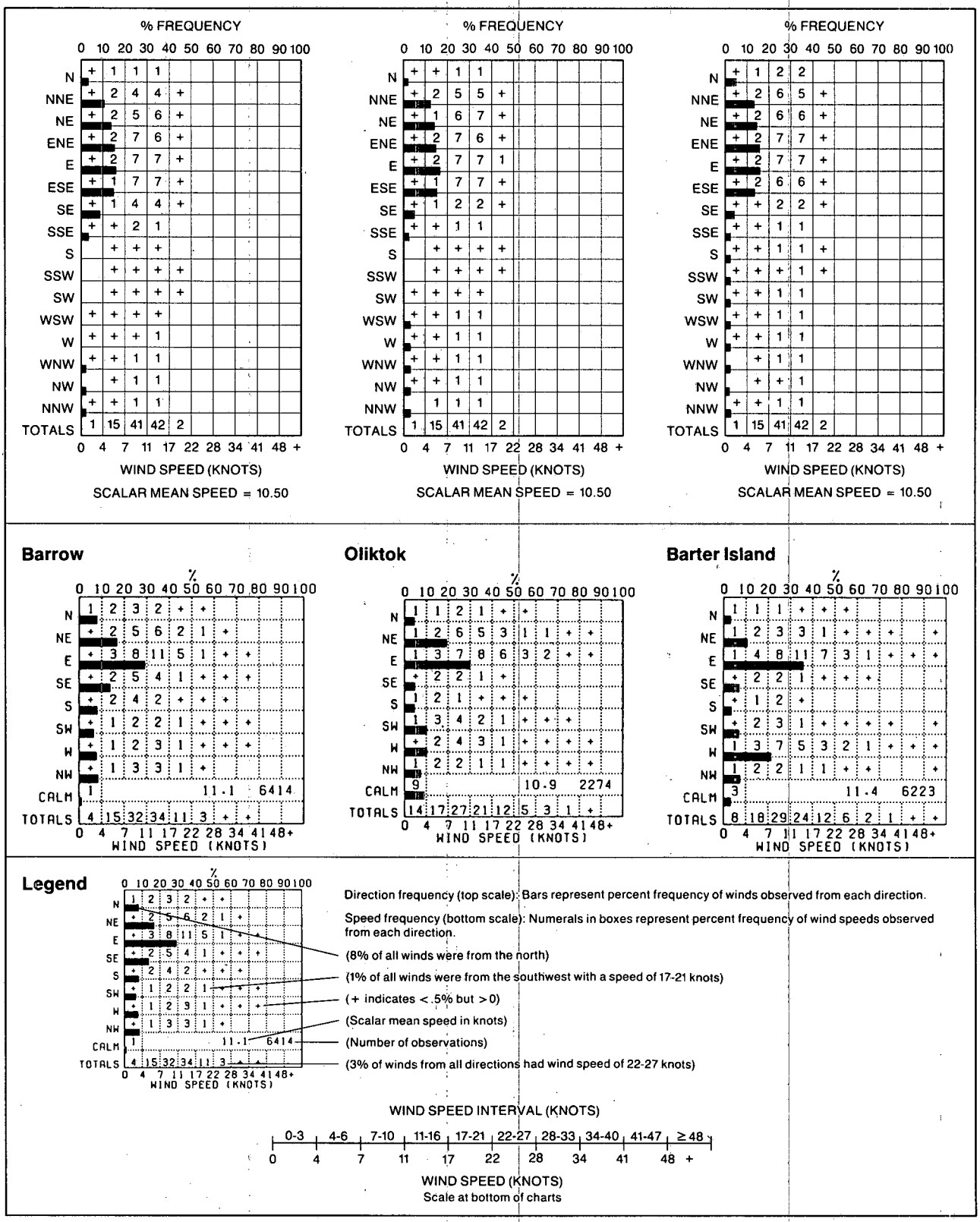


Figure 14.7—Statistics of winds used in Beaufort Sea trajectory calculations for September. Top figures adapted from Liu and Leendertse (1983), lower from Brower *et al.* (1977) for comparison.

winds (Liu and Leendertse 1981). The model incorporates the effect of variable ice cover and includes a stochastic weather submodel that provides wind sequences whose statistics match those of the long-term record.

Wind is the principal driving force causing motion of the water column and anything floating on it, whether ice with oil encapsulated in it, or the oil slick itself. The drag coefficients for wind ice and water, which are incorporated in the model, are known from other OCSEAP studies (Macklin 1983; Pease *et al.* 1983). Other studies have also successfully modeled the motion of ice in the Beaufort Sea as a function of wind stress and ice forces. Figure 14.7 shows the statistics of winds at points along the Beaufort Sea coast, together with the statistics actually used in the modeling of trajectories.

The Rand model divides the water column into several layers, with the property that momentum is exchanged between the layers. As a result, the response to wind stress at the surface, including motion of ice, changes as the rate of vertical momentum exchange changes. If the surface layer lies over a sharp pycnocline, vertical momentum exchange is inhibited. The energy of the wind, as it is imparted to the surface layer, is largely retained within the surface layer as a greater current velocity for any given wind speed. The vertical transfer rate for momentum is variable; therefore, the response of the oil slick to wind varies over a wide range. In addition, when the wind ceases or changes direction, the momentum previously imparted to deeper layers keeps the surface in motion.

Motion of ice must be simulated by the model, because even in the summer, onshore winds frequently drive pack ice into areas near shore that are normally ice-free during the open-water season. The model therefore includes an additional momentum equation for ice not seen in the usual hydrodynamic model (Liu and Leendertse, 1979, 1981):

$$\overline{\delta_t(\overline{H}^x u')}^t = -\delta_x(\overline{\overline{H}^x u'}^x \overline{u}^x) - \delta_y(\overline{\overline{H}^y v'}^x \overline{u}^y) + f\overline{H}^x v'^{-xy}$$
$$- \frac{1}{\overline{\rho}^x}\overline{H}^x \delta_x p + \frac{1}{\overline{\rho}^x}\Big[c^* \rho_a \omega_a^2 \sin\Psi - (E'_x \delta_z \overline{u}^{2t})_{K=3/2}$$
$$+ \delta_x(HA'_x \delta_x u)_- + \delta_y(\overline{\overline{H}^x \overline{A}_y^x}^y \delta_y u')_-\Big]$$

at $i+1/2, j, l, n$

Only the equation in the x direction is shown above. As a result of the exchange coefficients, Ex and Ax, momentum propagates horizontally and therefore the ice responds to the effect of nearby land or ice masses of different velocities. Figure 14.8 shows the modeled motion of ice of varying degree of cover under a typical easterly wind of 9 kts, as derived by the Rand model.

Figure 14.9 shows a comparison between modeled trajectories and the motion of floating buoys placed in the eastern Beaufort Sea by the U.S.

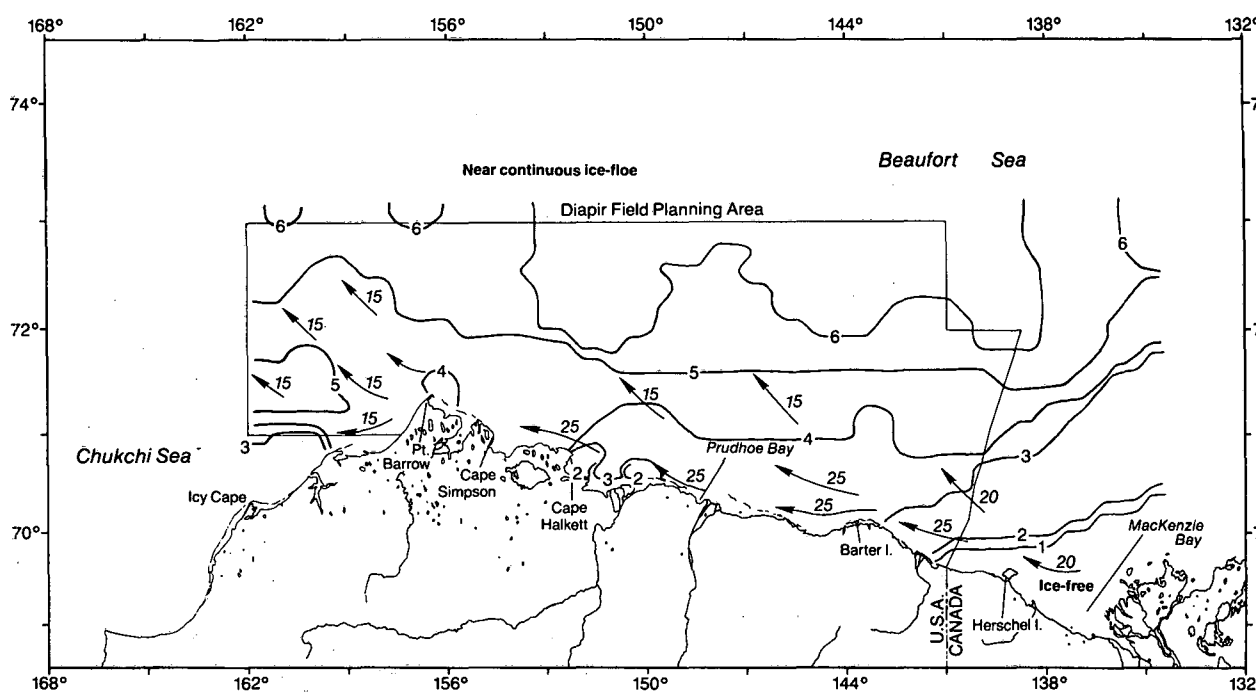


Figure 14.8—Beaufort Sea model under summer conditions showing distributions of ice concentrations (in oktas) and ice velocities (cm/sec) under a constant 9.9 knot wind from the east for 12 hours (wind angle = 94 degrees).

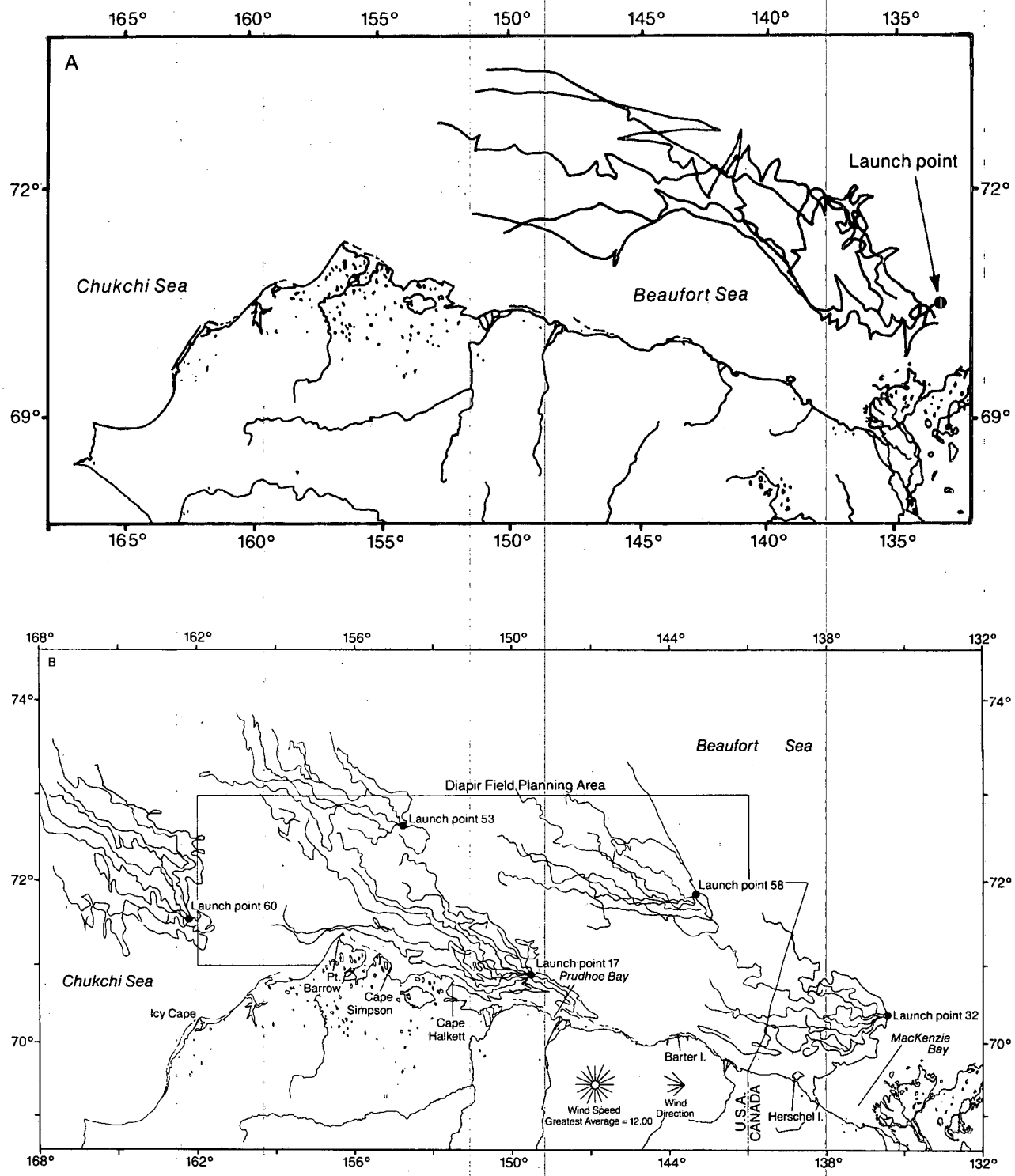


Figure 14.9—Comparison between (A) trajectories of five satellite-tracked buoys deployed by the U.S. Coast Guard during the period between August and October 1979 from eastern Mackenzie Bay, Canada, and (B) 30-day trajectories launched from five locations computed by the Rand oil trajectory model and the 2-dimensional stochastic weather simulation model (Liu and Leendertse 1983).

Coast Guard in 1979 (Murphy *et al.* 1981). While the Rand model trajectories were chosen at random, and the Coast Guard buoy trajectories are for a particular year (1979), the similarity is apparent.

14.2.2 Summer Oil Spill Scenario

An individual spill event and trajectory calculation can be examined in detail to place in perspective the nature of an oil spill in open water near the Arctic coast. Table 14.2 gives statistics of all simulated spills, as requested by MMS, that resulted in at least one landfall. From among these we selected Site 26 near Barter Island to examine in detail.

Table 14.2 shows for each spill site the number of landfalls, the x coordinate in terms of the arbitrary grid of Figure 14.1, the standard deviation of the extent of coastline that is vulnerable to impact, and the relative concentration of oil at the centerline at the point of landfall.

Thirty trajectories were launched at Site 26 near Barter Island, with winds selected at random from a sample population with statistics as in Figure 14.7. Twenty-one of these trajectories made landfall within 30 days. The mean position of landfalls along the coast was at grid location 35.7 (Katakturuk River). These points of landfall were spread out along the coast, with about 70% (21/30) landing within 3.8 horizontal grid lengths (Anderson Point to Brownlow Point). The mean time before landfall was 276 time steps, or 138 hours, and the mean distance traveled was 3.8 grid lengths (Fig. 14.6), or approximately 39 nautical miles.

Site 26 is only 30 miles from the mean point of landfall. The extra distance given in Table 14.2 is due to the meandering path that results from variability of winds and currents. The direction from which the mean trajectory approaches the shoreline reflects the mean winds in the area in September, which are from the northeast.

The spreading of an oil slick in response to currents and turbulent diffusion processes was reviewed by Schlueter and Rau (1981). They concluded that modeling the movement and spreading of patches of oil in a slick should be according to oceanic dispersion theory, following Murray (1972). The latter showed that beyond a few hundred meters of the origin, a slick from a blowout of 1,000 barrels per day widened in accordance with turbulent diffusion theory, with a constant diffusion coefficient, i.e., Fickian diffusion. Because we are concerned here with diffusion over longer distances compared to those in the studies cited, we use a diffusion theory that allows an increasing diffusion coefficient as the length scale increases.

Table 14.2—Statistics of oil spill trajectory behavior for two selected spill sites. The coordinates for the spill-site locations correspond to the coordinates presented in Figure 14.5. Landfall of the mean trajectory for each spill site is identified by the "x" coordinate at the point of landfall. Duration of the trajectories is expressed in number of half-hour intervals; the distance traveled is given in grid units (approximately 10 nm per grid-length); and the angle of approach to the beach is given relative to true north. The concentration of oil is expressed relative to unity at the orgin; this value may be used to estimate the amount of oil expected to come onto the beach in any unity area, along the centerline of the spill (from Liu and Leendertse 1983).

	Spill Site 1	Spill Site 26
Spill-Site Coordinates:		
X	6.140	38.666
Y	15.738	10.212
Number of Landfalls	1	21
Landfall (X Location):		
Mean	7.217	35.719
STD	0	8.838
Duration:		
Mean	339.50	276.24
STD	0	142.58
Distance:		
Mean	1.642	3.868
STD	0	3.113
Angle:		
Mean	139.0	−47.3
STD	0	105.4
Concentration at Surface:		
Mean	0.0030	0.0043
STD	0	0.0015

The diffusion of pollutant particles from a constant source with scale-dependent diffusion coefficient may be computed from

$$C = Co*erf[1.5/((1 + 0.67*beta*x/b)**3 - 1)]**0.5 \quad [1]$$

and,

$$Width = b*(1 + 0.67*Beta*X/b)**1.5 \quad [2]$$

where:

Co = concentration at the source
C = concentration along the centerline
b = the source width
X = distance along the path of the plume
Beta = 12*Eo/U*b
Eo = diffusion coefficient for a source of width b,
U = current velocity
erf = standard error function (Brooks 1960).
(Note: The double asterisks (**) indicate the raising of a value to a power.)

From Table 14.1 it is seen that in 5 hours the spill will have moved 2.7 km in a 10-kt wind. Assuming an oil with properties similar to those of Prudhoe Bay crude oil, the weathering processes will cause the slick to spread out over an area of 12,000 m^2 (Kirstein *et al.* 1983; Payne *et al.* 1984).

At this point it is assumed that the oil slick, which is approximately 1 mm in thickness, is sufficiently thin that it separates readily into patches in the presence of waves (Kirstein 1983b). This assumption is reasonable because of the relatively high viscosity and low tensile strength of the oil film. These patches will separate from one another and spread in response to current shears and turbulence. Figure 14.10 shows the surface concentration along the centerline and the width of an oil slick relative to a point 2.7 km downwind of a source of spilled oil. This assumes that subsequent behavior of the slick is according to turbulent diffusion theory, equations [1] and [2].

The concentration along the centerline at the origin of our hypothetical spill is 1.0 kg/m^2 (0.1 cm thick). Due to the spreading processes described above, the concentration at the beach will be 4.0 g/m^2, less the quantity lost due to weathering processes, evaporation, and dissolution into the water column (Table 14.1), leaving approximately 2.4 g/m^2. The rate at which Prudhoe Bay crude oil is dispersed into the water column is generally less than 5 g/m^2/h, as shown in Table 14.1 (Payne *et al.* 1984). As a result of the slow rate of dispersion into the water column, the accumulation in the water column does not exceed a few parts per billion

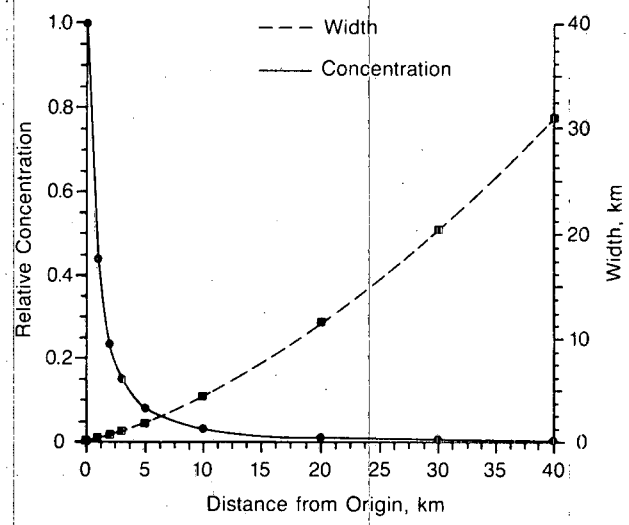


Figure 14.10—Concentration and width, relative to the source, along the centerline of an oil slick, using the formula by Brooks (1960). Assumes oceanic diffusion processes and a width of 100 m at the origin of the slick.

under the conditions expected in the Beaufort Sea (Pelto *et al.* 1983). This is consistent with wave tank experiments in which the concentrations remained below 500 ppb even though the tank was of limited depth (Payne *et al.* 1984). When quantities of oil reach the surf or swash zone, however, there may be higher concentrations locally, very near the oil slick itself. There is presently no way to estimate the water column concentrations in the surf zone or the thickness of oil in patches on the beach.

Figure 14.11 shows a summary of the appearance of a spill lasting 5 days from a location near Barter

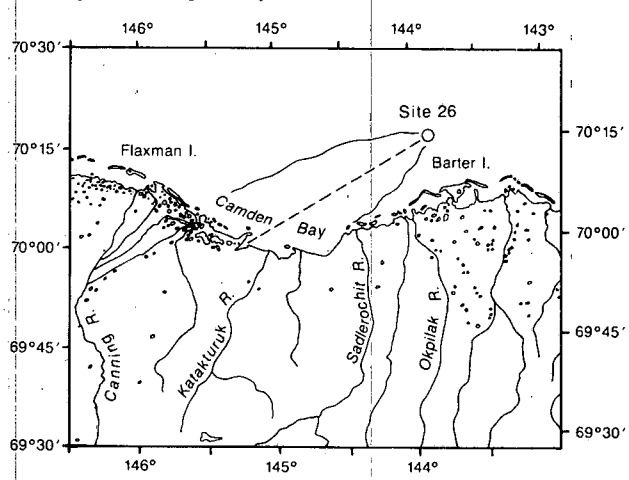


Figure 14.11—Summary of the appearance of a spill of 5 days' duration originating from a location (Site 26) near Barter Island. Direction and spreading are in accordance with the statistics of Table 14.2.

Island. The direction is in accordance with the statistics predicted by the Rand model summarized in Table 14.2. While the most likely direction that a spill would move is as shown, the probability of its approach to shore from the direction shown is low due to the variability of winds.

The total quantity of oil left on the beach from a spill of 2,000 bbl/day for 5 days will be approximately 6,500 barrels, spread out over a distance of 30 km along the beach. Due to patchy distribution, it is not possible to predict how thickly the oil may accumulate in any given place. In the event that a summer spill does approach close to the shore, it will be subjected to nearshore transport processes, which may include inflow into lagoons due to winds and tides (Hachmeister and Vinelli 1983).

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Chapter 15
Oil Spill Response Systems for the Beaufort Sea

by P. A. Tebeau

The recent discovery of oil and gas along the Alaskan coast has led to full-scale exploration and development on shore. Offshore exploratory drilling has begun on the continental shelf and is certain to increase rapidly within the next several years. The best planning and the most modern safety techniques cannot insure that accidental oil spills will not occur. Thus there is a definite need for oil spill contingency plans and response systems for Alaskan waters. The severest test of these plans and response systems will be in the arctic regions of Alaska, specifically in the Beaufort and Chukchi seas. Here the seasonally and spatially changing ice conditions will require at least three distinct types of oil spill response.

15.1 OIL SPILL BEHAVIOR IN THE BEAUFORT SEA

The behavior of oil spilled in arctic waters is far more complex than in temperate waters due to the changing ice conditions throughout the year (Fig. 15.1). Different sequences of physical and chemical processes may be expected for oil spilled in landfast first-year ice; in dynamic broken ice, as in the shear zone; or in multiyear pack ice offshore.

A spill occurring during the winter in level ice would result in oil being deposited on the ice, underneath the ice, or both. The case of an oil spill under the ice (spill 1 in Fig. 15.1), as caused by a subsea pipeline rupture or oil well blowout, has been described in detail by NORCOR (1975) and Lewis (1976). Briefly, the oil rises through the water column and is trapped underneath the ice. Maximum oil slick thickness is controlled primarily by the depth of the under-ice depressions (the bottom relief), which is typically about 20% of the ice thickness. Within a matter of hours of the oil coming in contact with the ice, an ice lip forms around the oil and restricts horizontal movement. The ice continues to grow around and underneath the oil and completely entraps the spill. Once entrapped, the oil is stabilized until spring. Properties of the oil remain unchanged within the ice, and there is little weathering.

As the temperature of the ice sheet increases during the spring thaw, brine channels in the ice begin to open, starting at the upper surface of the ice sheet and moving toward the lower surface. Once these channels reach the entrapped oil, the oil begins to migrate toward the surface. Late in the spring, when the ice is very porous, the oil flows freely through the sheet.

On reaching the surface of the ice, the oil saturates the snow cover and substantially reduces the albedo, thereby accelerating the melting process. Oil is splashed on the surrounding ice and snow by wind and wave action so that the oiled melt pools enlarge and become interconnected. Oil is released continuously until the melt reaches the initial level of the oil lens.

Once the oil reaches the surface of the ice it is subjected to various physical and chemical processes, collectively termed weathering. Under arctic conditions, the dominant and perhaps only significant weathering process of oil on ice is evaporation, which is responsible for the loss of a considerable fraction of the oil mass spilled. Evaporation leads to changes in the physical properties of the oil; namely, density, viscosity, interfacial tension, solubility, flash point, and fire point. In addition, once melt pools form and the oil comes in contact with water, wind-generated mixing may cause formation of highly stable water-in-oil emulsions. Because these emulsions have higher density, viscosity, and flash and fire points, they behave quite differently from the parent crude oil.

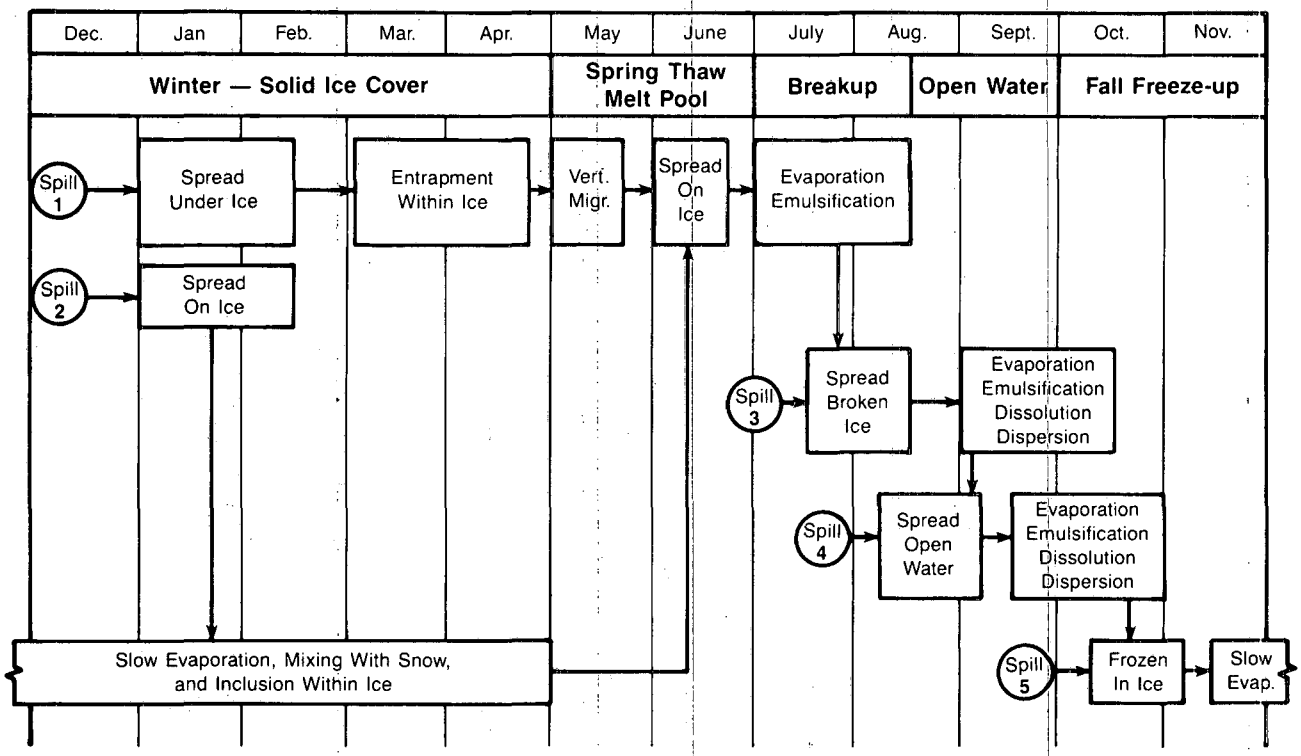

Figure 15.1—Schematic showing five possible evolutions of an oil spill in arctic waters.

As indicated in Figure 15.1, if the oil was discharged on the surface of the ice (spill 2), as in the case of an above-ice pipeline rupture or a blowout from a well on a gravel or ice island, the spill would spread over the surface of the ice. Studies indicate that the spread would be controlled largely by the roughness of the upper ice surface. Snow cover and ridging would probably cause the oil to be confined to a relatively small area. In the case of substantial ice deformation (pressure ridges and hummock fields), some of the oil could be incorporated in the ice.

Oil on the ice surface during the winter will be subjected to slow weathering due to low temperatures, reduced solar radiation, and the substantial thickness of the oil layer. With the onset of spring, melt pools will rapidly form, the oil slick will thin out, temperatures and solar radiation will increase, and the weathering process will be accelerated.

As breakup begins, the oil on the surface of the ice will enter the leads and cracks between the various floes and again spread to some equilibrium thickness governed by the ice concentration and the physical properties of the oil. The same situation will occur for a spill during breakup in which the oil immediately flows into the cracks and leads (spill 3). The ice will probably restrict the spread of the oil initially, so that the spill area will be less than that predicted for a spill in open water. However, once breakup progresses to the point where the ice floes move freely under the influence of winds and currents, the effect of the ice becomes uncertain. At some point, the motion of the ice may cause the oil to contaminate a greater area than would be predicted under open-water conditions. The oil would again be subjected to evaporation and emulsification, although at different rates. In addition, the lighter components of the oil would begin to dissolve, and the remaining oil would disperse in the water column through entrainment and sinking of oil droplets.

Eventually, as the ice disappears, a spill will behave the same as an open-water spill (spill 4): it will spread to some equilibrium thickness and area and then undergo evaporation, emulsification, dissolution, and dispersion as in temperate waters. However, the physical and chemical nature of these processes indicates the rate of weathering will be significantly decreased at the arctic temperatures. In fact, heavy or extensively weathered oil may solidify, and further slow down these processes.

Finally, if the oil persisted until freeze-up, or the spill occurred at freeze-up (spill 5), the oil would rise to the surface of the grease ice and be pumped laterally onto the surface of pancake ice. Thus the oil would be confined to the surface or upper few centimeters of the young first-year ice. Again the oil would be subjected to slow weathering, mixing

with snow, and inclusion within the ice throughout the winter. Portions of the oil spill would undoubtedly persist until the spring thaw.

15.2 DEVELOPING SPILL RESPONSE SYSTEMS

It is clear from the various possible evolutions of an oil spill in arctic waters that personnel involved in cleanup operations can be faced with a variety of situations. Conducting successful cleanup operations will require implementing a comprehensive spill response effort tailored to the specific oil-ice configuration. Such a comprehensive effort will include several specific response functions; namely, detection, surveillance, containment, recovery, temporary storage, transfer, disposal, logistics, ancillary support, and emergency evacuation.

The first function is detection, whereby a yes/no response to the presence of oil is obtained. A positive signal from an oil spill detection sensor therefore serves to initiate the spill response effort.

The second function is surveillance. The surveillance subsystem must be capable of monitoring the movement of the oil spill and the progress of the spill response effort. The three parameters which are most important to the surveillance effort are the areal extent of the oil, regions of high oil concentration, and the drift of the spilled oil. This information is required for command and control to direct the spill response effort in an effective and efficient manner. Knowledge of the areal extent and drift of the spilled oil is required for the efficient placing of containment devices and the implementation of protective measures. The identification of regions of high oil concentration assists in the effective placing of oil spill recovery equipment.

The containment function includes those initial actions of the spill response, to first stop the release of oil from its source, and second, to limit the spread of the oil through the use of containment devices. The use of containment booms to gather the oil into a thicker layer generally results in more effective oil spill recovery operations.

The recovery function is concerned with the removal of spilled oil from the environment. Generally, the recovery function refers to the physical removal of spilled oil, such as through the use of a mechanical recovery device, after which there is an independent disposal function associated with the final disposal of the spilled oil. However, there are other techniques which are commonly called recovery techniques, but which inherently include both the removal and disposal of the oil, such as *in situ* burning.

The storage function generally consists of some form of temporary storage, usually as a buffer between the continuous oil recovery operation and the discontinuous oil disposal operation. The storage function can be separated into two stages: (1) immediate storage of the recovered oil for 3 days or less, and (2) temporary secure storage, for more than 3 days to 1 year.

The disposal function is concerned with the disposition of the oil and the associated contaminated material recovered from an oil spill, in an environmentally safe and acceptable manner.

The logistics function provides for the movement, maintenance, and disposition of equipment, supplies, facilities, communications network, and any other services required for the support of the spill response effort. Because of the remoteness of the arctic regions and harsh environmental conditions for response operations, the logistics function is a major consideration in arctic oil spill response.

The major ancillary subsystems related to an arctic oil spill response system include weather forecasting, ice forecasting, spill behavior prediction, and the establishment of temporary navigational aids for support aircraft and vessels.

Finally, the emergency evacuation function provides for the immediate evacuation of personnel from hazardous ice conditions and affords access to medical facilities.

In designing an arctic spill response system, or in evaluating any proposed system, it is critical to use this comprehensive systems approach. Extensive development and refining of any specific function without attention to the other functions is likely to produce a response system of limited effectiveness.

15.3 PREVIOUS TECHNOLOGY ASSESSMENT EFFORTS

In 1977 the Coast Guard Office of Research and Development commissioned ARCTEC, Inc. to undertake a study to determine the optimum arctic oil pollution response system package through the application of cost effectiveness analysis techniques to selected oil spill response scenarios for Alaskan waters. The study (Schultz *et al.* 1978) examined six spill scenarios which were selected so as to encompass the majority of spill and environmental conditions likely to be encountered in coastal and offshore Alaska. These six scenarios consisted of the rupture of a subsea gathering pipeline in the

nearshore Beaufort Sea, an oil well blowout from a very large reservoir in the nearshore Chukchi Sea, crude oil tanker casualties in Norton Sound and in the Navarin Basin region of the Bering Sea, an oil well blowout from an average-sized reservoir in Bristol Bay, and a fuel oil spill resulting from the collision of a fuel oil barge in Unimak Pass (Fig. 15.2). Response scenarios were then developed for each of the spill scenarios. For each of the first five spill scenarios, three levels of response capability (25%, 50%, and 80% of oil recovered) were considered. A single level of response (25%) was considered for the Unimak Pass spill scenario. The manpower and equipment associated with these 16 spill response scenarios formed the basis for development of alternative arctic oil spill response systems. Tables 15.1-15.4 summarize response techniques for four of these scenarios at each response level (25%, 50%, and 80%). Although only one of these spill scenarios is in the Beaufort Sea, they all represent spill situations which may occur in the Beaufort Sea at a specific site during a specific season.

Alternative arctic spill response systems were developed on the basis of cost effectiveness after grouping common response situations and techniques: those for thick, stable, level ice; dynamic, hummocky ice; and open water and light ice (Table 15.5). Six alternative systems were defined, such that response capability extended from a minimum response level of 25% in all six scenarios to a maximum of 80% in all but the Unimak Pass scenario, where 25% was considered the maximum attainable level. The optimum system, as defined by the cost effectiveness analysis, resulted in the capability to respond at the 25% level to the Norton Sound, Navarin Basin, Bristol Bay, and Unimak Pass scenarios. In terms of the response situation in Table 15.5, this capability corresponds to a 50% response for thick, stable, level ice conditions, and a 25% response for the remaining conditions.

Several major conclusions of a general nature were drawn from development of the scenarios:

1) There can at present be a substantial degree of capability for responding to spills in ice-infested waters. This potential capability results

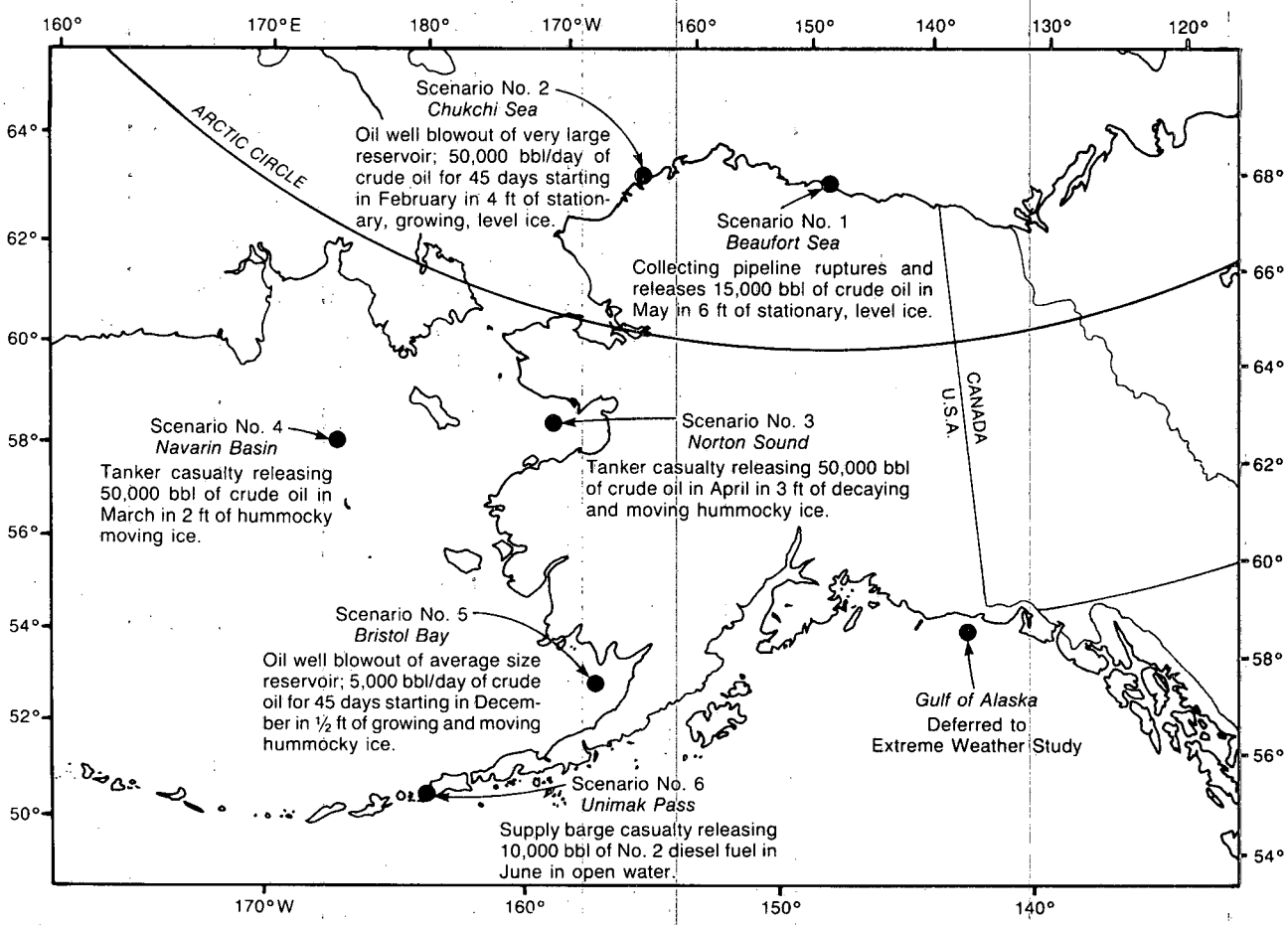

Figure 15.2—Summary of selected oil spill scenarios in Alaskan waters. (Adapted from Schultz *et al.* 1978.)

Table 15.1—Summary of preferred spill response techniques for the Beaufort Sea Scenario (Schultz *et al.* 1978)

Function	25% Response Level	50% Response Level	80% Response Level
Detection	Monitor pressure and flow rate	Same	Same
Surveillance	Diver observation beneath ice	Same	Same
Containment	Natural under-ice topography	Natural under-ice topography	Natural and open-water booms
Recovery	Drill holes in ice to gain access, burn *in situ*	Same plus divers flush thinly spread oil to collection holes	Same plus accelerate ice deterioration and skim oil from open water
Storage	None	None	150 bbl floating bladders
Transfer	None	None	Conventional pumps
Disposal	Burn *in situ*	Burn *in situ*	Burn *in situ* with open-flame burner
Logistics	Prudhoe Bay to slope camp to spill site, ice road, fixed-wing aircraft, helicopter	Same	Same
Ancillary	Weather and ice forecasts, marking beacons, communications equipment	Same	Same
Emergency Evacuation	Dedicated helicopter, personnel emergency beacons	Same	Same

Table 15.2—Summary of preferred spill response techniques for the Chukchi Sea Scenario (Schultz *et al.* 1978)

Function	25% Response Level	50% Response Level	80% Response Level
Detection	Observation by operating personnel on drill rig	Same	Same
Surveillance	None	None	Drill holes in ice to determine presence or absence of oil
Containment	Natural under-ice topography	Same	Same
Recovery	Gain access to oil through natural processes, burn *in situ*	Same	Same
Storage	None	None	None
Transfer	None	None	
Disposal	Burn *in situ* after blowout is arrested	Burn *in situ*, start while blowout is underway	Same
Logistics	Through Ft. Wainwright to spill site, construct ice landing strip near site for Hercules aircraft, all support facilities flown in	Same	Same
Ancillary	Weather and ice forecasts, marking beacons, communications equipment	Same	Same
Emergency Evacuation	Dedicated helicopter, personnel emergency beacons	Same	Same

Table 15.3—Summary of preferred spill response techniques for the Norton Sound spill scenario (Schultz *et al.* 1978)

Function	25% Response Level	50% Response Level	80% Response Level
Detection	Visual observation by ship's crew	Same	Same
Surveillance	None	Drill holes in ice to determine presence or absence of oil	None
Containment	Natural under-ice topography	Same	Same
Recovery	*In situ* burning	Drill through ice to oil pools and remove oil by direct suction	Special oil/ice recovery vessel
Storage	None	Portable bladder tanks	Special oil/ice recovery vessel
Transfer	None	Portable pumps	Special oil/ice recovery vessel
Disposal	Burn *in situ*	Burn *in situ* with open-flame burner	Special oil/ice recovery vessel
Logistics	Helicopter transportation from Nome to spill site	Same Plus use of icebreaker or tanker as field base, helicopters between Nome and spill site	Same plus getting special oil/ ice recovery vessel
Ancillary	Weather and ice forecasts, marking beacons	Same	Same
Emergency Evacuation	Dedicated helicopter, personnel emergency beacons	Helicopter and paramedical facilities of icebreaker	Same as 25% level

largely from the application of currently available hardware and equipment in novel ways. Therefore, while much of the equipment composing the optimum arctic pollution response system is available, the techniques for applying the equipment to the spill response effort in ice-infested waters are often new.

2) Although significant research and development effort would have to be devoted to new equipment for optimum arctic pollution response systems, the greatest effort would have to be devoted to evaluation of equipment alternatives and demonstration of the proposed spill response techniques in both laboratory and field test programs.
3) The type of oil spilled and the environmental conditions surrounding the spill place practical limits on oil spill response capability. These are the major factors which affect the loss of portions of the spilled oil due to natural processes such as evaporation and dissolution in the water column, which in turn, determines the amount of recoverable oil remaining at any particular time.
4) The presence of continuous and discontinuous ice features in the oil spill situation both hinders and helps the response effort. In spill response operations conducted in light ice where the spill response effort closely parallels that for open-water conditions, the presence of ice clearly hinders the spill response operation. In situations where there is a substantial thickness of stable ice cover, the ice cover is helpful in that it serves as a base of operations for heavy equipment used in the spill response effort. In addition, the ice provides for natural containment of oil in the under-ice surface relief.
5) The optimum arctic oil pollution response system incorporates both equipment which is used in all three types of spill response, and equipment which is used in only one type of spill response. The oil spill scenarios were selected to be representative of a range of environmental conditions and spill situations. Noncharacteristic conditions require the application of unique equipment and techniques rather than universal response equipment and

Table 15.4—Summary of preferred spill response techniques for the Bristol Bay spill scenario (Schultz *et al.* 1978)

Function	25% Response Level	50% Response Level	80% Response Level
Detection	Abnormal well-pressure readings and visual observation	Same	Same
Surveillance	Visual observation from aircraft during daylight and good weather	Same plus remote electronic devices to extend operations into periods of darkness	Same plus remote electronic devices to extend operations into periods having decreased visibility
Containment	Sweeping with conventional heavy duty containment booms in open-water regions	Same, but two systems	Same
Recovery	Conventional open-water devices having ice processing capability	Same, but two systems	Same plus special oil/ice recovery vessel plus shore-fast ice edge recovery system
Storage	Barge	Barge	Same plus onboard storage of special vessel plus open-top containers for ice edge
Transfer	Conventional pumps having some solids-passing capability	Same	Same
Disposal plus disposal system of special vessel	Open-flame burner	Same	Same
Logistics	Port Heiden as staging area for marine operations	Same	Same
Ancillary	Weather current and ice forecasts, spill behavior prediction model	Same	Same
Emergency Evacuation	Dedicated helicopter, personnel emergency beacons	Same	Same

techniques. The optimum arctic oil pollution response system is therefore a combination of several types of response systems which takes advantage of equipment commonality where it exists.

15.4 TECHNOLOGY ASSESSMENT FOR THE BEAUFORT SEA

A rigorous assessment of oil spill response system technology for the Beaufort Sea will probably require a study similar to the previous effort, updated to the current technology and focusing specifically on the Beaufort Sea. However, in the interim, it is perhaps possible to extrapolate the general approach and some of the information from the previous study to the present problem, recognizing that the three ice condition groupings, as summarized in Table 15.5, generally encompass the oil-ice configurations outlined in Figure 15.1. Table 15.6 is an attempt to extract some of the information from the earlier research, updated with some recent developments, and define the possible techniques for each type of response situation that may be encountered in the Beaufort Sea. A general description of the response strategy and some general comments on each are as follows.

15.4.1 Response in Thick, Stable, Level Ice

The general response strategy for thick, stable, level ice is to locate the oil trapped in pockets under the ice, gain access to the oil through drilling, and burn the oil either *in situ* in the pools where the oil rises or through transfer to a high-volume flar-

Table 15.5—Oil spill response groupings for the Beaufort Sea

GROUP I:	Thick, stable, level ice. A release of oil beneath thick, stable ice results in a degree of spill containment in the rough or undulating under-ice surface features. The thick ice prevents ready access by most marine vehicles, but also provides a working platform for heavy land-type construction vehicles. The response effort is primarily concerned with gaining access to the oil trapped beneath the ice by working on the ice surface.
GROUP II:	Dynamic, hummocky, ice. A release of oil in a hummocky, moving ice-field requires a primarily marine-vessel-oriented response, but operations may be possible on the ice surface. Depending on the ice field dynamics, the released oil at some point in time will be incorporated in discontinuous ice features, such as hummocks and pressure ridges, at which point recovery becomes extremely difficult, and is judged to require the use of a specialized vessel.
GROUP III:	Open-water or light ice-conditions. This type of response is characterized by a generally open-water spill behavior. Response efforts must be exclusively marine-based and oriented toward the recovery of oil from the surface of water. The light ice-conditions eliminate the possibility of ice-based response methods, and complicate the application of open-water spill recovery techniques and equipment.

ing device. A primary problem is locating the oil. Possible surveillance techniques include reconnaissance drilling through the ice, placing divers under the ice, remote sensing from the surface or under the ice, and using cameras mounted on remote-controlled submersibles. The most promising technique is remote sensing; reconnaissance drilling is labor intensive and provides limited coverage, diving raises a number of safety problems, and remote-controlled submersibles under ice represent a new technology. Future surveillance efforts will probably focus on the development of both electromagnetic and acoustic techniques for detecting oil under ice.

For the most part, containment is provided by the natural under-ice and surface relief. Additional containment around a potential spill site could be provided by altering the under- and above-ice topography. For instance, building ice dikes around drill sites (using a water gun) would provide for effective surface containment. Placing insulation or piling snow on the surface of the ice would retard ice growth locally and provide for under-ice containment. In stable ice it could be possible to cut trenches in the ice and insert deep-draft containment booms.

The response function involves gaining access to the oil and disposing of it through burning. The technology for accomplishing this is already available through the development of rapid drilling techniques, air-deployable incendiary devices, and high-volume flaring burners. For small spills close to shore, physical recovery of the oil from the ice and removal from the site may be more practical.

The logistics, ancillary, and emergency functions provide support services for equipment and personnel on the ice. On thick, stable, level ice these functions are simplified in that the ice provides a stable operating base for personnel and equipment, and a landing platform for aircraft. In nearshore areas, access to the spill site can be provided by ice roads.

15.4.2 Response in Dynamic, Hummocky Ice

Dynamic, hummocky ice is probably the most difficult response situation. Oil spilled in this environment is incorporated underneath, within, and on the surface of the broken ice. Finding the oil, separating it from the ice, and disposing of it require more effort than for spills involving level ice or open water. Locating oil on the surface may be possible through visual observation or airborne remote sensing. Locating the oil within or underneath the ice is not easy. Drilling in broken ice is difficult, diving under it is dangerous, and remote sensing techniques are generally ineffective due to scattering of the detection signal. The use of remote-controlled submersibles offers some promise, but this is a new concept which will require some development.

Containment in this situation is provided by the broken ice features. Additional containment in brash ice in a lead or in a ship's track may be provided by a water-jet containment system.

The recovery, storage, transfer, and disposal of the oil are complicated by having to gain access to the oil and separate it from the broken ice. Drilling in areas of known high oil concentration and burning the oil *in situ* or with a high-volume flaring device may provide a limited response. However, greater levels of response will probably call for some type of dedicated oil-in-ice recovery vessel. The original conception of this vessel was that it would break up the ice in the ship's path, process the oiled

Table 15.6—Oil spill response systems for the Beaufort Sea

Function	Thick, Stable, Level Ice	Dynamic Hummocky Ice	Open Water or Light Ice
Detection	—Monitor pressure, flow loss —Observation on drill rig —Observation by ship's crew	Same	Same
Surveillance	—Drill holes in ice —Divers under the ice —Remote sensing (electromagnetic or acoustic) —Remote-controlled submersible	—Drill holes in ice —Divers under ice —Remote-controlled submersible	—Visual from vessels —Visual from aircraft —Airborne remote sensing
Containment	—Natural under-ice topography —Man-induced topography —Trenching and deep booms	—Natural ice features —Water jet systems	—Sweeping with conventional heavy duty booms in open-water regions
Recovery	—Drill holes, collect oil, burn *in situ* on surface —Drill holes, pump out oil, flare or remove from scene —Trenching, pump out oil, flare or remove from scene	—Drill holes, burn *in situ* —Drill holes, pump out oil, flare or remove from scene —Oil/ice recovery vessel	—Conventional open-water devices having ice-processing capability inherent or added
Storage	—Tanks on sleds —Bladders on sleds	—Portable bladders —Oil/ice recovery vessel	—Barge or tank vessel —Oil/ice recovery vessel
Transfer	—Portable high-viscosity pumps	—Portable high-viscosity pumps	—Conventional pumps —Pumps having some solids-passing capability
Disposal	—Burn *in situ* with incendiary devices —High-volume flaring device —Shoreside disposal	—Burn *in situ* with incendiary devices —High-volume flaring device —Oil/ice recovery vessel and shoreside disposal	—Use dispersants —High-volume flaring device on ship or barge —Tank vessel and shoreside disposal
Logistics	—Ice road from shore —Heavy-lift helicopters —C-130 fixed-wing aircraft —Icebreaker	—Heavy-lift helicopters —Icebreakers —Oil/ice recovery vessel	—Marine vessels with some ice reinforcing —Air-deliverable pollution response equipment
Ancillary	—Weather and ice forecasts —Marker beacons —Communications —Spill-behavior model —Shelter for personnel	—Weather and ice forecasts —Marker beacons —Communications —Spill-behavior model	—Weather forecasts —Trajectory forecasts —Communications —Spill-behavior model
Emergency Evacuation	—Dedicated helicopters and fixed-wing aircraft —Personnel emergency beacons —Icebreaker standing by	—Dedicated helicopters —Personnel emergency beacons —Icebreaker standing by	—Dedicated helicopters —Marine vessels

ice on board to remove the oil, and return the ice to the water. A more recent concept, developed by Schultz and Zahn (1982), involves outfitting a conventional icebreaking supply ship with conventional dynamic oil mop and skimming devices modified for recovery in ice. The vessel would also serve as a landing platform for helicopters deploying incendiary devices. The recovered oil could either be stored on the ship or flared on board using a high-volume flaring device. This concept would also cover the logistics and emergency evacuation functions that would have to be provided by an icebreaker in any event.

15.4.3 Response in Light Ice or Open Water

The response strategy for spills in light ice or open water is similar to that used in temperate waters: the oil is concentrated and recovered, or dispersed. The oil is located and the extent of the spill defined through visual observations from vessels and aircraft, and also through airborne remote sensing. Containment and recovery are accomplished in the open water and lighter ice areas by using heavy duty booms and skimmers modified to operate in ice (such as the ARCAT skimmer). In areas of heavier ice concentration where the ice provides containment, a smaller version of the oil-in-ice recovery vessel described above could be employed. The recovered oil could be transferred to a barge or tanker, or flared on the scene using a high-volume device. Logistics would be provided by marine support vessels.

15.5 CONSIDERATIONS FOR FUTURE DEVELOPMENT

Additional research is needed to refine current response techniques and better adapt them to arctic conditions, and to expand the current technology to insure the long-term upgrading of our response capabilities.

Efforts to refine and adapt the current technology will focus on laboratory and field tests of existing methods and equipment. Here again, these tests should be planned and conducted using the total systems approach. In order to attain a balanced response system, emphasis should be placed on the least-developed response functions. For instance, the disposal function for thick, stable, level ice is fairly well developed, with both high-volume flaring burners and air-deployable incendiaries already tested and available. However, the surveillance function for oil under ice still requires further development. Although several promising prototype oil-under-ice detection systems are under development, none can be considered field operational at this time. Our success in developing disposal techniques will be of little value if we cannot develop a technique for locating the oil.

In addition to further developing current techniques, a concerted research and development effort should continue in both government and industry to explore new techniques for arctic spill response. Technological achievements in petroleum exploration and production in the arctic clearly demonstrate that although the problems of operating in the arctic are formidable, they are by no means insurmountable. What is needed is a long-term effort which ensures that the level of technology applied to petroleum development is also applied to oil spill response.

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Chapter 16
Arctic Marine Oil Spill Research

by H. R. Hume, I. A. Buist, D. A. Betts, and R. H. Goodman

When northern nations began to develop the hydrocarbon potential of their arctic and subarctic regions, it became apparent that oil spill countermeasures used in temperate and tropical waters were unsuitable for colder northern waters. Ice and icebergs, cold sea and air temperatures, and fluctuating salinities all severely limited existing southern oil spill technology.

This chapter reviews the work done by Canadian government agencies, industry, and academics to understand and minimize the impact of hydrocarbon spills in the northern environment. The first section summarizes the historical and organizational contributions to the oil spill research. The major portion of the chapter covers the various research themes that have been pursued by Canadian organizations, and the final section summarizes areas of future research.

Similar research is being undertaken by the United States, Norway, the U.S.S.R., and Great Britain. There are strong affiliations between Canada and the United States in oil spill research in offshore Alaska and the Yukon to prevent duplication of effort and to share information. The United States, Norway, and Great Britain are currently participating in a major research project in Canada's eastern Arctic.

Arctic oil spill research in Canada has been undertaken by the federal government through the Arctic Marine Oilspill Project. Joint oil industry and government research includes the Beaufort Sea Project and the Baffin Island Oil Spill Project. Oil industry research has been done by individual companies such as Dome Petroleum in the Beaufort Sea, or cooperatively through the Arctic Petroleum Operators Association and its research group, the Canadian Offshore Oil Spill Research Association.

16.1 OIL SPILL RESEARCH PROGRAMS IN ARCTIC CANADA

Various government and oil industry agencies have conducted arctic marine oil spill research in Canada, both individually and jointly since 1970. Oil industry research, unless it involves commercial advantage, is normally done cooperatively both to share the cost and to overcome the problems of confidentiality when done in isolation. The major exception was work conducted by Dome Petroleum in the mid-1970's where because their offshore drilling activities were ahead of the rest of the industry in the western arctic, they were obliged to conduct research in isolation. Joint research projects were done initially through APOA for arctic research, where interested companies shared the cost. More recently, joint projects have been done through COOSRA, where the cost is spread across the entire offshore oil industry. The arctic oil spill research arm of government has been AMOP since 1977.

The larger research projects, because of the high costs involved, have been done jointly by government and industry (*e.g.*, the Beaufort Sea Project and BIOS Project).

16.1.1 Arctic Marine Oilspill Program

In 1977, following the government decision to allow drilling for oil in the Canadian Beaufort Sea, the Department of the Environment initiated the $7.5 million Arctic Marine Oilspill Program (AMOP) to develop oil spill countermeasures for ice-infested waters. The 8-year program is managed by the Environmental Protection Service (EPS), Environment Canada, with the assistance of an interdepartmental committee of government and oil industry specialists.

AMOP consists of engineering projects in such areas as oil spill recovery and containment devices, combustion and incineration systems, dispersant equipment and strategies, remote sensing equipment, and shoreline cleanup methods. AMOP also studies the fate and physical effects of oil and the movement and behavior of spills in ice-infested waters. Finally, AMOP includes biological assessment, particularly that related to spill-treating agents such as chemical dispersants.

Presently, approximately 100 projects have been conducted under contract by consultants, university researchers, and government scientists, and most of this work is performed by private companies. Much of the work is jointly funded by other government agencies, by the oil industry, and sometimes by other arctic nations.

AMOP reports are published as government technical reports, which are often summarized in the *Spill Technology Newsletter.* Also, project updates are provided at annual AMOP seminars, which are an international review forum. Appendix B lists published AMOP research reports.

16.1.2 Beaufort Sea Project

The Beaufort Sea Project was a set of studies jointly funded and managed by government and the oil industry that investigated wildlife, marine life, oceanography, meteorology, sea ice, and oil spill countermeasures. When the federal cabinet granted Approval-in-Principle for exploratory drilling in the Beaufort Sea in 1973, it stipulated that the Drilling Authority would be issued subject to operating conditions developed by this project.

The oil spill studies were based on a need to react to a large blowout in which thousands of tonnes of oil could escape into the ice-infested sea and could continue for a year or longer. Innovative work was conducted on the underwater dynamics of a blowout plume (Topham 1975). Results of these studies have been published in the *Beaufort Sea Project Technical Report Series* and in the APOA reports, series 72 (Appendix A). Ross *et al.* (1977) have also summarized this work.

16.1.3 Baffin Island Oil Spill Project

In the late 1970's AMOP undertook responsibility for identifying and coordinating research into experimental oil spills in cold waters. Some of this research was integrated into a single 4-year project called the Baffin Island Oil Spill (BIOS) Project.

This $5 million project is administered by the Environmental Protection Service, and directed by an international management committee of representatives of the funding agencies. These include the Canadian Offshore Oil Spill Research Association, Department of the Environment, Department of Indian and Northern Affairs, Department of Fisheries and Oceans, Canadian Coast Guard, U.S. government, Norwegian government, and British Petroleum.

The primary project objectives are to determine whether the use of chemical dispersants in the arctic nearshore marine environment will reduce or increase the environmental effects of spilled oil, to assess the fate of spilled oil, and to compare the relative effectiveness of other shoreline protection and cleanup techniques.

The site of the BIOS Project is Cape Hatt, Baffin Island. Baseline environmental information was collected throughout the study area in 1980. In the summer of 1981, one small bay was treated with an experimental oil slick, two bays were treated with different subsurface doses of oil and dispersant mixture, and another bay remained an uncontaminated control. During the springs of 1981 and 1982, the effects of oil and chemical treating agents on the under-ice biology were examined. Monitoring will continue until 1984 on the physical and chemical fate of oil and on its biological effects. Besides dispersants, other experimental shoreline protection and cleanup techniques are being evaluated on nearby beaches.

Technical reports are published annually and the research is discussed at annual BIOS Project workshops. Final reports will be available in 1985.

16.1.4 Dome Petroleum Ltd.

Before starting its drilling program in the Beaufort Sea in 1976, Dome Petroleum Ltd. undertook an oil spill research program to develop appropriate oil spill countermeasures. Besides developing containment, recovery, and disposal techniques and systems for the Beaufort Sea, Dome initiated studies in the areas of contingency planning, *in situ* burning, tracking and monitoring, shoreline protection and cleanup, and bird and wildlife protection techniques. Research is conducted every year to develop new technologies and to improve the existing oil spill cleanup capabilities in the Beaufort Sea. Recently, much of this work has been done through the Arctic Petroleum Operators Association and the Canadian Offshore Oil Spill Research Association.

16.1.5 Arctic Petroleum Operators Association

The Arctic Petroleum Operators Association (APOA) was formed in 1970 to coordinate arctic research and avoid duplication of effort (Hnatiuk *et al.* 1980). APOA's area of concern reaches from the Alaska-Yukon border across the arctic archipelago to Davis Strait.

Much of APOA's research involves environmental and engineering studies. Together with the Eastcoast Petroleum Operators Association (EPOA), APOA conducted a series of oil spill studies from 1970 to 1979. These are listed by Pallister (1982) and are available in photocopy or microfiche. Appendix A lists APOA research projects.

Since 1980, the APOA/EPOA Oil Spill Committee has limited its activities to operational and contingency planning, while oil spill research has been undertaken by a specialized research agency, the Canadian Offshore Oil Spill Research Association.

16.1.6 Canadian Offshore Oil Spill Research Association

The Canadian Offshore Oil Spill Research Association (COOSRA) was formed in 1980 as the oil spill research arm of the Arctic Petroleum Operators Association and the Eastcoast Petroleum Operators Association. Initially it was to provide the oil industry's contribution to the Baffin Island Oil Spill Project.

COOSRA originally had 16 full members and two associate members; one associate has since become a full member. Each member's costs are shared on the basis of offshore acreage and drilling days for each year. Membership in COOSRA overcomes the problems of confidentiality and duplicated research effort that could hamper spill research.

COOSRA has a technical advisory committee of approximately 12 members who review all research proposals, assess priorities of projects, and assign a regional applicability factor to each project for assessing an individual company's cost share. The recommendations of the technical advisory committee are then passed to a management committee, and finally to a members' committee for acceptance or modification.

All COOSRA projects to date have been either wholly or partially applicable to the arctic. Appendix C lists COOSRA projects from 1980 to 1982.

The above organizations have individually and in combination funded arctic marine oil spill research from the early 1970's up to the present. Since the mid-1970's, there has been a conscious effort to coordinate government and industry research in order to prevent duplication, and to approach oil spill research in a systematic manner. One of the major advantages Canada has in this field of research is the close working relationship between government (federal, provincial, and territorial), oil industry, and academic operational and research personnel. Although a complete systems approach to oil spill research in arctic waters has not been achieved, the following section describes the main categories of research themes that have been pursued to date.

16.2 OIL SPILL RESEARCH THEMES

Arctic marine oil spill research since the early 1970's has followed several well-defined themes. These include fate and behavior studies, which help to improve the effectiveness of countermeasures such as monitoring and surveillance, mechanical containment and recovery, combustion, subsea containment, shoreline cleanup, and chemical dispersants.

Initially, mechanical containment and recovery was the only proven technology for open water. However, such definite countermeasures are ineffectual in high seas and in ice-infested waters. Since the mid-1970's, considerable progress has been made in improving combustion and shoreline cleanup techniques and in reducing dispersant toxicity. Major efforts are currently underway in the recovery of oil from ice, in more effective cold-water dispersants, in chemical solidifying agents, and in designing and testing feasible subsea containment systems.

16.2.1 Fate and Behavior of Spilled Oil

A basic understanding of oil, its chemical and physical changes, and its interaction with open water and ice is of primary importance for spill response. Both mechanical recovery and chemical dispersion depend upon the nature of the oil. Since the behavior of an oil slick is highly dependent on the type of oil and ambient climatic conditions, studies have been carried out on both under-ice and open-water conditions.

Ice Conditions

Much effort has been devoted to the fate and behavior of oil under sea ice, commencing with the Beaufort Sea Project. One study in a small bay southwest of Cape Parry, N.W.T. (NORCOR 1975) involved nine controlled discharges of approx-

imately 45 m^3 of two types of crude oil under fast ice at various stages of growth. Fundamental data on the interaction of oil with arctic ice were collected to study the mechanics of transport, the area of contamination, and albedo modification. Rosenegger (1975) studied the mechanics of movement of oil in ice-covered water in the laboratory. Results of these two studies are as follows:

1. Throughout the winter, oil penetrates only 5-10 cm into the loose skeletal layer on the bottom of an ice sheet.
2. Penetration of the oil into the ice sheet is not normally expected until brine drainage channels are open.
3. The oil's effect on ice growth tends to be relatively insignificant in comparison to natural variations.
4. The equilibrium thickness of two crude oils under ice was 0.80 and 0.88 cm.
5. Oiled areas are likely to be free of ice 1-3 weeks before the gross failure of the sheet.
6. Data enabling calculation of minimum currents required to move an oil bubble were presented.

These studies recommended that further work be carried out on the weathering and degradation of oil, entrainment and migration of oil in multiyear ice, the effect of oil on sea ice formation, the pumping action of leads that open then close, and ice movement.

Walker (1975) discussed the effects of a blowout on the arctic ice. He concluded that the formation of ice would not be much delayed, because wind would push oil into leads and these would be quickly covered over by snow. In late 1982, COOSRA will study oil in pack ice to understand the mechanisms of oil moving in leads to simulate freeze-up and breakup conditions.

Milne *et al.* (1977) found that the porosity of multiyear ice was 0.2% to 0.03% and anticipated that most, if not all, of any light to medium crude oil trapped in and under multiyear ice would migrate upward through the ice. In another study of the fate of oil in multiyear ice, the mean maximum thickness of oil was 0.6 cm if gas venting occurred (NORCOR 1976b).

The spreading of oil beneath sea ice depends on the undersurface characteristics and oil and gas effects. Purves (1978) explained that the configuration of the ice/oil/gas/water system that will be energetically favored would be determined by various interfacial tensions. Purves concluded that oil layers as thin as 0.2 cm would probably occur when well blowout products accumulate under ice. The presence of gas would greatly increase the area contaminated, but would have little or no effect on the timing of release of oil trapped under first-year ice. The time of release of oil and gas might be predicted by ice thickness, salinity profile, and meteorological data.

In the winter of 1979-80, Dome Petroleum Ltd. (1981a) simulated an oil and gas blowout under shorefast ice near McKinley Bay, N.W.T. The major study objectives were to (1) understand further how oil and gas behave when discharged under ice, (2) investigate water-in-oil emulsion formation, (3) field test the effectiveness of *in situ* burning of oil on sea ice, and (4) assess the capability to clean up a blowout under ice. Oil formed buoyant droplets that adhered to the undersurface of the ice. Oil discharged under new, flat, December ice occurred mainly as droplets, but oil released in April and May collected in pools in undulations beneath the ice. The amount of gas released greatly affected the area of the ice undersurface contaminated by oil. Oil was encapsulated by the growing ice sheet within 24-48 h. A sample of oil from the undersurface of the ice showed loss of lighter fractions up to C^{12}. This loss was due to the interaction between air and oil, but would not take place during a real blowout. *In situ* burning efficiencies averaged 80%.

Oil released in moving sea ice has a very different fate from oil under stable fast ice. A 7,000-ton bunker-oil spill off Nova Scotia in March 1979 left an average oil-in-ice concentration of 100 ppm (Reimer 1980). Due to large-scale mixing, the oil was dispersed into progressively smaller particles, so that burning and mechanical removal were not feasible. Crude oils from a blowout would rise through the frazil and brash ice, and form an emulsion that would be distributed vertically as was the bunker oil.

Some years ago, there were concerns that oil pollution of arctic waters could change the earth's climate by altering the surface albedo and consequently reducing ice cover (Milne 1978). NORCOR (1975) studied the effects of entrained and free oil on the surface heat exchange. Although there were measured changes in albedo, no appreciable effect on the growth of an ice sheet was demonstrated.

Open Water

Early mathematical models of the behavior of surface oil slicks were developed by Mackay and Leinonen (1977). These have been refined to include calculations for dispersion and solution of oil

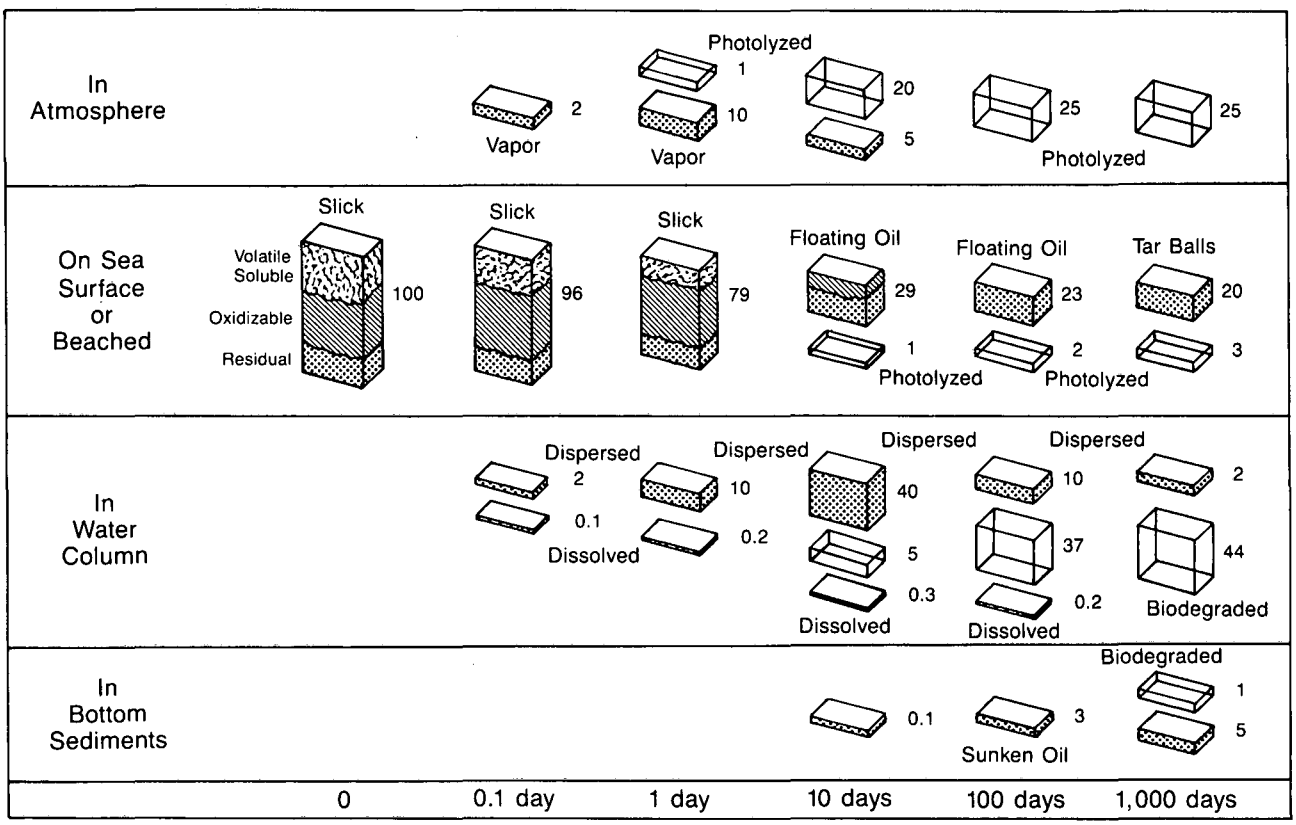

Figure 16.1—Speculative mass balance for batch spill. Empty (unshaded) boxes represent oil converted to another chemical form. (Adapted from Mackay *et al.* 1980.)

in the water column, emulsification, oil properties, and blowout versus instantaneous release conditions (Mackay and Paterson 1980a, 1980b). Figure 16.1 is a mass balance of oil on open water, illustrating the modeling attempts of Mackay and his coworkers. Spreading equations have been based on Fay's surface tension-viscosity equation. These are solved numerically to accommodate the complex behavior of oil spills. The models have a thick slick (1 mm to 1 cm) surrounded by a thin slick (1-10 μm) eight times the size (Mackay, Buist, Mascarenhas, and Paterson 1980). Allowance has been made to simulate the spreading of the thick portion of the slick to form the thinner portion of the slick. Figure 16.2 illustrates the spreading of oil on water as a function of time and volume.

Evaporation changes the properties of oil slicks, such as volatility, solubility, density, viscosity, and surface tension. Mackay and his coworkers have quantified these changes in relation to temperature, area, time, and wind speed. This work is a behavioral model that not only predicts location with time, but also incorporates weathering processes. Such modeling provides exposure data that can be linked to an ecosystem model. Tebeau (1982) has shown that these behavioral models can be used in slick trajectory models to predict the weathering of crude oil under arctic conditions.

Oil rising in a blowout plume consists of droplets 0.5-1.0 mm in diameter (Topham 1975). The hydrodynamics of the plume are controlled by the volume of natural gas. LeDrew and Gustajtis (1979) speculated on the interactions between pack ice and a hypothetical blowout plume in the Labrador Sea. They expected that, under calm conditions, the 0.5-m/s induced currents would largely prevent ice floes from crossing the wave ring at the top of the plume. During turbulent conditions, however, the wave ring would be covered by ice, and the oil would become entrained in a variable mixture of water and ice.

The importance of understanding why certain oils form emulsions and their rate of water uptake was illustrated by the Ixtoc I well blowout, where countermeasures for recovering the oil were severely limited by the changing properties of oil-water emulsion.

The tendency of oil to form water-in-oil emul-

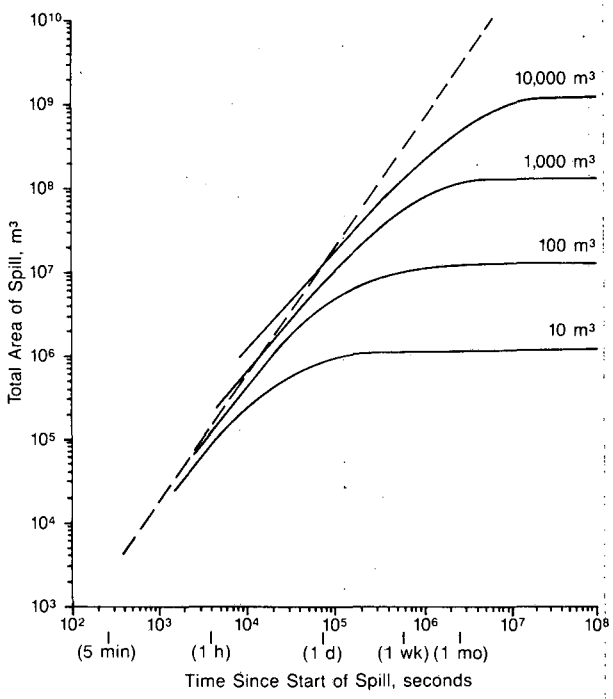

Figure 16.2—Area versus time per spill volume. (Adapted from Mackay *et al.* 1980.)

sions has been studied by Mackay and Zagorski (1981, 1982). It has been hypothesized that the turbulent mixing within a blowout causes emulsions to form. Mackay suggests that the presence of certain chemical compounds influences the stability of an emulsion. Stability is hypothesized to be controlled by a combination of wax and asphalt content (Fig. 16.3).

Shorelines

During the BIOS experiment, 15 m³ of oil were spilled into one test bay and 15 m³ of dispersed oil in others. The bulk of the untreated oil washed ashore on a rising tide and the remaining oil was mechanically collected from the water surface. Preliminary results (D. Thornton, pers. comm.) indicate that oil concentrations of a few parts per million occur in the sublittoral sediments, perhaps as a result of leaching from the beach. Stranded oil weathered and bonded to the beach within 24 h. Photographs taken after the ice receded in the summer of 1982 show a large amount of oil still present. The dispersed oil had a small but rapid sediment penetration rate and contaminated the adjoining strait to 10 m deep within a few days.

16.2.2 Monitoring and Surveillance

Once an oil spill has occurred, one of the main concerns is a determination of the motion, size, and thickness of the spill. This information is essential to optimize spill response and to determine potential impacts on various ecological communities. A major component of any integrated oil spill mitigation package is remote sensing of the oil spill, tracking it, and predicting its motion. This information is useful to the On-Scene Commander and his support staff in the technical planning of the response, and is essential to give adequate public information concerning the spill. While remote sensing, tracking, and trajectory prediction are independent, this information is a complementary set of data for a fuller understanding of the oil spill. The problems of remote sensing, tracking, and prediction of oil spill trajectories are further complicated by the presence of ice during most of the year in northern waters.

Remote Sensing

Oil on the water surface is most readily detected by aerial reconnaissance. Should weather conditions permit, the cheapest and best method of detecting oil on the sea surface is to see it from an aircraft. Aerial reconnaissance is routinely used in most oil spill responses to give the On-Scene Commander a first quick look at the size of the oil spill and of his task. A trained observer is required because there are many other sea features that can resemble floating oil, including cloud shadows, beds of seaweed, or suspended particles in nearshore waters. The experienced observer can distinguish these features and positively identify an oil slick. However, in fog, cloud, rain, or at night, visual observation cannot be used. Such conditions occur frequently in Canadian coastal waters and darkness is prolonged during winter in arctic Canada. Canadian researchers have tried to develop an all-weather, day-and-night operational remote sensing system to detect oil spills.

The Arctic Marine Oilspill Program supported a project of the Canada Center for Remote Sensing (CCRS) to determine the most suitable integrated sensor package for Canadian requirements. Sensors included side-looking airborne radar (SLAR), UV/IR dual-channel line scanner (DCLS), laser fluorosensor, low-light-level television (3LTV), and annotated photographic cameras. Each of these sensors was independently evaluated. Subsequently, an integrated system consisting of suitable sensors and a real-time display with operator interaction was developed. The system was tested

in four experiments: around Montreal Island, the site of major refining activities; Scott Inlet, a natural oil seep in the Canadian Arctic; the Wallops Island experimental oil spill sponsored by NOAA; and the *Kurdistan* spill, which occurred in ice in the spring of 1979 (O'Neil 1982). Particular requirements for all-weather operations, detailed identification of the spill source, and operation in ice were unique features investigated under the AMOP-CCRS program.

The recommended combination of sensors is a laser fluorosensor, dual-channel line scanner, side-looking airborne radar, low-light-level television, and conventional photographic cameras with suitable filters. The output of the first three of these sensors is fed into an on-board computer system that allows analysis, displays the information, and integrates it with positional information derived from the navigational equipment aboard the aircraft. Total weight of the system, including operational personnel, is approximately 1,850 kg.

The laser fluorosensor gives a positive identification of the presence of oil, using a cross-correlation technique with previously recorded spectra. This sensor helps the operator identify the type of oil and its thickness. The dual-channel line scanner operates in the ultraviolet (300-370 nm) and infrared (8.5-12.5 nm) bands, and can discriminate between the thick and thin components of the oil. The UV channel is particularly sensitive to the sheen, while thermal differences associated with differential adsorption of solar radiation by thick oil are detected in the IR channel. Unlike the laser fluorosensor, the dual-channel line scanner only detects oil shape with some indication of thickness, and presents no information on the nature of the oil. The SLAR can be used for quick coverage of large areas. The system has been used by the U.S. and Swedish Coast Guards (U.S.C.G. 1979) and is incorporated in the Canadian system. SLAR requires a dedicated aircraft, which limits the selection of aircraft.

A 3LTV, portable video recorder, and annotated photographic cameras with suitable filters aid visual observations in difficult lighting conditions and improve the ability to discriminate between oil and other features. These two systems have been extensively developed and tested as part of the Canadian Remote Sensing Program.

The ability to detect and operate under low illumination during an oil spill is another project of AMOP. A night light, consisting of a commercially available UV light with suitable filters, aids visual detection (Fingas 1982). The system is hand portable and readily operable from a small boat. While such a system is less complex than aerial remote sensing equipment, it helps to extend the operational time of an oil spill response.

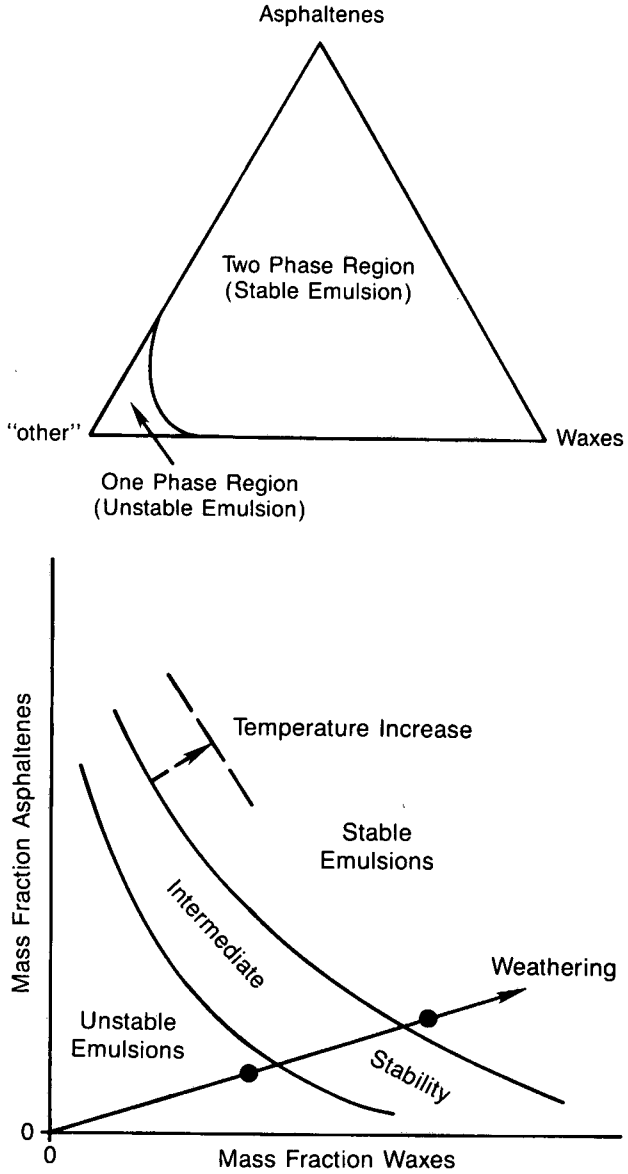

Figure 16.3—Triangular and rectangular phase diagrams showing stability regions. (Adapted from Mackay *et al.* 1982.)

Tracking

If sophisticated remote sensing equipment is not available or bad weather interferes with aircraft operation, an alternate method of tracking an oil spill is required. Initial experiments with a wide variety of drifting buoys, drift cards, plywood

sheets, and other surface tracking devices have been carried out in Canada to determine the system that follows the track of the oil accurately (Fingas and Lea 1981). This is not a simple problem, since oil may be at several depths from the surface to several meters below it, and all oil must be tracked. No single piece of equipment will follow thin oil, thick oil, and oil in the water column. A series of buoys has been developed to track the various components of an oil spill.

A 1976 AMOP study evaluated the need for various types of buoys. One capable of close support for strategic decisions and another to determine the long range trajectories were required (Goodman 1978). These two systems, a micro and a macro, were independently developed. The micro system was developed by Orion Electronics in Nova Scotia with AMOP funding. This system is a top-hat buoy containing a transmitter. The shape was chosen so the transmitter would remain in the surface sheen. This system is used in a bearing mode, and a fixed-wing aircraft or a boat is used to find the target buoy. The location is determined by the navigation system of the search vessel. Such buoys are widely used in Canada for tracking spills.

A more sophisticated system has been developed by Esso Resources Canada Limited and Orion. It uses a transmitter-receiver in the buoy and a range/bearing system, so that the location of the buoy may be determined from a single land location. The system has been tested and found effective (Roddis 1982). Both the top-hat tracking-buoy system and the range/bearing tracking systems are limited to line of sight characteristic of the operating frequencies of this equipment.

A joint industry and government experiment to determine the tracking characteristics of several buoy types were conducted by the Bedford Institute of Oceanography in Dartmouth. Various sizes of masts and a variety of buoy shapes were studied, to determine the drift characteristics of the buoys and their reaction to both wind and surface currents (MacLaren Plansearch 1982). These experiments indicate the nature of ocean surface currents and the trajectories of oil spill buoys. The measurements indicate the nature of the horizontal dispersion process and thus the accuracy of oil spill trajectories.

Oil Spill Trajectories

Canada has had a major role in the use of computer simulation to determine oil spill trajectories. Eight of the thirty-five oil spill simulation models reviewed in a recent American Petroleum Institute publication (Huang and Monastero 1982) were Canadian. Most trajectory models have three components: advection, spreading, and state of the oil. The advection component is generally physically based and uses a wind drift of 2-4% of the wind speed with a direction of 0-30° to the right of wind direction (Northern Hemisphere). Typical of these models is one developed by the Atmospheric Environment Service of the Government of Canada for use in Canadian oil spill trajectory prediction. This model uses a wind factor of 3.5 and a Markov chain for predicting future wind speeds. The model accounts for spreading, dispersion, and advection. It has been updated by a Canadian firm (MEP 1982) to include other processes and to use forecast rather than Markov-predicted winds. An ocean current component of the advection is being added.

A major research effort on the fate of oil has been led by Dr. Don Mackay (Mackay, Mascarenhas, Hassain, and McGee 1980; Mackay, Paterson, and Trudel 1980) of the University of Toronto. He has developed elaborate models for spreading theory, emulsification, natural dispersion, and other fate parameters of an oil spill. These trajectory models have been incorporated into a biological model to determine the effect of oil and oil dispersants in the marine environment (Trudel 1982). This work has been supported by both the Government of Canada and the Canadian oil industry.

The use of trajectory models for both impact assessments of oil spills and for the real-time support of an oil spill response was reviewed by a working group of federal government and oil industry scientists, consultants, and academics. This group evaluated many models for both requirements (Bedford Institute of Oceanography 1980). Suitable models were chosen for both scenario work and real-time support.

The evaluation of new models, in terms of advection, will be undertaken using the calibrated drifter buoys that were developed as part of the buoy tracking experiment.

Canada, through both the petroleum industry and government involvement, has undertaken numerous experiments in remote sensing of oil spills, tracking of oil spills using buoys, and prediction of oil trajectories in computer-based models. This information has been integrated with work in other nations to enable Canada to respond to any oil spill that might occur there. Many areas still require development, including detection of oil under and on ice, improvement of modeling capabilities in ice-infested waters, and improvement of the abili-

ty to track oil in pack ice. These are areas under active investigation by the Canadian research community, with the support of both government and industry.

16.2.3 Mechanical Containment and Recovery

Oil can be mechanically contained on the sea surface by floating barriers or booms, which prevent the spreading of an oil slick and facilitate the recovery of contained oil with devices that skim oil from the water surface. This is a tried and tested technology in temperate waters, in wave heights up to approximately 2 m.

Many boom and skimmer systems have been developed for ice-free coastal waters (Solsberg 1982). An arctic oil spill in summer open-water conditions would be similar to a spill in more temperate regions, except that low water temperature would increase oil viscosity. During winter, recovery would be severely limited by landfast ice, first-year pack ice, or multiyear pack ice. AMOP, APOA, and COOSRA have supported many projects to develop containment and recovery devices for cold, ice-infested waters. A special workshop on the recovery of oil in ice will be sponsored by COOSRA in 1982.

Ice Conditions

Problems with conventional containment booms in ice-covered waters were identified by Logan *et al.* (1975). They found that (1) most equipment had not been tested in ice-infested waters, and so it was impossible to predict its effectiveness; (2) booms with internal tension members fail by rotating on the ice; (3) booms with external tension members eventually undergo structural or mooring failure; and (4) the connectors and end plates of all booms should be improved.

Of the available skimmers, disc-drum or oleophilic belt recovery devices are the most promising for development.

The effectiveness of open-water containment and recovery devices is limited when ice concentrations exceed 10-20%. Handling, blockage, and damage to oil booms are serious problems in brash ice. Large floes make booms ineffective. AMOP developed an ice-oil boom which yields, reduces its angle to the ice, and then swings back under its restoring moment (Tsang and Vanderkooy 1979). This concept is based on the glance boom principle used by the pulp and paper industry.

Canadian Marine Drilling Ltd. (CANMAR) developed a solid flotation boom (Nadeau *et al.* 1976). This boom can contain oil in waves up to 1.5 m, and is deployed with a modified Lockheed R-2003 skimmer (Schultz 1976). The modifications include ice processing pumps (Western Canada Hydraulic Ltd. 1979), greater oil recovery ability, ice fenders, and a space heater.

Little recovery can occur in fast ice. Although trenching is successful on ice-covered rivers (Canadian Petroleum Association 1978), specialized equipment is necessary to cut through thick ice. Blasting of trenches is successful in the high Arctic (Van Ieperen 1980). Oil trenches 1-2 km in circumference can be blasted around offshore rigs in strong multiyear ice in 2-3 days. Best results are with holes drilled to within 0.7 m of the undersurface of the ice, spaced 1 m apart, and with 4.2 kg of explosive per meter of trench length.

Open Water

AMOP developed an Arctic Boom for oil recovery in remote arctic localities (Meikle 1981c). Due to requirements for light weight and minimum mechanical support systems, this boom is self-inflating (McAllister 1980). Tests of the Arctic Boom and a compacting Zoom Boom compared favorably to the VIKOMA Ocean Pack system (Purves *et al.* 1980).

A skimmer with a skimming head that moves at the same speed as the surface current was developed and tested by AMOP for cold ocean waters (Abdelnour *et al.* 1981). It will be used with the Beaufort Sea Co-op oil recovery barge, which has a separator, heat treater, and burner capable of processing 800 m^3/d (Pistruzak 1981).

16.2.4 Burning

This section discusses Canadian research and development into burning arctic marine oil spills in ice-infested waters and in cold open water. This section also discusses research to develop disposal burners for recovered oil.

Burning of Oil Entrapped in Ice

In 1976, APOA and Environment Canada studied a controlled spill of crude oil under first-year arctic sea ice (NORCOR 1975). This study found that most of the oil could be disposed of by *in situ* burning the following spring. This led to research and development studies of the *in situ* combustibility of various types of oils under arctic conditions and to the development of oil slick ignition devices.

Research on the *in situ* combustibility of spilled oil in Canada initially concentrated on only crude

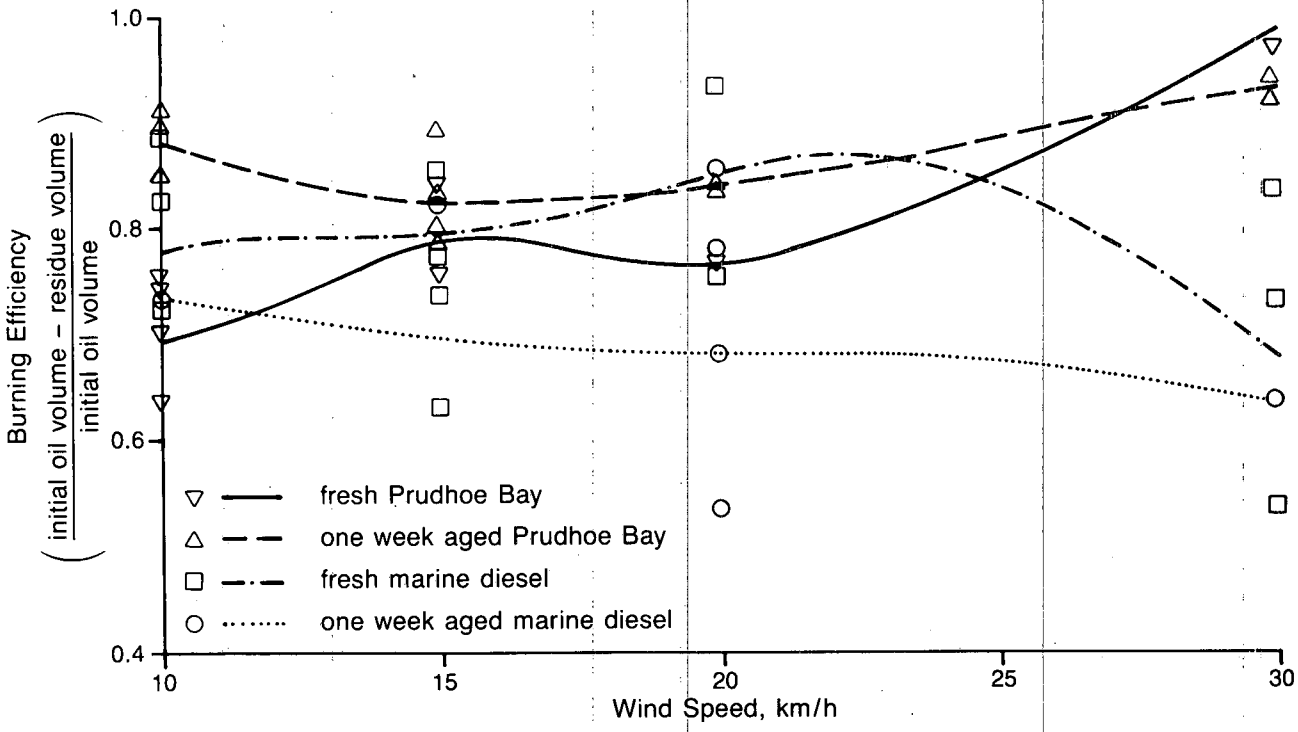

Figure 16.4—Burning efficiency at different wind speeds.

oils (Arctec 1977; Energetex 1977; NORCOR 1976a). Further work investigated weathered and emulsified crude oils and other types of oil (including diesels and bunker fuels) under simulated arctic environmental conditions (Energetex 1980a, 1981a). The major conclusions of this work were as follows. It is possible to burn oils *in situ* in ice conditions. Minimum ignitable thickness is approximately 1 mm for fresh crude oil and diesel fuel, 3-5 mm for weathered crude oil, and up to 10 mm for bunker oils and heavily emulsified crude oils. It is possible to burn oil *in situ* at wind speeds up to 45 km/h, at ambient temperatures as low as −40°C and with entrained snow and slush contents as high as 60% by weight. Burning efficiencies as high as 98% have been achieved, with an average for weathered crude oil under wind-herding conditions in the 80% range. Burning efficiency (on a volume basis) is generally lower than for fresh crude oil, for weathered oils, emulsified oils, and heavy oils. Thicker slicks burn more completely. In concentrations below 30% by weight, entrained snow increases combustion efficiency, although higher snow concentrations tend to reduce efficiency.

Figure 16.4 shows results of some research into *in situ* burning in wind.

There has also been much research into techniques to ignite oil *in situ*. These efforts have concentrated on developing devices suitable for use from aircraft. Early development focused on the selection of suitable materials for an oil slick igniter (Energetex 1977, 1978). Solid propellant was the most appropriate and reliable ignition agent. Subsequent work concentrated on the design and testing of air-deployable igniter packages (Dickins 1979; Energetex 1980b; Meikle 1981a). Figure 16.5 shows the two igniter designs selected.

Dome Petroleum Ltd. (1981a) recently simulated an oil blowout under ice in the winter of 1979-80. The oil released in this experiment appeared on the ice surface in pools the following spring. Approximately 80% of the oil discharged was burned before breakup (Fig. 16.6). One-third was burned *in situ* using igniters dropped from a low-flying helicopter. Burning efficiencies for oil pools averaged 80% (Dome Petroleum Ltd. 1981a).

Investigations into the logistics of helicopter deployment and into ice drift trajectories indicate that most of the oil from a major winter subsea blowout in the Beaufort Sea could be disposed of by igniters dropped in spring (Ross Environmental Research Ltd. 1981). Thus a novel countermeasure has been developed for ice-infested waters. Tracking oiled iced over winter, burning oil that appears

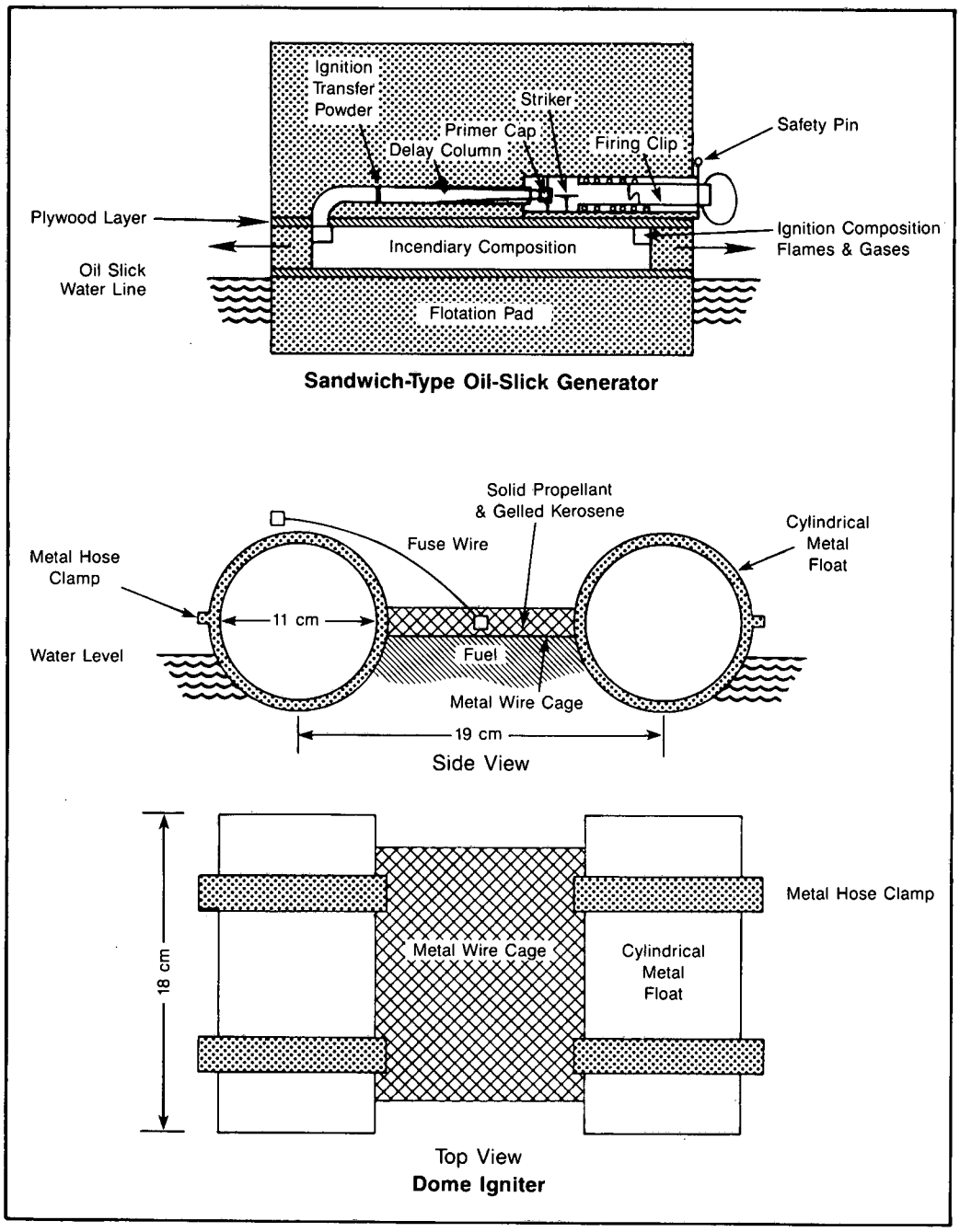

Figure 16.5—Igniter designs. Both the igniters shown are designed to be dropped from helicopters onto oiled melt pools on ice. They have been successfully field tested. (Adapted from Dome Petroleum Ltd. 1981.)

in leads and ice cracks, and deploying igniters from helicopters in the spring would enable cleanup of much of a major oil spill before breakup.

Open Water

The Ixtoc I incident and the sinking of the *Atlantic Empress* provide evidence that it is possible to burn oil on open water with some success (Ross *et al.* 1979; Horn and Neal 1981). Canadian industry and government research has shown that ignition of oil on water requires a certain minimum oil thickness.

Prototypes of fireproof booms have been developed to thicken floating oil and contain it during combustion. Work has been conducted on several design concepts (*e.g.*, Purves and Daoust 1978;

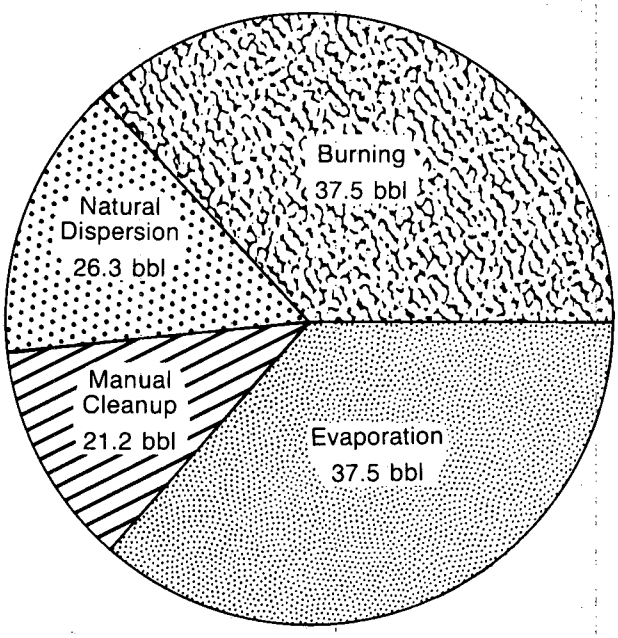

Figure 16.6—Mass balance for oil (122.5 bbl) discharged under ice.

Roberts and Chu 1978; McAllister 1979; McAllister and Buist 1980). Stainless steel booms can contain burning crude oil for long periods, in waves equivalent to sea state 2-3 (the highest tested to date), and in currents up to 0.5 m/s (McAllister and Buist 1980; Dome Petroleum Ltd. 1981b). Final offshore durability trials of this boom are underway. It is possible to collect and dispose of large volumes of oil from a blowout with only moderate lengths of the boom and minimal logistical support (Fig. 16.7). A less robust fireproof boom design is also being tested (Meikle 1982).

The completion of work on fireproof booms and their eventual stockpiling in Canada will be a valuable complement to conventional oil spill response technology.

Disposal of Recovered Oil

A problem in any oil spill cleanup operation is the disposal of recovered oil and oiled material, particularly in remote areas and on rocky or tundra coasts.

Canadian research has focused on controlled burning techniques to dispose of oil material collected in remote arctic and subarctic sites. The basic approach has been to divide recovered material into three categories: fluid oils and emulsions with viscosities less than 500 cS; oiled debris (driftwood, seaweed, sorbents) and viscous emulsions; and oiled beach material and tar balls. The primary design criterion for burners is portability by medium-lift helicopter.

Research on fluid oil burners has concentrated on atomization techniques and system design. Early work showed that simple pneumatic atomization burners were suitable for light oils with low water content (Nikolaychuk and Thornton 1976; Pistruzak 1981). However, auxiliary equipment, particularly the compressors required for these systems, limited transportation by helicopter. One such burner does form an integral part of the Beaufort Sea Co-op response barge. The barge carries oil separators, heaters, and the necessary auxiliary equipment to burn as much as 800 m^3/d of recovered oil with as much as 40% water content by volume (Pistruzak 1981).

Another technique is mechanical atomization. A burner, portable by helicopter, has recently been developed for shoreline land near shore cleanups (Dome Petroleum Ltd. 1982). The burner has a rotary cup to atomize the oil. The system can burn up to 80 m^3/d of a wide variety of oils, including emulsions with as much as 60% water content by volume. This system is also routinely used for slop and waste oil disposal.

Two types of incinerator have been developed to dispose of oil debris and heavy emulsions during shoreline cleanup. The Air Curtain Destructor is a pit dug in the ground, with a blower and ducting to force air into the pit from one side (PROSCARAC 1980). The resulting vortical air flow burns large amounts of oiled debris very efficiently.

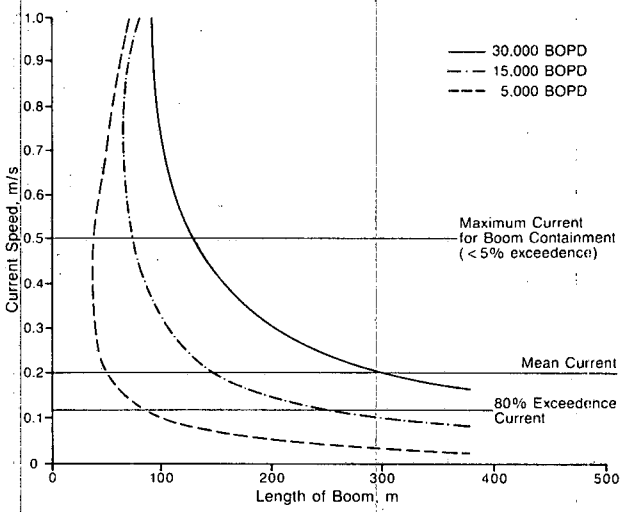

Figure 16.7—Lengths of fireproof boom required to burn certain volumes of oil *in situ* per day (BOPD = barrels of oil per day). As the current increases, the required boom length decreases.

However, this type of incinerator is not suitable for ice-rich soils.

A second incinerator is the box type, consisting of components light enough for helicopter transportation. The device has been tested with a wide range of oiled debris and has a capacity of 1 tonne/h (Twardus 1979). Work is continuing to improve the design of box incinerators, in order to reduce weight for helicopter transport and minimize field assembly.

A reciprocating kiln has been developed to clean and replace oiled beach sediments (Gill and Stevens 1980). This device is made of empty oil drums. Oiled sand is shoveled in one end and tumbled by the reciprocating action. Burning wood or waste oil in a chamber beneath the kiln preheats the oiled sand. Oil in the sand is burned off and clean sand exits. The entire unit can be carried by helicopter. Work is continuing to extend the operating life of the kiln by substituting rolled stainless steel for oil drums. The entire unit can be carried by helicopter.

16.2.5 Dispersants

Chemical dispersants may be the only practical oil spill countermeasure in many arctic and subarctic areas during breakup, the open-water period, and freeze-up. Remoteness and the danger to field personnel may prevent physical containment and recovery of oil, while the thinness of oil slicks may prevent *in situ* burning.

Using chemical dispersion of oil to accelerate natural dispersion entails five problem areas:

1. Logistics—how to get the right dispersant to the right place at the right time in the right quantities.
2. Application techniques—how to apply the chosen dispersant most effectively to the oil slick at the best application rate and correct droplet size.
3. Effectiveness—of the dispersant on fresh and aged oil at the ambient temperatures and salinities.
4. Toxicity—the lethal and sublethal effects of dispersant that can be expected and tolerated.
5. Authority to make decisions—how and when decisions to use dispersant are made by the operator and the regulatory authorities.

Logistics

Betts and Golob (1982) assessed the logistics needed to develop a dispersant response plan and to to systematically prepare for dispersant application. They outlined three planning and three implementation steps for a response plan capability. They looked at two recent case histories, and concluded that systematic planning could help avoid a repetition of past problems.

Application Techniques

Hildebrand *et al.* (1977) studied the feasibility of various methods of dispersant application in the Beaufort Sea. These included application by fixed- and rotary-wing aircraft, and by air cushion and surface vessels. Using a hypothetical oil spill scenario, the study concluded that any method would be very expensive, but that aircraft could be suitable for arctic dispersant application.

A series of trials of aerial application of dispersant have been carried out by an oil industry and government group, the Canadian Offshore Aerial Applications Task Force (COAATF). The trials used a Conair DC-6B aircraft. There were land-based trials at Riviere du Loup, Quebec in 1978; Abbotsford, B.C. in 1979; Suffield, Alberta in 1980; and a marine trial off St. John's, Newfoundland in 1981. A land-based helicopter trial is scheduled for Dartmouth, Nova Scotia in October 1982. The last two trials are COOSRA projects. These trials measured the effectiveness of aerial application and measured dispersant drift and swath width, droplet size, application rates, and overall coverage (Gill and Ross 1980, 1981). The Abbotsford and Suffield trials achieved a dosage rate of approximately 190 l/ha using nozzles or pipes, depending upon atmospheric conditions. These trials also showed that a decrease in dispersant viscosity may be associated with reduction in droplet size (Gill 1981).

Effectiveness

Because dispersant use is an expensive oil spill countermeasure, one must know whether chemical dispersants will in fact disperse different types of crude oil, at different stages of weathering and emulsification, and at various temperatures and salinities.

Much of the early work in the effectiveness of dispersants in Canada was conducted at the microscale level in laboratories by Mackay and coworkers (Mackay *et al.* 1978; Wells and Harris 1979; Harris and Wells 1980; Mackay, Mascarenhas, Hassain, and McGee 1980; Mackay and Wells 1982). They tried to devise a satisfactory method of rating dispersant effectiveness both in sea water and in simulated ice conditions. To coordinate this work with other international research, a symposium was

held in Toronto in 1980, where several papers were given on laboratory tests by U.S., British, French, and Dutch researchers (Mackay, Wells, and Paterson 1980).

To test dispersant effectiveness in a cold open-water environment, COAATF performed the St. John's experimental oil spill trial using Corexit 9527 and fresh Lago Media crude. Preliminary reports indicate problems in sampling the water column for dispersed oil. There were good results from remote sensing, which showed a brown cloud of oil-in-water emulsion that lasted for 3 hours (Gill and Ross 1981). To obtain better water samples, the 1982 COAATF trial will be conducted at an air base in Dartmouth, Nova Scotia with water tanks and application by helicopter.

A standard dispersant effectiveness test is need for two reasons. First, new and existing commercially available chemical dispersants must be tested by regulatory agencies. Second, operators must have a quick and easily conducted test to use during oil spills, to establish whether the available dispersant is effective at that particular time and place on the type of crude oil involved. Such a test would determine whether the operator should regard dispersants as a feasible oil spill countermeasure.

Ongoing research includes laboratory studies and field trials in a project of British Petroleum and Petro-Canada, and studies by Exxon to develop an effective cold-water dispersant for arctic and subarctic regions.

Toxicity

Following the *Torrey Canyon* oil spill in 1967, there has been much study of the acute and sublethal toxicities of dispersants and dispersed oil to phytoplankton, zooplankton, benthos, fishes, birds, and marine mammals. Little of this work deals with arctic conditions, because it is difficult to simulate an arctic environment in the laboratory. Good summaries of toxicity research are in Wells and Harris (1980), Mackay and Wells (1981), and Sprague *et al.* (1982). Blackall and Sergy (1981) describe the preliminary design of the BIOS Project, which will investigate the toxicity of dispersed oil to nearshore organisms.

Dispersant Use Decisions

In Canada, unless there is a danger to human life or safety at a spill site, approval for the use of chemical dispersants must be sought from the Environmental Protection Service. The present "Guidelines on the Use and Acceptability of Oil Spill Dispersants" (Environment Canada 1973) are based on freshwater toxicity tests with fingerling rainbow trout. These guidelines will be replaced in 1982 by new effectiveness, toxicity, and use standards (Mackay and Wells 1982).

Because of the need to plan the logistics of a large-scale chemical dispersant application, the Canadian oil industry must know in advance the conditions under which approval to use dispersant would be given. Such approvals would involve an evaluation of the relative risk of driving dispersed oil into the water column, where it may affect pelagic and benthic organisms, versus leaving untreated oil on the water surface, where it could affect shorelines, seabirds, and marine mammals (Trudel 1980). Scenario modeling can aid such evaluations. Trudel (1980) used the oil fate model of Mackay and Peterson (1980a) to assess the impact of oil to a Common Murre colony and to Atlantic cod stocks off southeastern Newfoundland. This model has since been modified to include several additional species and applied to the mobil Grand Banks environmental data set as a COOSRA project. It is anticipated that once this model is operational, a series of joint government and industry workshops will be conducted to establish criteria for approvals to use dispersants.

16.2.6 Subsea Containment

The concept of a subsea device that would contain the oil and gas escaping from a blowout has been considered for years. Chen (1979) and Abdelnour *et al.* (1977) have studied the engineering feasibility of subsea containment. A joint industry and government workshop in 1981 reviewed various aspects of subsea containment and identified areas for further research (Meikle 1981b).

Since the 1981 workshop, Canadian government and industry investigations into subsea containment systems for arctic marine waters have focused on six areas: (1) the flow of gases and liquids in risers; (2) collector and riser model testing; (3) environmental loads; (4) *in situ* incineration of oil and gas at the water surface; (5) preliminary design and feasibility testing of a floating cylinder incinerator system; and (6) preliminary design and feasibility testing of a converted oil tanker system for separation and recovery of the oil.

Topham *et al.* (1982) investigated two-phase flow (of liquids and gases) in risers, using computer simulation techniques. They confirmed that the water:oil ratio in the fluid collected strongly depends upon riser resistance, collector and source separa-

tion, and pipe diameter. They calculated that, for a blowout of 4,800 m^3 oil/d with a gas-to-oil ratio of 160:1, a 75-cm-diameter riser could handle the flow up to a water-to-oil ratio of 50:1 to 70:1.

Small-scale-model tests by C-CORE (1981) of riser and collector types showed that if a riser could be brought close enough to a blowout source, no collector would be required. The airlift action of the gas in the riser would draw in all the escaping fluid at the bottom. Flexible and semipermeable risers were also evaluated. These were very susceptible to fluttering, which in actual conditions may produce unacceptable wear.

CanOcean (1981) analyzed the environmental loads on one system, and included calculations of the forces exerted on the collector, riser(s), and incinerator by waves, wind, currents, level sea ice, small ridges, and large ridges. Since no mooring system could withstand large ice masses, a limiting ice criterion was set whereby the incinerator would be submerged by a large ice mass and break through thinner ice once the large mass had passed. The results of the environmental load study were reduced to simple equations and nomographs, so that the effect of system design changes could be easily and quickly examined.

A concept for disposal of the collected products of an Arctic subsea blowout is to burn the oil and gas *in situ*. To evaluate the feasibility of this concept, Energetex Engineering (1981b) tested both an atomizing-tip and a pool-type burner. Oil, gas, and water were pumped into the burners to simulate gas-to-oil ratios of 200:1 to 400:1 and oil-to-water proportions of 0 to 100%.

These tests indicated that the atomizing burner was more effective for water contents up to 50% and it produced a clean burn. If water content was more that 50%, the pool burner was more effective. Since the water content of the collected product could vary considerably, the incinerator design should incorporate both types of burner, as shown in Figure 16.8. A full-scale system to deal with a 2,400 m^3/d blowout would require an atomizing tip approximately 1 m in diameter and a pool burner approximately 30 m in diameter.

CanOcean (1982) made a preliminary system design that combined all these features to determine the feasibility of an arctic subsea containment system. CanOcean examined the structural design, construction materials, and availability and deployment of the collector, riser, and incinerator (Fig. 16.9). An important criterion was the capability for assembling most of the system within 3 weeks, thus

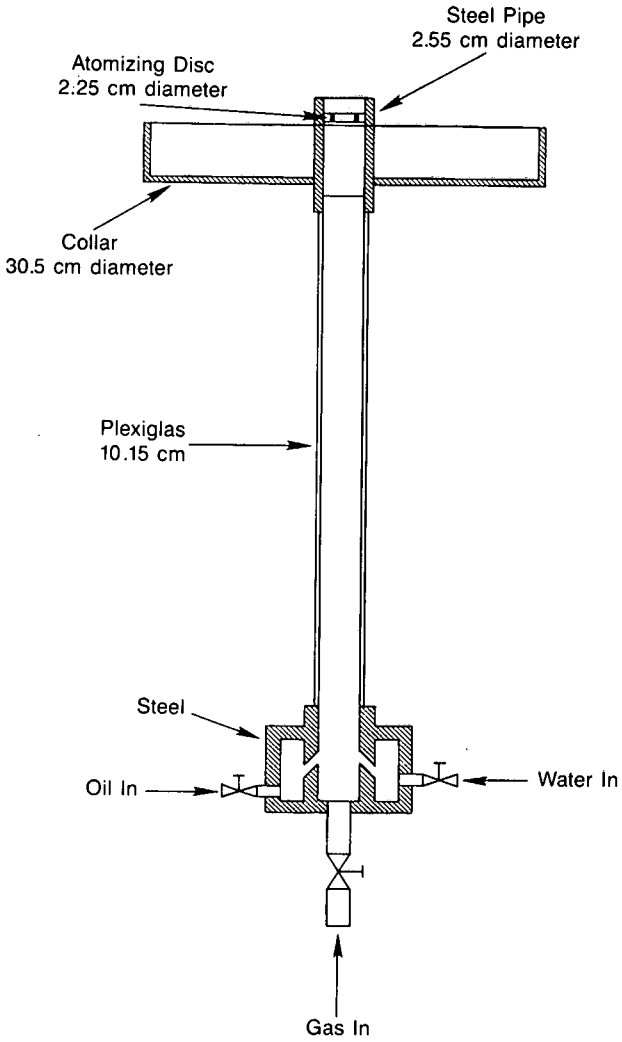

Figure 16.8—Scale-model floating incinerator. The concept for a subsea containment system surface incinerator consists of both an atomizer and a pool burner. The atomizer would combust the recovered products with a water content less than 50%, while the pool burner would burn products with water contents in excess of 50%.

eliminating expensive preconstruction and stockpiling. Rapid assembly would also allow the choice of appropriately sized components for the flow rates observed at the blowout site. CanOcean concluded that, for severe ice conditions, such a system would be extremely expensive and require a long time to construct. In particular, the mooring system required to resist the design ice load would be difficult to obtain. The major limitation on the mooring strength is the anchor holding power required to resist ice loads. The deployment of such a massive system would be immensely difficult, if not impossible, and it would be beyond existing marine tech-

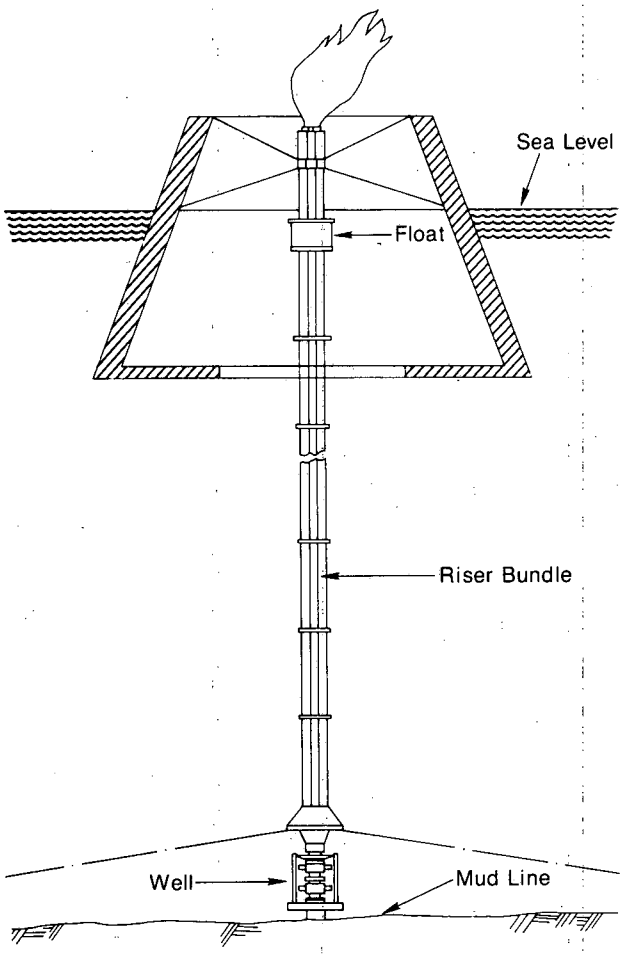

Figure 16.9—Concept for an icebreaking subsea containment system. This system for collecting and burning the products of an Arctic oil well blowout under the sea will be the subject of continuing research and development.

nology to remotely pretension the anchor chains.

An alternative to a collector and incinerator system is to collect the blowout products and pass them to a platform for separation and recovery of the oil. German and Milne Inc. (1982) studied the feasibility of converting a conventional VLCC to an appropriate subsea containment platform. This concept entails cutting a moon pool into the bow section of a tanker through which a collector and a riser could be lowered (Meikle 1981b). The tanker would move over the blowout, position the collector over the source, recover the collected fluids, separate oil, water, and gas in cargo tanks, store the oil, flare the gas, and discharge the water (Fig. 16.10). Initially, the concept seems feasible and there are no classification society rules or regulations that could not be met. Inert gas systems, water sprays, and other systems can be installed with present technology. The positioning of the tanker accurately over the blowout would require some further investigation. The system would operate only in open water.

16.2.7 Shoreline Protection and Cleanup

The Canadian approach to the protection and cleanup of its vast arctic coastlines has three components. Coastal areas are being catalogued with standardized shoreline classification systems. Protection and cleanup strategies are being designed to be consistent with the various shoreline types and logistical limitations. Techniques and hardware are being developed to clean up polluted coastal areas and to dispose of oil and oiled debris in remote areas of the arctic.

Shoreline Classification

One of the initial projects in this field was the Beaufort Sea Shoreline Study (Worbets 1979). This study was a sensitivity mapping of all coastal regions between the Alaska-Yukon border (141° W) and the Baillie Islands (128° W), and was based on two seasons of extensive fieldwork. Combined with the Beaufort Sea Atlas, the shoreline study was used to design countermeasure options for the southern Beaufort Sea coastline.

In the late 1970's, further classifications were conducted by AMOP and the Geological Survey of Canada, designating coastal types of Labrador and Baffin Island. Since then, there have been major advances in the methods of collecting and presenting coastal geomorphological information. The Victoria, B.C., office of Woodward-Clyde Consultants has used a videotaping technique for much of the arctic and subarctic shoreline, for both Dome Petroleum and Petro-Canada. The raw footage is annotated and used to produce a physical shore zone analysis manual.

Oil Spill Response Strategies

The results of these shoreline classification studies (Worbets 1979; Robilliard *et al.* 1980; Robilliard and Owens 1981) are then incorporated with the shore zone analysis into oil spill cleanup manuals. The manuals rank geological, biological, and human sensitivities and areas of potential disturbance. They also outline response actions and potential cleanup methods for specific geographic areas and sometimes indicate local and regional logistic facilities available.

The pioneering of these methods is legitimate

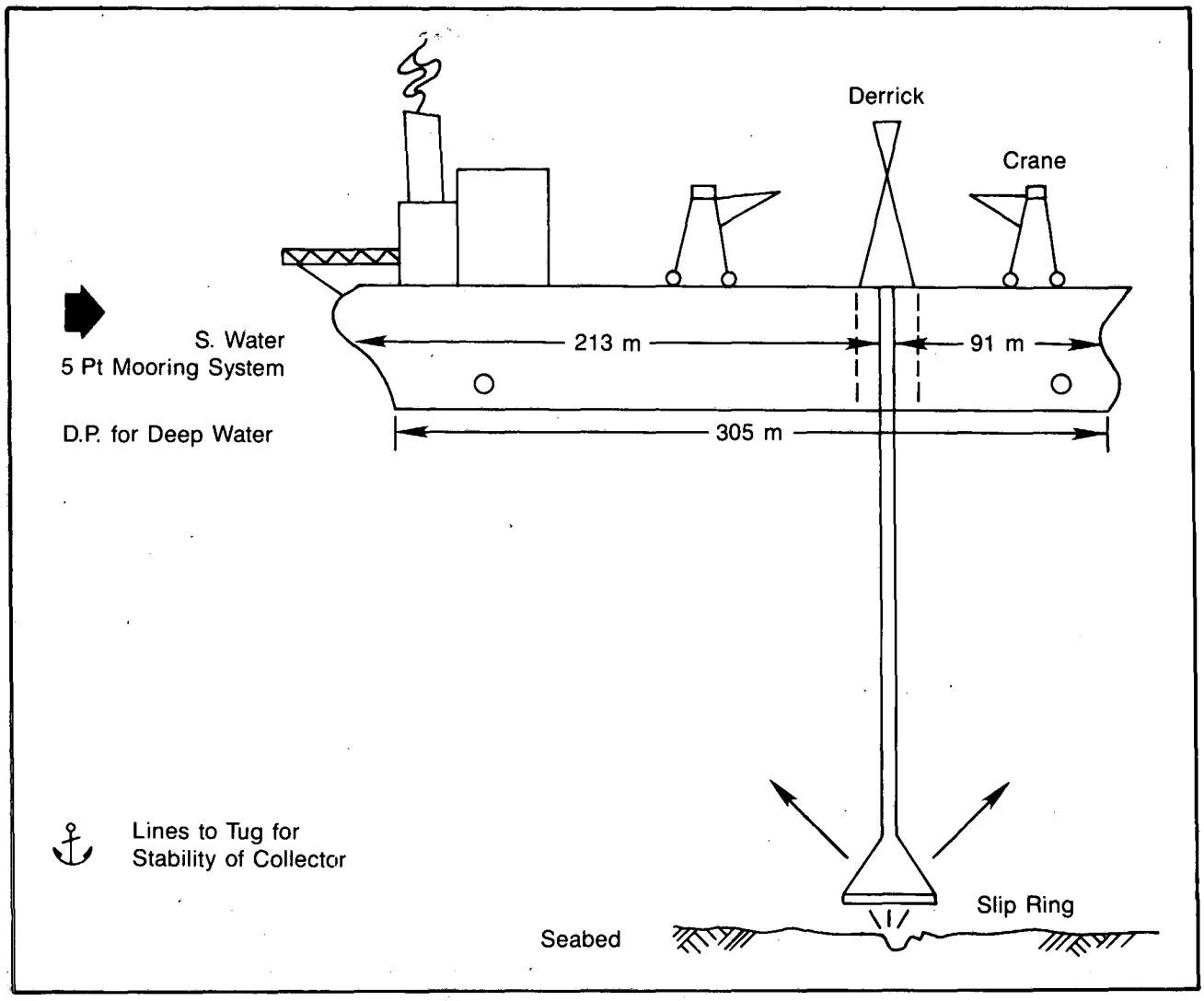

Figure 16.10—Tanker system for subsea blowout containment. This system was suggested by Capt. T. Robinson of Dome Petroleum Ltd. at the recent workshop on subsea containment. Further analysis has indicated that a converted VLCC could be used.

oil spill research, although further development will emphasize operational techniques.

Shoreline Cleanup and Waste Disposal

Hardy Associates (1979) investigated oiled debris disposal and storage sites along the Beaufort Sea coast and the problems involved in site selection and construction in permafrost areas. The report, however, was not applicable to the central and western arctic, where the shorelines were sufficiently different to make this approach impractical.

Twardus (1980) evaluated *in situ* combustion as a shoreline cleanup technique. This work indicated that low-viscosity oils rapidly penetrated beach sand, making *in situ* combustion impossible. However, the same oil, when emulsified by rain, was combustible because of its reduced viscosity. The addition of peat moss also improved *in situ* combustion.

Dickins (1981) performed a follow-up study on the work by NORCOR (1975) in Balaena Bay. He found that, although the initial spill was considered well cleaned up, approximately 5% of the applied crude oil remained at the experimental salt marsh site after 6 years. Oil residues left on the test core shoreline were reduced in volume from about 1 m^3 to less than 0.2 m^3 since August 1975.

The most recent work on shoreline countermeasures in the Canadian Arctic has been the shoreline component of the BIOS Project. In 1980, eight test plots were oiled using aged Lago Media crude oil

and an emulsion of water in aged Lago Media crude oil. The oils were spilled on both back-shore and intertidal test plots in both high- and low-energy areas of the beach. At the high-energy beach plots, 50-90% of the oil was removed in 24-48 h; at the low-energy or sheltered plots, 30-90% of the oil was removed by tidal action (Woodward-Clyde Consultants 1981).

This work provided the baseline data for the 1982 field season (Owens *et al.* 1982), when the following countermeasures were investigated in a medium-energy shoreline: (1) *in situ* combustion using the DREV igniter; (2) chemical surfactants designed to disperse oil; (3) mechanical mixing of oil-contaminated sediments; and (4) application of a surface solidifying agent.

Results indicated that the incendiary device was not effective in igniting either the aged crude oil or the emulsified oil. The water-based dispersant effectively reduced the total oil loading, partly by driving oil deeper into the sediments. This dispersant appeared to be less effective on the emulsified oil plot. The oil-based dispersant also drove the oil more deeply into the sediments, but by day 40, all the total hydrocarbon values were reduced to trace concentrations. This may be significant where it is necessary to removed stranded oil from the beach surface in shorter periods than could reasonably be expected from natural cleaning processes.

The mixing operation, not surprisingly, reduced the surface concentrations of stranded oil, but increased the subsurface concentrations.

The solidifying agent caused much of the oil to form a bonded compound that retards sediment reworking, but facilitates physical recovery.

In 1982, it is planned to determine if oil can be more readily removed from low-energy environments, mainly by the application of dispersants. These low-energy environments make up almost 40% of the total shoreline in the arctic, and they tend to be biologically productive. It is therefore important to have some basic understanding of the persistence of oil in these areas.

In general, little research has been conducted on arctic shorelines, because of the logistical problems of conventional shoreline cleanup. BIOS remains the best practical field study in shoreline cleanup countermeasures.

16.3 FUTURE RESEARCH DIRECTIONS

At the present time arctic marine oil spill research is being conducted by AMOP and COOSRA. These two organizations are the major funders of the BIOS Project, which is scheduled to be completed in 1983. AMOP was planned as an 8-year study from 1977 to 1984. COOSRA was conceived as an industry association with an initial 4-year life (1980-83) and the option of continuation or termination in 1983. Recent legislation in Canada has introduced the concept of two Environmental Studies Revolving Funds (one north of 60° N latitude and one south of 60° N), both funded by the oil industry and managed by the federal government with input from industry representatives. The revolving funds may eventually replace or incorporate COOSRA.

Major areas of future arctic oil spill research are seen as:

(1) *Monitoring and Surveillance.* Improved oil-spill-following buoys for both surface and subsurface tracking of oil. Following the *Kurdistan* oil spill, it was found that thick, weathered bunker-C oils traveled at subsurface depths below the ice and finally contaminated beaches tens of kilometers away. A promising technique for detecting oil under ice is sonar penetration from the upper ice surface. Modeling of oil-under-ice trajectories is an area of research that requires further investigation.

(2) *Mechanical Containment and Recovery.* A workshop on the recovery of oil in ice is scheduled for Calgary in October 1982. It is expected to look at past technology and make recommendations for future research in an area where there is currently little available effective equipment.

(3) *Dispersants.* From the BIOS results, it is anticipated that guidelines for dispersant use, shoreline protection, and cleanup will be produced for arctic waters. Further work on the B.P./Petro-Canada and Exxon cold water dispersants can be expected. Effectiveness and toxicity tests and field trials can be expected. The B.P. polymer solidifying agent was tested at Cape Hatt in the spring of 1982. Because this seems to be a promising countermeasure for both oil under ice and arctic shoreline cleanup, further development research is expected. AMOP is considering a series of applied field trials in arctic conditions.

(4) *Subsea Containment.* Further work on subsea containment systems in both open water and light ice can be expected to reduce mooring system stresses and loads (Buist and Potter 1982).

(5) *Miscellaneous.* Because of the high cost of conducting arctic marine oil spill research in the field, both AMOP and some oil companies have set money aside so that oil spill scientists and

countermeasure specialists may visit accidental spills in the arctic to better understand the fate, behavior, and effect of oil in the arctic environment.

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APPENDIX B

Arctic Marine Oilspill Project (AMOP) Publications, 1977-82

1977:

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Novel Countermeasures for an Arctic Offshore Well Blowout. EPS-3-EC-77-14.

The Feasibility of Oil Spill Dispersant Application in the Southern Beaufort Sea. EPS-3-EC-77-16.

A Field Study of the Permeability of Multiyear Ice to Sea Water with Implications on its Permeability to Oil. EPS-4-EC-77-11.

Field Evaluation of Oil Mop and Preheat Unit. EPS-4-EC-77-12.

1978:

Pumps for Oil Spill Cleanup. EPS-4-EC-78-3.

Field Evaluation of the Super Seahawk and Marco Class V Oil Skimmers. EPS-4-EC-78-2.

Field Evaluation of Eight Small Stationary Skimmers. EPS-4-EC-78-5.

The Interaction of Crude Oil and Natural Gas with Laboratory-Grown Saline Ice. EPS-4-EC-78-9.

Probabilities of Blowouts in Canadian Arctic Waters. EPS-3-EC-78-12.

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Arctic Oil Spill Countermeasures Logistics Study: Summary Report. EPS-3-EC-78-8.

Testing of Air-Deployable Incendiary Devices for Igniting Oil on Water. EPS-3-EC-78-11.

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Theory, Development and Testing of an Ice-Oil Boom. EPS-4-EC-79-2.

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1980:

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1981:

Microwave Systems for Detecting Oil Slicks in Ice-Infested Waters: Phase I—Literature Review and Feasibility Study. EPS-3-EC-81-3.
The Use of Satellite Imagery for Tracking the *Kurdistan* Oil Spill. EPS-4-EC-81-5.
An Evaluation of Oil Pumps and Skimmers. EPS-4-EC-81-4.

1982:

Deep Water Blowout Trajectory Models for the Lancaster Sound Region. EPS-4-EC-82-2.

APPENDIX C

Canadian Offshore Oil Spill Research Association (COOSRA) Projects, 1980-82

1980:

Baffin Island Oil Spill Project
Beaufort Sea Oil and Gas Under Ice Experiment
Portable Burner Development
Fireproof Boom Development
In situ Combustion Against Ice Edges

1981:

Baffin Island Oil Spill Project
Offshore Dispersant Trial
NOAA Real time Oilspill Trajectory Model Conversion
Fireproof Boom Testing at the OHMSETT Facility
Dispersant Use Model
Ring Containment System Design
Return to Balaena Bay

1982:

Baffin Island Oil Spill Project
Fireproof Boom Field Trials
Subsea Containment Field Trials
Emulsions in Ice Study
Oil in Pack Ice Study
Dispersant Effectiveness Trial
Mechanical Recovery in Ice Workshop
Portable Incinerator Development

Chapter 17
Biologically Sensitive Areas

by Joe C. Truett

With contributions from Peter G. Connors, George J. Divoky, Stephen R. Johnson, Peter C. Craig, and Kenneth H. Dunton

In these discussions, emphasis is on the species or groups of species that, from a commercial, subsistence, recreational, or aesthetic standpoint, are significant resources, or that are unique or regarded as threatened or endangered. The areas delineated as sensitive for these resources are places where individuals of the species concerned habitually congregate for some important life function (or in the case of live-bottom communities, places where scarce or unique communities are known to exist) and where the species are potentially vulnerable to adverse impact from petroleum-related activities.

17.1 SENSITIVE AREAS AND THEIR BIOTA

The following discussions are organized by area. Sensitive areas (Fig. 17.1) are addressed in sequence from farthest west to farthest east in the coastal, nearshore, and offshore environments.

17.1.1 Nearshore Zone, Peard Bay to Point Barrow

The nearshore zone (0-20 m deep) from Peard Bay to Point Barrow appears sensitive for both live-bottom communities and some birds. Kelp beds occur in shallow waters near the Skull Cliffs. Further, Peard Bay provides the most northerly protected habitat for Pacific Arctic marine flora. A large proportion of the world's Ross' Gull population feeds along the coast and in coastal shallows of this region in late September and early October. Concentrations of Oldsquaws molt in Peard Bay during 20 July-10 August; migrating Oldsquaws congregate there in mid-September to early October. Large numbers of Sabine's Gulls, Arctic Terns, and phalaropes concentrate at Point Franklin during the late summer.

17.1.2 Seahorse Island

Black Guillemots, Common Eiders, Arctic Terns, and Oldsquaws nest on Seahorse Island from mid-June to mid-August. The island is also used as a roosting site by large numbers of Arctic Terns in early August.

17.1.3 Offshore Zone, Point Franklin to Point Barrow

The offshore zone (20 to >200 m deep) from Point Franklin to Point Barrow is used by several species of marine mammals and birds. Bearded seals, walrus, and gray whales feed there in large numbers in July through September. Bowheads migrate through the area in spring (April-May) and fall (October-November). Migrating eiders and Oldsquaws pass along the flaw leads, occasionally resting on the water, in mid-May to late June.

17.1.4 Oarlock Island and Southwest Smith Bay

Oarlock Island (in Admiralty Bay) and southwest Smith Bay are known haul out areas for spotted seals in summer and fall. The only other area where spotted seals haul out in appreciable numbers in the Alaska Beaufort Sea is in the Colville River delta.

17.1.5 Elson Lagoon and Plover Islands Shoreline

A large proportion of the world's population of Ross' Gulls feeds along the coast and in the lagoons from late September to early October. Oldsquaws molt in large numbers in the lagoons (20 July-10 August) and congregate there in migrating flocks (mid-September to early October). During the open-water period (August and September), large numbers of phalaropes and other shorebirds, gulls,

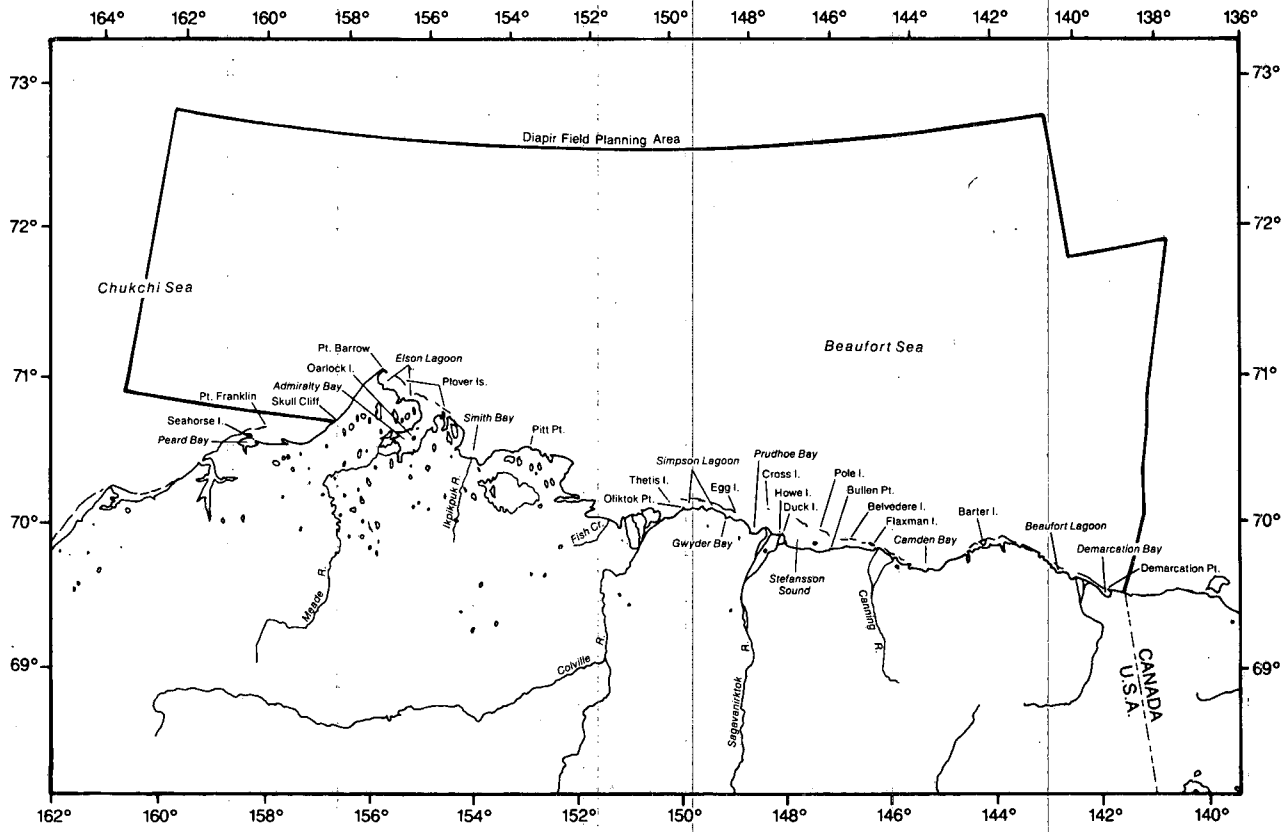

Figure 17.1a—Ecologically sensitive areas in the Diapir Field Lease Area.

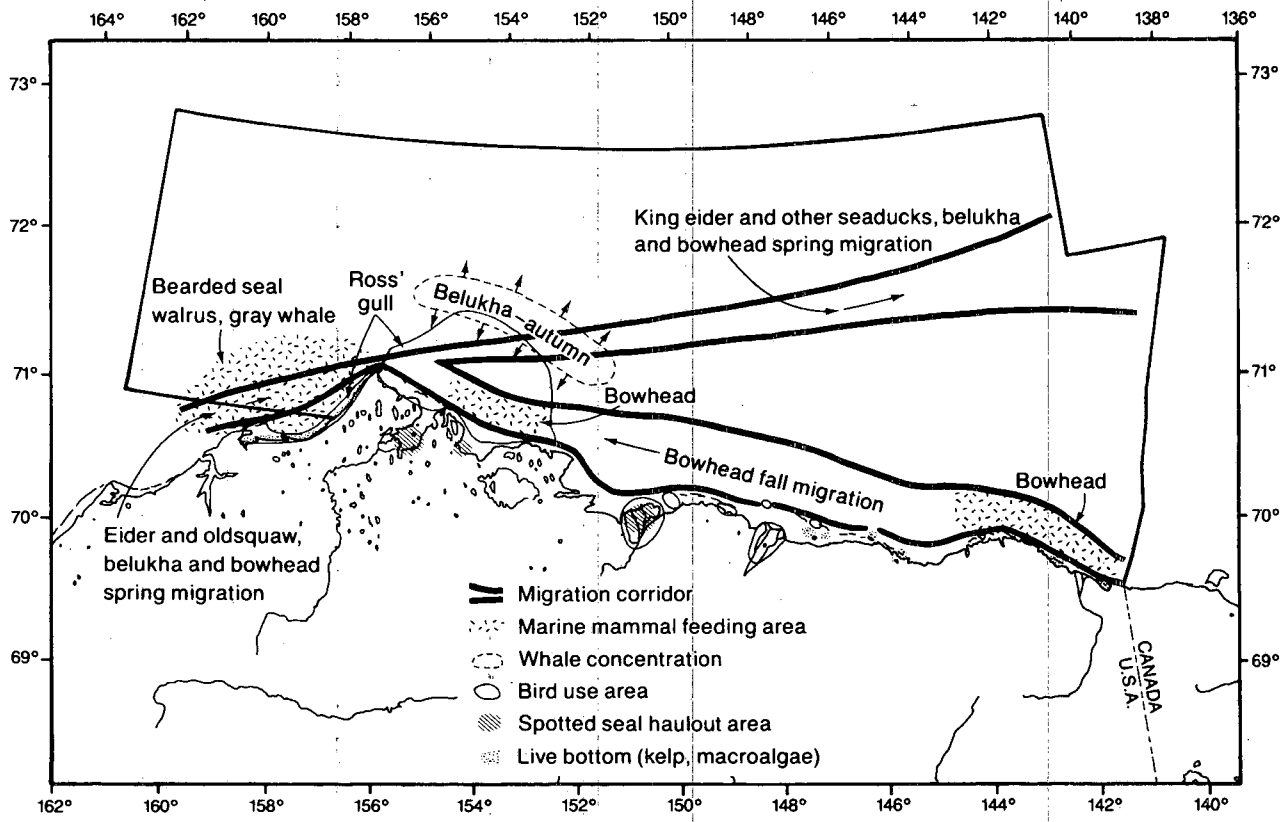

Figure 17.1b—Habitat areas and migration routes of major species in the Diapir Field Lease Area.

and terns feed on dense concentrations of marine zooplankton along the coastline.

17.1.6 Plover Islands

Water birds, including a Black Guillemot colony, use the Plover Islands for nesting from June through August.

17.1.7 Point Barrow to Pitt Point, 10- to 200-m Depths

Phalaropes, gulls, kittiwakes, terns, and shearwaters feed from Point Barrow to Pitt Point from late July to late September. Bird densities generally decrease with water depth, and are normally much lower than waterbird densities in the 0- to 20-m zone of the Beaufort Sea. Bowheads migrate through the area in spring and fall. They move rapidly (along ice leads) through the region from late April to early June, but sometimes stop to feed during the return migration from August through October. Belukhas congregate in large numbers along the pack ice edge in this region in September and October, perhaps to feed. The majority of the Bering-Chukchi-Beaufort population of belukhas might be in this area at that time.

17.1.8 Colville River and Fish Creek Deltas

Water birds, anadromous fishes, and spotted seals congregate in the Colville River and Fish Creek deltas during important life history stages.

Large numbers of birds, particularly Brant and other species of geese, as well as shorebirds and ducks, breed and feed in extensive salt marsh habitats in these deltas in summer. The eastern portion of the Colville River delta, in particular, supports large numbers of nesting Brant and other geese (Norton and Sackinger 1981). The central part of the delta supports high densities of Tundra Swans.

The river channels of the Colville River delta provide passage, as well as spawning and overwintering habitat, for large runs of anadromous fishes. These fishes support commercial and subsistence fisheries in the Colville River delta. The runs of whitefishes in the Colville River are the largest on the north coast of Alaska (Norton and Sackenger 1981).

The Colville River delta is the easternmost-known area in the Beaufort Sea where spotted seals regularly haul out. These seals are resident in the delta during the open-water period and probably depend upon local fish stocks for food.

17.1.9 Thetis Island and Vicinity

Thetis Island and nearby waters appear to be important to waterfowl and boreal smelt. Thetis Island has the third largest eider colony in the Alaskan Beaufort Sea after Cross and Pole islands. Nesting occurs from mid-June to early August. Molting Oldsquaws concentrate in the waters surrounding Thetis Island (20 July-10 August), particularly between Thetis Island and Oliktok Point on the mainland. The waters near Thetis Island are an overwintering area for boreal smelt (Norton and Sackinger 1981).

17.1.10 Simpson Lagoon-Gwydyr Bay

Simpson Lagoon, like a number of others along the coast, appears to be an important feeding area for birds and anadromous and marine fishes in summer (Norton and Sackinger 1981).

17.1.11 Egg Island

Egg Island supports appreciable numbers of nesting common eiders from mid-June to early August.

17.1.12 Howe Island

Howe Island and nearby Duck Island, both in the outer Sagavanirktok River delta, support the only known Snow Goose nesting colony in the United States.

17.1.13 Sagavanirktok and Canning River Deltas

The Sagavanirktok and Canning River deltas are important to birds and anadromous fishes, but to a lesser extent than is the Colville River delta. Salt marshes and other emergent habitats support nesting and feeding waterfowl and shorebirds in summer. Arctic char are the most important fish that pass through the delta channels in spring on their way to summer habitats and in fall on their way to winter habitats.

17.1.14 Stefansson Sound Boulder Patch

The Boulder Patch contains a unique assemblage of invertebrates which inhabit a kelp community associated with a boulder and cobble substrate. The boulder bottom and its biological community are not duplicated elsewhere in the Alaskan Beaufort Sea. The Boulder Patch is bounded by points:

148°00′ W, 70°30′ N

148°00′ W, 70°21′ N
147°20′ W, 70°20′ N
147°35′ W, 70°15′ N

17.1.15 Cross Island and Pole Island

Cross and Pole islands, approximately 20 km offshore, support the two largest Common Eider colonies in the Alaskan Beaufort Sea from mid-June through early August.

17.1.16 Live-Bottom Communities East of the Boulder Patch

Relatively small kelp communities are found at four locations east of the Boulder Patch: (1) south of Belvedere Island, (2) offshore of Flaxman Island, (3) inshore of Camden Bay, and (4) Demarcation Bay. A macroalgae bed is located in Beaufort Lagoon.

17.1.17 Sheltered Lagoons East of Prudhoe Bay

All these lagoons, similar to Simpson Lagoon, appear to be important feeding areas for birds and anadromous fishes in summer.

17.1.18 Camden Bay to Demarcation Point, 15- to 60-m Depths

The region from Camden Bay to Demarcation Point at 15- to 60-m depths is an area where bowhead whales pause to feed in September and October during their westward fall migration. Most whales have been seen in the area between Barter Island and Demarcation Bay.

17.1.19 Point Barrow to Demarcation Point, 10- to 60-m Depths

The general migration route of bowheads in fall (September and October) along the Alaskan Beaufort coast is between the 10- and 60-m isobaths.

17.1.20 Point Barrow to Demarcation Point, Depths >60 m

The general migration route of bowheads in spring (late April to early June) along the Alaskan Beaufort coast is beyond the 60-m isobath.

17.2 ADDITIONAL CONCERNS

Additional concerns relate to animals that (1) are not particularly concentrated at any time, (2) have sensitivities in space that are speculative because data about their use of areas is lacking, or (3) are mainly terrestrial and therefore clearly outside the lease area, but nonetheless might be impacted by onshore support activities. These concerns include the following:

(1) Polar bears, whose denning site locations are poorly known. Females and young are widely distributed in the lease area (mostly in the nearshore zone) in winter and may be sensitive to human activities nearby.

(2) The Meade and Ikpikpuk river deltas may be important for nesting, molting, and/or staging water birds in June and July, but the data needed to establish this are somewhat limited.

(3) It is known that arctic fox populations increase in the vicinity of human habitations associated with development (Eberhardt *et al.* 1982), and that human health hazards (such as rabies) might be more likely. Since some development sites will presumably be at inland locations, this should be considered.

(4) Caribou insect-relief sites (sites where caribou gather to avoid insects that bite) are widely distributed along the Beaufort Sea coast east of the Colville River, and at least two caribou calving areas are near the coast (one southeast of Oliktok Point and one south of Bullen Point; see Cameron *et al.* 1981). These sites are well outside the lease area, but could be affected by onshore development associated with the Federal leasing program.

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Chapter 18
Subsistence

by John J. Burns and Marsha Bennett

With contributions by Jack Kruse, Rosita Worl, and Ron Nalikak.

This OCSEAP synthesis meeting, concerning the Diapir Field OCS Planning Area, was the first such meeting at which issues affecting the subsistence/wage economy were specifically addressed. It has long been recognized that the juxtaposition of a western cash-income-oriented economy and the historical subsistence-based economy of the Beaufort Sea region set in motion a series of changes which have continued to expand and intensify.

The initial interests of westerners in the Beaufort Sea region were in commercially valuable animal products, primarily those from bowhead whales and furbearers. The quest for these commercial products involved direct harvest by westerners (mainly of bowheads), by North Alaskan Eskimos (Inupiat) in the employ of westerners, and by Inupiat harvesting independently for domestic use and sale or barter of nonedible by-products to westerners. From the onset of contact among cultures, the interests of westerners have been largely related to pursuits that generate a cash income. Inupiat residents have maintained as a primary goal the continuation of a hunting, fishing, and gathering life-style in which cash has only recently become an important component.

The environmental setting, including the resource base, played a major role in circumscribing the nature and extent of social and economic change in the Beaufort Sea region. Early western entrepreneurs mostly operated as individuals (*i.e.*, traders) or in small groups (*i.e.*, overwintering whaling crews) who had only limited opportunity to bring western technology with them. They relied heavily on the direct adoption or slight modification of Inupiat technology and on the cooperation of the Inupiat in order to survive and to secure the resources of commercial interest. National and international economics, in concert with the abundance of commercially important living resources such as whales and arctic foxes, determined the financial success of westerners dealing in these products.

The Inupiat were strongly influenced by the newcomers. Settlements around trading posts became more permanent. Activity patterns were altered to harvest valuable resources, such as arctic foxes, for cash or barter. Western technology useful for harvesting living resources was rapidly adopted (steel traps, guns, manufactured nets), as well as a myriad of durable utensils and staple foodstuffs.

These changes were balanced by the Inupiat traditions, culture, and institutions, in interaction with the environment and its living resources. During the early period of western influences, the environment, particularly the habitats of major living resources, remained virtually unaffected, although the living resources were sometimes exploited heavily.

A succession of people representing the Americanized western culture continued to influence local people of the Beaufort Sea coast. This succession included missionaries, educators, health care specialists, representatives of government, the military, and now those involved with industrial development such as production of oil from the large petroleum reserves.

Each step in this process created more change and a potentially wider dichotomy between the traditional economic system and that based on wage income. For most permanent residents of the smaller settlements along the Beaufort Sea coast the choice has not been between the traditional and wage economies, but rather of where, along the continuum from one economy to the other, they wish to function. Most permanent residents have expressed the desire to remain as closely oriented

toward the subsistence economy as contemporary factors permit. Others demand some flexibility in the opportunities to function at different points along the continuum.

To maintain these options a productive and abundant base of living resources is required. Maintenance of productive populations of harvestable resources requires that they be protected from direct threats, as well as threats that would adversely affect their habitats and supporting food webs.

18.1 WORKSHOP OBJECTIVES

Workshop members were not presented with a set of predetermined objectives, but were asked to examine how petroleum development in the Beaufort Sea region may impact subsistence-oriented economies in the region. We met several times during the course of the synthesis meeting in order to develop objectives and to meet those objectives.

Clearly, the contemporary subsistence/wage economy of the Beaufort Sea region is a multifaceted subject, of which any segment could have occupied all of the available time and energy of participants. Many aspects of the subsistence/wage economy were discussed:

- Historical and contemporary use of resources
- Historical and contemporary demographics
- Inupiat Eskimo land use patterns
- Cultural anthropology
- Economic changes
- Economics of the contemporary subsistence system
- Technological changes
- Political changes
- Major subsistence resources
- Natural history of key living resources
- Threats to resources through pollution, disturbance, habitat destruction, and alteration of carrying capacity
- Critical habitats of key resources
- Pollution transport
- Jobs and the subsistence/wage economy
- Effects of international, federal, state, and local regulations
- Public input to decision making
- Other subjects

As our efforts progressed it became apparent that a focus on one or a few of those subjects would contribute to only a small part of a rather large issue. However, the evolution of our major objective was clearly taking place. It became apparent that *agents* of social and economic change along the Beaufort Sea coast could be recognized though one might not be able to predict the eventual result of the dynamic change. Furthermore, the desires and concerns of people that are (or perceive themselves) participants in the subsistence/wage economy have continuously been voiced on matters ranging from single-issue concerns such as regulation of bowhead whale or caribou hunting, to broad concerns such as cultural preservation.

Our focus developed from those kinds of concerns. Our primary objectives became (1) recognizing the array of major factors affecting subsistence users of living resources in the Beaufort Sea region, and (2) determining which of those factors are strongly linked to petroleum development. A secondary set of objectives was to determine which living resources are of significant importance to subsistence-oriented users and how those resources may be impacted by petroleum development. Thus, we examined how subsistence users of resources and resources are, or might be, affected by petroleum development.

Three major topics were addressed in our workshop: (1) socioeconomic impacts of OCS oil and gas lease development on participants in the subsistence/wage economy, (2) major fish and wildlife resources harvested by subsistence users in the Beaufort Sea region, and (3) possible impacts of OCS development on the major fish and wildlife resources.

18.2 SOCIOECONOMIC IMPACT

Socioeconomic impact was the main topic on which we focused. The discussions of numerous subjects relating to the economic and social well-being of North Slope Borough Inupiat residents resulted in development of a matrix or flow diagram that shows the primary factors operative on the contemporary subsistence/wage economy and the recognized interactions among those factors (Fig. 18.1). The factors, all bearing on economic and social well-being, can be grouped into four broad categories:

1) OCS-induced impacts on culture and local economics;
2) OCS impacts on the North Slope Borough (NSB) government and Arctic Slope Regional Corporation (keeping in mind that the NSB is the largest employer of Inupiat on the North Slope);

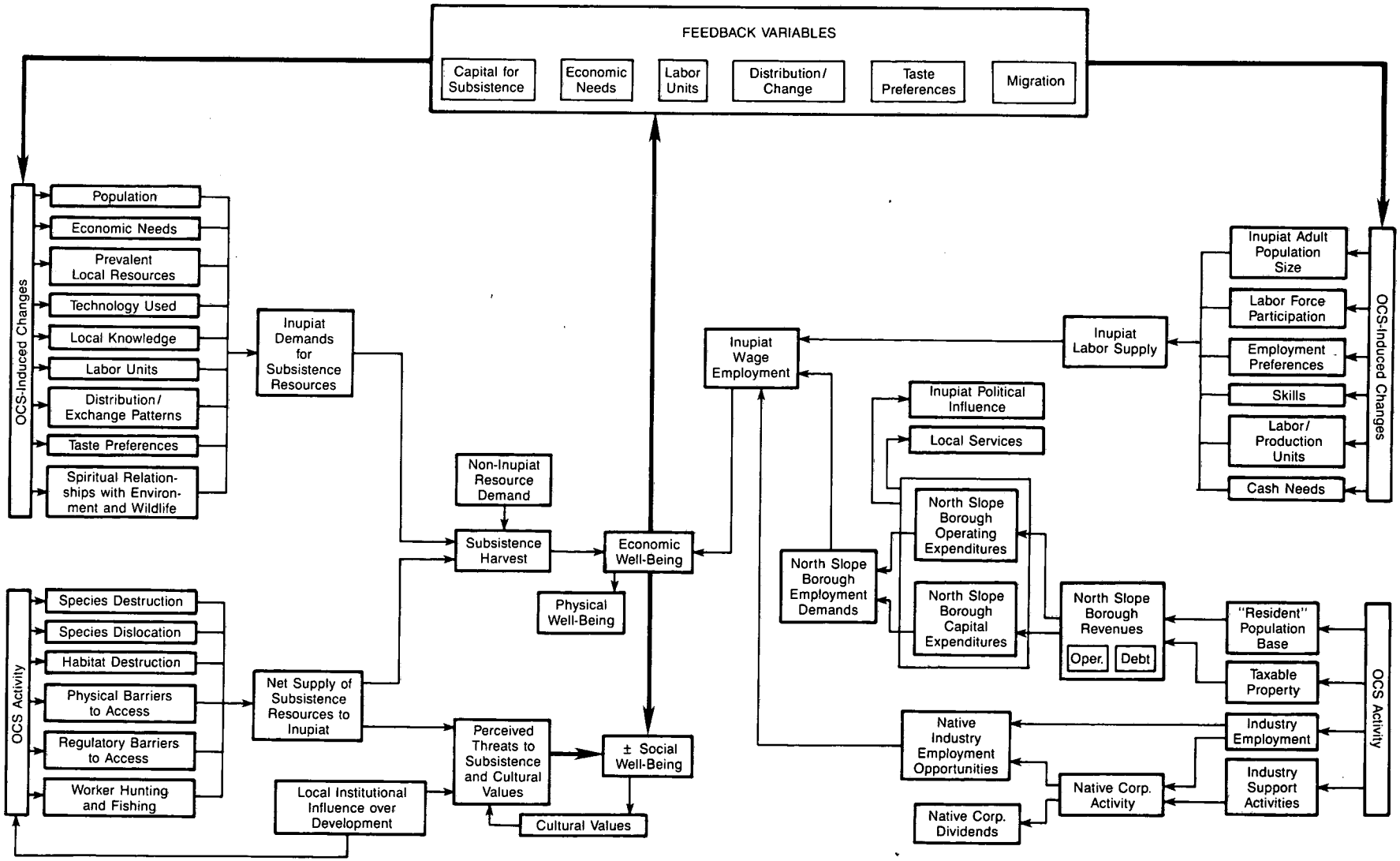

Figure 18.1—Interactions of primary factors affecting the contemporary subsistence/wage economy on the North Slope, specifically related to OCS oil and gas lease development activities. (Developed by Jack Kruse, on the basis of workshop discussions.)

3) OCS-induced changes which affect demands for, and uses of, fish and wildlife important to subsistence-oriented harvesters; and
4) OCS activities as they affect (or are perceived to affect) abundance, availability, or access to major subsistence resources.

It was recognized that essentially every aspect of OCS impacts on the economic and social well-being of subsistence-oriented residents (Fig. 18.1) is a subject about which information is incomplete or lacking. There were differences of opinion among workshop participants concerning the importance of different factors influencing contemporary participants in the subsistence/wage economy, or how the factors actually relate to each other. Some (perhaps most) of the differences of opinion were related to the perspectives (disciplinary involvements) of the participants. For example, it can be argued that the most important factor affecting subsistence-oriented residents of the North Slope is the impact of OCS lease development on the abundance, productivity, and availability of fish and wildlife harvested by subsistence users; while on the other hand, one can make a forceful case that OCS development as it affects cultural values, exchange patterns, demography, or kin-based labor units is of paramount importance. Yet another forceful argument is that change in the economic status of residents is the major driving force.

In reality, all of the factors probably come into play and the significance of each varies among settlements. Certainly Barrow, where there is great opportunity for wage employment in the setting of a "home community," is a very different situation from that of Kaktovik. Each community may be affected to different degrees by the same factor.

Rosita Worl provided the group with a list of topics that are important from the perspective of subsistence/wage economies:

I. Subsistence Economics
  A. Production
    1. Resources
      a. Primary
      b. Secondary
    2. Cycles
    3. Geographic areas
    4. Labor units
      a. Individual
      b. Extended family
      c. Hunting crew
      d. Whaling fleet
    5. Technology
      a. Indigenous
      b. Western
  B. Distribution/exchange/sale
    1. Initial distribution
    2. Secondary distribution
    3. Exchange
      a. Resources
      b. Goods
      c. Services
    4. Sale
  C. Consumption/utilization
    1. Food
    2. Clothing
    3. Arts and crafts
II. Elements Affecting Economic Behavior
  A. Social organization
    1. Kin-based labor units
    2. Integration of production and distribution among family, community, and region
    3. Elderly and needy—welfare
  B. Cultural
    1. Knowledge/training
    2. Values
      a. Sharing
      b. Cooperation
    3. Ideology—Spiritual relationship with environment/wildlife
  C. Political
    1. Traditional organization and authority
      a. Umealik
      b. Whaling captains
    2. Tribal government—Aboriginal title claims
    3. State and federal regulations
    4. Food preferences
  D. Health
    1. Physical
    2. Psychological

Representatives of the North Slope Borough indicated their concerns about the potential impact of OCS lease development in the form of a list of community-specific issues:

I. Barrow
  A. Bowhead whale (problems thought to be related primarily to noise)
    1. Interference with spring hunt
    2. Seaward displacement of fall migration route. (Hunters indicate this is now happening and they are of the opinion that noise, especially that associated with seismic exploration, is pushing whales seaward by the time they get to Barrow.)

3. Interference with reproductive activities in spring after whales pass by Point Barrow (if the whales do, in fact, breed in the Beaufort Sea)
4. Disruption of, or displacement from, feeding areas such as Point Barrow to Smith Bay, Barter Island to Demarcation Point, and off Flaxman Island
5. Oil spill effects

B. Ducks and seals
1. Oil spill effects
2. Disruption of habitat

C. Caribou—Impact of pipelines

II. Nuiqsut
A. Bowhead whale
1. Displacement of fall migration route
2. Displacement from feeding areas

B. Fishes—Effects of causeways on movements (especially in the Colville River and Fish Creek)

C. Caribou—Impact of pipelines

III. Kaktovik
A. Bowhead whale
1. Displacement of fall migration route
2. Displacement from feeding areas

B. Fishes—Effects of causeways

C. Caribou—Impact of pipelines

18.3 SUBSISTENCE RESOURCES

Of the array of fish and wildlife resources used for subsistence purposes by residents of the coastal North Slope, the following were identified as being of primary importance: bowhead whale, bearded seal, ringed seal, eiders, geese, whitefishes, and caribou. Resources of secondary or moderate importance from the standpoint of use by subsistence harvesters were identified as polar bear, spotted seal, belukha whale, sheep, ptarmigan, Oldsquaw, and arctic fox.

18.4 POTENTIAL IMPACT ON RESOURCES

A relatively small portion of the time available to our group was devoted to consideration of the potential impact of OCS development on fish and wildlife of primary and secondary importance to subsistence users. Such evaluations have been the subject of considerable biological research and are the subject of research reports, environmental impact statements, and previous synthesis efforts.

In the final plenary session of the synthesis meeting, results of deliberations by the subsistence workshop were presented. This presentation was mainly an explanation of the factors influencing the contemporary subsistence/wage economy (Fig. 18.1). In addition, the list of primary and secondary resources was presented to the group as a whole. The objective was to determine, from a multidisciplinary perspective, consensus opinions about potential OCS impacts on the resources.

Five categories of potential impacts were recognized: direct mortality of fish and wildlife, habitat destruction, displacement and dislocation of fish and wildlife species by physical barriers and noise, changes in access to resources, and regulatory barriers affecting harvesting activities. Impact in the first three categories—direct mortality, habitat destruction, and displacement—was recognized as potentially significant, and is discussed below. OCS oil and gas lease development would probably not have any impact related to access to primary and secondary fish and wildlife resources, nor to regulatory barriers affecting harvesting.

18.4.1 Direct Mortality

Fishes

An oil spill which results in the presence of oil in waters of the nearshore system would result in mortality of egg and larval stages of fishes.

Birds

Direct mortality of eiders could occur if oil were spilled in the lead systems during the period of spring migration. Similarly, significant numbers of Oldsquaws would be killed by oil in lagoons during midsummer. OCS lease development was anticipated to have no significant direct impact on geese.

Mammals

No direct mortality of whales, caribou, arctic foxes, or seals beyond the age of weaning was anticipated. Nursing ringed seals in the immediate vicinity of a spill would be subjected to ingestion of oil and fouling of their fur. Some pups would probably die as a result. Oiling of polar bears would probably result in the death of animals ingesting it in the course of grooming their fur. The baleen of bowhead whales would become fouled if feeding activity occurred where oil was present. The effects of ingested oil or reduced feeding efficiency of bowheads are unknown but presumed to be debilitating and perhaps fatal.

18.4.2 Habitat Destruction

Fishes

The habitat of whitefishes could be impacted by gravel mining operations or by the removal of significant amounts of water from overwintering areas.

Birds

The presence of oil in salt marshes would probably disrupt the feeding activity of geese, particularly Snow Geese. The Teshekpuk Lake area was recognized as important and would be adversely impacted by transportation corridors and activities such as gravel mining. The nesting habitat of Oldsquaws occurs over a wide area and would therefore not be significantly impacted. There would be very little impact on nesting habitat of eiders.

Mammals

Roads, pipelines, oil collecting facilities, and other structures ancillary to OCS development may affect the movement patterns and distribution of caribou. No destruction of marine mammal habitat, on a significant scale, was anticipated by participants of the plenary session. However, it was thought that use of nearshore feeding areas by bowhead whales may be altered in years of extensive ice cover during summer months.

18.4.3 Displacement and Dislocation by Physical Barriers and Noise

Fishes

Causeways may result in the dislocation of fishes which move close to shore. The possibility of lowered recruitment was raised.

Birds

Noise was thought to present little if any problem to birds. The response of birds to oil slicks in the marine environment may be avoidance.

Mammals

Belukha and bowhead whales may be displaced from nearshore areas by noise. Belukhas seem more susceptible to such disturbance than bowheads. Responses of bowheads to noise appear to be highly variable. Comparative data from whales in nearshore (shallow water close to the mainland) versus more distant waters are not available. In the eastern Beaufort Sea bowhead whales were reported to not be significantly displaced by noise.

Chapter 19
Noise and Marine Mammals

by W. John Richardson and Charles R. Greene

Marine mammals, terrestrial mammals, and birds are the three groups industrial noise could most obviously affect. The effects of noise on terrestrial mammals and birds were considered in previous synthesis meetings for lease sales in the Beaufort Sea and were not discussed at the Sale 87 meeting.

Recent reviews of the topics discussed in this chapter appear in Geraci and St. Aubin (1980), Acoustical Society of America (1981), Fraker *et al.* (1982), and Richardson *et al.* (1983a). The last of these reviews provides more details concerning almost all points covered in the workshop, and includes a comprehensive bibliography.

19.1 IMPORTANCE OF SOUND TO MARINE MAMMALS

Hearing is believed to be an especially important sensory modality for marine mammals because sound, unlike light, can propagate long distances through water. Many marine mammals produce a large number or variety of sounds. It is assumed that these sounds have important functions, even when they are not well understood. These functions can include communication with one another; passive detection of prey sounds, ice sounds, or other important environmental sounds; and, in toothed whales, echolocation for detection of prey and other purposes.

Many of the activities associated with offshore oil and gas lease exploration and development also produce sounds, which are often quite intense and generally at low frequencies. These sounds, like mammalian sounds, can propagate long distances, and could potentially affect marine mammals over a wide area.

Possible effects of industrial sounds on marine mammals are of several types. Disturbance could cause them to abandon the area near the noise source, either temporarily or perhaps permanently. This could be harmful to the animals if the abandoned area is important for feeding, hauling out, or other purposes, particularly if suitable alternatives are absent. Displacement could be important to subsistence hunters whether or not it is harmful to the animals. Disturbance could also disrupt normal activities such as feeding, reproduction, and molting even if the animals do not leave the area. It could increase stress, which might in turn result in increased sensitivity to food shortages, cold, and other natural pressures.

Direct mortality as a result of industrial noise presumably is rare, but could occur in the case of pinnipeds hauled out and exposed to aircraft overflights. Young seals and walruses have been reported to be abandoned or crushed when the adults stampede into the water in response to the noise (see Richardson *et al.* 1983a for review).

Whether noise from offshore industrial activities would ever be sufficiently intense to cause direct damage to the auditory organs is uncertain. Seismic exploration produces by far the most intense noise of any routine offshore activity. Explosives are now used only rarely in marine seismic exploration, and it is unclear whether noise from other sources such as airguns might ever damage the auditory organs.

Masking of other sounds is a potentially important result of industrial noise. A marine mammal can detect a sound of interest (*e.g.*, call from conspecific, echolocation sound, ice noise) only if the received intensity of that sound signal exceeds the background noise level by a certain amount. The exact signal-to-noise ratio required for detection is difficult to define, but any increase in noise level reduces the range to which a mammal can detect sounds of similar frequency. A large increase in

noise can cause a marked reduction in communication range. A 20-dB increase in noise, which is not uncommon, could cause a 10-fold reduction in communication range; *e.g.*, from 10 km to 1 km. A 40-dB increase in noise level could cause a 100-fold reduction in communication range. The significance of such reductions to marine mammals is uncertain; natural noise levels in the sea vary widely. Mammals must be adapted to occasional increases in ambient noise levels. Nonetheless, elevated noise levels will inevitably reduce the potential range of communication or detection of other important sounds.

19.2 AMBIENT NOISE

The characteristics of the background noise in the sea are important in evaluating the importance of the additional noise from industrial activities. The background noise results from many sources; wind, waves, biota, and distant shipping are important in ice-free areas. In the arctic, ice deformation, snow blowing over the ice, wave action at the edge of ice, melting icebergs, and calving icebergs contribute significantly. Shipping is not an important contributor in most parts of the arctic, although a single ship can raise the noise level in its locality.

Noises may be characterized as transient, such as impulsive signals from airguns used in seismic surveys; or continuous, such as noise from a ship's propellers. Each type of noise can be described in terms of energy at various frequencies, *i.e.*, its spectrum. Continuous noise sources may have discrete noise components called tonals. These are periodic components arising from repetitive events, such as the firing of cylinders in an engine or the turning of propeller blades. Transient signals can be characterized by their peak levels, duration, and spectral composition. The background noise in the ocean, in general, will have both transient and continuous sounds.

Wenz (1962) summarized the sources and characteristics of ocean noise. Figure 19.1 shows the spectral distribution of noises and the range of levels that one can expect. Noise spectrum levels are given in decibels with respect to 1 $\mu Pa^2/Hz$, a reference unit representing noise power density (pressure squared per unit frequency). Decibels provide a logarithmic scale on which 10 dB represents a change in noise intensity by a factor of 10.

Ambient noise levels in the Beaufort Sea have been measured at particular locations and times during various studies, but the only long-term data have come from several drifting satellite-tracked buoys (Greene 1981). Deep water noise in the Beaufort Sea was monitored for over a year in 1975-76. Five to eight buoys were operating at any given time. One buoy drifted into the shallow (depth <200 m) water of the Chukchi Sea and provided data there from November to July. In general, noise levels in arctic waters can be extremely intense because of ice noise, but at other times can be well below Wenz's sea-state 0 values. Spectrum levels generally decrease by about 5 dB per octave in open water, and the same is often true under ice.

Ambient noise levels are important in determining the range to which a specific industrial sound can be heard, and the range to which an animal can hear a sound of interest in the presence of background noise. Workshop participants agreed that more data on ambient noise levels in the Alaskan Beaufort Sea would be desirable. For comparative purposes, data should be obtained both before and after extensive offshore exploration begins. To allow for variability, it would be necessary to use a technique that permits long-term automated measurements.

19.3 SOUND PROPAGATION

Sound diverges from any source and therefore its intensity undergoes "spreading loss." Near a sound source deep in the ocean, far removed from reflecting surfaces, sound spreads in all directions and the intensity is an inverse square function of distance. This is known as spherical spreading. With perfect spherical spreading, intensity decreased 20 dB per 10-fold change in range, or 6 dB per doubling of distance.

In shallow water, with reflecting surfaces at the top and the bottom of the water, the sound intensity is channeled between the surfaces and cylindrical spreading occurs. In the ideal case, the intensity diminishes by 10 dB per 10-fold increase in range, or 3 dB per doubling of distance. Cylindrical spreading can occur even in deep water when salinity, temperature, and ice conditions cause channelization of sound by refraction and reflection processes. Because the rate of attenuation of sound with increasing range is less with cylindrical than with spherical spreading, it is important to know the type of spreading that pertains at each range from a sound source if one is to calculate how far that sound will be detectable above the ambient noise level.

In general, reflections of sound from the surface and bottom are imperfect and sound energy is lost

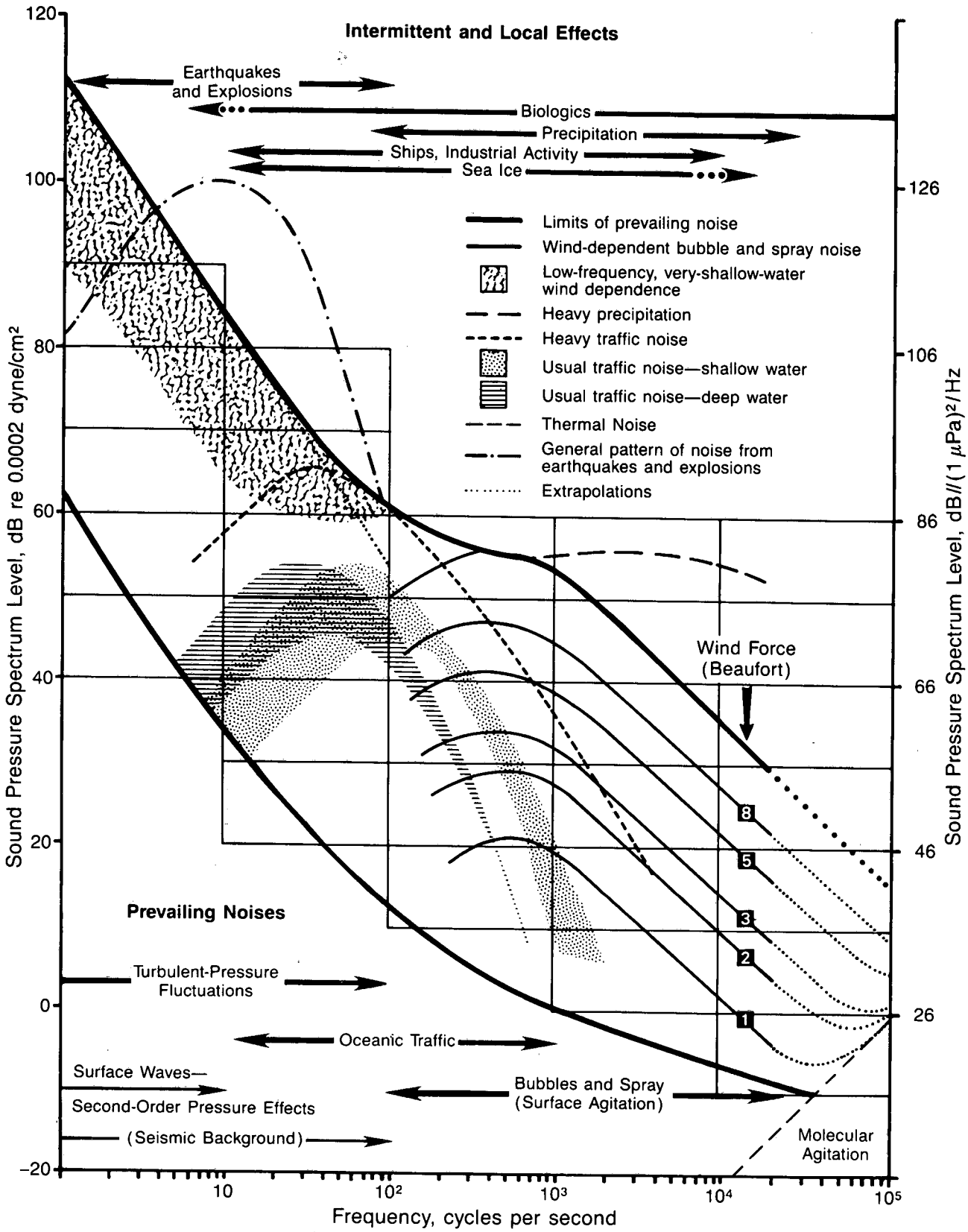

Figure 19.1—Acoustic sources contributing to typical oceanic ambient noise spectra. (Adapted from Wenz 1962.)

with each reflection. For example, sound energy may be absorbed by the bottom and scattered by a rough surface of ice or waves. These effects give rise to a loss in decibels that is a linear function of range; this loss is in addition to the cylindrical or spherical spreading loss. Reflection losses are generally greater for high than for low frequencies. When reflection and absorption losses are taken into account, total propagation losses in shallow water can be >20 dB per 10-fold increase in range.

Acousticians generally agree that, in the absence of empirical information, it is very difficult to predict the rate of propagation loss that will occur in any specific shallow water area. Greene (1982, 1983, 1985) has provided some measurements of propagation losses of industrial noises recorded in shallow portions of the Canadian Beaufort Sea during the open-water season. Figure 19.2 presents the results for the most significant components of several of these sources. Also included are lines demonstrating the rate of change of sound intensity with range for cylindrical and spherical spreading. However, little information on propagation in the Alaskan Beaufort is available (Davis *et al.* 1985). Because of different bottom conditions in the two areas, the direct applicability of results from the Canadian Beaufort Sea to the Alaskan Beaufort is by no means certain.

19.4 AIRCRAFT NOISE

Aircraft, unlike other sources of noise considered here, transmit no sound directly into the water. All of the sound energy passes first through the air and then some enters the water. The theory of the air-to-water transmission of aircraft sound is reasonably well known (*e.g.*, Young 1973), but few direct measurements of aircraft noise in water have been reported. In general, aircraft noise is detectable in the water for only a brief period as the plane passes over; this period is longer if the water is shallow than if it is deep. Greene (1982) found that noise from a Bell 212 helicopter was detectable for 16-27 seconds, depending on its altitude, when it flew directly over a hydrophone in water 25 m deep. The sound is intense for only a few seconds, when the aircraft is almost directly overhead (Greene 1985).

The limited available evidence indicates that belukhas and bowhead whales often react to low-flying aircraft by diving precipitously or by other alterations in behavior. The response tends to be more marked when the aircraft is low than when it is high. There sometimes appears to be seasonal or circumstance-specific variability in sensitivity to aircraft (*e.g.*, Ljungblad 1981). Bowheads sometimes react to an aircraft flying at 1,000 feet (Fraker *et al.* 1982; D. K. Ljungblad unpubl. data), and occasionally react to aircraft at 1,500 feet (Fraker *et al.* 1982; Richardson 1985; Richardson *et al.* 1985).

Pinnipeds on land or ice often rush into the water when an aircraft approaches, sometimes resulting in separation of young from their mothers or crushing of the young during the stampede (Tomilin and Kibal'chich 1975, cited by Fay 1981; Johnson 1977). Low-altitude flights over known haulouts should be avoided at the appropriate times of year. These sites would include walrus haulouts in the northeastern Chukchi Sea and spotted seal haulouts in the Beaufort Sea. Reactions of pinnipeds in open water to aircraft have rarely been reported.

As discussed in previous synthesis reports, low-altitude flights over waterbird colonies, such as those at Thetis and Howe islands, should be avoided during the nesting season.

19.5 BOATS AND SHIPS

Disturbance of marine mammals by vessels is a concern because of the large number of vessels in use, their mobility, and the considerable noise that many produce. Many authors have commented on reactions or lack of reactions of marine mammals, especially cetaceans, to vessels, but most accounts are anecdotal and it is difficult to judge whether the observed behavior was appreciably different than the behavior that would have occurred in the absence of the vessel. It is rarely certain that observed reactions to vessels are specifically to noise rather than to sight of the vessel. However, many reactions to vessels probably are responses to vessel noise, given (1) the long distances to which ship noise often propagates, and (2) documented reactions to change in engine and propeller speed.

Characteristics of ship noise have been studied extensively; for reviews of this information, much of it classified or unpublished, see Ross (1976, 1981), Brown (1982), and Richardson *et al.* (1983a). The dominant sources are propeller cavitation, propulsion machinery, and propeller "singing" (Ross 1981). Most of the energy is at low frequencies, from a few hertz to a few hundred hertz. Tonal components from the propeller blades usually dominate the spectrum up to about 50 Hz. Overall levels are roughly correlated with ship size and speed, but ship design and condition can also have a considerable effect on radiated noise. The

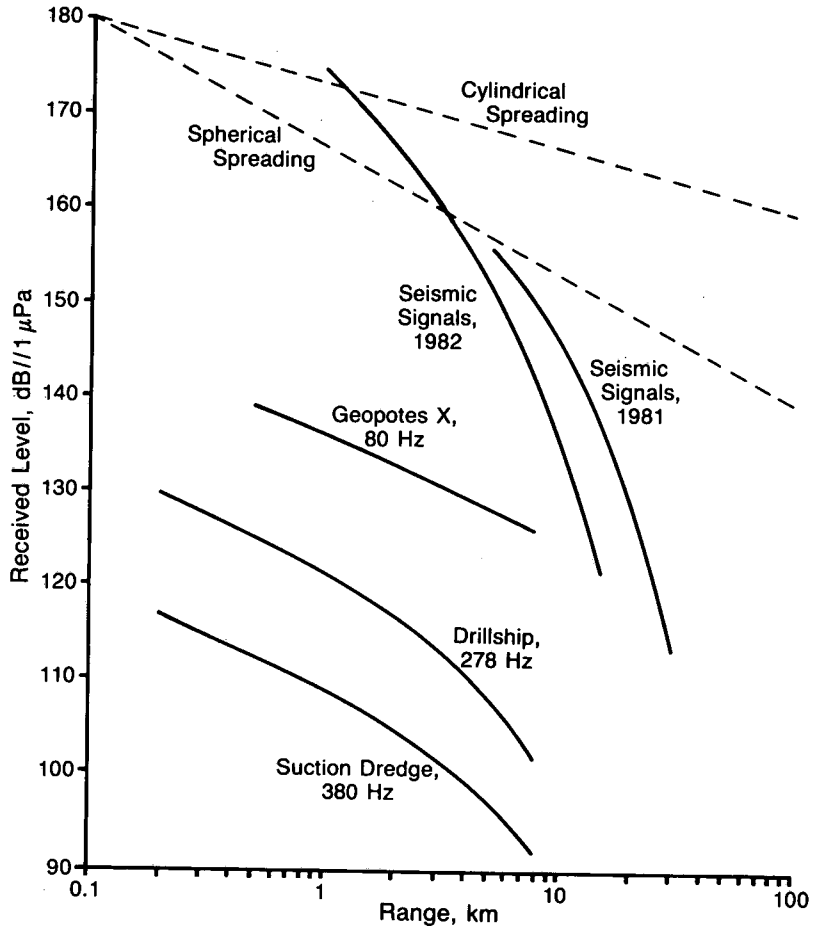

Figure 19.2—Received levels of underwater sounds from various industrial sources in relation to range, Canadian Beaufort Sea, 1981-82. (Adapted from Greene 1982, 1983.)

overall levels from the largest and fastest vessels, including supertankers, large container ships, passenger liners, or aircraft carriers, are about 192-203 dB//1 μPa referred to 1 m (Brown 1982). Small ships that do not operate at high speeds produce overall levels up to about 182 dB. Smaller vessels, such as crew boats, sometimes produce sounds with higher frequency components than those from large vessels (Greene 1982, 1985).

Specific studies of the reactions of bowhead, gray, and humpback whales to vessels have been made, and anecdotal information is available for some other species of baleen whales (Baker *et al.* 1983; Mansfield 1983; Richardson 1985; and Richardson *et al.* 1985). Close approach, especially by a rapidly or erratically moving boat, causes avoidance responses. Bowheads react more strongly to boats than to any of the other types of offshore industrial activities studied by Fraker *et al.* (1982). These investigators found that the bowheads begin to flee when an approaching vessel is 1-3 km away; no clear relationship between size of vessel and radius of response was found. Bowheads cease fleeing when the vessel is 1-3 km beyond the whales, but they sometimes remain scattered for a longer period. Eskimo whalers consider that bowheads are more sensitive to noise from small power boats in spring than in autumn. Long-term effects of ship traffic on bowheads are unknown; gray whales apparently abandoned at least one calving lagoon when ship traffic and onshore activities increased (Reeves 1977). Bowheads appear to be more sensitive to close approach by vessels than are gray whales, at least in the short term (Fraker *et al.* 1982).

Toothed whales, including belukhas, often show considerable tolerance of ships. However, belukhas sometimes turn and swim rapidly away from approaching vessels when the vessels are as much as 2.4 km away. Groups sometimes split or disperse in apparent response to vessels (Fraker 1977a, 1977b, 1978). Belukhas in leads appear to be

especially sensitive (Fraker and Fraker 1982; LGL Ltd. 1984). Responses to fast and erratically moving boats also seem more pronounced than responses to vessels moving slowly and regularly (Macfarlane 1981). Nonetheless, the reaction to vessels seems to be a short-term one: Belukhas return each summer to estuaries where they are pursued by hunters in boats.

The effects of vessel traffic on bowheads and belukhas migrating through leads in spring are a particular concern. Circumstantial evidence indicates that both species are especially sensitive to boat noise when in leads during spring (LGL Ltd. 1984). Because both whales and vessels would probably concentrate in the leads, a high percentage of the whales could be exposed to close approach by vessels during this season.

The literature contains little detailed information about reactions of pinnipeds to boats.

19.6 ICEBREAKING

Icebreaking is believed to result in noise levels greater than those normally associated with ship traffic (Thiele 1981). This may result from both the high power necessary for icebreaking and the noise from the breaking ice itself. The workshop did not address this noise source in any detail because of the lack of specific plans for increased icebreaking during offshore exploration in the Alaskan Beaufort Sea. Icebreaker noise would become an issue if plans are advanced for icebreaking tanker traffic or other icebreaking activity. The issue is discussed in Peterson (1981) and LGL Ltd. (1984).

19.7 VEHICLES ON ICE AND SHORE

The effects of noise from trucks, hovercraft, and other vehicles on ice and shore were not discussed in any detail in the workshop, but were recognized as potential sources of both waterborne and airborne noise. The main concern would be with respect to ringed seals and polar bears on the ice in winter.

19.8 SEISMIC EXPLORATION

Some forms of seismic exploration produce the most intense sounds introduced into the Beaufort Sea by any activity, industrial or otherwise. Two situations, seismic exploration on ice in winter and in open water in summer, were considered in detail.

19.8.1 Seismic Exploration on Ice

In recent years, Vibroseis™ has been the main method of seismic exploration used on landfast ice in winter. Vibroseis produces sound and vibration for several seconds, with the fundamental frequency sweeping from a few hertz up to about 70 Hz. The spectrum of underwater noise contains detectable energy at frequencies up to about 2,500 Hz, as reported by Cummings *et al.* (1981). Measurements by those authors indicate that the source level for horizontal propagation is over 184 dB re 1 μPa re 1 m when measured in water below the ice and perpendicular to the line of Vibroseis sources. The level is some 20 dB less when measured off the end of the line of sources. The source level is considerably less than levels from airgun arrays used for seismic exploration in open water, but the noise from Vibroseis continues for many seconds whereas airgun noise is impulsive.

Recent measurements of noise and vibration in simulated subnivean polar bear dens apparently have not demonstrated any elevation in received levels until the Vibroseis sources were within a few hundred meters (J. Lentfer pers. comm. to J. Burns). No details concerning this work were available to the workshop.

Surveys by the Alaska Department of Fish and Game over several years have suggested that, in spring, densities of ringed seals may be reduced by about 50% in areas where seismic exploration was conducted during the winter (Burns *et al.* 1981). However, these results are equivocal because the surveys were not designed to test effects of seismic exploration. Recent Alaska Department of Fish and Game studies specifically designed for this purpose conclude that "some localized displacement of ringed seals occurs in immediate proximity to seismic lines [within 150 m] but, overall, displacement resulting from this activity is insignificant in the nearshore Beaufort Sea" (Burns *et al.* 1982, p. 4). This conclusion pertains to the overall population of ringed seals in Alaskan waters. Workshop participants agreed that even localized and limited displacement would be a concern if it occurred near settlements, where local accessibility of seals is important.

It is suspected that the repeated passage of heavy equipment along seismic lines, rather than the Vibroseis itself, is responsible for the limited displacement that was detected. Burns also believes that any detailed studies of the displacement phenomenon should be made in some area

where the density of ringed seals is higher than in the Alaskan Beaufort Sea.

19.8.2 Seismic Exploration in Open Water

Nowadays, airgun arrays and, less commonly, sleeve exploders are the usual sources of energy for seismic exploration in the Beaufort Sea during summer. Both produce intense pulses of noise for a fraction of a second; there is then a silent period of several seconds before the next pulse. Source levels of airgun arrays are typically 245-252 dB re 1 μPa re 1 m (Johnston and Cain 1981). However, the effective source level for propagation in a particular horizontal direction varies depending on array geometry and aspect. Most of the energy in the seismic pulse is at low frequencies— <100 Hz. However, at long horizontal ranges, most of the low-frequency energy has disappeared, and the received signals are predominantly at 100-300 Hz (Greene 1982; Moore *et al.* n.d.; and Greene 1985).

The rate of attenuation of seismic signals with increasing range depends on water depth and bottom type. In the Canadian Beaufort Sea, Greene (1983) found that seismic signals attenuated more rapidly in water depths of about 9 m in 1982 than in 15-30 m in 1981, despite the fact that the seismic gear in use in 1982 had a higher source level (Fig. 19.2). Nonetheless, noise from seismic exploration sometimes can be detectable, even in shallow water, at distances of 30 km or more (Fig. 19.2). In deeper water, we have recorded strong signals from an airgun array at distances as great as 60 km (Greene 1983, 1985; Moore *et al.* n.d.).

To date there have been no controlled measurements of the attenuation of seismic sounds with increasing distance in Alaskan waters. Available data are insufficient to predict the rate of attenuation in various parts of the Alaskan Beaufort Sea. A further complication is that levels of impulsive sounds such as seismic noise are not easily measured; the results are affected by the technique used. It is not clear whether the methods being used in the Canadian and Alaskan sectors of the Beaufort Sea are comparable.

Bowheads have been seen as close as 6 km to seismic vessels operating in the Canadian Beaufort Sea in summer, and 9 km to vessels in the Alaskan Beaufort in early autumn (Ljungblad *et al.* 1980; Fraker *et al.* 1982; Reeves and Ljungblad 1983; Richardson *et al.* 1983b; Ljungblad *et al.* 1985; Richardson 1985; Richardson *et al.* 1985, 1986). In no case has there been clear evidence that the whales were trying to swim away from the ship. Bowheads often continue to produce their usual types of calls in the presence of strong seismic sounds (Richardson *et al.* 1983b; Ljungblad pers. comm.). The only indication of gross changes in behavior has been one or possibly two instances in the Alaskan Beaufort in which bowheads have aggregated at about the time that seismic noise began (Reeves and Ljungblad 1983; Ljungblad pers. comm.). This type of behavior (termed "huddling") has not been seen in either the presence or absence of seismic noise in the Canadian Beaufort Sea, and whether its occurrence in the Alaskan Beaufort Sea is attributable to seismic noise is uncertain.

Quantitative analysis of the behavior of bowhead whales in the presence and absence of seismic noise has revealed no detectable effects in some instances, including two cases when bowheads were 6-8 km and 13 km from a seismic ship (Fraker *et al.* 1982). However, observations in the Canadian Beaufort Sea suggest that surface times, number of respirations per surfacing, and perhaps dive durations tend to be reduced in the presence of seismic noise (Richardson *et al.* 1983b). These indications of an effect must be treated cautiously because the evidence comes from uncontrolled, opportunistic observations, and because the trends were not evident on all occasions when bowheads were seen near seismic vessels. Indeed, Reeves and Ljungblad (1983) found indications of increased, not decreased, surface times in the presence of seismic noise.

In view of the inconsistencies in available data, it is impossible to assess the effects of seismic exploration on bowhead whales. There are indications of behavioral effects in at least some circumstances. Corroboration of these apparent reactions is needed, preferably via controlled experiments in which the effects of confounding variables can be ruled out (Ljungblad *et al.* 1985; Richardson 1985; Richardson *et al.* 1985, 1986).

It is not possible to determine from short-term behavioral observations whether seismic noise results in increased stress, damage to the auditory system, or long-term changes in distribution. Radiotelemetry of physiological parameters may ultimately provide a way to study stress effects. Information about the auditory sensitivity of bowheads (or any baleen whale) would be helpful in assessing the potential for auditory damage from strong seismic sounds; the evoked potential method provides a possible way to obtain such data (Ridgway and Carder 1981). Hunters from Barrow report that bowheads have traveled unusually far offshore during the westward migration in recent

years, and suggest that this might have some connection with increased levels of seismic exploration. However, bowheads continue to return each summer to feeding areas in the Canadian Beaufort Sea and in the fall to the Demarcation Bay area, where seismic exploration has been underway for many years.

Very little information is available about the reactions of marine mammals other than bowheads to seismic exploration (Malme *et al.* 1983, 1984, 1985). Gray whales have been observed in the presence of seismic sounds (Fitch and Young 1948; Ljungblad *et al.* 1982); no flight or avoidance behavior was noticed. Payne and McVay (1971) found that humpback whales continued to sing in the presence of noise from distant dynamite blasts. Fish and Vania (1971) reported that attempts to keep belukhas out of a salmon river by chasing them with motorboats and dropping small charges of explosives into the river were not very successful.

19.9 DREDGING NOISE

Dredging is a major component of offshore oil exploration in the Canadian Beaufort Sea, where two suction and four hopper dredges were in use by 1982. Suction dredges remain in one location and pump a slurry of dredged material and water through a floating pipeline to a nearby discharge site. Hopper dredges pick up dredged material at one site, retain it in hoppers within the vessel, and travel to another site to dump the material. Industry representatives indicate that dredging will not be as widely used during exploration in the nearshore zone of the Alaskan Beaufort Sea as it is in the Canadian Beaufort. However, participants in the workshop considered it desirable to review the effects of dredge noise on marine mammals.

Sounds from a stationary, operating suction dredge are clearly detectable at a range of several kilometers, even in shallow waters of the Canadian Beaufort Sea (Greene 1982). The strongest component in the noise signature from the suction dredge Beaver Mackenzie was a tone at 380 Hz (Fig. 19.2). Sounds from a loaded hopper dredge while it was traveling to its dumping site were considerably more intense, with the strongest component at 80 Hz (Fig. 19.2—Geopotes X curve). In fact, the hopper dredge was the strongest nonseismic industrial noise recorded by Greene (1982). Sounds from a hopper dredge while it is loading or unloading have not been reported (Greene 1985).

Both bowheads and belukhas have been observed to approach within 1 km of an operating suction dredge (Fraker 1977a; Fraker *et al.* 1982). No strong avoidance reactions have been reported. Both species react more strongly to rapidly changing sounds, notably those from boats and aircraft, than they do to continuous noise from a suction dredge (Richardson 1985).

No data are available on reactions of other types of marine mammals to suction dredges (Malme *et al.* 1983, 1984, 1985) or on reactions of any marine mammals to hopper dredges.

19.10 DRILLING NOISE

Sounds from drilling on islands have been studied under the ice in winter but not in open water (Greene 1985). Under quiet conditions, low-frequency sounds are detectable under the ice up to several kilometers from drilling rigs on islands in the Alaskan Beaufort Sea (Malme and Mlawski 1979). Underwater sounds from drillships and semisubmersibles have also been reported. In the Canadian Beaufort Sea, drillship sound has been detected as far as 13 km from a ship; the strongest tonal was at 278 Hz (Greene 1982). Propagation of drilling sounds from islands, caisson-retained platforms, or "cones" into open water has not been studied and may differ considerably from the results for ice-bound islands or drillships (Greene 1985).

Bowheads have been observed on several occasions within 20 km of drillships, and once as close as 4 km (Fraker *et al.* 1982; Richardson *et al.* 1983b). Belukhas have often been seen within a few kilometers of artificial islands during drilling operations (Fraker 1977a, 1977b; Fraker and Fraker 1979). Industry personnel have reported both species even closer to drillships or artificial islands with active drilling. Virtually no information is available concerning occurrence or behavior of pinnipeds near drilling sites.

In 1982, drillship noise was broadcast underwater near bowheads so that their behavior before and during the noise playbacks could be compared. These limited experiments revealed, at most, only a mild avoidance response (Richardson *et al.* 1983b, 1985). More extensive playback experiments involving drilling noise and gray whales were conducted off the California coast in early 1983 by Bolt Beranek & Newman, Inc.; results are not yet available (Malme *et al.* 1983, 1984, 1985).

In general, whales seem to be less sensitive to

continuous noise from drilling and dredging than to the rapidly changing noise from passing boats and aircraft.

19.11 PRODUCTION PLATFORMS

Noise from production platforms and reactions of marine mammals to such platforms were not discussed in the workshop. Gales (1982) reviewed most of the available information (Malme *et al.* 1983, 1984, 1985).

19.12 AREAS OF CONCERN

Available information is, in many cases, too meager to allow detailed predictions about reactions of marine mammals to industrial noise. Furthermore, the majority of the relevant information is from areas outside the Sale 87 area. Nonetheless, workshop participants identified a few general situations that are special concerns because of potential noise effects.

Three areas of concern with respect to bowhead whales are the nearshore lead through the northeastern Chukchi Sea in spring, the feeding area between Kaktovik and Demarcation Bay in early autumn, and the feeding area just east of Barrow in autumn.

The lead through the northeastern Chukchi Sea is an area of particular concern because the entire population of bowhead whales is confined within a narrow corridor. They may be unable to avoid any vessels or other noise sources that they might encounter in the lead. If seismic exploration on fast ice bordering the lead were allowed to continue into April, it could overlap with bowhead migration. Belukha whales might also be affected by noise in this lead.

The bowhead feeding areas east of Kaktovik and east of Barrow were identified as areas of special concern. Reasons for concern include (1) the considerable numbers of whales sometimes present, (2) the presumed importance of autumn feeding, when the caloric content of invertebrate prey is high, and (3) the importance of these areas for the autumn harvest of bowheads. Some workshop participants were especially concerned about the occurrence of seismic exploration in these areas in early autumn.

Aircraft traffic over major spotted seal and walrus haulouts was another area of concern. In summer, many spotted seals haul out at the Colville River delta and Oarlock Island; walruses haul out on ice in the northeastern Chukchi Sea. Terrestrial mammals and birds were not discussed in detail during the workshop. However, concern was expressed about aircraft disturbance (1) at eider colonies on barrier islands including Thetis and Cross islands, (2) at Alaska's only Snow Goose colony, on Howe Island, and (3) to caribou concentrated near the coast. Oldsquaws molting in lagoons during summer may also be sensitive to aircraft disturbance.

Although Burns *et al.* (1982) concluded that displacement of ringed seals by on-ice seismic exploration was not significant to the seal population as a whole, workshop participants agreed that any displacement of seals near settlements was a matter of concern.

19.13 CONCLUSIONS

Workshop participants agreed that effects of noise on marine mammals were a real concern, and that available data on many relevant points are either lacking or too meager for conclusions to be drawn. *A priori,* noise is a concern because of the apparent importance of natural sounds to marine mammals, the high intensities of underwater sound created by many offshore industrial activities, and the long distances to which many of these sounds propagate. Experiments and observations show that some marine mammals react to certain industrial sounds. Observed reactions generally are brief and displacement, if it is observed at all, is over relatively short distances. However, this may be a function of the difficulty in detecting longer-term and larger-scale effects. Aside from observation of short-term behavioral reactions, there is very little information with which to assess possible stress effects or other deleterious influences.

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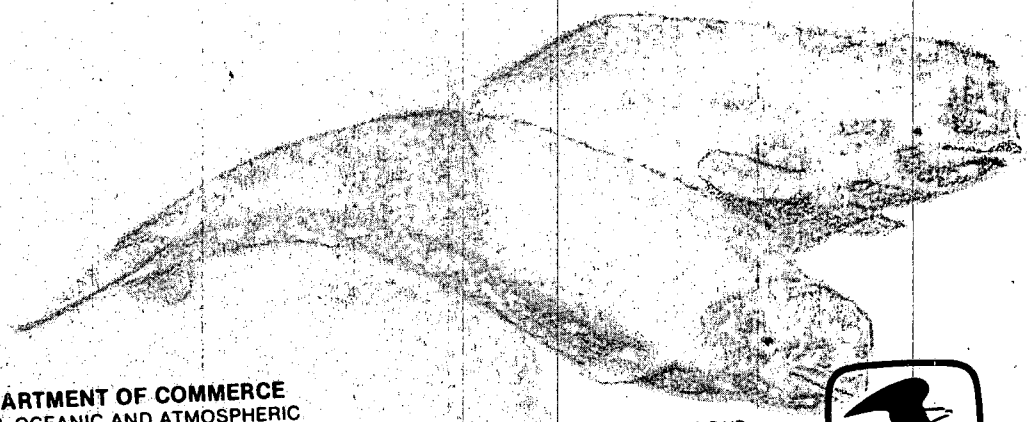

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